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Detailed Investigations and Reconstructions of Real Accidents Involving Vulnerable Road Users

Abstract

The aim of this research is to improve knowledge about vulnerable road users accidents and more specifically pedestrians or cyclists. This work has been based on a complete analysis of real accidents.

From accidents chosen from an in-depth multidisciplinary investigation (psychology, technical, medical), we have tried to identify the 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.

A first simulation has been performed on this starting configuration. Next, 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 was 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.

This double approach associating an in-depth accident analysis and a numerical simulation has been applied on pedestrian-to-car and bicyclist-to-car accidents. It has allowed us to better understand the real kinematics of such impacts. Even if this method is based on a case to case study, it underlines which parameters are relevant on a vulnerable road user accident investigation and reconstruction.

Introduction

The theme of this research concerns the study of vulnerable road users and more precisely the study of collisions of car-to-pedestrian and car-to-cyclist. The results of these two categories of vulnerable road users, in terms of road safety, show that the stake is substantial. In fact, even if the global evolution of road safety in France was quite positive in 2003, about 19000 pedestrians or cyclists were however injured, representing 16.4% of all road accident casualties. With a number of 782 people killed, these vulnerable road users represent also about 13.6% of all the deaths in fatal accidents [1]. This category of transport users has been qualified as vulnerable because of their lack of protections. Furthermore, in the past few years, their safety has not been always taken into account compared to the means invested in the field of car safety.

So the aim of this research is to improve knowledge about vulnerable road users accidents more specifically pedestrians or cyclists run over by cars. The objective was to perform complete and detailed analysis of real accidents. Several studies have been carried out in this field with different approaches. Some authors established relationships between impact velocity and injuries in order to provide information concerning the accident reconstruction [2, 3]. Other works modelled the movement of pedestrians from simplified mechanical equations [4]. A more complex approach considers the human body as a single segment rigid body [5].

The methodology set up here is a joint effort performed at INRETS (French National Institute for Transport and Safety Research) between two complementary approaches: an active safety approach based on an in-depth multidisciplinary investigation (psychology, technical, medical) of real accidents and a passive safety approach based on a numerical simulation of the crash.

Concerning the active safety approach, the Department of Accident Mechanism Analysis of INRETS has been carrying out in-depth investigations on road accidents since the beginning of the 80s. 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. The present study is mainly orientated on primary safety. It is focused on the study and the identification of the accident production mechanisms but covers also the field of secondary safety and allows collaborations and exchanges notably with the INRETS Laboratory of Applied Biomechanics. In-depth study of accident cases belongs to the research field we could call “clinical accidentology“, and it is complementary with statistical and epidemiological studies [6-8]. In-depth accident studies allow moreover the understanding of the dysfunction of the driver-vehicle-infrastructure system [9]. Accident cases corresponding to the type of collision studied were selected among the most well documented, to be used as examples for the conception and adjustment of simulation models of crashes.

With regard to the passive safety approach, the Laboratory of Applied Biomechanics has studied the pedestrian impact for many years in collaboration with mainly Chalmers University and Faurecia [10-12]. The principal objectives of previous studies were to gain a better understanding of the influence of bumper design on pedestrian lower leg injuries and pedestrian behaviour [10, 12, 13]. However, such studies concern only the pedestrian impact in a well known configuration close to the standard recommendations: frontal impact for the car, lateral for the pedestrian, speed less than 40km/h … But are such configurations representative of reality? Do we observe the same pedestrian behaviour (in terms of kinematics for example) in real accidents? The same injuries? This is also one of the purposes of this study. Another objective is to extend our knowledge to the field of the behaviour of cyclists impacted by a car. In the future, this study could be used to compare kinematics between pedestrians and bicyclists like [14]. Is it close to the pedestrian? Do we observe the same injuries? Will pedestrian safety countermeasures suggested or imposed on car manufacturers be useful to bicyclists?

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Method

In-Depth Accident Investigation

The principal aim of this investigation is to study and identify the accident production mechanisms. So we try to understand the dysfunctions of the driver-vehicle-infrastructure system and we accord a particular attention to interactions between all its three components. However, since 1992 our in-depth accident investigation has also covered the field of secondary safety. Our data base contains around 500 accidents cases aged less than 10 years, and we have now collected about 50 cases a year.

The survey area circles the town of Salon-de-Provence (37000 inhabitants) and covers about 600km^2. It is characterized by a large diversity of road infrastructures: motorways, major and minor roads and also a few winding roads. To complete this principal survey sector with a more urban area, we have also investigated, since the year 2000, the accidents in the town of Aix-en-Provence (137000 inhabitants).

Investigators are on duty one week in three, 24h/24h. They are alerted by means of a short message system (SMS) sent by the central computer of the rescue service when there is a road accident in our investigation area.

The intervention on the accident scene is made as quickly as possible (about 15 minutes after the accident happened) in order to collect fugitive data. For the technician, they are, for example, final positions of vehicles, position of the point of collision, skid marks, occupancy and load of vehicles… For the psychologist, it is very important to rapidly interview the persons involved and the possible witnesses to collect the story, the scene, they have been lived through or rather the perception they have of it. If possible, it is preferable to collect these labile data before these persons undergo a thorough questioning by the police. It is necessary to remember that the aim of our study is completely different from that of the police. They are looking for the person responsible for the accident; we are looking for an understanding on how and why the accident happened. So statements are sometimes different. The technician films the scene of the accident, takes pictures and makes measurements to later draw up a precise plan, the psychologist records the interviews (see figure 1).

Both investigators pool the data collected in this first phase in order to guide the second one. A few days after, the technician checks the vehicle: state of safety parts, brakes, tires, suspensions… He also measures the deformations, and checks the interior of the vehicle to understand if possible how lesions appeared on occupants (see figure 1).

Fig. 1: In-depth investigation on the scene of the accident

Medical data concerning the victims is collected by the emergency service of the Salon-de-Provence hospital. The psychologist makes a second interview to improve knowledge of the persons involved, their health conditions, their experiences of driving, their experience of the car and the road they drove on…

After that, an important amount of work is necessary to format all these data and to capture them in computer.

An engineer computes the reconstruction of the accident generally using a kinematics method [15]. Starting from the final position of the vehicle, the principle consists of going back on the time and on the trajectory of each vehicle by applying a chain of simple kinematics sequences. The parameters are determined by taking into account all signs or indications collected on the scene of the accident like skid marks on the road for example. When the reconstruction proposed is in agreement with all indications available, we adopt it for this case as being the most probable one.

Finally, a global synthesis of the accident is drawn up by both investigators relating the whole story of the accident.

Numerical Simulation

In order to gain a better understanding of the real kinematics and the injury mechanisms of the vulnerable road user during the impact, we have decided to simulate numerically the real accidents with a multibody software. The Madymo V6.0 has been used to develop the numerical models and to perform the simulations.

Model Description

The whole multibody model is divided into two parts: the car and the vulnerable road users (the pedestrian or the bicyclist).

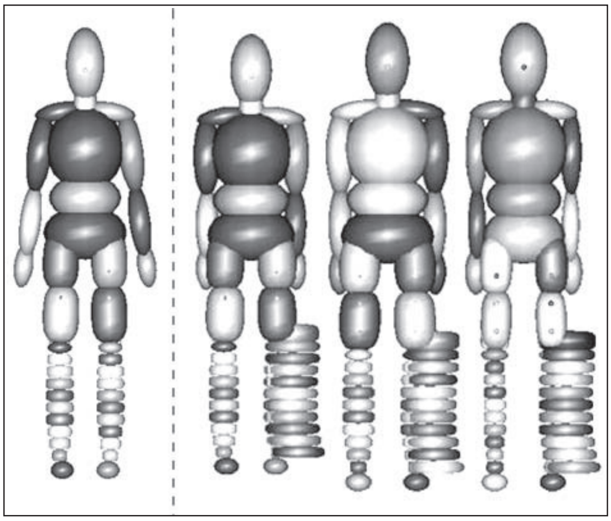

Fig. 2: Multibody model of the pedestrian and morphology adaptation

The human body model has been previously developed by the University of Chalmers [11] and then improved by Faurecia [12]. It represents a human body close to the 50th percentile male: 1.75m, 78kg. It includes 35 bodies with 35 joints and it is represented by 85 ellipsoids (see figure 2). Joint and body segment characteristics are based on available biomechanical data [16, 17]. The specific characteristics of this model concern its lower leg because it is predictive of some injuries. In particular it includes a human-like knee joint (femoral and tibial condyles, anterior and posterior cruciate ligaments, medial and lateral collateral ligaments) and a breakable leg which can simulate multiple lower leg fractures. Moreover, this model has been improved in order to simulate upper leg fracture so this body segment has been divided into several bodies.

Because the morphology of the subject is a relevant parameter in terms of kinematics or injuries during a pedestrian impact, we have adapted the human body model geometry to the real dimensions of the person involved in the

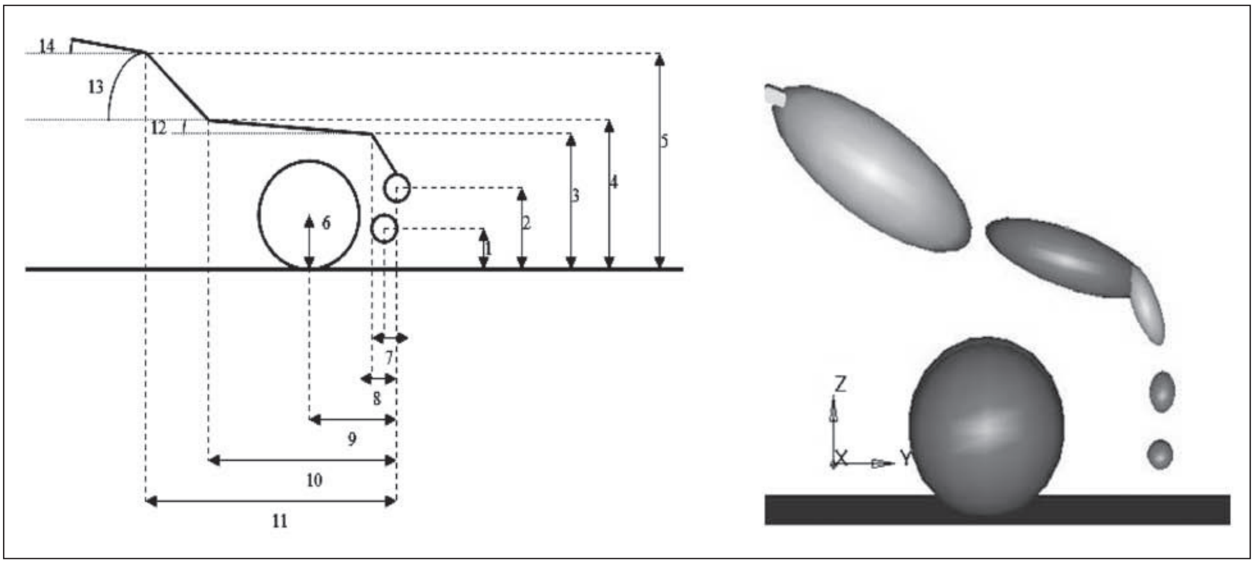

Fig. 3: Multibody model of the car and geometry measurements

accident. To do this work, we have used information (such as height, and weight) provided by the medical records available in the in-depth investigation. The model adaptation is divided into three steps: a scaling of the height, a dimension adjustment from more than 50 anthropometric measurements (if available), a new repartition of the weight in function of the new morphology (see figure 2).

Concerning bicyclist modelling, a classical French bicycle (VTT) has been added and then the pedestrian is placed on the bicycle in a standard position.

As for the vehicle model, it has been represented using more than 10 bodies. Its geometry is based on 19 measurements performed directly on the car involved in the accident when it is possible (see figure 3). If necessary some complementary measurements are performed on a similar vehicle using a 3D arm Faro.

Model Validation

This model has already been validated qualitatively but also quantitatively in pedestrian configuration by comparison with PMHS (Post Mortem Human Subject) experimental tests performed at INRETS-LBA [10]. This validation has been based on different car geometries (family or small urban cars) at different impact speeds (32km/h and 40km/h) [12]. So it could be considered that this model is representative of the kinematics for an impact speed less than 40km/h.

Concerning the configuration of a bicycle impact, no validation has been made. In this way, new full-scale impact tests (crash-tests) with PMHS have been 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 frontal for the car and lateral for the bicyclist (nearest perpendicular to the front of the car). The overall kinematics of the human body model appears to be in agreement with observations from high speed films (see figure 4). The time histories of the linear accelerations show good correlations with test measurements.

Real Accident Simulation

The next step is to use this multibody model in order to simulate real accidents. From accidents chosen in the in-depth investigation database, we have tried to identify the configuration of the impact in terms of: car speed, impact orientation, pedestrian or cyclist positions… This work has been performed in particular during the kinematics reconstruction based on in-depth investigation.

Then, we have made the corresponding multibody model of this configuration with Madymo V6.0. In particular, we have reproduced the anthropometry of the victim and the front shape of the car as it was described before.

A first simulation has been performed on this starting configuration provided as being the most probable one by the reconstruction. Next, effects of some parameters such as car velocity or victim position at impact have been numerically studied in

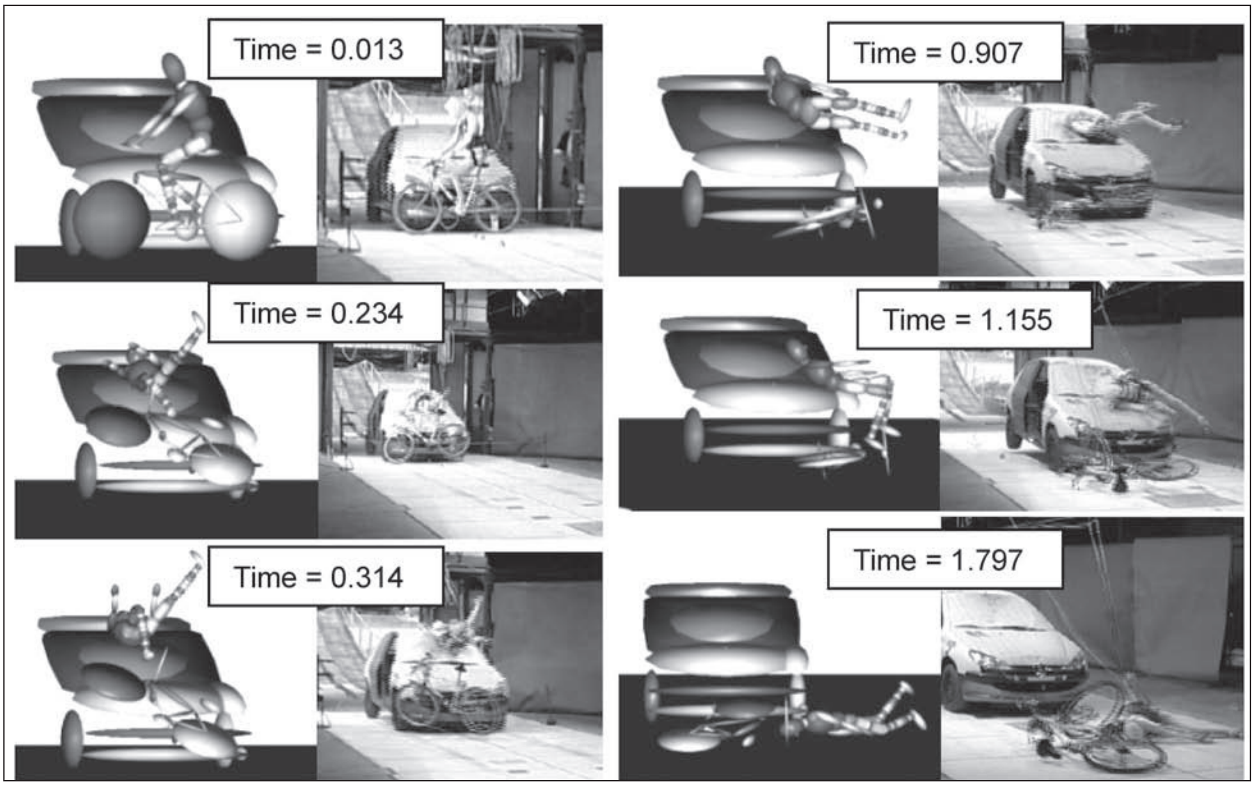

Fig. 4: Qualitative validation of the multibody model in car to bicyclist configuration

order to find the best correlations with all indications produced by the in-depth analysis.

Finally, the retained configuration 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.

Results

In order to illustrate this general methodology associating a detailed investigation and a multibody simulation of real accidents involving vulnerable road users, two cases are presented below. The first one concerns a pedestrian impact close to the "classical" configuration studied in experimental tests. The second one is a bicyclist accident in a different configuration.

For both of them, we first describe the configuration of the accident and then the multibody simulation.

Real Pedestrian Accident

In-Depth Investigation

On a January day, at 9 a.m., it is light and the weather is clear, Mrs X is driving a Citroën Xantia on a Salon-de-Provence boulevard. She is coming back home to a small village in the south of Salon. She was driving at about 45km/h, she said, when she perceived, at the last minute, an old man, in the middle of her lane on a pedestrian crossing. She braked in emergency but the impact was unavoidable. Her car crashed into the right side of the pedestrian who died on the spot (see figure 5). Mrs X was not injured but she was badly shaken by the accident.

Several impact areas were observed on the Xantia: one on the low bonnet (1), one on the high bonnet (2) and one on the windscreen (3) (see figure 5).

Thirteen meters of skid marks were measured and we evaluated the deceleration during the braking phase to -8m/s2. Finally, the cinematic reconstruction of this accident using the methodology described in [15] shows an approaching speed for the car of approximately 60km/h and an impact speed of about 55km/h. Moreover, these speeds are in correlation with the usual speed measured on this road.

The pedestrian was 85 years old; he was 1.65m tall and weighed 75kg. His injuries estimated on the scene of the accident by a doctor were: open fracture of the right shoulder, right ribs fractures, fractures of the two femurs, face wounds.

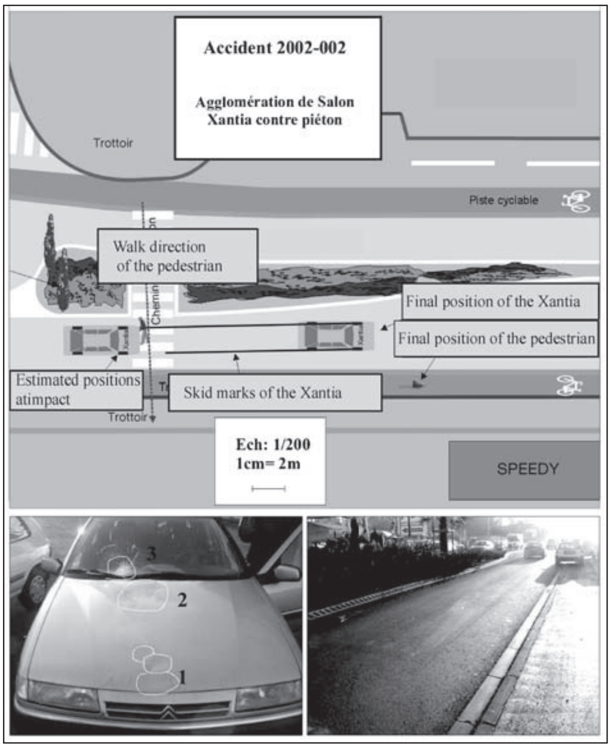

Fig. 5: Accident map, impact points on the Xantia and skid marks

Comparisons between injuries and impact areas on the car could provide a first estimation of the pedestrian cinematic. In this first estimation we could associate femurs fractures to the low bonnet impact, ribs and shoulder fractures to the high bonnet and face injuries to the windscreen impact.

Numerical Simulation

First of all, the multibody model was modified in order to correspond to this accident. The human body model was adapted to the anthropometry of the old man (1.65m, 75kg) and the front shape of the Citroën Xantia was represented from measurements carried out on a car of the same type.

Then a first simulation was performed on the configuration provided by the in-depth investigation. The Car speed was fixed to 55km/h, the pedestrian was placed in a walking position from the left to the right side of the car in order to be impacted on the right side of his body. A first hypothesis was made on the position of the legs. We decided to start this study with the left leg in the front and the right one in the rear.

This simulation provided good results with real indications in terms of impact areas and injuries except for the femur fractures. Tibia fractures were observed on the third superior part but not on the femur. In fact, 4 impacts during the simulated kinematic were observed: the lower leg on the bumper, the upper leg on the low bonnet, the shoulder on the high bonnet, the head on the windscreen.

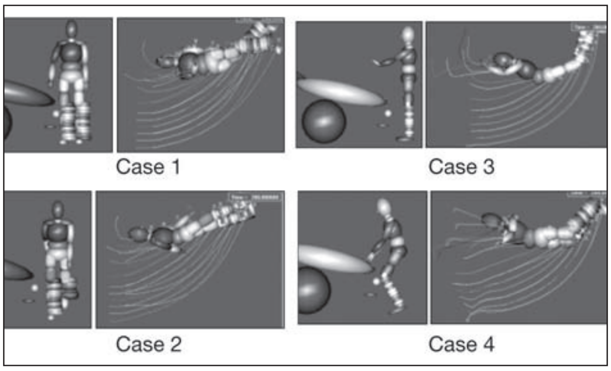

Fig. 6: Variation of the pedestrian kinematic with its position at impact

Because femoral fractures were not retrieved, a parametric study based on this configuration was performed. Parameters concerned:

- the velocity of the car
- the position of the pedestrian at impact
- the pitch angle of the car during the braking phase

Several situations have been simulated. figure 6 shows four different kinematics corresponding to a variation of the pedestrian position at impact. In case one, the pedestrian is walking, in case 2 he is running, in case 3 he is standing in the front of the car and in case 4 he is crouching in the front of the car.

Obviously, the initial position of the pedestrian at impact has a huge influence on his cinematic. So, all simulations which were not in accordance with real indications were rejected. For example, the driver declared that he saw the face of the pedestrian coming towards the car so it was important to be in correlation with this declaration. Consequently, simulations were not retained if they did not give a face impact on the windscreen.

Some specific configurations such as case 3 or 4 have been tested in order to retrieve femur fractures. But even if the pitch angle of the car has been increased, no simulation has given this kind of result.

Finally, hypotheses were made on these fractures and they could be due to the fall on the pavement.

Real Bicyclist Accident

In-Depth Investigation

On 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 (see figure 7).

For this case, skid marks measured approximately 11m. The kinematics reconstruction gave for the car an approaching speed of approximately 55km/h and an impact speed of about 45km/h. The driver statement is in accordance with this result because he declared a speed of around 50km/h. Impact areas were observed on the left headlight, the left corner of the bonnet and on the centre of the windscreen (see figure 7).

The bicyclist was 13 years old. The bicycle impact speed is roughly estimated at 15km/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 with the impact on the left bonnet (and headlight), head traumatism with the windscreen impact and minor injuries on the left side with the fall on the ground.

Numerical Simulation

As it was performed for the pedestrian accident, modifications were applied on the multibody model

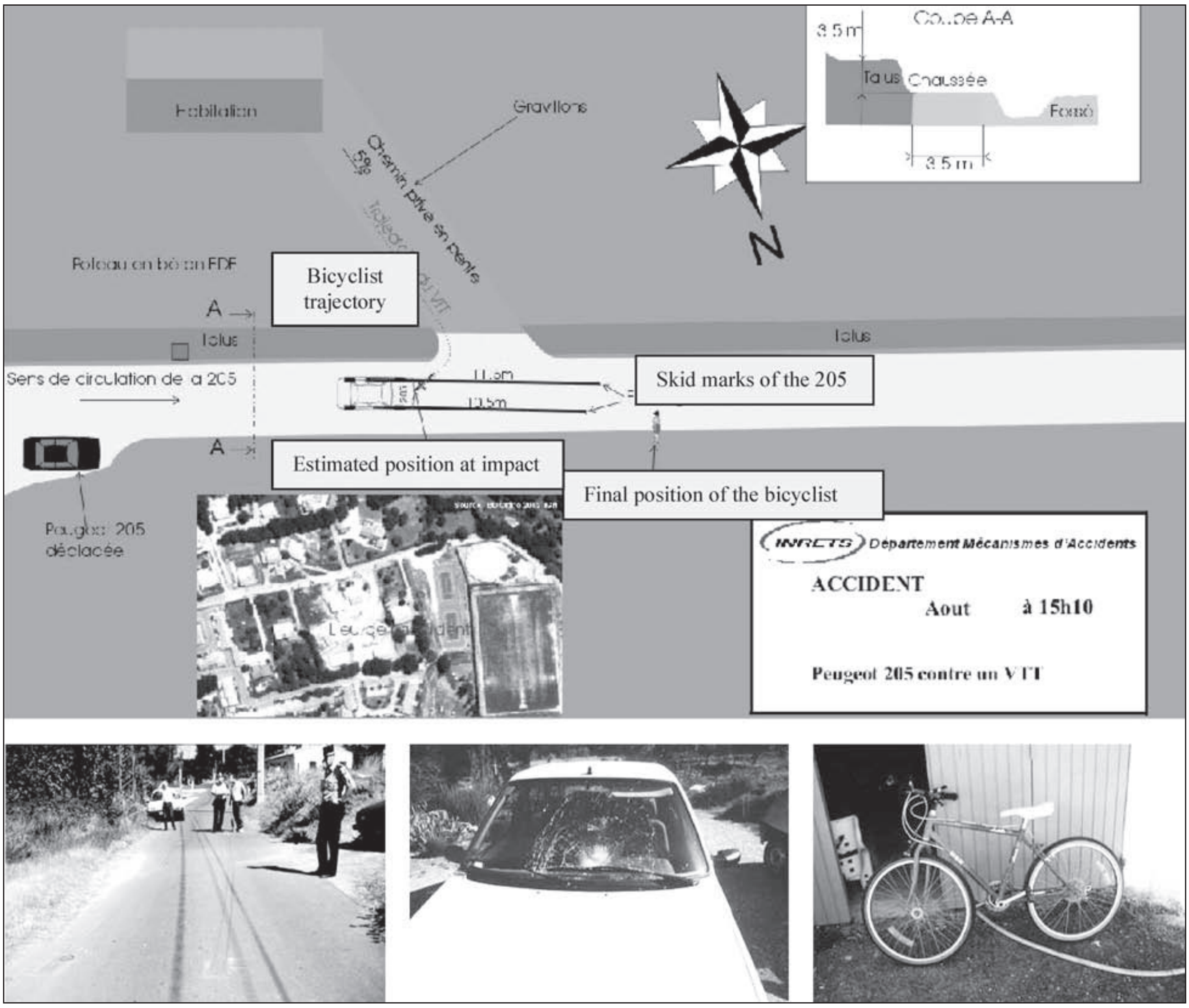

Fig. 7: In-depth investigation for the real bicyclist accident: plan, skid marks, impact points on the 205 and bicycle

to adapt it to the accident configuration. The human body model, the bicycle and the car front shape were modified with the help of clinical records or measurements collected by the investigators.

A parametric study was also performed for this case. Parameters variation concerned:

- the velocities of the car and the bicyclist
- the impact angle (see figure 8)
- the cyclist position on the bicycle

In this case, the orientation of the impact was the most difficult parameter to estimate because it completely changed the kinematic of the cyclist.

The retained configuration was the one which reproduced the same impact area and the same injuries. In particular, an angle of 30° was chosen for the impact orientation.

figure 8 illustrates in parallel, the main steps of this accident and the corresponding chronology. It was possible to decompose it 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, fall to the ground on the left side. Such kinematics could explain injuries observed in the clinical records of the cyclist.

Concerning quantitative results, the multibody model gave information on the accelerations for each body segment (see figure 9). In particular we observed a tibia acceleration of 180g at the impact time of the knee on the headlight and a maximal acceleration of 140g was computed for the head during the impact on the windscreen. Because the head acceleration was “only“ 60g during the impact on the pavement, this result confirmed the hypotheses of relationships between injuries and impacts expected during the accident analysis.

Discussion

The methodology of accident analysis presented here is an approach combining primary and secondary safety principles. It allows us to take advantage of both studies because they are complementary and closely linked.

Indeed, the primary analysis establishes first hypotheses on the configuration of the accident. In particular, it gives approximately the impact orientation and the speed of the car from simple mechanical equations (uniform decelerated movement). 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 with the car. This first estimation

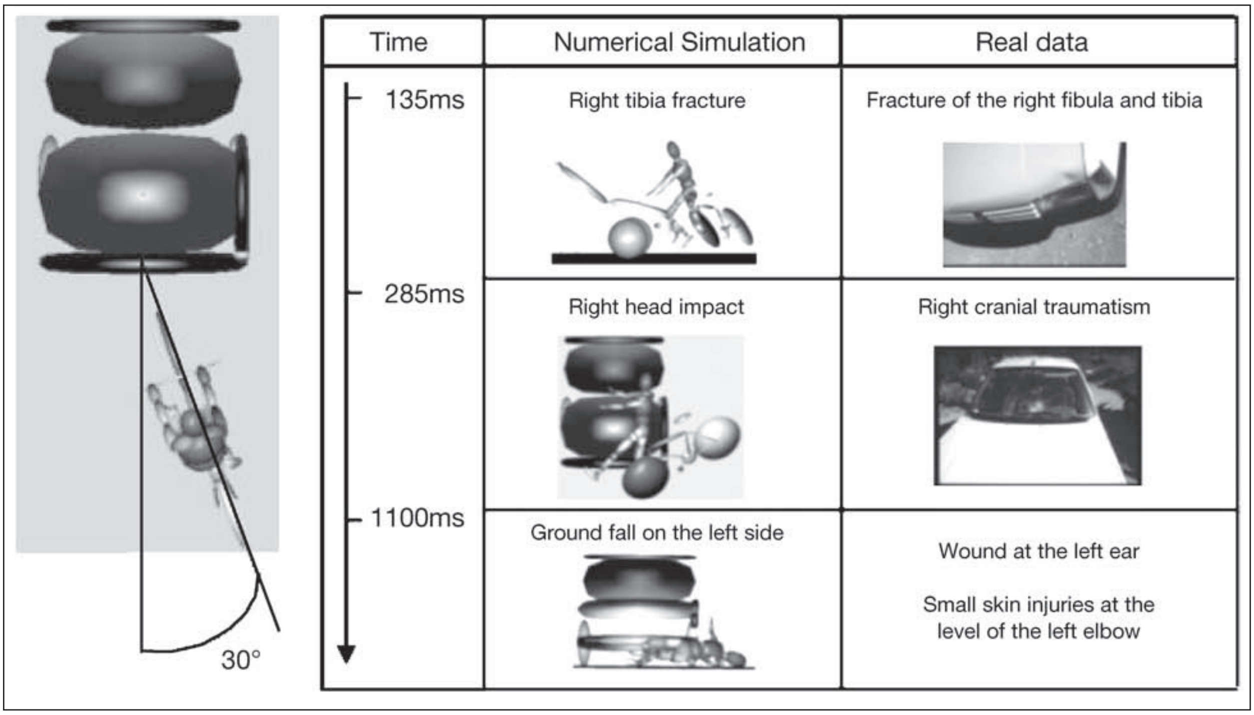

Fig. 8: Impact orientation and numerical simulation chronology

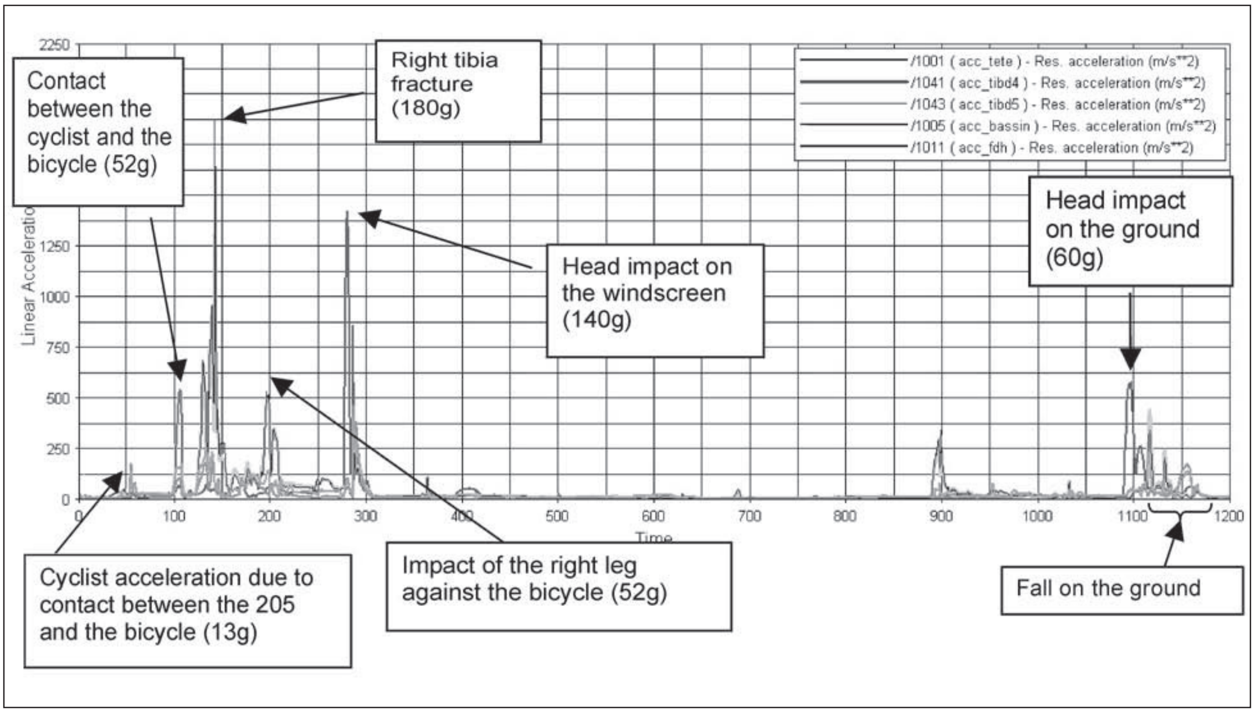

Fig. 9: Body segments accelerations during impact

of the accident parameters gives the input data for a parametric study during the secondary analysis.

This secondary 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 comparison with a finite elements method. In particular it allows a variation of some 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.

Concerning quantitative results, it has been specified that the multibody model used in this study is valid for car velocity lower than 40km/h. Both accidents described here have been simulated with higher speeds and presented nonetheless good correlations with qualitative information. Consequently, it could be considered that the multibody model can be extrapolated for higher speeds and used for real accident reconstructions.

Then this multibody model could be used to evaluate the human body tolerance during a real accident. In particular, it gives information on the levels of accelerations and forces endured by the involved person. Finally, these results can be used to compare experimental tests performed in the biomechanical field and reality.

With regard 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, we observed some of these contacts and it was possible to quantify them in terms of chronology for example.

For the pedestrian accident, its configuration is close to that used for crash test with PMHS. Globally, good correlations can be observed between experimental results and reality except in the case of femur fractures. Because no femur fracture has been noticed during experimental tests with PMHS, we have deduced that these fractures are due to the fall on the pavement.

As far as the bicyclist accident is concerned, its configuration is not the same as the one used in PMHS tests. So we cannot compare real injuries with those observed in the laboratory but we could expect to perform an experimental test of the same configuration for it to be validated.

Conclusion

The aim of this research was to improve understanding of the vulnerable users accidents. In particular, one of the objectives was to obtain a better knowledge of the cinematic behaviour of the pedestrian (or the bicyclist) when impacted by a car. It is based on a comparison between real indications and numerical results. Globally we can consider that the kinematics and the injuries are similar for cases presented here.

More specifically, this methodology allows to quantify the kinematic in terms of acceleration levels for example. It enables also to better interpret the injuries mechanisms and to compare the reality with experimental tests performed in the laboratory.

This research is part of the framework of the French project APPA. The aim of this project is to evaluate the future automotive regulations in terms of pedestrian accidents.

This work will continue with a comparative study between pedestrian accidents and bicyclist ones with the aim to search if pedestrian safety countermeasures suggested or imposed on car manufacturers will be useful or not to bicyclists.

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