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Real accidents involving vulnerable road users: in-depth investigation, numerical simulation and experimental reconstitution with PMHS.

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Abstract – This paper presents the methodology used to improve knowledge about vulnerable road users accidents and more specifically pedestrians or cyclists. 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. Accidents chosen from an in-depth multidisciplinary investigation are numerical modelled using a multibody software. Then, a parametric study focused for instance on car velocity and victim position at impact is performed 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 is reproduced experimentally by crash-test using cadavers. All results are finally compared in order to validate the real accident reconstruction. This methodology is applied on two real accidents involving one pedestrian or one cyclist.

INTRODUCTION

In the field of road safety, it appears important to well know how a real accident takes place. More specifically, accidents involving a vulnerable user in particular a pedestrian or a cyclist are more and more studied recently because this population represents about 17% of all road accident casualties [1]. Previous studies identified that the most frequent accident configuration is when the pedestrian – or the cyclist - is impacted by the front end of a light vehicle [2, 3]. However, for this kind of impact, the pedestrian kinematic - or the cyclist one - and the associated injuries mechanisms are difficult to evaluate in the reality.
In order to estimate them, accident investigations are performed but objective data collected concerns information on final conditions such as injuries or impact points on the car [4, 5]. To reconstruct the accident, the main difficulty is then to go back in time and make hypotheses regarding the process involved: direction of travel of the pedestrian (or cyclist), speed of the vehicle, etc. To improve the understanding of the accident production mechanism but also the collision conditions, in-depth investigations can be carry out, like at INRETS [6]. 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. Another way to reconstruct the accident is to establish the relationships between impact velocity and injuries in order to provide information concerning the real kinematic [7, 3].
Unfortunately, the kinematic are never completely validated only with such approaches. To complete this information, numerical methods are used to give new information on the car speed for instance. Some authors model the movement of pedestrians from simplified mechanical equations [8, 9] whereas others use more complex approaches considering the human body as rigid multibody model [10] or a finite element model [11].
This approach which links in-depth investigation and numerical simulation provide better knowledge on the real kinematic of the vulnerable user but it appears always some gaps on the kinematic validation [12].
In order to complete this coupled analysis, a third approach can be added. It consists in performing an experimental test of the same real impact.
These three approaches, accidentological, numerical and experimental are complementary but they are frequently studied separately or both coupled, rarely all together.
This paper presents such methodology which associate in-depth accident investigation, numerical modelling and experimental tests. It highlights more particularly the complementarity of the three approaches which constitutes the originality of this work. This methodology is then applied on two real accidents: a car-to-pedestrian one and a cyclist-to-pedestrian one.

METHODOLOGY

The general methodology is based on these three complementary approaches:

- An in-depth accident investigation
- A numerical modelling and simulation of the real accident
- An experimental test which reproduces the same accident configuration

Figure 1 summary the complementarity of the three approaches which is detailed below.

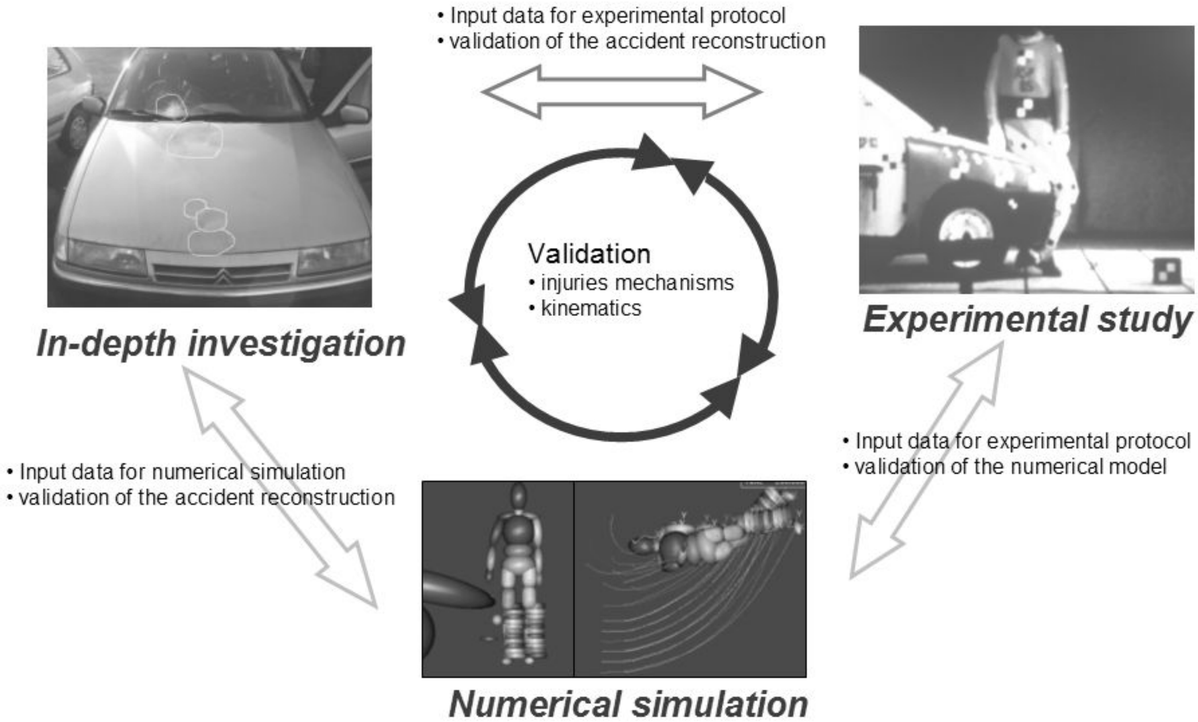

Figure 1. The complementary of the three approaches

The general process to reconstruct a real accident can be divided into seven steps.

Step1 – Numerical Modelling

The first step consists in elaborating a numerical model which has to include the representation of the pedestrian (or cyclist) but also the car (and the bicycle if necessary). Several methods exist to perform this work. Main ones are based on multibody theory [10] or on finite element models [11]. Because FE approach are rather time consuming and difficult to adapt to any accident cases, a multibody approach has been chosen. Indeed, the context of a real accident reconstruction implies an iterative process which is due to a parametric study (see step 5) so it appears important to use a method easily adjustable [12]. The Madymo software V6.0 has been employed to develop the numerical models and to perform the simulations in three dimensions [13].

Step 2 – Numerical model validation

This step aims at validate the numerical model in different configurations. This work consists in comparing numerical simulations with experimental tests from a qualitative point of view but also quantitative one. It concerns in particular the comparison of the kinematic in specific crash conditions (pure frontal or lateral impact) which do not correspond necessary to real accidents.

Step 3 – In-depth accident investigation

The principal aim of this investigation is to study the dysfunctions of the Human-Vehicle-Environment system and also interactions between its components, from several points of view: psychology, automotive mechanics, theoretical mechanics, road infrastructure and medicine. This work consists in collecting information on real accident from a multidisciplinary point of view.
For this research, most interesting data concern in particular the final positions of the vehicles, the point of impact on the vehicle (bonnet, windscreen, etc.), the direction of the impact, the marks left on the ground (tyres, fluids, debris, etc.), the statements of drivers, witnesses and a report of any injuries on the basis of the medical records.

Step 4 – First accident reconstruction

From the previous accident database, few cases are chosen to be reconstructed. All the data concerning a specific case are 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), position of the pedestrian (or cyclist) at impact, speed impact of the vehicle, etc.
Several methods can be used to estimate the speed of the vehicle [14]. These results are used as a basis for the numerical simulation and its validation. Complementary data such as vehicle characteristics or information on the anthropometry of the pedestrian (or the cyclist) have to be provided in order to adapt the numerical model to the identical conditions.

Step 5 – Parametric study

From the previous data, the numerical model is first adapted to the same real conditions. Then, a parametric study based on numerical simulations is performed around the first accident configuration identified in the step 4.
Parameters concern in particular the car speed, the pitch angle of the car due to braking phase, the pedestrian (or the cyclist) position on impact, the orientation of the impact [12]. For each simulation, criteria such as the points of impact, the Wrap-Around-Distance (WAD), the fall to the ground, the throw distance or virtual injuries are compared to the real data. At the end of this iterative process, the configuration which presents most similarities with the data collected during the accident investigation is selected.

Step 6 – Experimental test

Based on the previous retained configuration, a pedestrian (or a cyclist) full-scale impact experiment is performed using PMHS (Post Mortem Human Subject) [16]. One PMHS which has morphology close to the victim and a car corresponding to the one involved in the real accident are firstly selected. The subject is positioned in the same posture identified in step 5 and the car is propelled by a horizontal catapult to the same speed obtained by the numerical parametric study.
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.

Step 7 – Global validation

The last step consists in confronting all information provided by the three approaches. Impact points, car deformations, injuries, throw distance are in particular compared in order to validate the accident reconstruction. Finally the kinematics observed during the experimental test or the numerical simulation is approved or disapproved.

PEDESTRIAN CASE

This section illustrates the application of this methodology for the reconstruction of a real pedestrian case.

Step 1 – Numerical modelling

The human body model used in this part is the model which has been developed by the University of Chalmers [16], Faurecia [17] and validated in collaboration with the Laboratory of Applied Biomechanics [18]. 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 [19, 20]. The specific characteristics of this model concern its lower leg because it is predictive of fractures.

Step 2 – Numerical model validation

Then, the model is validated by comparison with experimental test in configurations not necessary representative of the reality [18]. Pure lateral impact for the pedestrian are more specifically studied because it represent the most frequent accident configuration. Figure 2 shows the qualitative validation of the kinematic by comparison with crash-test.

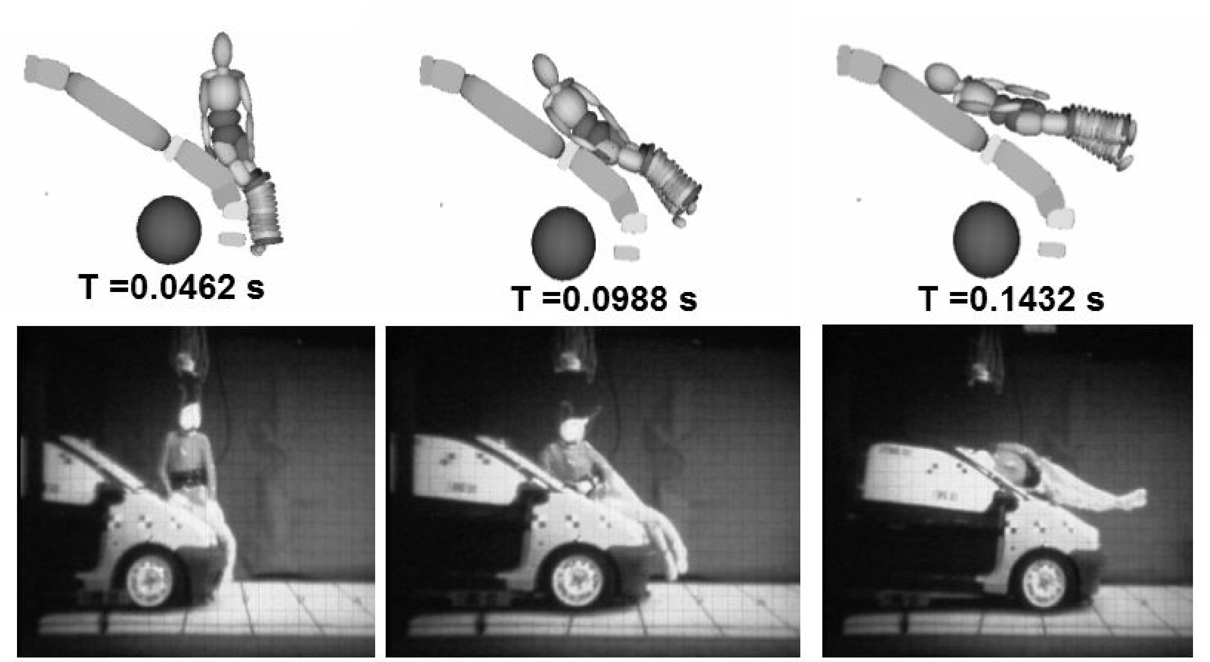

Figure 2. Kinematic validation of the multibody model by comparison with experimental test.

Step 3 – In-depth accident investigation

The chosen accident concerns a Twingo which impact an old woman on a pedestrian crossing. The driver didn't begin to brake before impact. 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 3 shows photograph taken at the scene. The driver stopped the Renault Twingo approximately 30 m after the point of impact without leaving any braking marks. The WAD was measured approximately as 2.02m and the pedestrian was projected over a distance of 19 m.

Figure 3. Photograph of the pedestrian accident scene.

Step 4 – First accident reconstruction

The initial configuration of this accident was derived from possible correlations between the injuries and the points of impact. 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 either 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. An estimation of speed using various methods [14] gave a range of $38 km.h^{-1}$ to $44 km.h^{-1}$.

Step 5 – Parametric study

The parametric study of this accident concerned more particularly the following parameters:

- impact speed of the vehicle
- initial position of the pedestrian at impact
- deceleration of the vehicle after impact

The influence of the variation of the impact speed on the WAD value and the distance of projection allowed us to obtain a better estimation of the car velocity. As the WAD measured on the accident was evaluated to 2.02m, figure 4 provides an impact speed of the Twingo estimated nearly to $40 kmh^{-1}$.

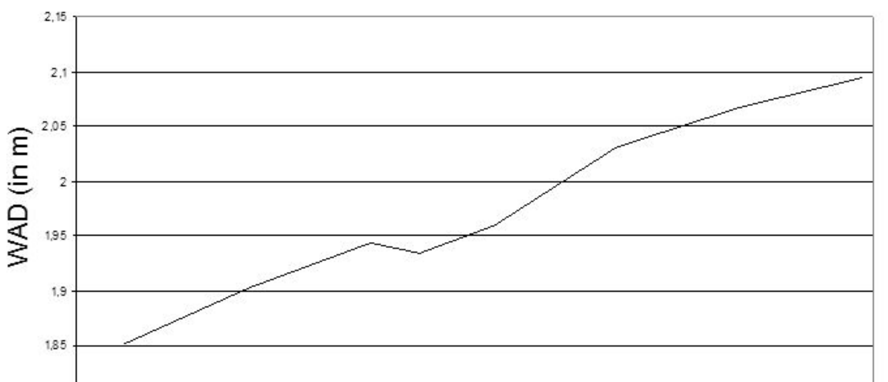

Figure 4. WAD variation as a function of the impact speed.

Concerning the position of the pedestrian at impact, several postures have been studied. Figure 5 shows the kinematics for both of them. In the first one it has been considered that the pedestrian facing the vehicle. In the second one the pedestrian turns his back to the car.

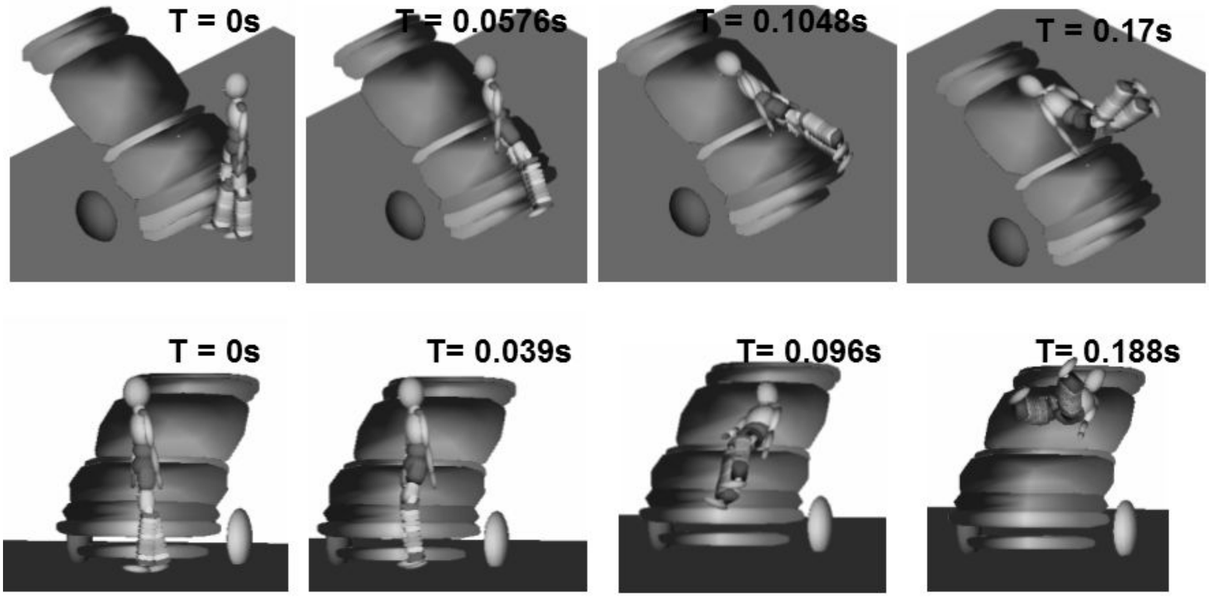

Figure 5. Two different initial positions of the pedestrian and corresponding kinematics.

By comparison of the impact points, throw distance, etc, the second configuration has been chosen as the most probably one.

Step 6 – Experimental test

The experimental protocol used to perform the accident reconstruction in laboratory with PMHS has been based on this configuration. The pedestrian was a small female (height=160 cm, weight=65 kg, 64 years old) and the vehicle speed at impact was 40.2km.h^{-1}. The throw distance was 12.5m and the WAD 2m. Injuries observed on the cadaver during the post-impact dissection were fractures of the right malleollus and fibula, rupture of the right anterior cruciate ligament and skin abrasion of the right elbow. Figure 6 shows the kinematic of the full-scale test.

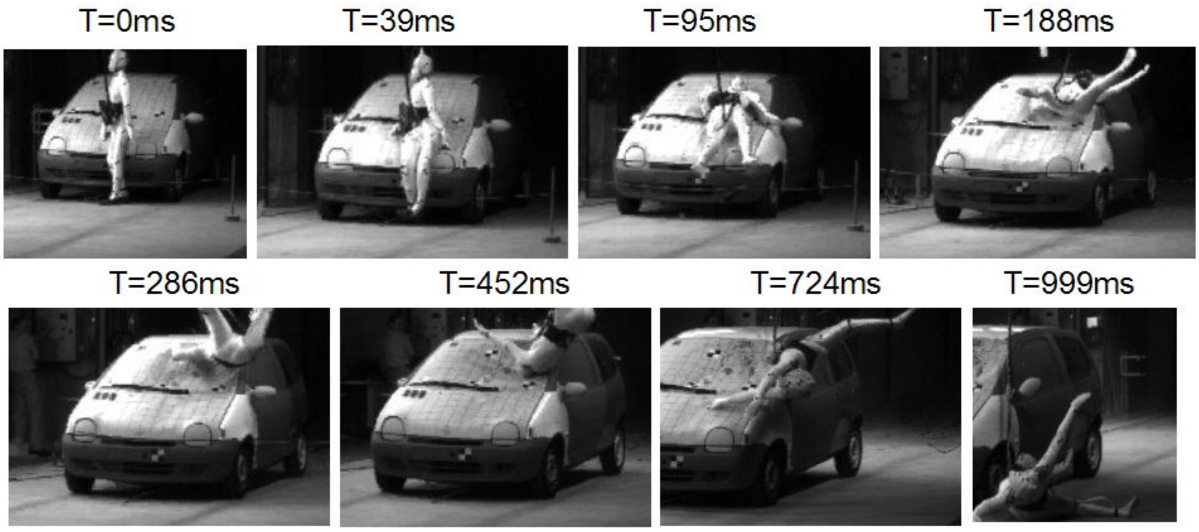

Figure 6. kinematic of the experimental reconstruction (pedestrian accident).

Step 7 – Global validation

The kinematics obtained experimentally and numerically are in accordance with the in-depth accident investigation. The same impact areas were found and fractures on the right lower leg was also simulated. Car speed was finally found equal to 40km.h^{-1} and it could be considered as validated due to the previous similar observations. Nevertheless it has to highlight the difference of the throw distance between the in-depth investigation and the experimental reconstruction. It was measured close to 12.5m for the full-scale test instead of 19m on the accident scene. This difference can be attributed to the deceleration of the vehicle after the impact. Indeed, this deceleration can be considered as close to -3m.s^{-2} for the real accident because no braking marks were observed. On contrary the experimental reconstruction impose this deceleration to –5m.s^{-2}.

CYCLIST CASE

This section is focused and dedicated to the cyclist-to-car accident. It demonstrates the application of the present methodology for the reconstruction of a real cyclist accident.

Step 1 – Numerical modelling

Modifications were applied on the multibody model used for the pedestrian configuration in order to adapt it to the cyclist configuration. The bicycle modelling was performed and added to the whole model and the human body model was positioned on the bicycle.

Step 2 – Numerical model validation

Because no validation of the whole model was made on the configuration of a bicycle impact, comparisons of numerical simulations with full-scale tests using PMHS were performed. The protocol of such tests was to achieve collisions between a car and a bicyclist in a configuration close to a pedestrian one. Impact was in frontal for the car and lateral for the bicyclist (perpendicular to the front of the car). In particular, the overall kinematics of the human body model appears to be in agreement with observations from high speed films (figure 7).

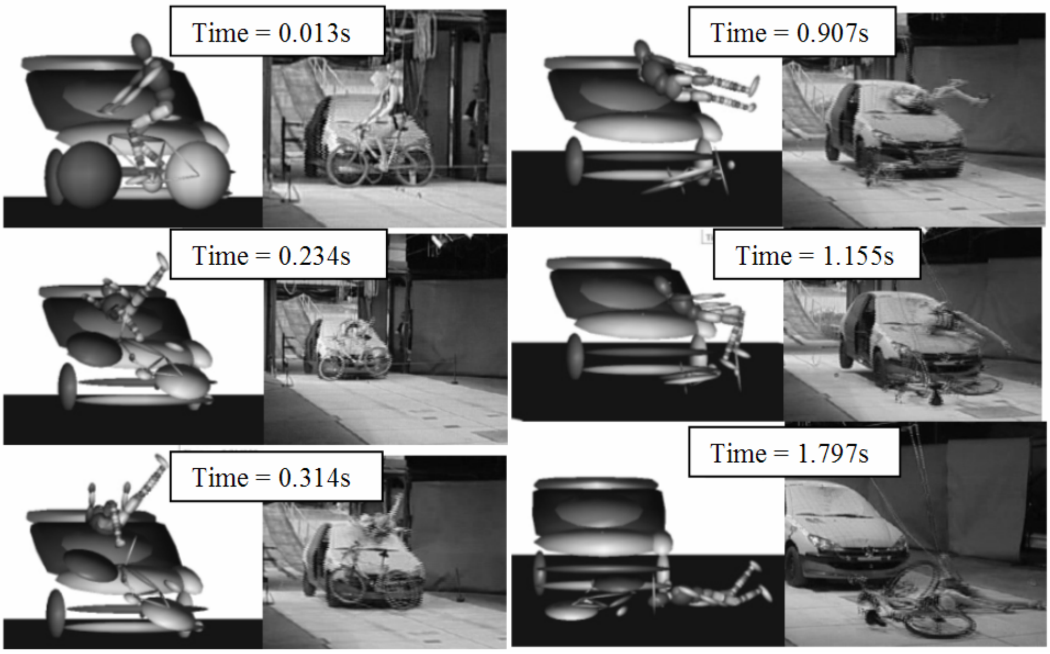

Figure 7. Kinematic validation for the numerical model in cyclist configuration.

Step 3 – In-depth accident investigation

A Peugeot 205 was travelling at approximately 50km.h^{-1} along a local road when a young cyclist appeared from the left. The cyclist struck the front of the car, went over his handlebars, hit the windscreen and then fell on the road. The braking marks were about 11 m long; the measured WAD was 1.95 m and the throw distance 14m. Several impact points were identified on the vehicle: impact on the right headlamp and the right corner of the bonnet as well as on the windscreen (figure 8). The cyclist, who was 13 years of age, suffered a number of injuries: cranial trauma, fractures to the right lower leg (tibia and fibula), dermabrasions to the left side (elbow, ear).

Figure 8. Vehicle deformations for the real cyclist accident.

Step 4 – First accident reconstruction

The chronology of the accident can be decomposed into three phases which associate injuries and impact areas on the car: the right leg on the bumper, the right side of the head on the windscreen, the fall on the ground on the left side. Such kinematics could explain injuries observed in the clinical records of the cyclist. An initial kinematic reconstruction of the accident on the basis of the braking marks gave an estimated approach speed for the vehicle of 50km.h^{-1} and the speed of the cyclist at the moment of impact has been assessed at approximately 15km.h^{-1}.

Step 5 – Parametric study

The numerical model developed and validated in step 1 and 2 have been firstly adapted to the real accident configuration. The front shape of the car was modified in order to represent a Peugeot 205 and the anthropometry of the human body model was adapted to the victim morphology with the help of clinical records collected by the investigators.
Then the parametric study was performed on:

- the velocities of the car and the bicyclist
- the impact angle between the vehicle and the cyclist
- the cyclist position 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 9). 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 (WAD=2.07m) and the cyclist fell to the ground on his left side (throw distance=13m) (figure 9).

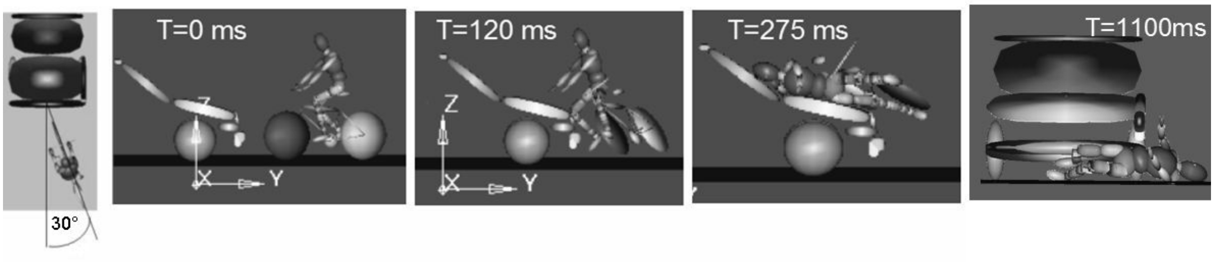

Figure 9. Cyclist position at impact and numerical kinematic.

Step 6 – Experimental test

Because no experimental test are performed with children, 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. The angle between the cycle axis and the car axis was 30° and the car speed was $42.2km.h^{-1}$. The throw distance was 12.2m and the WAD 2.11m. Injuries observed during the autopsy were left ribs fractures, right lower leg fractures (tibia and fibula) and rupture of the left collateral lateral ligament. Figure 10 illustrates the experimental kinematic.

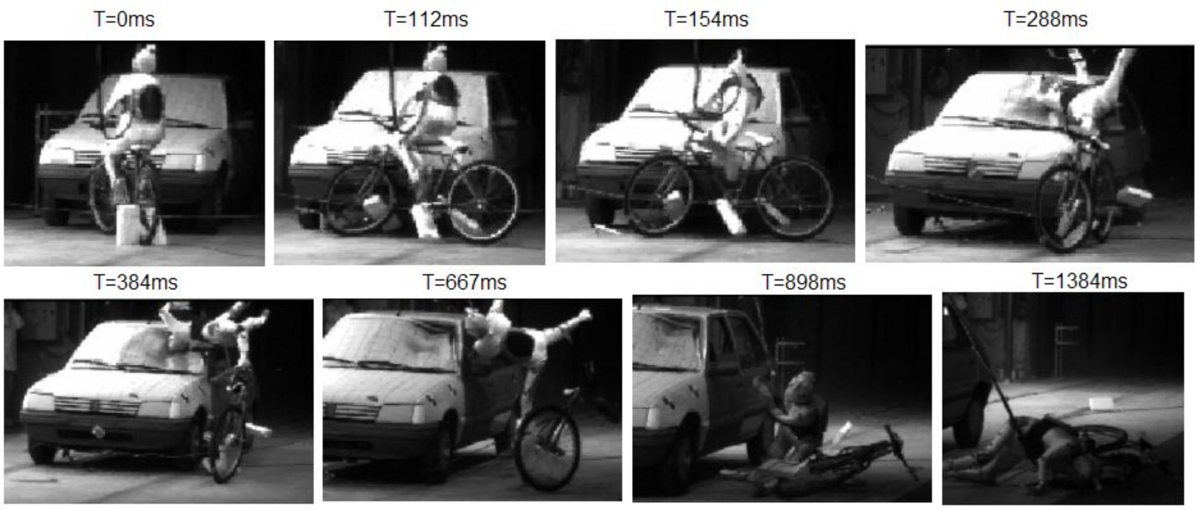

Figure 10. Kinematic of the experimental reconstruction (cyclist accident).

Step 7 – Global validation

From a kinematic point of view, it appears good correlations between the three approaches. Injuries, WAD value and throw distance are nearly the same. It highlights good associations between injuries and impact points on the car but also for the ground fall.

Nevertheless, some differences are observable on the impact point of the head on the car between the crash test and the real accident. Indeed, the impacts provided by the simulation and the experimental test were slightly further to the left of the windscreen than is shown on the photograph of the real accident. These differences can be attributed to the null speed of the bicycle during the crash test because it implied a pure forward wrap trajectory instead of an oblique one like it was supposed for the real accident.

CONCLUSION

The aim of this paper was to present a general methodology to perform a complete analysis of real pedestrian or cyclist accident. It is based on the triptych: accident in-depth investigation, numerical modelling and experimental test. It allows an accurate accident reconstruction and a correct validation of the kinematic.
Because this method is based on a case to case study, it can be used for instance in the forensic road accident reconstruction work. Indeed, it can provide judicial court evidence relating to the crash sequence, the collision configuration, the impact configurations and the respective behaviour and velocity of vehicles involved for each sequence.
Results can also be used to adapt European directives concerning the passive safety of a vulnerable road user in the event of a collision with a car [21] to the conditions observed in the reality.
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