Injury Evaluation in Teenage Cyclist-Vehicle Crash by Multibody Simulation

FILIPPO CAROLLO, GABRIELE VIRZI' MARIOTTI
Dipartimento Ingegneria Chimica, Gestionale, Informatica, Meccanica (DICGIM)
Palermo University
Viale delle Scienze, 90128 Palermo
ITALY
filippo.carollo@unipa.it gabriele.virzimariotti@unipa.it

EDOARDO SCALICI
Dipartimento di Biopatologia e Biotecnologie Mediche e Forensi (DIBIMEF),
Palermo University
Policlinico Universitario, Sezione di Medicina Legale, Via del Vespro, 129, 90127 Palermo
ITALY
edoardo.scalici@unipa.it

Abstract: Information on impact locations, impact situations and cyclist and pedestrian dynamics in impacts with passenger cars is fundamental for the development of effective solutions to improve cyclist and pedestrian protection. Accidentology research shows that cyclists typically have a higher impact location than the pedestrian, with a larger share of injuries from the windscreen area. Majority of accidents in Palermo, in the last years, happens at urban street (84%) that involve teenager (6.4%). In this paper simulation study captures dynamics and injuries to head and chest for teenager between a generic bicycle and a car model that is suitable for pedestrian or cyclist safety. Multibody simulation of the crash is executed by making use of Visual Nastran. Dummy, car and bicycle are those used in previous works. The attention is on a teenage cyclist, because the data on this scope are found in literature with difficulty. Twelve full-scale crash tests (passenger car versus cyclist) have as main parameters: vehicle speed (20, 30, 40 and 50 km/h), with three different positions of the cyclist respect to the vehicle: frontal, side and rear. Head impact location (top of bonnet, windscreen), given by crash test, shows that cyclist protection should be higher in the windscreen area than pedestrian countermeasures. In particular the injury of the head is analyzed using the parameter HIC and the chest injury is analyzed by 3 ms criterion; the likelihood AIS 4+ is calculated, concluding that head injury is more dangerous in the case of teenage pedestrian, while chest injury is more dangerous in the case of the teenage cyclist; moreover he has greater possibility of survival than the adult cyclist. Accidentology, simulation and crash test show that the windscreen is a frequent head and chest impact location.

Key-Words: - **Accidentology, teenage bicyclist, vehicle impact, severe (AIS4+) injury, HIC, 3ms criterion**

1. Introduction

Every day in Italy a cyclist loses the life, and other cyclists show more or less serious wounds, requiring hospitalization. The numbers show a true emergency because there are at least 1,000 deaths in the last 3 years. The risk of mortality, by calculating the average value of 1, for cyclists is 2.18, more than double of the base value. Mortality rate is equal to 0.78 for the cars, 0.67 for the trucks, 0.48 for buses, 1.06 for mopeds.

The causes of accidents are the conditions of the roads, too often inadequate and dangerous for the excessive presence of holes, manholes installed incorrectly and uneven ground. The greatest danger to the cyclist is determined by cars and trucks which are classified as the most dangerous means. The cause of possible accidents, however, is determined

by the carelessness of the cyclist or by a dissolute conduct in the management of the two wheels.
Reference is done to previous work for the study of anthropomorphic model of the human figure of a teenager [1], [2] or adult [3], [4], [5] understood as a complex of bones, muscles and joints; for the design of the frame and the bike geometry [6] [7], and finally for the model of the machine [8]. The injury on teenage cyclist is studied because the literature is lacking, while some paper is found for teenagers on scooters [9] or with helmet [10].
The papers on the vehicle - cyclist crash are frequent in the literature, such as [11], [12], [13], [14], [15], many Authors dwell on the comparison of the results on the vehicle-cyclist and vehicle-pedestrian impact as [16], [17], [18]; finally others Authors [19] dwell in head injury risk under tangential condition or with the analysis of the helmet [10] [20]. Many works are carried out by a statistical analysis of actual accidents, by running programs with evidence of numerical simulation; the most widely used programs are MADYMO and Pc Crash. In [21] Authors conclude that the windscreen is a frequent head and torso impact location; in [22] Authors indicate that car-mounted countermeasures designed to mitigate pedestrian injury have the potential to be effective even for bicyclists. In this paper a contribution is given to an engineering solution for the optimization of cars and bicycles, to limit the damage on the parties. Simulations are performed using Visual Nastran to quantify the damage on the head and on the chest. Head injuries are studied using HIC criterion while the chest damages are estimated using 3 ms criterion.

2. Statistics of vehicle-cyclist crash

Statistic [23] [24] shows that cyclists, interacting with others and especially with motor vehicles, are just users that least of all respect the rules of the law by adopting often unpredictable behavior.

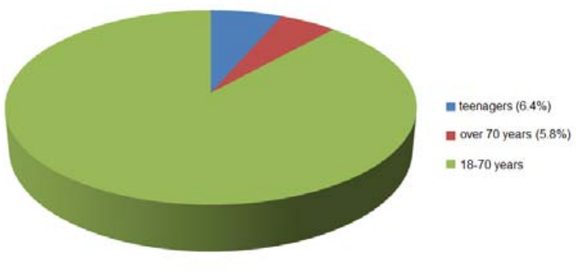


Fig. 1: age of cyclists involved in road accidents.

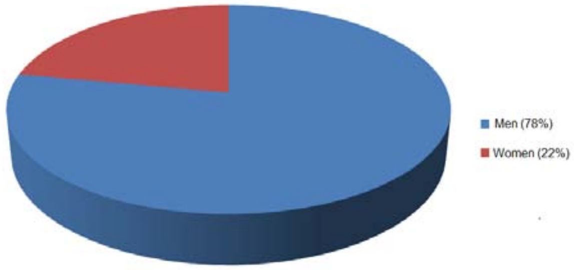


Fig. 2: sex of cyclists involved in road accident.

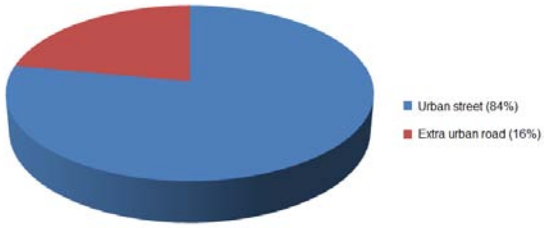


Fig. 3: place of the road accident

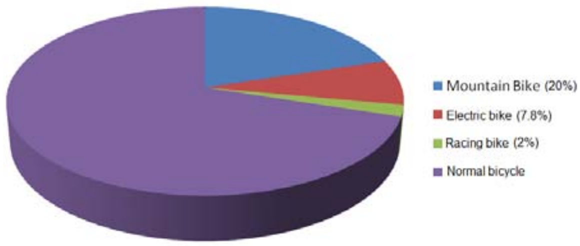


Fig. 4: typology of bicycle

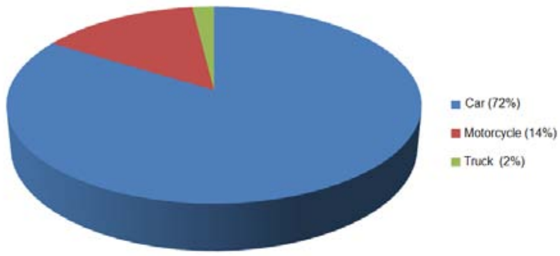


Fig. 5: typology of the involved transports

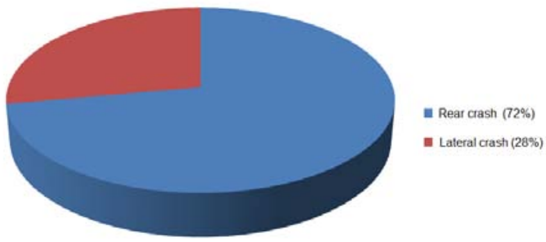


Fig. 6: accident dynamics

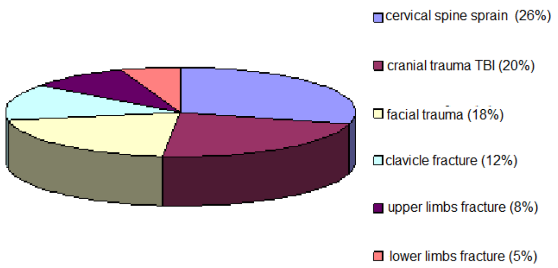


Fig. 7: injuries of the cyclist

Statistic results of accidents in Palermo are shown in fig. 1-6 and are carried out by analyzing the data of 154 accidents involving riders of bicycle. The data, on the last two years, are derived from the archives of the Municipal Police of the City of Palermo and from the archives of three insurance companies. Besides the personal data (age and sex) of the driver, the data are recorded at the accident site (urban, suburban), the type of bike, and damage to the vehicles involved, as well as physical damage reported by the cyclist. The most important data concern the injuries sustained by the cyclist; the data are disaggregated taking into account only the most important cause, because the injuries involve multiple body regions. In all cases excoriating lesions and/or contusions are present in various parts of the body (usually upper and lower limbs), they are reported in Fig. 7.

The most relevant data emerge from the integration of the injuries sustained by the cyclist with the accident; moreover the size and location of the lesions can give conclusive information on the speed of impact and on the dynamics (especially in situations with conflicting statements).

Analyzing the available data, the fracture (also of both bones - tibia and fibula) of the legs is achieved by shock with the bumper of the vehicle, or as a result of the fall with flattening of the limb on the ground (in this case the contralateral limb at the point of impact).

The more frequent case is the side impact at low/moderate speed, without loading or projection of the cyclist. Similarly, the isolated fracture of the contralateral clavicle to the impact point is obtained in the fall phase, in crash at low/moderate speeds.

As well as in the investment of a pedestrian, in the case of a driver of a bicycle, four stages can be differentiated, which are not always present and/or consequential:

- Phase of impact;
- Phase of reduction;
- Loading;
- Phase of propulsion (or boost);
- Phase of wheeling.

The phase of impact occurs with the first contact between the vehicle and the body and is the clearest sign of the investment.

The reduction phase occurs when the victim goes in contact with the ground after the collision, and is the predominant cause of damage of the projecting parts of the extensor surfaces of the limbs (elbows, knees, hands).

The loading phase occurs as the subject is "loaded", as a result of impact against the bonnet and/or windshield of the investor vehicle, this may cause injury to the head or face.

The boost phase is when the invested subject is projected forward with widespread injury or harmfulness excoriation to the limbs.

At last the phase of wheeling is when the wheel of the investor vehicle mounts over the victim body lying on the ground.

Analysis of the available data shows that the fracture (isolated or both bones - tibia and fibula) of the legs is achieved by shock or directed by the bumper of the investor vehicle, or as a result of killing ground of the subject resulting impingement and crushing the limb on the ground (in this case the contralateral limb at the point of impact).

Side impact at low/moderate speed is found in the vast majority of cases, such as not to determine neither the load nor the projection of the driver of the bicycle.

Similarly, the isolated fracture of the clavicle (contralateral to the point of impact) occurs in the reduction phase, in collisions at low/moderate speed.

Cranial trauma (with or without fractures, dental, maxillo-facial or nasal bones) are produced generally in the phase of loading or projection of the subject. Head injury with or without (dental, maxillo-facial, or nasal bones) fractures, is produced in the same phase. Moreover, injury of the facial mass or multiple injury to the upper limbs (outstretched onward in defense of the noblest districts: head and face) are obtained in the cases of telescoping (especially at medium speed).

At last, the complex and combined injuries (multiple fractures to the upper and lower limbs, as well as craniofacial trauma) are present in cases of projection, as result of a telescoping.

The integration and analysis of available data does possible a reconstruction (albeit brief) of the accident and the speed of impact determination.

3. Injury scale

Most widespread scale of anatomical lesion is AIS, (Abbreviated Injury Scale). It classifies the lesions present in a given region of the body through a system of global score based on anatomical aspects. It finds application in forensic medicine to quantify the extent of trauma found on a body so that higher values correspond to more serious injuries AIS. The scale of gravity is ordered in 9 points; the highest score corresponds to a fatal injury. The evaluation of the score of the injury severity is done by dividing the body into six regions, as table 1 shows.

The numerical value of the AIS scale is determined through studies of accident victims whose injuries had already been classified according to the AIS scale. A more detailed specification is found in the international literature, [7] or [1], [3], [4].

The study of the injury of the brain is very studied in the past; for example in [26] a study is conducted to determine the strain on the skull and on the brain by means of an elastic analysis by FEM. Today one prefers the use of risk criteria, based on statistical analysis, for the head and for the various parts of the body. The most common are: the Head Injury Criterion (HIC) and Gadd Severity Response (GSR) for the head, Viscous Injury Response (VC), and 3ms Criterion (3ms) for the chest, the neck, the femur and tibia, Thoracic Trauma Index (TTI) for the chest. Even in this case the international literature provides more insights on the various risk criteria [1], [3], [27], [28]. HIC is used to characterize the injury of the head in the impact of the several zones of the vehicle; it is also used to find correlations between the amount of deformation observed in the vehicle and the magnitude of the acceleration.

According to the directive FMVSS [29], HIC has not to be greater or equal to 1000 over a range of maximum width of 36 ms. It is based on processing the resulting acceleration of the center of gravity of the dummy head, according to the following formula:

$$HIC = \max_{T_0 \le t_1 \le t_2 \le T_F} \left[\left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} R(t) dt \right)^n (t_2 - t_1) \right] \le 1000 \quad (1)$$

where:

• R(t) is the resulting acceleration, in g, measured in the gravity center of the head;

• T_0 is the time of simulation beginning in seconds;

• T_E is the time of simulation end in seconds;

• t_1 and t_2 represent respectively the initial and final instant of a time interval in seconds; the amplitude of this interval is conventionally equal to 36 ms and it is chosen so that HIC assumes the maximum value.

The acceleration curve is constructed with the experimental values by accelerometers, and then a sliding time window is applied. The values of HIC are highest in correspondence of the windscreen pillars, of the sides of the bonnet and the windshield-bonnet junction area. The range of time duration is important; the proposal is done to short the interval from 36 to 15 ms [30] in the cases of impact of the head with rigid bodies.

HIC equal to 1000 identifies an accident of strong gravity, a value of HIC equal to 2000 has values of gravity more than a thousand, but the severity and probability of lethality of the event are not doubled. Head injuries of AIS scale are classified in Table 2. The correlation HIC-AIS is only used on the impact test that covers the head; the experiments for the development of this correlation were performed on dead bodies. This is reported for example in the papers [3] and [4].

Table 1 – Body segments in AIS scale

Body segments	specifications
Head or neck	including the cervical spine
Face	including the skeleton of the face, nose, mouth, eyes and ears
Chest	including the thoracic spine and the diaphragm
Abdomen and pelvic region	including the abdominal organs and lumbar spine
Extremities or pelvic girdle	including the pelvic skeleton
External Area	

Table 2: head injury on AIS scale.

AIS	Description
1	Skin and scalp: abrasions, superficial lacerations. Face: fracture of the nose
2	Skin: more abrasion. Simple fractures or broken down in the face, open fractures or displacements of the jaw, jaw fractures
3	Several fractures, total loss of scalp, contusion to the cerebellum.
4	Complex fractures to the face, exposure or loss of brain tissue, small subdural or epidural hematoma.
5	greater penetration of the brain injury, damage to the trunk and hematoma, subdural or epidural compression, diffusion axonal injury
6	mass destruction of both skull and brain

Trauma to the chest may involve the bony wall of the chest, ribs and spine, the pleura, the lung, the diaphragm or the contents of the mediastinum. Due to the potential of anatomical and functional lesion of the coasts and soft tissues, the thoracic injuries are medical emergencies: if not treated quickly and properly can lead to death. The thoracic injuries are from 20% to 25% of all deaths for injury, and complications of thoracic trauma plus 25% of all deaths.
The chest is the only part of the body that also benefits from the lack of seat belt and the air bag; in fact, supported by a seat belt, it suffered a crushing up to 20 mm with the only belt, 15 mm with the airbag. American standard [31] states that the critical value of crushing of the chest, for the Hybrid III is 76 mm (60g), and then this parameter is not too severe against the driver. In the case of the free dummy the value of crushing is just 3 mm.
The most frequent injuries are to the skeleton and soft tissues. Table 3 gives a complete overview of the types of injury and the parts involved according to the AIS.

Table 3: classification of injuries to the skeleton and soft tissue according to AIS.

AIS	Skeleton injury	injury to soft tissue
1	Rib fracture	contusion to the bronchus
2	fracture of 2-3 ribs; fracture of the sternum	partial tear of a bronchus
3	4 or more rib fractures on a side; 2-3 rib fractures with hemothorax or pneumothorax	pulmonary contusion; minor cardiac contusion
4	fracture of the chest, 4 or more rib fractures on each side, 4 or more rib fractures with emo-pneumothorax	bilateral pulmonary laceration; small aortic laceration; large bruise to the heart
5	bilateral rupture of the chest	severe aortic laceration; pulmonary laceration with pneumothorax tension
6		aortic laceration with hemorrhage

3 ms criterion is used for the chest in this paper, since it is particularly useful for the feedback on the cyclist and is used by rules of both the Europe and United States. It prescribes that the centers of gravity of the thorax and the head are not subjected to accelerations above 60g and 80g, respectively, for a greater time than 3 ms.
The probability of injury AIS4 + is given by the following expression:

$$Prob\ (AIS4+) = 1/(1+exp\ (4,3425-0,063 * g_t) \quad (2)$$

It is equal to 36% assuming g_t =60 g.

4. Virtual model

The indirect approach has the objective of the reproduction of a cyclist-vehicle accident under certain conditions, faithfully reconstructing the event.
Proser Pro is the ideal animation program for the implementation of the human model; it is effective in this kind of work, especially for the possibility of proportioning of each body segment. The human model represents a teenager, so that the model has a height of 1.45 m and a total mass of 45 kg [1] [8] and is a modification of the adult model [4].
The model is imported in Rhinoceros to not create incompatibility with Visual Nastran; the determination of speed, acceleration and inertia moment requires a reference system on the center of gravity of the head; successively each body segment is imported in Visual Nastran. The dummy is constructed without hands, because they have a random behavior (fig. 8).

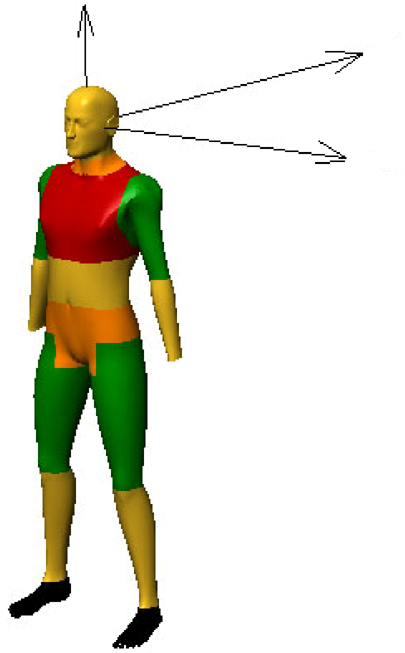


Fig. 8 – Anthropomorphic model with the references axes.

Multibody technique considers rigid the body elements; the forces are changed in correspondence of the constraints imposed during the assembly. It allows considering the representation of the impact between car and bike, without modification of the original shapes.

The position of the gravity center of each body segment is entered manually and one by one. To do it, studies conducted on cadavers [32] [33] [34] are taken as a reference.

The car chosen for the simulations is Audi subcompact car. The information on height, length is provided by the manufacturer. This vehicle is chosen for its characteristics: front angle is not much acute and the bonnet is not too high, since the first part of the machine that undergoes in contact is the front bumper in a frontal impact.

Also in this case the software Rhinoceros 4.0 is used to obtain the CAD model that is imported in Visual Nastran, then the masses, the gravity centers and the inertia moments of the single components as wheels, chassis, bonnet, front bumper are attributed.

The bicycle model is implemented for the study of stability and maneuverability [7], performing dynamic tests for different geometrical configurations. Element of fundamental importance is its center of gravity, which position significantly influences the dynamic behavior of the bike, especially in accelerating and braking.

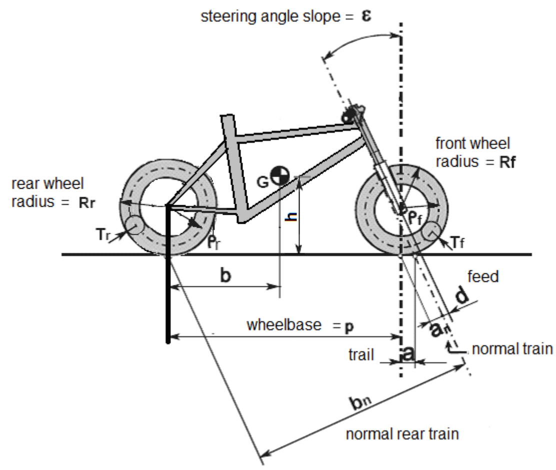


Fig. 9: bicycle geometry (G = gravity center).

Useful geometric quantities for the bicycle characterization are [6]: wheelbase, trail, steer inclination angle (fig. 9).

These quantities define the geometry and the handling of the vehicle; the effects of a single parameter cannot be tested independently from the others, because of their strong interaction. The position of the gravity center influences the dynamic behavior of the bicycle in a determining way, in particular in the phases of acceleration and braking.

International Cycling Union placed a limit to the inclination of the upper tube in the design of the frame to curb the production of bicycles, that are too different from each other, and to bring the performance differences to the physical abilities of the athletes. Top tube has to fit into a parallelogram having a maximum height of eight centimeters (fig. 10).

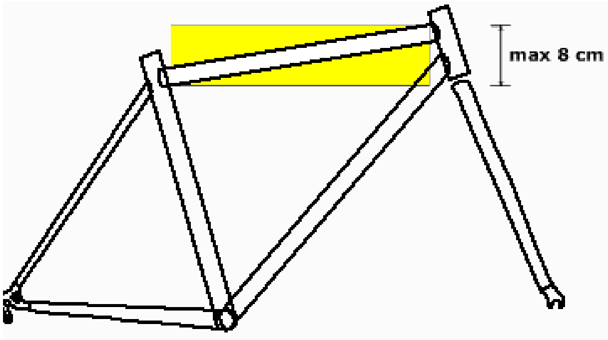
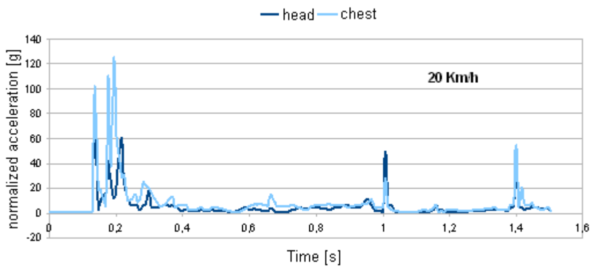
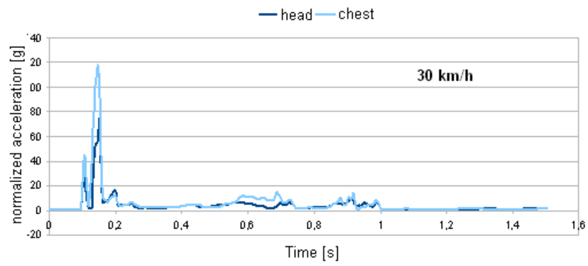


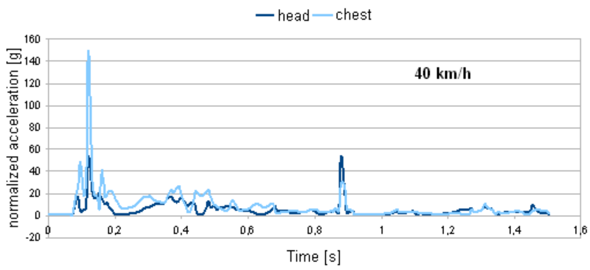
Fig. 10: example of chassis following the rules.

5. Simulation of vehicle-cyclist crash

In the general case the teenage cyclist is placed in position perpendicular to the longitudinal axis of the road, and proceeds at a negligible rate in the direction perpendicular to the oncoming vehicle.







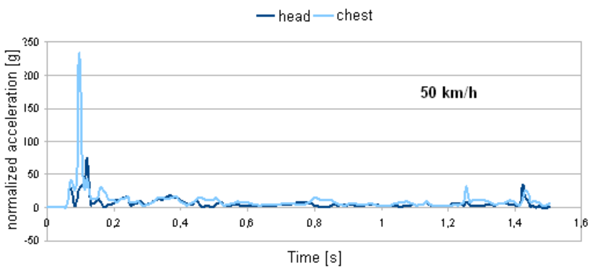
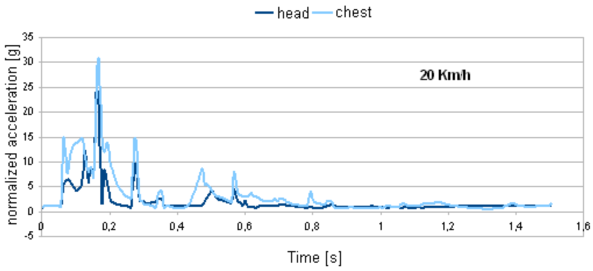
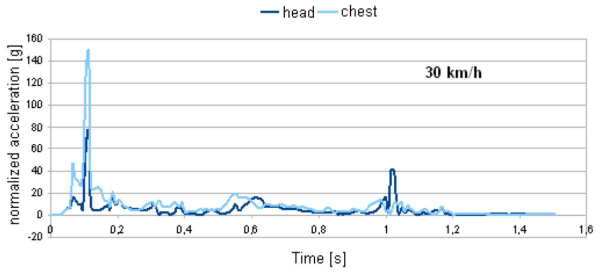
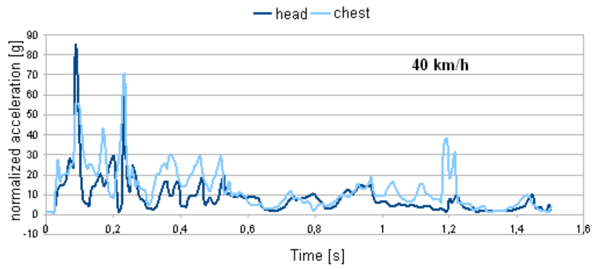


Fig. 11: accelerations in the frontal crash

The action of the vehicle driver takes a decisive role in the evolution of the accident. A speed reduction can only cause minor lesions on the cyclist respect to a constant or higher speed. In reality the actual decrease in the speed of the car is often very poor: even though the car has a brake power that imposes an average deceleration equal or greater than 0.6g, the effectiveness of the braking action may be achieved in a very close moment to that of impact.
This paper considers the teenage cyclist in three locations: in the first he is positioned as described above, and then he is on the road with the side facing the vehicle (side impact). In the second case, the cyclist is in front of the vehicle (frontal impact), while in the third and last case the vehicle is placed behind the bike (rear impact or telescoping)







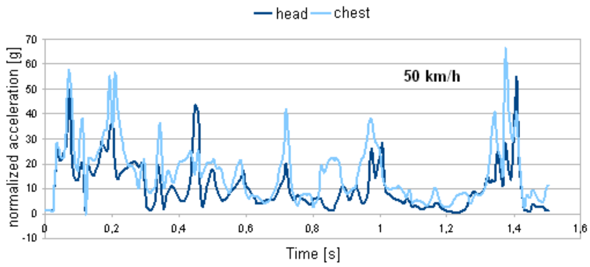
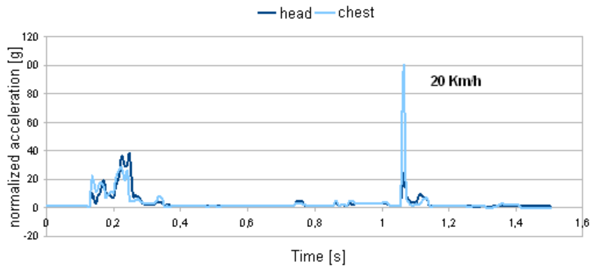
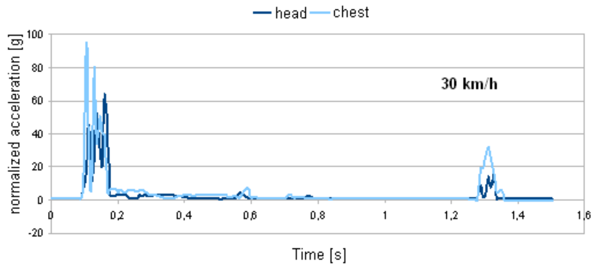
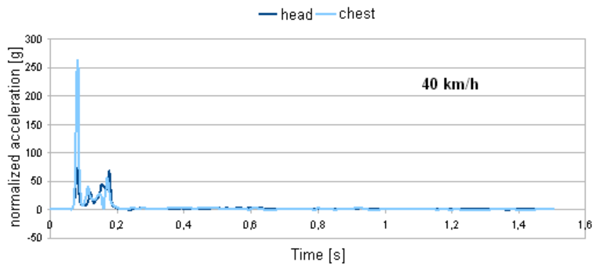


Fig. 12: accelerations in the side crash

Since the law sets the maximum speed equal to 50 km/h on urban road, although the evidence of crash tests complies with this limit. Whereas a speed of 50 km/h can be fatal in the event of impact, crash simulations at speed of 20 km/h, 30 km/h and 40 km/h are also performed.
Measured parameters during the simulations are the accelerations of the center of gravity of both the head and the chest. Fig. 11, Fig. 12 and Fig. 13 show the trends of the acceleration of the head and of the chest versus the time.







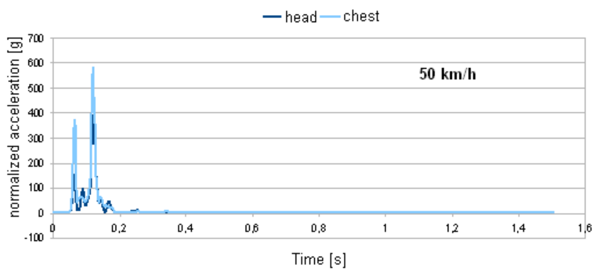


Fig. 13: accelerations in the telescoping

Side crashes see a series of peaks of acceleration caused by the impact on the lateral plane of the skull against the front of the vehicle (bonnet and the windscreen), in these cases the first contact on the bonnet occurs with the shoulder and in a second time with the head. These peaks are repeated usually in the short round of 0.01s due some rapid rotation of the head around the joint of the cervical articulation of the neck.

Graphics acceleration - time of front and rear crash depends on the speed assumed for the test so that they are very different at the several speeds. It occurs because the head is strongly projected backwards, due to the first contact with the bumper of the vehicle. In this way the center of instantaneous rotation of the cervical articulation varies, by determining a variation of the moment of momentum which results in a substantial increase of the angular acceleration of the head. When there is an overlap of impact of the head and the contact of the chest on the bonnet, there is a considerable increase of the measured accelerations of the chest.

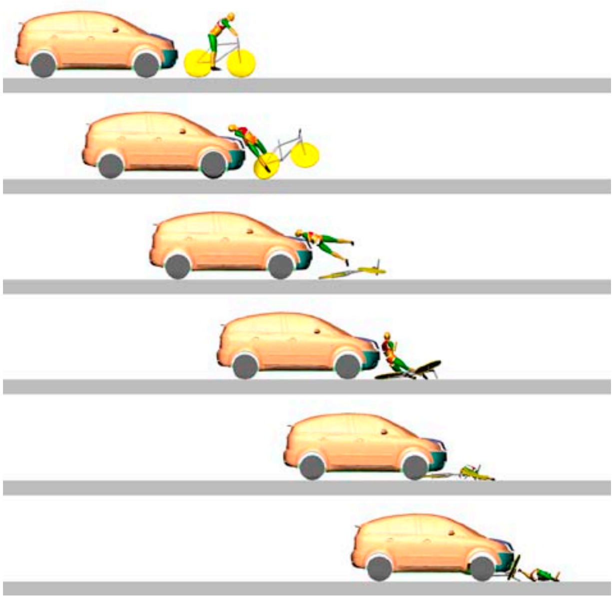


Fig. 14: telescoping at constant speed 20km/h.

Table 4: synthesis of the obtained results.

Test	Crash speed [km/h]	$A_{max\ head}$ [g]	HIC	AIS	%
1	20	18,1	11,9	1	0
2	30	15,9	13,2	1	0
3	40	21,1	25,9	1	0
4	50	73,2	384,9	1	0-5
5	20	25,3	34,8	1	0
6	30	76,8	521,8	2	0-5
7	40	84,7	607,6	2	5-10
8	50	77,5	644,1	2	5-10
9	20	36,5	100,2	1	0
10	30	64,0	316,4	1	0-5
11	40	69,9	344,2	1	0-5
12	50	148	499,1	2	5-10

The reconstruction of the events in Visual Nastran under certain conditions and circumstances allows the observation of the trajectories taken by the teenage cyclist during the crash.

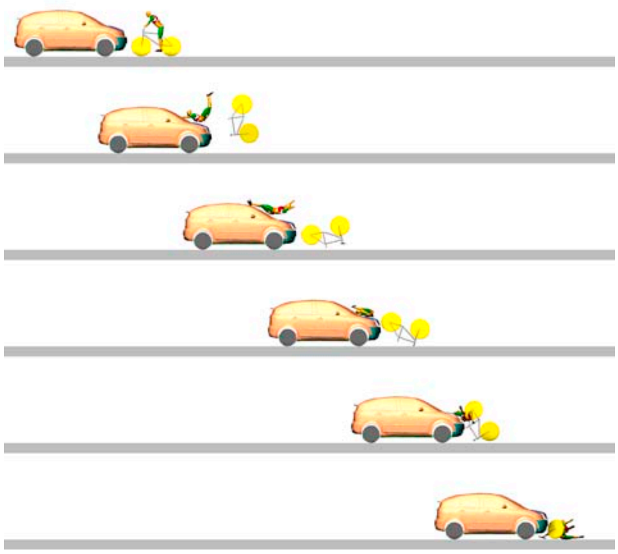


Fig. 15: frontal crash at constant speed 30km/h.

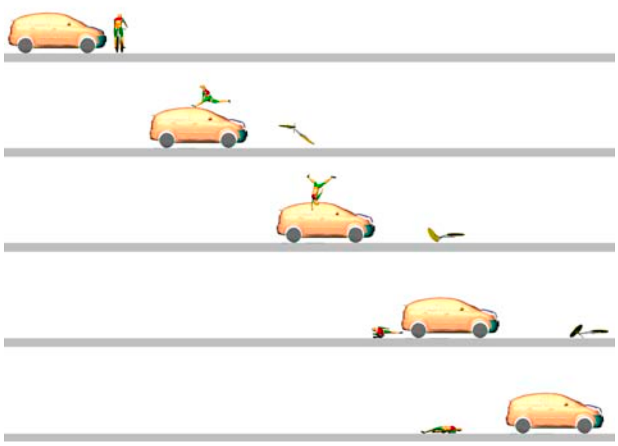


Fig. 16: lateral crash at constant speed 40km/h

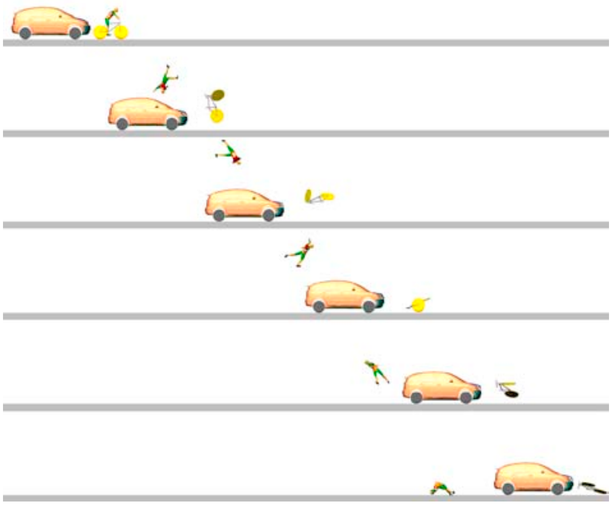


Fig. 17: telescoping at constant speed 50km/h.

Fig. 14 shows the dynamic rear impact test at 20 km/h; one can note the projection forward of the cyclist.

Fig. 15 shows the trajectory of the cyclist in the frontal crash with a vehicle on a constant speed of 30 km/h. One can note the loading on the bonnet and the gradual release of the rider body to the ground.

Fig. 16 shows the cyclist in a lateral position regard to the vehicle that goes on constant speed of 40 km/h. One can note the loading phase on the bonnet and the vaulting of the cyclist.

Fig. 17 shows the cyclist in a rear position compared to the vehicle which goes on constant speed 50 km/h. In this simulation one can note the vaulting on the roof of the car body, which is typical of accidents at high speed.

Table 4 shows a synthesis of the obtained results and of HIC values.

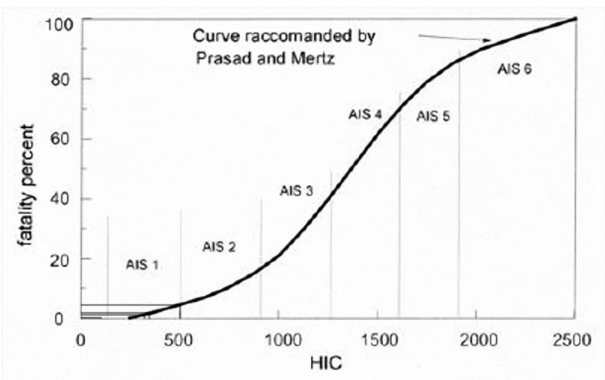


Fig. 18: HIC-AIS correlation (telescoping).

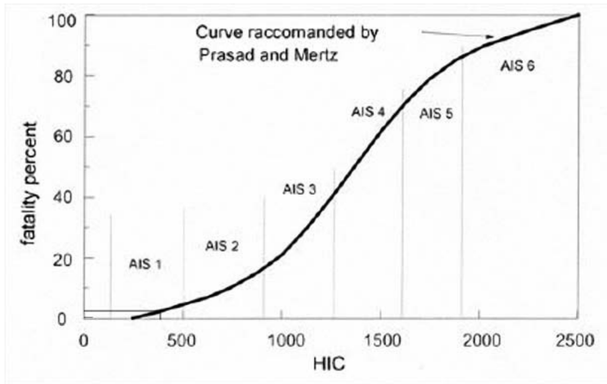


Fig. 19: HIC-AIS correlation (frontal crash).

Fig. 18 shows the correlation HIC-AIS in the case of telescoping. The HIC data obtained in the simulations, together with the scale of the lesion AIS, determine the percentage mortality of the event. In analogous way the correlation is determined in the other two cases of frontal crash (fig. 19) and side crash (fig. 20). The last two columns of Table 4 summarize the obtained AIS and lethality percentage.

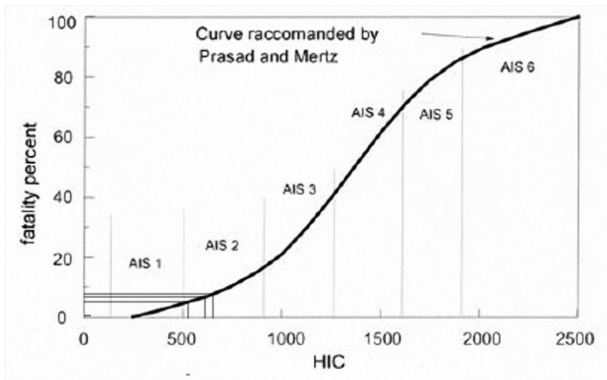


Fig. 20: HIC-AIS correlation (side crash).

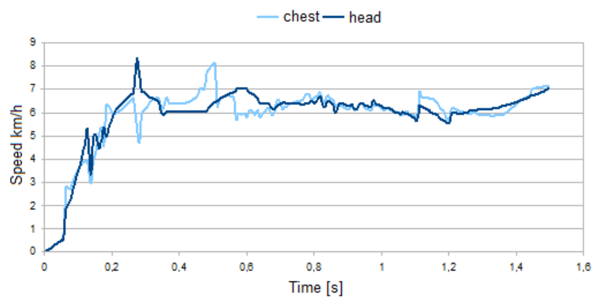


Fig. 21 – Speed of head and chest in the side impact at 20 km/h

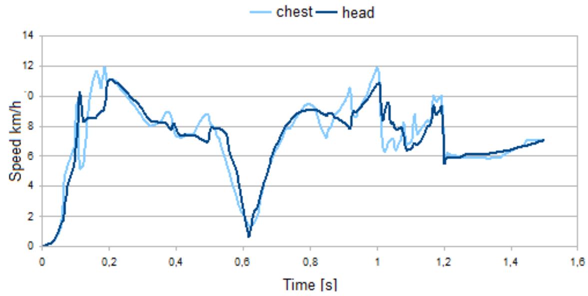


Fig. 22 – Speed of head and chest in the side impact at 30 km/h

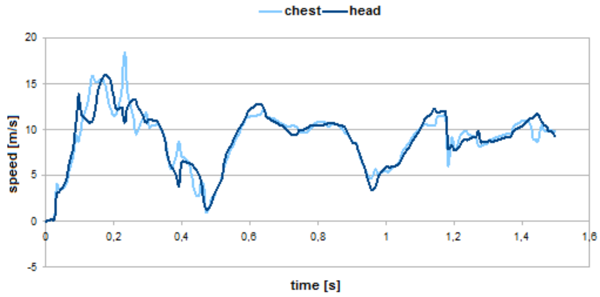


Fig. 23 – Speed of head and chest in the side impact at 40 km/h

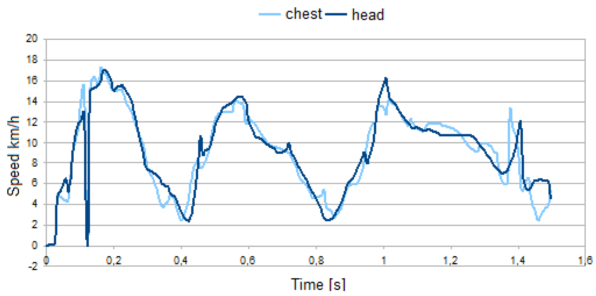


Fig. 24 – Speed of head and chest in the side impact at 50 km/h

Figg. 21-24 show the trend of the speed of both the head and chest in the case of side impact at the several speeds 20, 30, 40 and 50 km/h versus the time.

Table 5: 3 ms criterion and likelihood AIS4+.

test	Position	speed [km/h]	3ms [g]	Prob (AIS 4+)
1	frontal	20	125	97,2%
2	Frontal	30	115	94,8%
3	Frontal	40	145	99,2%
4	Frontal	50	225	100%
5	Lateral	20	31	8,4%
6	Lateral	30	28	7,1%
7	Lateral	40	58	33,4%
8	Lateral	50	57	32,0%
9	rear	20	22	4,9%
10	rear	30	92	81,1%
11	rear	40	250	100%
12	rear	50	565	100%

Table 6: comparison HIC cyclist - pedestrian.

Test	Position	Crash speed [km/h]	HIC percentage difference
1	Frontal	20	-95,4%
2	Frontal	30	-98,4%
3	Frontal	40	-98,5%
4	Frontal	50	-84,4%
5	Lateral	20	-62,6%
6	Lateral	30	-21,3%
7	Lateral	40	-46,0%
8	Lateral	50	-56,7%

A virtual accelerometer is added on the gravity center of the chest in order to obtain results of interest for the frontal simulations. Table 5 shows the results: the last column shows the likelihood of injury AIS4 + (fracture of the chest and tearing of the aorta) by making use of the relationship (2). The acceleration values of the chest in the front and back collision are very high. This is due to the capacity of the trunk to flex to direct contact of the chest with the vehicle.

6. Results comparison and discussion

Table 6 shows the percentage difference between the impact analysis teenage pedestrian – vehicle and teenage cyclist – vehicle, in terms of HIC.

Fig. 25 and Fig. 26 show the comparison: teenage cyclist has a better chance to survive in frontal and side impact than a pedestrian of the same age because HIC values are consistently lower.

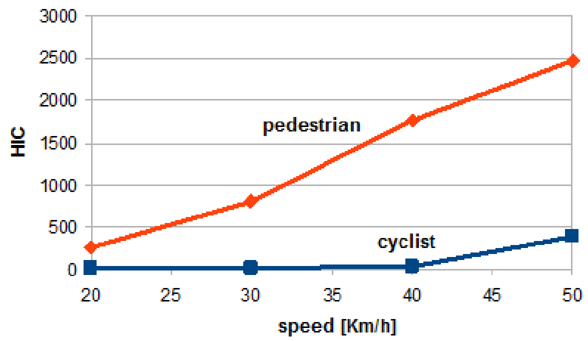


Fig. 25: comparison HIC teenage cyclist – teenage pedestrian in frontal crash [1].

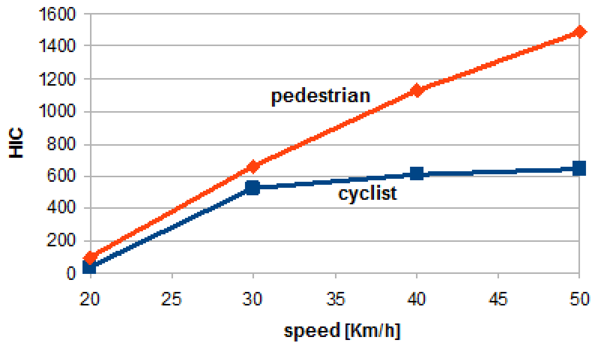


Fig. 26: comparison HIC teenage cyclist – teenage pedestrian in side crash [1].

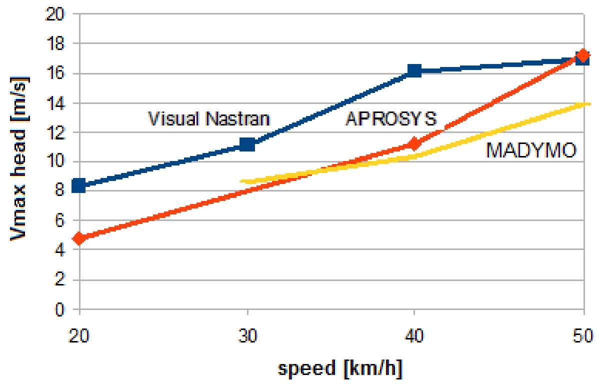


Fig. 27: comparison Vmax, among simulations in Visual Nastran, APROSYS and MADYMO.

Table 7 shows a synthesis of the obtained results and of the values of maximum impact speed with the time of contact. The data are reported by fig. 21-24, in the case of lateral impact, and are those useful for the comparison with analogous data in literature [13], [14] obtained by the software MADYMO and APROSYS. The graphic comparison is shown in fig. 27.

Table 7: maximum speed and the head contact time

test	Position	Impact speed [km/h]	V_{max} head [m/s]	V_{max} chest [m/s]	Time contact [ms]
5	Lateral	20	8,29	8,11	272
6	Lateral	30	11,13	11,96	208
7	Lateral	40	16,03	18,49	176
8	Lateral	50	16,98	17,26	176

The following considerations may be done:
- The difference in the value of the maximum speed of impact of the head, regard to the model developed with Visual Nastran, is attributable to the fact that the cyclist examined is a teenager (with mass and height less than that of an adult) and that the front of the vehicles has different geometry.
- The impact maximum speed of the head increases as soon as the speed of the vehicle increases.

A further comparison is possible from the data reported in [21]. Test of vehicle cyclist impact are executed by means of two other multibody software (MAYDMO, APROSYS). The adult cyclist is found in side or front or rear position respect to the vehicle that goes on speed 50 km/h. Tab 8 summarizes the more significant data.

Table 8: HIC at 50 km/h

	Visual Nastran HIC_{36}	[21] HIC_{15}
Side test	644	1433
Front test	384.9	753
Rear test	499,1	4429

These further considerations may be done:
- the difference of HIC values in the rear impact, respect to the model developed in Visual Nastran, is imputable to the fact that the cyclist is a teenager, with lower mass and height than an adult; it has greater likelihood to execute a similar trajectory to the roof vault. In this case the adult cyclist is lifted in high due to the combined effect of the impact speed and of the vehicle shape. At the end of the vault the cyclist body is found behind the vehicle.
- HIC values with MADYMO and Visual Nastran in the simulation of side impact can be considered suitable, because the first contact of the teenager with the bonnet occurs with the shoulder, and successively with the head. Another cause of the difference is due to the range time that is 15 ms in [21] and 36 ms in this paper. Of course the results of this paper do not take in account the deflection of the bodywork.
- WAD values reported in [21] are higher for analogous reasons.

The comparison shows that the teenage cyclist has greater possibility of survival than the adult cyclist, all the other condition being equal; the influence of the bonnet shape has to be evaluated with attention, since it can have a fundamental importance. In all the cases the impact with the bonnet has to be considered less dangerous than the impact with the windscreen, because the last is more rigid [35].

Table 9: percentage differences 3 ms criterion

Test	Position	Impact speed [km/h]	3 ms percentange difference with pedestrian
1	Frontal	20	+214,9%

2	Frontal	30	+84,3%
3	Frontal	40	+8,9%
4	Frontal	50	+66,9%

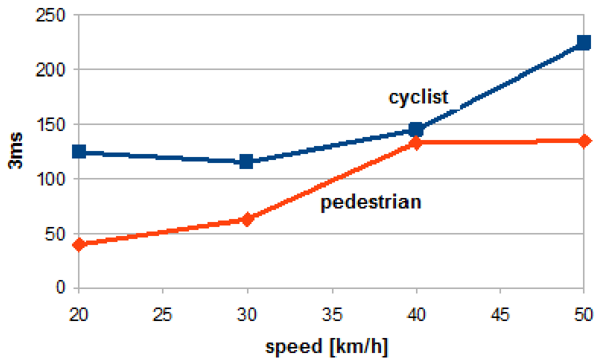


Fig. 28: frontal impact cyclist- teenage pedestrian

Table 9 shows the percentage difference between the impact analysis vehicle-teenage cyclist and vehicle-teenage pedestrian, following 3 ms criterion. Fig. 28 shows the trend and the comparison.
Teenage cyclist is more likely to suffer an injury to the chest, in the frontal impact than a pedestrian of the same age, because the values obtained by 3 ms criterion are consistently greater.
Fig. 29, Fig. 30 and Fig. 31 show the marking of the vehicle for the identification of areas of the bonnet involved when the subject head hits the front of the vehicle (WAD); it occurs according to the directives EURONCAP [36].
One can observe that the dispersion of the points of impact is localized in all cases in the area of WAD 1500 except for impacts at 20Km/h and for rear impact vehicle- teenage cyclist at 30km/h (WAD 1000).
Dispersion of points in the side impact involves a larger area than the frontal case. Furthermore, the analysis of the contact points of both cases, allows to obtain a new confirms of the values accuracy. The very intense acceleration peaks correspond to a collision against a rigid wall of the vehicle front.

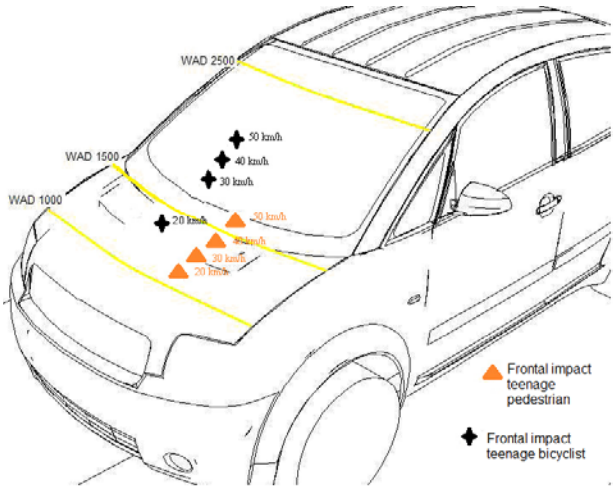


Fig. 29: head contact points in the frontal crash.

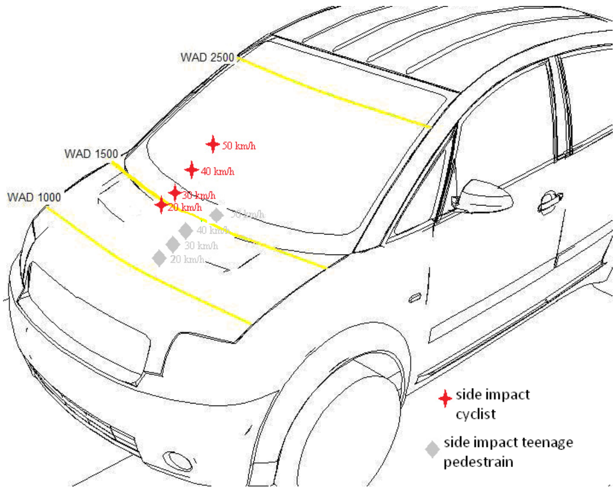


Fig. 30: head contact points in the side crash.

Fig. 29 and fig. 30 compare the points of contact with those of the pedestrian. Simulations stand the same impact zones (WAD 1000), at 20 km/h; the rider hits the underside of the windscreen (areas between 1500-2100 WAD) at 30 and 40 km/h, while the pedestrian hits the upper part of the bonnet (the area between 1000-1500 WAD). Impact points are on the windscreen but at a different height, at 50 km/h. The differences are due to higher position of the head. WAD value obtained in [21] in the case of adult bicyclist is 2500 about, due to greater height of the bicyclist.

7. Conclusions

The aim of this work is the evaluation of the damage in the case of accident in order to suggest improvements and solutions to the designers for the security increase, in order to limit the damage to the persons.
The analysis of experimental data and of the simulations shows the importance of key elements

such as: the height of the rider, the front profile of the car and the minimum height from the ground, the rigidity of the parts that come in contact with the cyclist at the moment of impact.

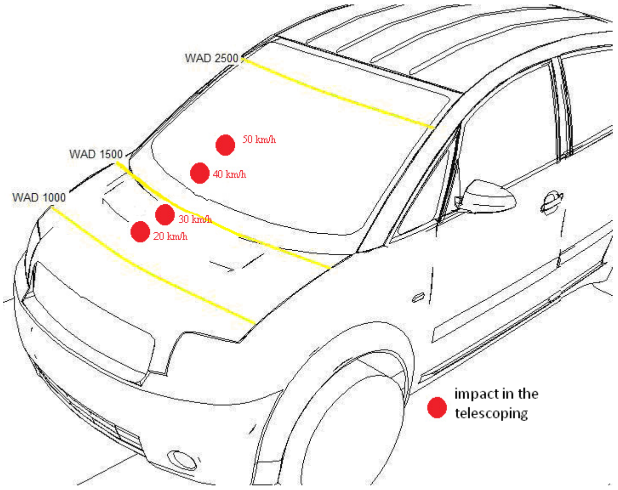


Fig. 31: head contact points in the telescoping.

Impact on the bonnet rather than on the windscreen, (it is the case between vehicle and pedestrian), has greater chance to evolve positively, since the bonnet of the car is much less rigid than the windscreen and the percentage of risk of suffering lethal damage is lower. The impact points of the cyclist head are much higher. They occur at a height such as to cause the fall in the vicinity of the windscreen. This difference occurs because the center of gravity of the rider is higher than that of the pedestrian.

Position of the rider at the accident time is very important: the side position is more damaging than the front, in fact the values obtained from the simulations show that HIC values are higher, because the head of the rider immediately strikes the bonnet; the bike would have to absorb the impact but cannot.

A different thing occurs in front and rear impact. In this case the car affects primarily the bike that absorbs the shock, then the impact point is highlighted in the vicinity of the wheel and the cyclist falls in a different way.

HIC values are within the value HIC 1000 in all the simulations; this is possible because a good part of the impact is absorbed from the bicycle and not from the body of the cyclist; the contrary occurs in the case of the pedestrian. Higher HIC values are obtained in both front and rear impact of the pedestrian.

The values of chest injuries by the criterion of 3ms are above the limit set by rule (60g), they are higher than those resulting from the simulations pedestrian-vehicle. Also the parameter AIS4+ (i.e. fracture of the chest and tearing of the aorta) is higher. Also this time the reason is the position of the gravity center of the cyclist; at the moment of impact the chest falls near the windscreen.

In general teenage cyclist has greater possibility of survival than the adult or teenage pedestrian and the adult cyclist, also if chest injury is more dangerous in the case of the teenage cyclist.

The use of the multibody software for the simulations is advantageous: in this case the simulations are executed starting from CAD models. In this way, the study of the vehicle, which must necessarily pass approval tests, is certainly easier and can lead to good results with reduction of the costs.

This kind of simulation has impact on safety, thanks to tests on the passive and active safety for a flawless and more efficient performance. Automakers have begun to focus their attention on the safety of cyclists, studying and patenting deformable bumper to mitigate, in case of accident with a bicycle, the violence of the impact. Other solutions include the introduction of airbags for head protection of the rider, positioned between the bonnet and the windshield, in those critical points of impact that are highlighted in the simulations.

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