PEDESTRIAN AND CYCLIST ACCIDENTS: A COMPARATIVE STUDY USING IN-DEPTH INVESTIGATION, MULTIBODY SIMULATION AND EXPERIMENTAL TEST

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ABSTRACT

The aim of this research is to analyse real accidents involving a pedestrian or a cyclist from three different approaches: in-depth investigation, numerical simulation with multibody model and experimental reconstitution with PMHS subject.
Real accidents chosen from an in-depth investigation are modelled using a multibody approach. Effects of many parameters (car velocity, victim position at impact, etc) are numerically studied in order to find the closest configuration to the presumed real accident conditions. This configuration is then reproduced experimentally by crash-test using cadavers. Finally, the three approaches are compared in terms of impact points on the car, injuries and kinematics.

Keywords: Accident reconstruction, pedestrian, bicycle, cadavers, multibody

PEDESTRIAN OR CYCLIST ACCIDENTS are more and more studied during these last years in order to prepare new European directives concerning the passive safety of a vulnerable road user in the event of a collision with a car. The aim of these directives is in particular to make the front end of cars less aggressive (JO of EU, 2003). One of the works consists to adapt these directives to the conditions observed in the reality. So it appears crucial to well know the behaviour of a pedestrian (or a cyclist) during real accidents.

Several approaches have been used to perform this work and the main ones are the in-depth accident investigation, numerical modelling and experimental tests. These three approaches are complementary but they are frequently studied separately or both coupled, rarely all together.

Concerning the accidentology, the principal aim of this in-depth investigation is to study and to identify the accident production mechanisms (Girard, 1993). It allows having good information about the unfolding of the accident and also the collision conditions. In addition, it takes part in the identification of the typical injuries encountered during a pedestrian or a cyclist accident (Karger, 2000) (Teresinski, 2002) or the main collision configurations. It appears that the most frequent accident configuration is when the pedestrian is impacted by the front end of a light vehicle (Ravani, 1981) (Berg, 2003). In this case of accident configuration, it is used to associate injuries with the various points of impact between the vehicle and the vulnerable user: impact between the lower limb and the bumper, impact between the pelvis and the base of the bonnet and impact between the head and the bonnet or the windscreen (Teresinski, 2002).

About numerical modelling, several methods exist to reconstruct a real car-to-pedestrian accident. All of them are based on a ”model” which is the abstract simplified representation of the reality (Depriester, 2005). Both of them allow the biomechanical study of the human body. The first one is based on the mutibody theory (Anderson, 2003), (Linder, 2005), (Moser, 1999), (Yang, 2000), (Mizuno, 1998) and the second one concerns the finite element modelling (Arnoux, 2005). Multibody model allows simulating the global behaviour of the vulnerable user. Thus, the kinematic can be analysed from the first impact point (lower leg against bumper) to the fall on the ground. Finite element method allows studying more precisely the local behaviour of a body segment. Injury mechanisms can be accurately identified and analysed in order to establish for example injury criteria (Arnoux, 2005).

Finally, the third approach concerns experimental tests. These tests can be performed with classical dummies, with animals but also with whole cadavers or human body segment (Cavallero, 1983) (Kerrigan, 2005) (Masson, 2005). Objectives are the same as the numerical approach i.e. the study of the kinematic, injury criteria, car aggressivity …

The work proposed in this article is based on a complete analysis of real accidents from these three different approaches. The complementarities and the comparison between them constitute the originality of this research. First, this article describes the general methodology and the necessary tools to perform this work. This methodology is then applied on car-to-pedestrian and car-to-cyclist cases. Because this work is based on a case to case study, only two real accidents have been considered: a pedestrian against a Renault Twingo and a cyclist against a Peugeot 205. Finally all approaches are compared in the discussion part.

METHOD

GENERAL OVERVIEW : From accidents chosen from an in-depth multidisciplinary investigation (psychology, technical, medical), we have estimate a first configuration of the impact: car speed, pedestrian or cyclist orientations… Then, we have made a numerical modelling of the same configuration with a multibody software. In particular, we have reproduced the anthropometry of the victim and the front shape of the car. Effects of some parameters such as car velocity or victim position at impact have been numerically studied in order to find the best correlations with all indications produced by the in-depth analysis. Finally, the retained configuration close to the presumed real accident conditions was reproduced experimentally by full scale using cadavers. The three different approaches are compared in particular in terms of impact points on the car, kinematics, throw distance, chronology, injuries, acceleration curves when available, etc.

IN-DEPTH INVESTIGATION : Accident data comes from the Department of Accident Mechanism Analysis from INRETS where an in-depth investigations is carried out since the beginning of the 80's (Girard, 1993). The particularity of these in-depth studies is that the investigations of the multidisciplinary team, composed of a psychologist and a technician, are actually made on the scene of the accident, at the same time as the intervention of the rescue services. This survey has been implemented to gain a better understanding of the mechanisms responsible for accidents and injuries. The survey zone is located around the town of Salon-de-Provence and the survey is conducted 24 hours per day one week in three. Those performing the survey were asked to collect a maximum amount of data. Generally, this data consisted of the final positions of the vehicles, the marks left on the ground (tyres, fluids, debris, etc.), the point of impact on the vehicle (bonnet, windscreen, etc.), the direction of the impact and also to collect statements of drivers, witnesses and make a record of any injuries on the basis of the medical report, etc. (figure 1)

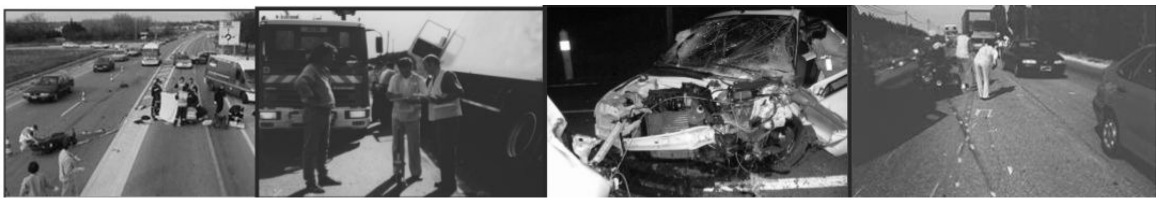


Fig. 1 - In-depth accident investigation

All this data was then pooled and compared in order to make an initial reconstruction of the accident and to make hypotheses regarding the process involved: direction of travel of the pedestrian (or cyclist), speed of the vehicle, etc. Several methods were used to estimate the speed of the vehicle (Depriester, 2005). Finally, all the data were used as a basis for the numerical simulation and its validation. The two selected vehicle/pedestrian and vehicle/cyclist accidents, which we will describe in the Results section, were issued from this database.

NUMERICAL SIMULATIONS : In order to gain a better understanding of the global kinematics (from the first impact to the fall on the ground) and the injury mechanisms of the vulnerable user during the impact, we have decided to simulate numerically the real accidents with a multibody software. The Madymo software V6.0 has been employed to develop the numerical models and to perform the simulations.

The whole multibody model is divided into two parts: the car and the pedestrian or three parts: the car, the cyclist and the bicycle (figure 2). The human body model has been developed by the University of Chalmers (Yang, 1993), Faurecia (Glasson, 2000) and validated in collaboration with the Laboratory of Applied Biomechanics (Yang, 2000). The original model represents a human body close to the 50th percentile male: 1.75 m, 78 kg. It includes 35 bodies with 35 joints and it is represented by 85 ellipsoids. Joint and body segment characteristics are based mainly on available biomechanical data (Yang, 1993) and do not include muscles activities. The specific characteristics of this model concern its lower leg because it is predictive of fractures. Fracture criterion of lower leg is based on Nyquist experiments which have identified a rupture for a bending moment equal to 317±88 Nm for male and 278±30 for female (Nyquist, 1985). This model has already been validated qualitatively but also quantitatively in pedestrian configuration by comparison with PMHS experimental tests performed at INRETS-LBA (Cavallero, 1983).
The vehicle model has been represented using more than 10 bodies. Its geometry is based on 19 measurements performed directly on the car involved in the accident. Stiffness of the vehicle parts are adapted to the accident from data coming from experimental tests. Main of these tests have been performed in the framework of the EuroNcap procedure about the pedestrian protection (sub-system).

Concerning the real accident reconstruction, the multibody model was first adapted to the corresponding configuration of the accident: orientation of impact, anthropometry of the victim, front shape of the car.

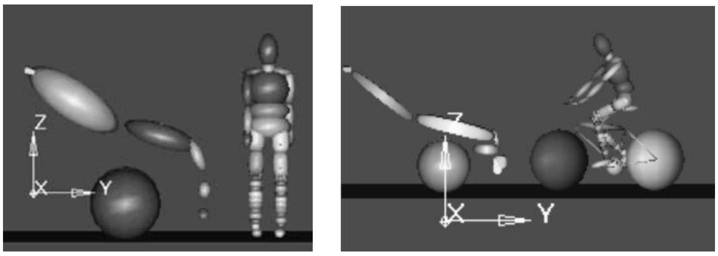


Fig. 2 - Multibody model. Left: pedestrian configuration. Right: cyclist configuration

A first simulation has been performed on the starting configuration provided as being the most probable one by the in-depth investigation. The pedestrian orientation and position are approximated by associating the pedestrian injuries with the car impact points (Karger, 2000) (Teresinski, 2002), ground fall, interview of witnesses. The pre-impact braking and the vehicle deceleration are estimated by the braking marks observed on the ground, the final position of the vehicle and the interview of the driver. Next, effects of some parameters such as car velocity or pedestrian position on impact have been numerically studied in order to find the best correlations with all indications produced by the in-depth analysis.

Finally, the configuration retained is close to the presumed real accident conditions because it reproduces in particular the same impact points on the car, the same injuries, and is according to the driver statement (Serre, 2004).

EXPERIMENTAL TESTS : Based on the previous retained configuration, a pedestrian (or a cyclist) full-scale impact experiment was performed using PMHS (Post Mortem Human Subject). The PMHS are obtained through the Body Donations to Science at Timone Faculty of Medicine in Marseille (France). They are embalmed and preserved at 3°C in Winckler's preparation which is made of many standard embalming ingredients: phenol, alcohol, formalin, glycerin, sodium and magnesium sulfate, potassium nitrate. Based on Crandall study, this fluid distorts only a few of the properties of hard tissues and the results for Winkler fluid appeared to approximate most closely those of the fresh tissue (Crandall, 1994). It allows to keep supple the sampling and to preserve for several months the soft tissues elasticity. Prior to testing, anthropometrical measurements are made and X-Rays radiographs of the body are taken to verify the osseous integrity.

Prior to the vehicle striking him, the PMHS is maintaining in initial position by a controlled electromagnetic system attached to the head. It is switched off 10 milliseconds before the impact so the subject is submitted to the gravity during the 10 ms before the impact. This allows for the subject to be nearly freestanding at the initial bumper contact and to take into account the friction shoe-ground as it is in reality.

After positioning of the subject is complete, the car is propelled by a horizontal catapult toward the pedestrian or toward the cyclist and decelerates 10ms after the impact.

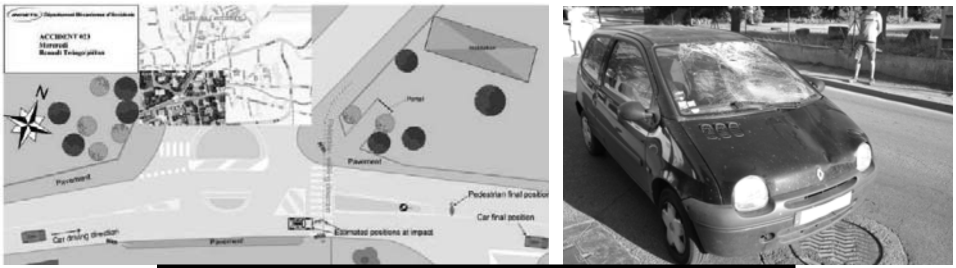
The post-mortem human subject is instrumented with accelerometers fixed on the lower limb and the head. Four high-speed video cameras operating at 1000 frames per second are placed in order to record the kinematics during the impact event. After the test, the car deformations, the Wrap Around Distance (WAD) to head strike was measured. The WAD corresponds to the distance between the head impact and the floor along the front end of the car. An in-depth necropsy is performed. Trajectory and velocity data for the head are calculated from films (figure 3). Injuries of the vulnerable user have been attributed to the car or to the ground fall from video films and from acceleration curves.

Fig. 3 - Experimental tests with PMHS

RESULTS

CASE N°1 CAR-TO-PEDESTRIAN:

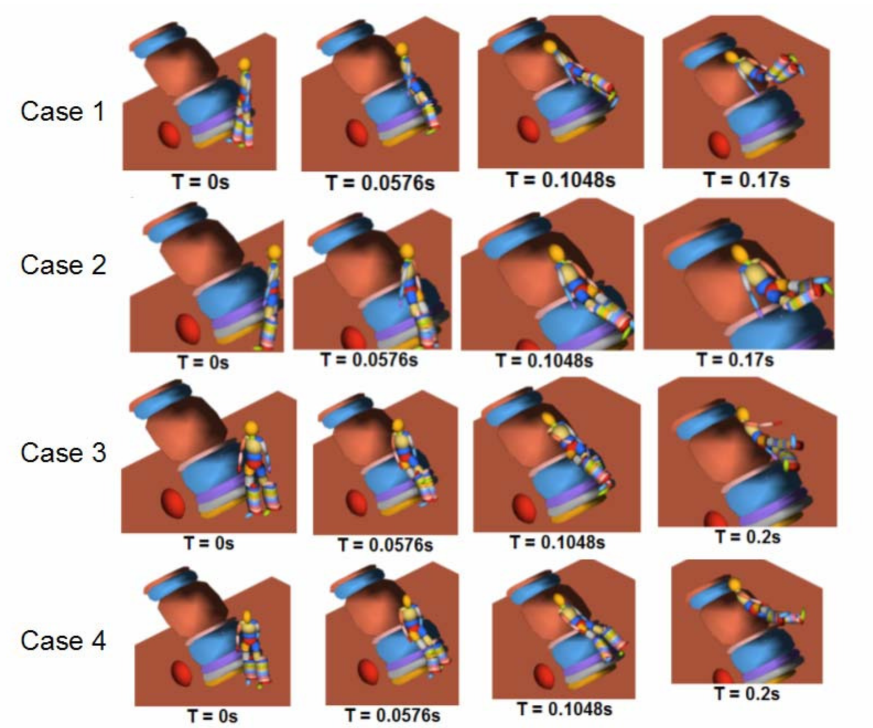
<u>In-depth investigation</u> : A June day, about 8 a.m., the weather is dry and sunny. A Renault Twingo vehicle was driving through a village. It crashed into the left side of an old woman on a pedestrian crossing. The vehicle driver was a priori dazzled by the sunlight. He did not see the pedestrian and didn’t begin to brake before impact (figure 4). The victim was 69 years of age, 1.60 m tall and weighed 60 kg. She was seriously injured (fractures to the leg, pelvis, forearm, second cervical vertebra and cranial trauma) and died the day after the accident. Figure 4 shows a diagram of the accident and photographs taken at the scene. The driver stopped the Renault Twingo approximately 30 m after the point of impact without leaving any braking marks. The injuries to the pedestrian’s right leg support the view that she was crossing from the left and was struck on her right side, a version of events which is corroborated by the driver’s statement. The deformation of the bumper means that the right leg can be positioned 0.06 m from the centre of the car. The dent in the bonnet approximately 0.18 m from the middle of the car is due to the impact of the pelvis and caused injuries to the pelvis. The two finger marks identified on the vehicle bonnet suggest that the front or the back rather than the side of the pedestrian’s body struck the bonnet. The higher of the two impacts on the windscreen is ascribed to impact with the head because of the presence of hair and the second impact in the windscreen is due either to the impact of the shoulder or elbow. The WAD was measured as 1.96 m and the pedestrian was projected over a distance of 19 m (figure 4).



Injury	Localisation	AIS Code
Fracture	Right Lower leg ▪ Tibia ▪ Fibula ▪ Patella	 8 5 34 22 3 8 5 16 06 2 8 5 24 00 2
	Right forearm	7 5 32 04 3 7 5 28 04 3
Fracture	Hip Spleen	8 5 26 04 3 5 4 42 99 2
Fracture	Cervical vertebrae (C2)	6 5 02 16 2
Cranial trauma		1 6 02 14 5 1 4 06 28 4 1 4 06 84 3

Fig. 4 – Case n°1 Twingo/pedestrian: map of the scene, global view of the car, injuries

Numerical simulation : Initial car speed was fixed to 45km/h and the pedestrian position placed in walking posture with the right leg ahead. The parametric study concerned in particular the position of the pedestrian at impact (5 configurations have been considered), the influence of the car impact speed (from 20 to 50 km/h) on the WAD and the throw distance value, the deceleration of the car (from 3 to 8 m.s^{-2}). Figure 5 shows some results of this parametric study and more specifically the pedestrian kinematic with respect to its initial position (4 different initial positions out of 5), the WAD and the throw distance values with respect to the car speed impact.



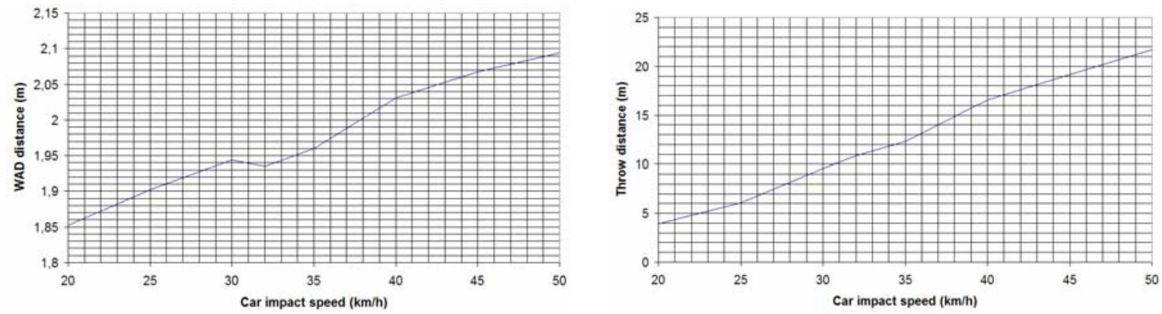


Fig. 5 – Parametric study: differences on the pedestrian kinematic with respect to its initial position (above), variation of the WAD and the throw distances with respect to the car speed impact (bottom).

After the parametric study, the retained configuration provided a kinematic in agreement with the in-depth accident investigation (figure 6 and table 1). Same impact areas were found and fracture on the superior third of the lower leg was simulated. Car speed was finally found equal to 40 km.h^{-1} and the throw distance close to 18m.

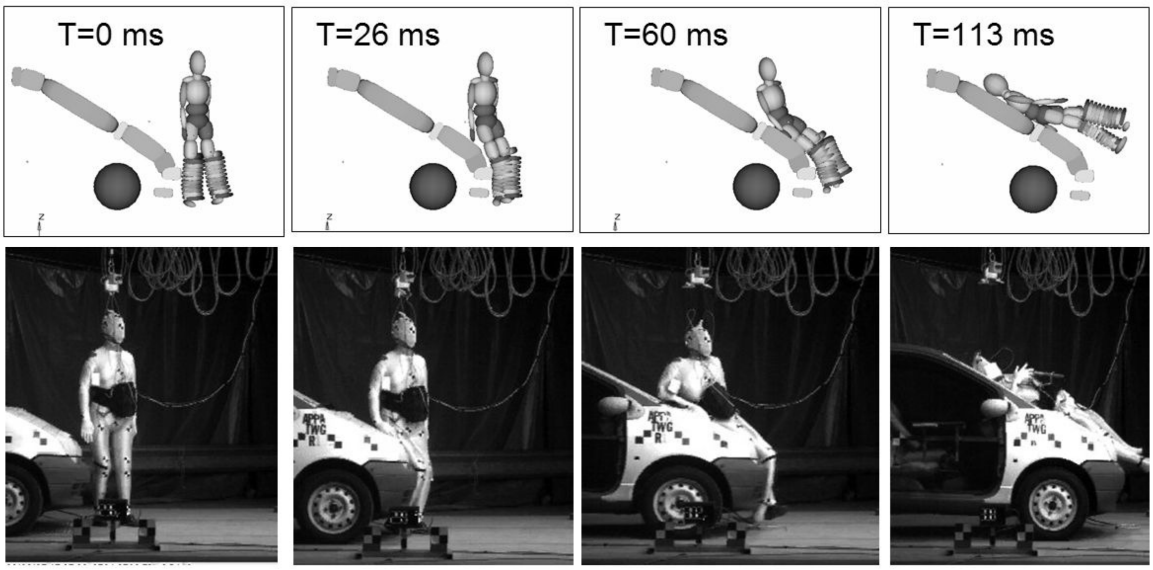


Fig. 6 – Kinematic comparison between Multibody simulation and experimental test

Experimental test : For the experimental test, the pedestrian was a small female (height=160 cm, weight=65 kg, 64 years old). She was impacted on his right posterior lateral side. Because of this tendency of the subject to rotate counter-clockwise (toward its anterior), we chose to position the pedestrian with the struck limb slightly back for this test. Arms were free to swing around. With the pedestrian fully supported in this prescribed stance, the subject was ready to be impacted with a vehicle. The measured impact speed was 40.2km.h^{-1}. The subject was fully thrown from the vehicle after the impact and was allowed to hit the ground. The distance between the car impact and the final position of the subject on the ground was 12.5m in forward axis with a 1.5m of gap in lateral axis on the left. The breaking distance of the car was 10.5m.
3DAccelerometers were fixed in the head, on the 3rd cervical vertebra, on the pubis, on the femur and on the tibia. Unfortunately, many channels broke at the impact and did not allowed the acceleration recordings. Injuries observed on the cadaver during the post-impact dissection are presented in table 1.

Table 1. Injuries observed in the experimental test

Type	Localisation	AIS
Bone fracture	Fracture of the right external malleolus Fracture of the right internal malleolus Fracture at the 1/3 superior right fibula	8 5 16 08 2 8 5 34 12 2 8 5 16 06 2
Ligaments	Rupture of the anterior tibia-fibular ligaments Rupture of the right anterior cruciate ligament Condylar avulsion of the right medial collateral ligament	8 4 04 02 2 8 4 04 04 2 8 4 04 04 2
Skin	Skin abrasion of the right elbow	7 1 02 02 1

Bone fractures and ligament ruptures have been assigned to the impact with the car. Abrasions have been associated to the fall on the ground.

Comparative table : In order to summary the comparison between the several approaches, a comparative table have been established. It allows having an overview concerning the following data: injuries, WAD, throw distance, maximal accelerations of the lower leg, the pelvis and the head, impact speed and angle of the head with the windscreen (table 2).

Table 2. General comparison between the three approaches

	In-depth investigation	Multibody simulation	Experimental test
Injuries	Right tibia fracture Right fibula fracture Right patella fracture	Right tibia/fibula fracture	Right double malleolus fracture Right fibula fracture
WAD	1.96m	2.03 m	2 m
Throw distance	19m	18m	13m
Accelerations: - head - pelvis - tibia	 - - -	 1800 $m.s^{-2}$ 1840 $m.s^{-2}$ 2750 $m.s^{-2}$	 - 1350 $m.s^{-2}$ 2300 $m.s^{-2}$
Head angle at impact	-	118°	119°
Head speed at impact	-	7.36 $m.s^{-1}$	7.11$m.s^{-1}$

Concerning the comparison of the injuries, it has to be notified without specific explanation that the ankle fractures observed during the experimental test have not been collected by the in-depth investigation.
Figures 7 and 8 show respectively the comparison between the impact points and the accelerations curves for the right tibia. It can be observed that similar impact points were obtained. Concerning the deformation of the car, similarities can also be highlighted more specifically on the hood. About the windscreen impacts, it seems that the chosen initial position does not allow to reproduce exactly the locations of the impact points. Perhaps a short variation of this position should given better results.

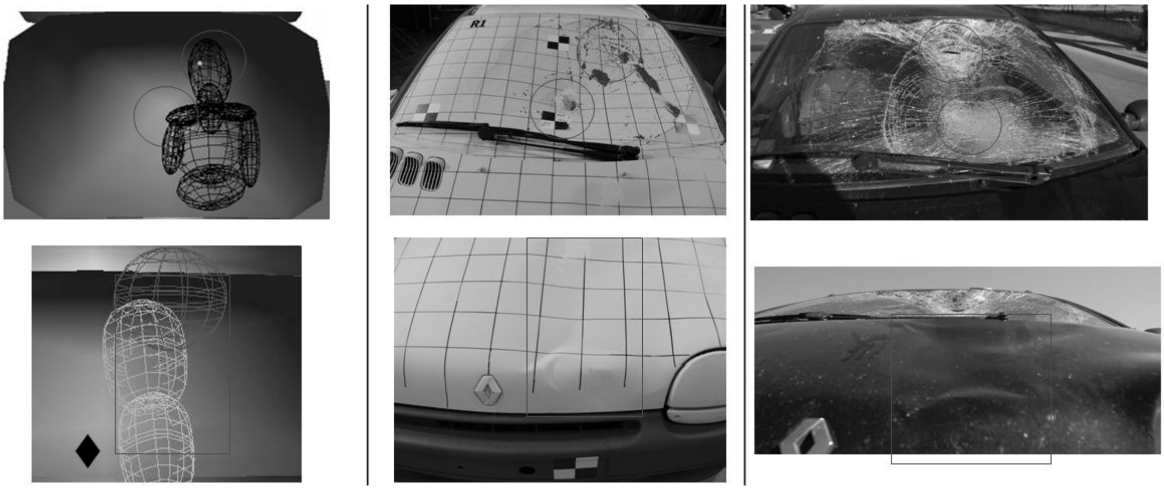


Fig. 7 - Comparison of the impact points between the three approaches:
Left: numerical simulation, middle: experimental test, right: in-depth investigation

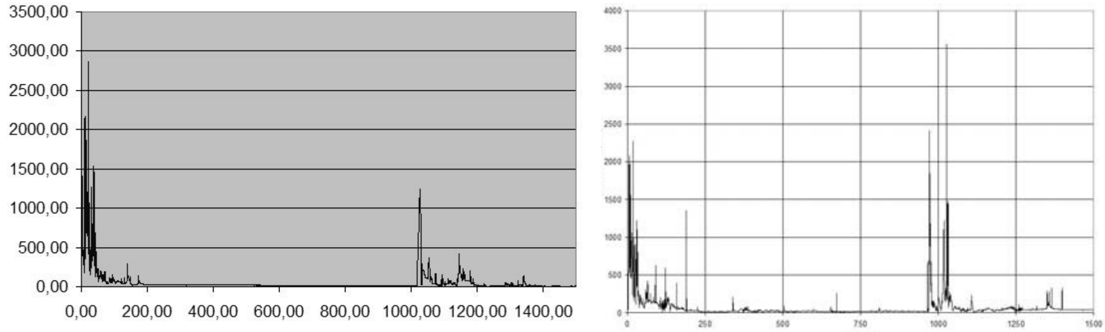


Fig. 8 - Tibia acceleration in m.s^{-2} versus time (in ms)
left: numerical simulation, right: experimental test

From the chronology point of view, it has to notify that a good correlation have been obtained between the numerical simulation and the experimental reconstruction. In particular, the ground fall appear about 1s after the first impact on the tibia.

CASE N°2 CAR-TO-CYCLIST:

In-depth investigation : An august day, at 3:10 p.m., the weather was clear, Mr X was driving his Peugeot 205 on a minor road linking his home to the nearest village when suddenly a young bicyclist emerged from a villa access on his left. Mr X braked in emergency in vain and could not avoid the bicyclist who was riding straight into him (figure 9). For this case, skid marks measured approximately 11m.

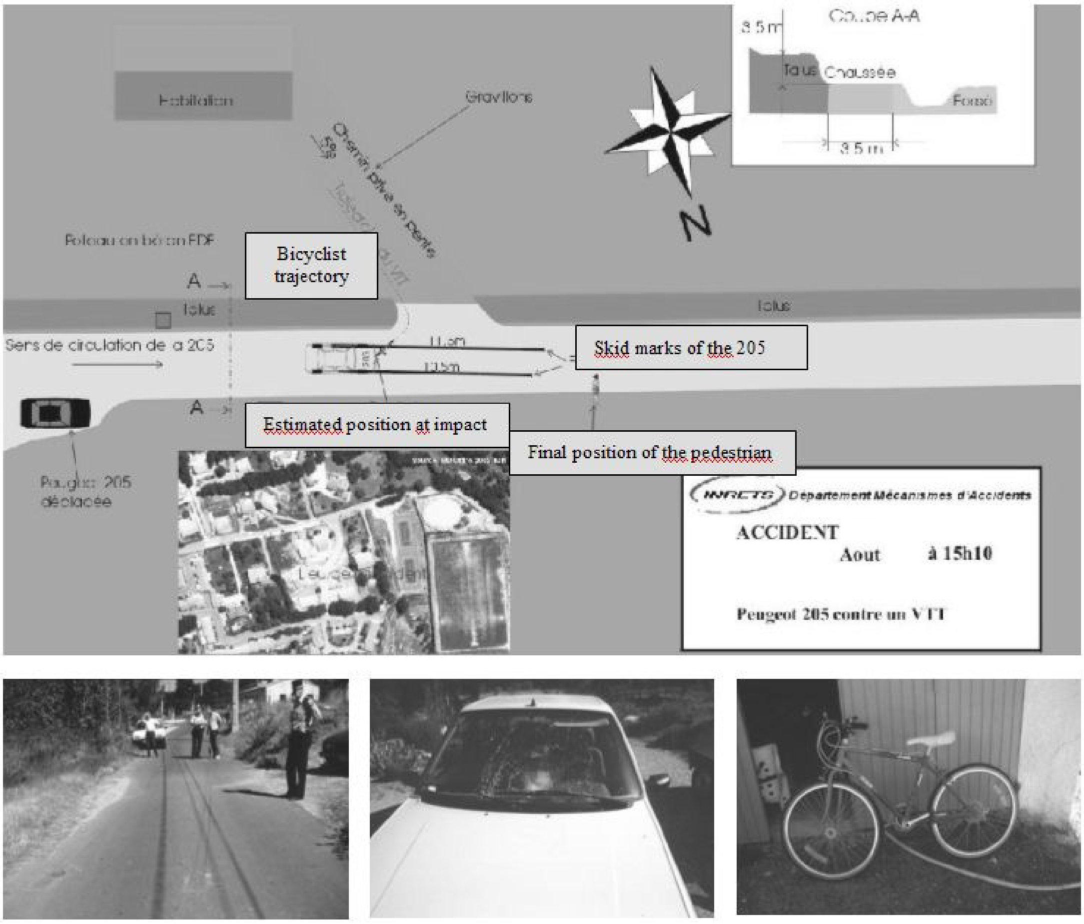


Fig. 9 – Case n°2 Peugeot 205/cyclist: map of the scene, skid marks, global view of the impact points on the car and bicycle

The kinematic reconstruction gave for the car an approaching speed of 55km.h^{-1} and an impact speed of about 45km.h^{-1}. The driver statement is in accordance with this result because he declared a speed of around 50km.h^{-1}. Impact areas were observed on the left headlight, the left corner of the bonnet and on the centre of the windscreen (figures 9 and 11).

The bicyclist was 13 years old. The bicycle impact speed is roughly estimated at 15 km/h. Injuries observed at the hospital were: cranial traumatism without blackouts located on the parieto-occipital right bone, 1/3 superior right fibula fracture, spiroid fracture of the 1/3 superior right tibia, wound at the medial condyle level on the right leg, left ear wounds, minor skin injuries at the level of the left elbow.

Relationships between injuries and impact areas were done in order to estimate a first configuration of the accident. Tibia and fibula fractures were associated to the impact on the left bonnet (and headlight), head traumatism to the windscreen impact and minor injuries on the left side to the fall on the ground.

<u>Numerical simulation</u> :

The parametric study for this accident case considered the variation in the angle of impact between the vehicle and the cyclist, the impact speeds of the car and the cyclist, but also the position of the cyclist on the bicycle. The direction of the impact was the most difficult parameter to estimate as it has very major influence on the kinematics of the cyclist. The various simulations have resulted in a selection of an impact speed of the Peugeot 205 of 40km.h^{-1} and an angle of 30° between the cyclist and the car (figure 10). The model output a fracture to the upper tibia caused by the impact with the headlamp. The right side of the head struck the lower part of the windscreen, but the impact provided by the simulation was slightly further to the left of the windscreen than is shown on the photograph of the actual car. The cyclist fell to the ground on his left side and the impact to the left of the head can be noted.

Figure 11 shows the plots of the resultant accelerations of the right tibia, the right femur, the pelvis and the head. These plots confirm, in particular, the chronology of the injuries by linking them with the level of stress applied to each impacted part of the body. Thus, the fracture to the right tibia is ascribed to a $1800 m.s^{-2}$ impact with the right headlamp of the car, the cranial trauma to a $1400 m.s^{-2}$ impact with the windscreen.

Experimental test :

In the accident, the cyclist was a child of 13 years old. Because no test are performed with a child, the subject chosen for this test was a small female (Height=160cm, Weight=52kg, 65 years old). The subject was sitting on a cycle with the hands on the handlebar and the feet on the pedals. Both pedals were at the same height from the ground. The angle between the cycle axis and the car axis was 30°. The car speed was $42.2 km.h^{-1}$. The subject was fully thrown from the vehicle after the impact and is allowed to hit the ground. The distance between the car impact and the final position of the subject on the ground was 12.2m in forward axis with a 1.6m of gap in lateral axis. The breaking distance of the car was 11.2m. 3DAccelerometers were fixed in the head, on the pubis, on the femur and on the tibia. Table 3 summaries injuries observed on the PMHS after the test.

Table 3. Injuries observed in the experimental test

Type	Localisation	AIS
Bone fracture	Left ribs fractures : 3 ; 4 ; 5 ; 6 ; 7 ; 8	4 5 02 30 3
	Fracture of the left radius	7 5 28 02 2
	Comminuted fracture of the right tibial diaphysis	8 5 34 22 3
	Fracture of the neck of the right fibula	8 5 16 06 2
Ligaments	Partial rupture of the left anterior cruciate ligament	8 4 04 04 2
	Rupture of the left collateral lateral ligament	8 4 04 04 2

The lower limb injuries and the radius fracture have been assigned to the impact on the vehicle. For the ribs fractures, it was not possible to associate them to a specific contact.

Comparative table :

As it was performed for the previous accident case, a comparative table has been established in order to provide an overview of the results (table 4). Figures 10, 11 and 12 show the comparisons respectively for the kinematic, the impact points and the acceleration levels. It appears that good correlation have been obtained between the three approaches. From a qualitative point of view, kinematic, but also injuries are nearly the same except for the thoracic injuries. This difference could be explained by the age of the PMHS because the thoracic injury risk increases with age (from less than 2% at age 20 to almost 20% at age 80). Some differences are observable on the impact point of the head on the car between the crash test and the real accident, probably due to the null speed of the bicycle during the crash test. From a quantitative point of view, WAD value, the throw distance and characteristics of the head impact (speed and angle) are closely but it has to be observed differences for the accelerations.

Table 4. General comparison between the three approaches

	In-depth investigation	Multibody simulation	Experimental test
Injuries	Right Tibia Fracture	Right Tibia Fracture	Right tibia fracture
WAD	1.95 m	2.07 m	2.11
Throw distance	14 m	13 m	12m
Accelerations:			
- head	-	$1400 m.s^{-2}$	$900 m.s^{-2}$
- pelvis	-	$250 m.s^{-2}$	$850 m.s^{-2}$
- tibia	-	$1800 m.s^{-2}$	$6000 m.s^{-2}$
Head angle at impact	-	76°	128°

Head speed at impact	-	4.64 m.s^{-1}	5.1 m.s^{-1}

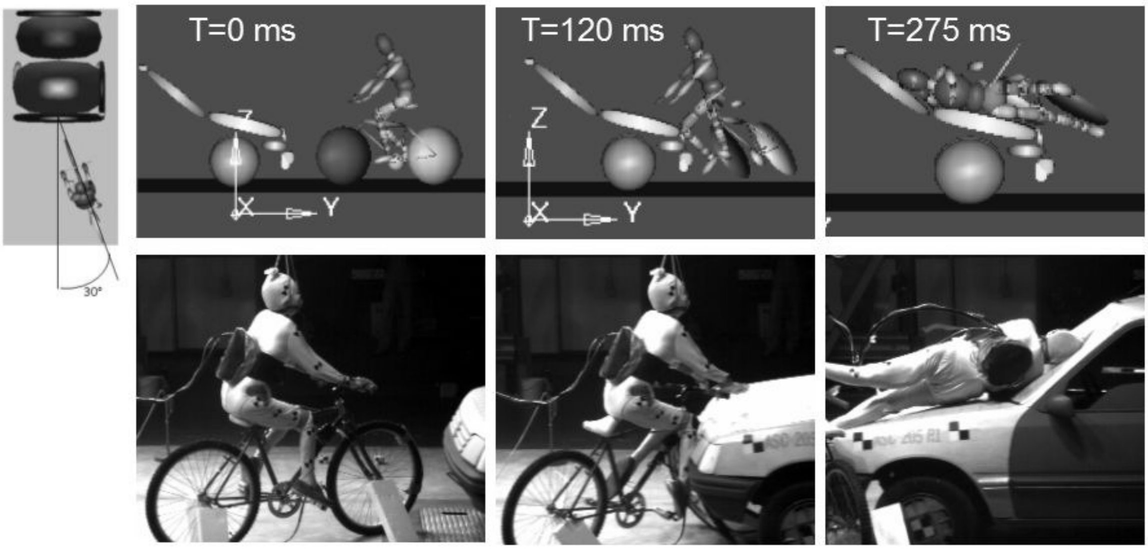


Fig. 10 – Kinematic comparison between numerical simulation (above, left lateral view) and experimental test (under, right lateral view)

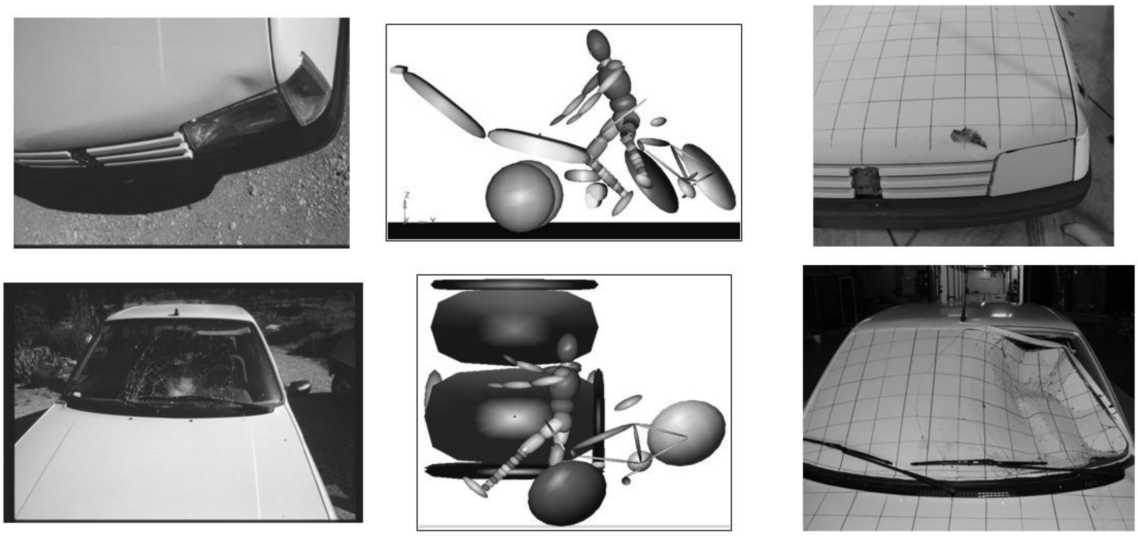


Fig. 11 – Comparison of the impact points between the three approaches: Left: in-depth investigation, middle: numerical simulation, right: experimental test

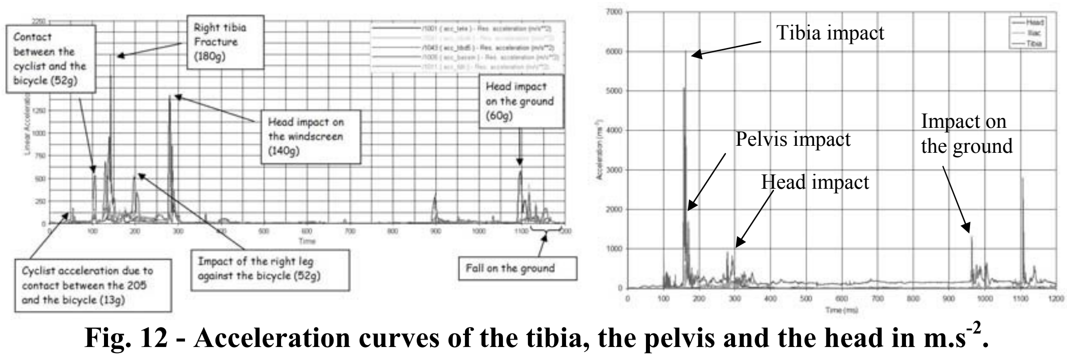


Fig. 12 - Acceleration curves of the tibia, the pelvis and the head in m.s^{-2}. Left: numerical simulation, Right: experimental test

Concerning the chronology of the impact, it has to highlight good associations between injuries and impact points on the car but also for the ground fall. Indeed, for numerical simulation and the experimental test, the cyclist falls in his left side and it is correlated with left wounds observed on the victim. Moreover, in both approaches (numerical and experimental) the ground fall appears about 1s after the first impact on the lower leg.

DISCUSSION

This work is based on a complete analysis of real accidents from three different approaches: in-depth accident investigation, numerical simulation with multibody model and experimental reconstitution with PMHS subject. The methodology of accident analysis presented allows taking advantage of the three different fields because they are complementary and closely linked.

Indeed, the in-depth investigation establishes hypotheses on the configuration of the accident. In particular, it gives first estimation of the impact orientation and the speed of the car. Moreover, in the case of accidents involving vulnerable road users, and more specifically pedestrians or cyclists, the in-depth investigation also enables us to associate injuries and impact areas on the car. This first estimation of the accident parameters gives the input data for a parametric study during the secondary analysis.

This second analysis is based on numerical simulations using multibody models which are predictive of injuries. The advantages of such an approach are to be simplified in the modelling work. In particular it allows variations of many parameters because simulation times are very short. Relevant parameters can be the velocity of the car, the impact orientation, the initial position of the involved person … Results of simulation (injuries, contact areas …) are then compared to the real signs collected during the in-depth investigations. The simulation which provides best correlations is considered as the most probable configuration of the accident. So, the numerical simulation is in return validated by the primary analysis in terms of qualitative results. From a quantitative point of view, the numerical model gives information on the levels of accelerations endured by the involved person. These results can be used to compare experimental tests performed in the biomechanical field and reality.

The retained configuration from both previous analyses is then used to be reproduced experimentally in laboratory. It consists on performing a crash-test with the same car and a PMHS which has morphology close to the victim. One of the main difficulties for this step is the availability of PMHS subject with specific anthropometry like a child of thirteen years old. Moreover, it has to notify that if the speed impact of the car can be accurately controlled, the braking deceleration can not be managed. Particularly, in the case n°1 (car-to-pedestrian) no braking marks have been observed for the Renault Twingo which is signified only a low deceleration (evaluated to about 3 $m.s^{-2}$ by the in-depth investigation). Because of the ground surface, this kind of deceleration can not be reproduced experimentally and it implies significant differences on the throw distance (table 2). Same remarks can be made on the cyclist speed. Indeed, during the crash-test the vulnerable user (pedestrian or cyclist) is static and has no initial speed. If the pedestrian speed can be neglected, the cyclist one should be taken into account. Unfortunately, this initial speed can not be reproduced experimentally. This difference has not a major influence on the impact of the lower leg with the bumper but divergences are observed along the kinematic more specifically on the head impact on the windscreen. In particular, deviations on the WAD value or on the location of the head impact have been observed. Nevertheless, with regards to the kinematics of the pedestrian or the cyclist, this could be divided into five main contacts:

- the lower leg on the bumper,
- the upper leg on the low bonnet,
- the thorax on the high bonnet,
- the head on the windscreen,
- the fall on the ground.

In the cases detailed above, some of these contacts can be observed and it was possible to quantify them in terms of chronology. If good correlations globally exist between experimental results, numerical simulation and reality we can observe some differences too. It is the case for the injuries sustained by the pedestrian. In the experimental test, no head or neck injuries were noted and the struck lower limb was specially injured. The choice of the pedestrian initial position can explain the difference between both injury reports. More explanation can be provided by the human biologic variability. Victims of the accident have obviously not the same biomechanical characteristics than the cadavers used for experimental test. In particular, they have not the same age and for old people it appears more disparities on the injury risk. Moreover, the ligament injuries because they are not leading cause of mortality could have been minimized in the real accident. However, the analysis focused on the head impact showed that same angle and speed impact for the head on the windscreen are similar. Concerning the fall on the ground, good similarities in terms of throw distance, kinematic (ground fall on the same body side) and injuries have also been observed.

Lastly, the relatively good coherence between the results of these three approaches takes part to the validation of the simulation of this kind of collision. It allows a better understanding of the kinematic and the chronology of impacts. More particularly, associations between injuries and impact point including the fall on the ground can be identified.

CONCLUSION

Three complementary approaches have been compared to reconstruct a real accident involving a pedestrian or a bicyclist.

The first one concerns the in-depth investigation. If it allows to make assumptions on the impact configuration, it can not give precisely all of the kinematic or the acceleration levels for example.

The second approach which is based on multibody simulation aims at evaluating several possibilities concerning the crash configuration but does not allow to validate all of injuries.

The last one consists on reproducing in laboratory the same accident through an experimental test with PMHS. This approach provides a lot of information on the real accident but can not be reproduced several times because it costs a lot and needs a significant setup. So the test protocol has to be well defined in particular for the configuration of the crash: speed car, position of the vulnerable user at impact, etc.

The complementarity between these three approaches improves our ability to identify injury mechanisms by identifying the principal functional characteristics of car/pedestrian or car/bicyclist impacts. In particular, the majority of the injuries which are mentioned in the casualties' medical records may be correlated with the deformations of the vehicle observed by the accident investigation team. If some differences have been observed on the injuries between the three approaches, one factor that can explain these differences is the human biologic variability. Indeed, it appears in particular difficult to adapt the biomechanical characteristics of the numerical model to the victim. Moreover, the experimental reconstruction is performed with a cadaver who does not correspond exactly to the victim.

Nevertheless, this methodology provides a means of reconstituting all of the chronology of the impact kinematics and main of the injuries. It allows to validate from a general point of view the reconstruction a real accident.

This work will continue by reconstructing new real accidents involving vulnerable users. Other pedestrian and bicyclist accidents will be reconstructed but also moped and motorcyclist accident will be studied.

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