Injury and Throwing Distance in Teenage Cyclist- Vehicle Crash

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Abstract: The study of the injury caused by vehicle-teenage cyclist crash is presented in this paper. The results of the crash with three vehicles: sedan, SUV and Pick up are compared. Three different positions are analyzed: front, rear and lateral position. The injury on the cyclist head is examined by HIC criterion, in the way indicated by the rules. A comparison is done between the results of the simulations for Pick up, SUV and sedan, concluding that the injury of the head is more dangerous for Pick-up impact than SUV or the sedan, but only at greater speed than 40 km/h. Teenage cyclist is more likely to suffer an injury to the chest in rear impacts with the sedan, because 3 ms values remain above the values obtained with the SUV and Pick up. Unlike Pick up could cause greater injury to the chest in the front and side impact because of greater height from the ground. The vehicle mass has not great importance, but only to low speed. Consideration is made that teenage cyclist has a better chance of surviving in the front impact collision than adult pedestrian, because HIC values remain consistently below the determined values. A further comparison is done between the impact points of the three vehicles concluding that both the shape of the bonnet and the height of the front part must be studied carefully in order to reduce the damage to cyclists and pedestrians. At last the throwing distance are calculated and compared with the literature data, concluding that they are strongly dependent on the relative position.

Key-Words: teenage bicyclist, vehicle impact, (AIS4+) injury, HIC, 3ms, throwing distance, biomechanics

1 Introduction

Many works are found in literature on the impact between vehicle and teenager [1] [4] or adult pedestrian [2] [3] [5] [10] [18] [23] [28] [29], also numerous works study the impact between the vehicle and the adult cyclist [9] [11] [13] [16] [17] [20] [21] or both cyclist and pedestrian [6] [7] [8] [12] [22], but the papers on the accident vehicle - teenage cyclist; are not numerous in literature [14] [15] [19] [35] [36] [37]; other works are not found on this scope. In [21] Authors indicate that car-mounted countermeasures designed to mitigate pedestrian injury have the potential to be effective even for bicyclists, while in [33], [34] Authors investigates the deploying time (or response time) of an active hood lift system (AHLS) of a passenger vehicle activated by gunpowder actuator.

In general multibody technique is the applied method for numerical simulation; the most widely used programs are MADYMO, Aprosys, PC Crash, while Sim Wise is effectively used in this paper.

Studies give an idea of the shape of the front of the vehicle in order to reduce injuries, that may arise due to the impact [18] [29], but these works are not frequent in literature. In particular the works [21] [22] [23] also address the crash between SUV vehicle against cyclist or pedestrian, but other papers on Pick up – cyclist impact are not found, over the paper [42]. This extends the results already achieved in the papers [14] [15] [37] where the damages caused by the energy impact of a teenage cyclist with a sedan car are taken into account and analyzed. Analogous crash is studied in case of vehicle constituted by a SUV [35] [36] instead than a normal sedan, in order to fill the gap in literature:

references are found only to an adult or to a child, in many cases without taking into account the type of vehicle.
A campaign of virtual simulations is conducted with the availability of the virtual model Pick Up-teenage cyclist [42], in order to quantify the damage caused to the head and chest on the basis of certain criteria such as HIC and 3 ms criterion [24] [25].

2 Implementation of Virtual Models

The paper [1] is very useful for the study of anthropomorphic model of the human figure of a teenager, understood as a complex of bones, muscles and joints, while the paper [3] has analogous value for the adult; the book [26] and the paper [27] are very useful for the chassis design and the geometry of the bike (fig. 1). The implementation of the virtual model of the bike is the same for SUV and sedan simulations [35] [36].
Virtual simulations, performed with Sim Wise, allowed quantifying the damages in the teenager cyclist – Pick Up impact on head and chest. Specifically HIC criterion is used regard to head injuries and 3 ms criterion for chest injuries.

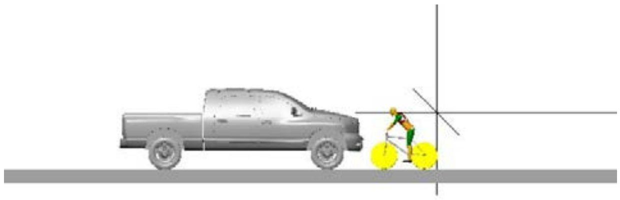

Figure1: cyclist model in Sim Wise

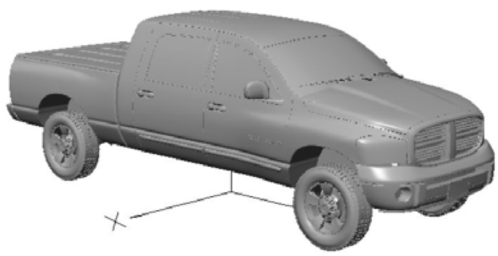

Figura2: Pick-up in Sim Wise

The vehicle for the simulations is Pick-up of the automaker Dodge. The information on pitch, height, length was provided by the manufacturer itself. Taking into consideration the impact mode, this type of Dodge Ram was chosen for its characteristics: the chassis has been completely redesigned for high-strength steels that increase stiffness and decreasing torsion vibrations and power; aerodynamics is better than every other Pick up, despite the new aggressive front. Autodesk 3D Studio Max software is used to get the STL model, which was subsequently imported into Sim Wise (fig. 2), attributing the masses, the centers of gravity and moments of inertia of the individual components such as wheel, body, chassis, bonnet, front bumper; these parameters are essential for the proper conduct of the tests and the acquisition of results.

3 Pick up - cyclist crash test

This article illustrates, through the use of charts, tables and representations, the tests to assess the damage produced on teenage cyclist under varying condition of impact, in order to calculate HIC as regards the trauma to the head and the application of 3ms criterion for the evaluation of damage to the chest. Dynamic of impact of teenage cyclist – Pickup are reconstructed by Sim Wise. Greater information is reported in the paper [42].
The relative positions between the vehicle and the cyclist are the same as those used for already examined vehicles [14] [15] [35] [36] [37]. The positions are three: In the first the teenage cyclist is positioned on the roadway with the side facing the Pick up about to occur (side impact); in the second case the cyclist is located opposite the Pick up about to occur (frontal impact), while in the third and last case the cyclist is placed behind the pick up (telescoping or rear impact).
Also in this paper, crash tests are executed at four different speeds: 20 km/h, 30 km/h, 40 km/h and 50 km/h.

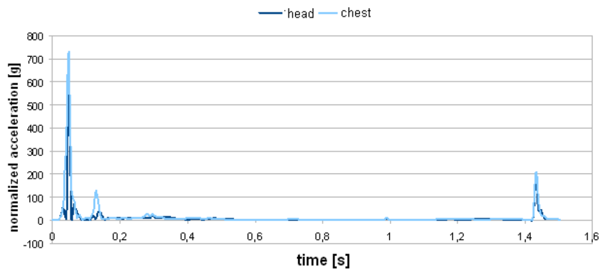

Figure 3: Head and chest acceleration in the side impact at 40km/h

The parameters measured during the tests are:
- Acceleration in the head gravity centre;
- Acceleration in the chest gravity centre.

An example of acceleration performances of the head and thorax is shown in fig. 3.

3.1 Test Analysis

Events reconstruction in Sim Wise in certain conditions and circumstances allows observing the trajectories taken by the adolescent cyclist throughout the collision, by comparing each time the extracted data from the trials with the test frames. The sequence, represented in fig. 4, shows the cyclist in a lateral position with respect to the pickup that proceeds at constant speed 40 km/h. One may notice the loading on the hood and on the same vault of the cyclist body. Other sequences are reported in the paper [42]

The tests carried out revealed a host of very useful information to analyze the most important aspects.

Table 1: obtained results and HIC values

Test	Position	Impact speed [km/h]	$A_{max\ head}$[g]	HIC
1	Front	20	69,51	372,18
2	Front	30	78,94	411,72
3	Front	40	99,19	784,78
4	Front	50	177,01	4464,56
5	Side	20	111,85	213,04
6	Side	30	76,41	362,75
7	Side	40	563,19	4832,44
8	Side	50	236,56	7726,09
9	Rear	20	40,14	54,46
10	Rear	30	68,74	277,26
11	Rear	40	73,85	473,88
12	Rear	50	285,44	7543,26

Table 1 summarizes the obtained results and HIC values. Figure 5 shows the trend of HIC versus the impact speed for the three examined positions.

Figure 6 shows the correlation HIC-AIS in the case of side impact at constant speed. HIC data obtained in the tests with the injury scale AIS determine the fatality percentage. Analogous procedure can be used using the same correlation graphics for the other impact conditions; the values are reported in table 2.

3.2 Results and discussion.

Test can be distinguished in 3 groups:

1. tests 1 - 4 conducted for front impact;
2. tests 5 - 8 conducted for side impact;
3. tests 9 - 12 conducted for rear impact.

In all the cases the graphs (fig. 3) show a series of acceleration peaks caused by the impact on the lateral plane of the skull against the front of the Pick-up (bumper and bonnet); the first contact with the bonnet occurs at the shoulder and at a later time with the head. These peaks are repeated generally in the short around the 0.01s, due to some rapid rotations of the head around the articulation of the cervical neck.

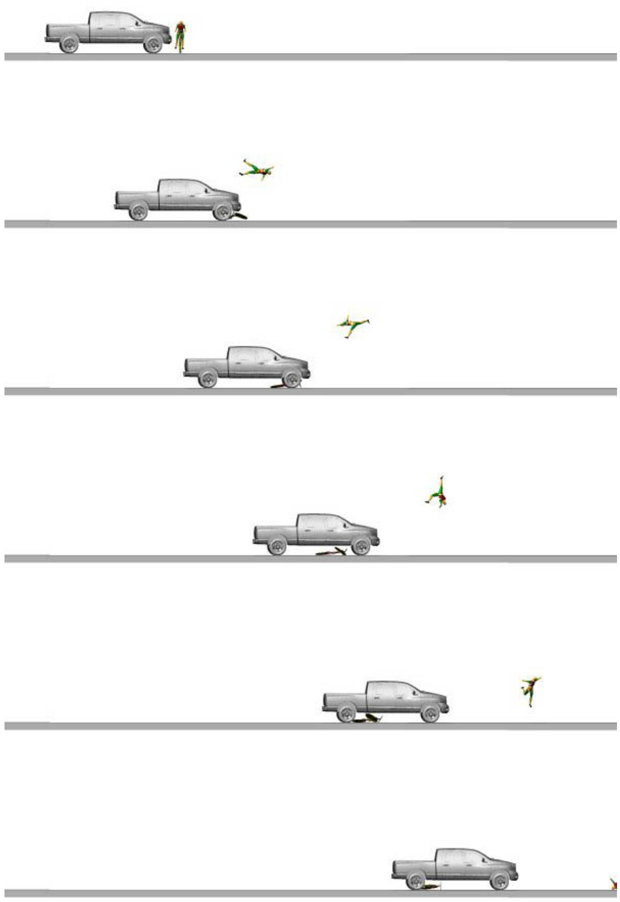

Figure 4: telescoping at 40 km/h, constant speed.

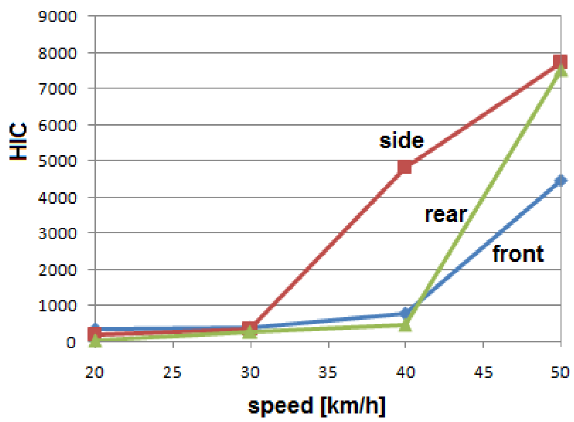

Figure 5: HIC values in the several positions

The subsequent peaks are quite random and not dependent on the assumed speed for the test, so that the graphics acceleration - time appear very different at different speed. This is because the head of the teenage cyclist is projected back strongly, due to the first contact with the vehicle bumper. In this way the centre of the instantaneous rotation of cervical joint varies by determining a variation of the moment of momentum which results in a substantial increase of the angular acceleration of the whole head.

A considerable growth of the chest accelerations is noted when, in some cases, there is an overlap of the head bump and of the chest contact on the bonnet.

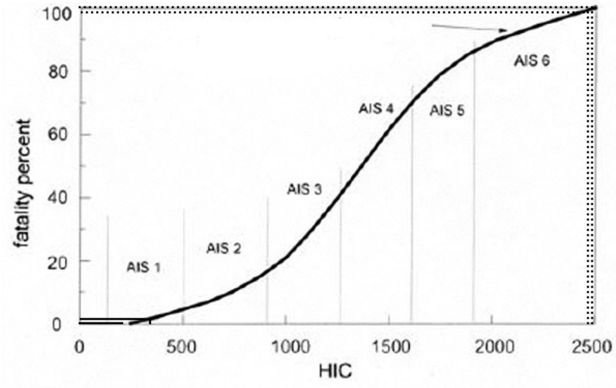

Figure 6: HIC-AIS correlation (Side impact at constant speed)

Table 2: fatality percentage following the correlation HIC – AIS

Test	Posit.	Impact speed [km/h]	AIS	fatality [%]
1	Front	20	1	0-5
2	Front	30	1	0-5
3	Front	40	1	10-20
4	Front	50	6	100
5	Side	20	1	0
6	Side	30	1	0-5
7	Side	40	6	100
8	Side	50	6	100
9	Rear	20	1	0
10	Rear	30	1	0-5
11	Rear	40	1	0-5
12	Rear	50	6	100

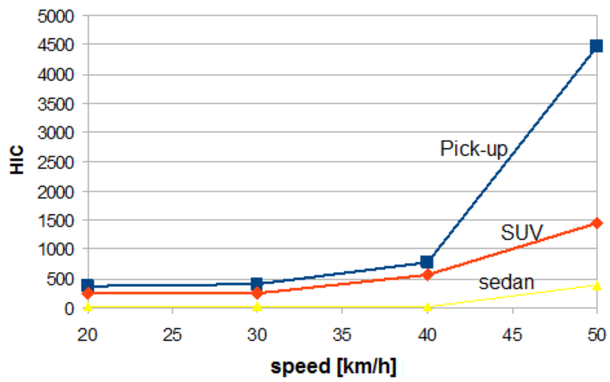

Figure 7: HIC in the frontal impact

3.2.1 Results Comparison

Table 3 shows the percentage difference between the impact analysis Pickup-cyclist with SUV-Cyclist [35] [36] and sedan-cyclist [14] [15] [37], in term of HIC. The small differences at low-speed can be attributed to the acceptable imprecision of the elaboration.

Table 3: comparison HIC PickUp– SUV and sedan

Test	Posit.	Impact speed [km/h]	HIC Difference with	
			SUV	sedan
1	Front	20	+55,39%	+3027,53
2	Front	30	+32,74%	+3019,1
3	Front	40	+37,83%	+2930,4
4	Front	50	+207,17%	+1059.93
5	Side	20	+1934,77%	+512,18
6	Side	30	+90,62%	-30,48
7	Side	40	+754,86%	+695.33
8	Side	50	+486,57%	+1099.52
9	Rear	20	+16,37%	-45,65
10	Rear	30	+52,37%	-12,37
11	Rear	40	-42,42%	+37,68
12	Rear	50	+146,85%	+1411,37

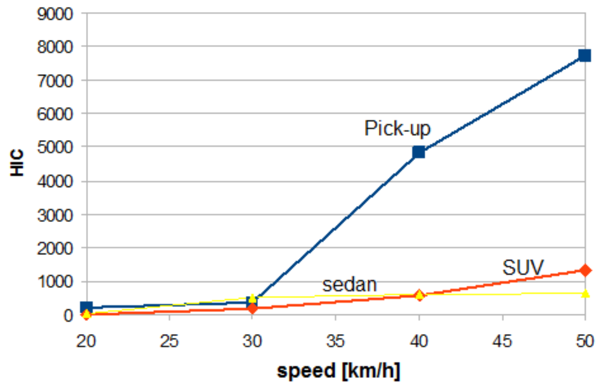

Figure 8: HIC in the side impact

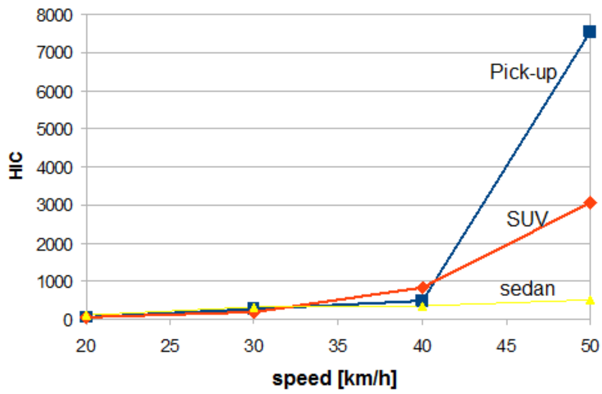

Figure 9: HIC in the telescoping

Figures 7, 8 and 9 show the trend and the visual comparison.

Teenage cyclist has even more limited possibilities to survive in the front, side and rear impact with Pickup in the speed range of 40-50 km/h since HIC values are consistently above the previously reported values for SUV or Sedan.

3.2.2 Comparison with adult pedestrian

In the literature are quite frequent works on the impact pedestrian vehicle, including [28] [29] [30] [31] [32]. A comparison is possible with some data available from [38], where the impact testing vehicle - adult pedestrian, are carried out through the use of multibody program MADYMO; the pedestrian is located in a front position relative to the vehicle at 40km/h. Figure 10 shows the trend and the comparison.

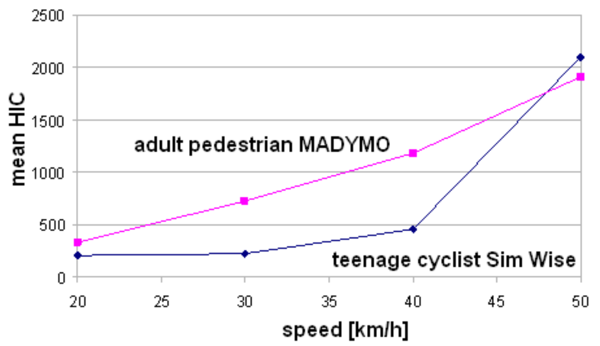

Figure 10: mean HIC comparison (sedan, SUV, Pick up) between teenage cyclist and adult pedestrian (frontal impact)

Consideration can be made that teenage cyclist has a better chance of surviving in the front impact collision than adult pedestrian, because HIC values remain consistently below the determined values. This is because part of the energy of impact is dissipated by the frame of the bicycle.

3.3 Chest injury evaluation by means of 3ms criterion.

Chest injuries caused by frontal impact are reconstructed with the use of 3 ms criterion. It provides that the center of gravity of the chest and the center of gravity of the head are not subjected to accelerations greater than 60g and 80g respectively, for a time greater than 3ms.

A virtual accelerometer is inserted in the mass center of the chest to derive the results of interest for the simulations. Table 4 shows the values.

Figure 11 shows the trend of the values found by applying the criterion of 3ms versus the impact speed.

Table 4 – values by 3 ms criterion

test	Position	speed [km/h]	3ms [g]
1	front	20	63
2	front	30	68
3	front	40	180
4	front	50	260
5	lateral	20	142
6	lateral	30	230
7	lateral	40	470
8	lateral	50	900
9	rear	20	27
10	rear	30	32
11	rear	40	170
12	rear	50	260

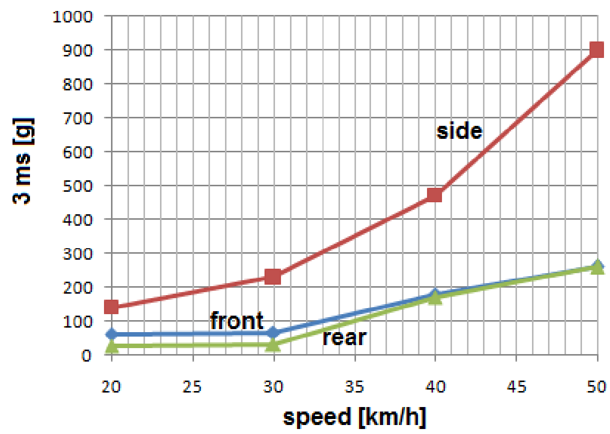

Figure 11: values of 3 ms criterion

Table 5: injury probability AIS 4+ with 3 ms criterion

test	Posit.	speed [km/h]	(AIS 4+)
1	front	20	40,77%
2	front	30	48,54%
3	front	40	99,91%
4	front	50	100,00%
5	lateral	20	99,01%
6	lateral	30	100,00%
7	lateral	40	100,00%
8	lateral	50	100,00%
9	rear	20	6,65%
10	rear	30	8,90%
11	rear	40	99,83%
12	rear	50	100,00%

Probability of injury AIS4 + (chest fracture and aorta laceration) can be obtained by the following relationship:

$$Prob\ (AIS4+) = 1/(1+\exp\ (4{,}3425-0{,}0630 * g_t))\quad(1)$$

that is reported for the reader convenience. Table 5 highlights the probability of AIS4 + for the examined cases.

In frontal and rear collisions, at speeds of 40-50 km/h, acceleration values suffered from chest are very high. This is due to the trunk ability to flex to the direct contact of the chest with the Pick up. Acceleration values suffered from chest are always high in the case of side impact, due to the vehicle front.

3.3.1 3 ms criterion comparison

Table 6 shows the percentage difference between the analysis of Pick up - cyclist impact and both SUV-cyclist and sedan cyclist, in terms of the values obtained using the criterion of 3ms.

Table 6: comparison of the obtained results with 3 ms criterion Pick up – SUV and Pick up - sedan

test	Posit.	speed [km/h]	3 ms difference with	
			SUV	sedan
1	front	20	-16,00%	-49.6%
2	front	30	-41,88%	-40.87%
3	front	40	+12,50%	24.14%
4	front	50	+44,44%	15.56%
5	lateral	20	+735,29%	358.06%
6	lateral	30	+259,38%	721.43%
7	lateral	40	+710,34%	710.34%
8	lateral	50	+500,00%	1478.95%
9	rear	20	+12,50%	22.70%
10	rear	30	-61,45%	-65.22%
11	rear	40	-49,10%	-32,00%
12	rear	50	-29,73%	-53.98%

Figures 12, 13 and 14 show the trend and the comparison.

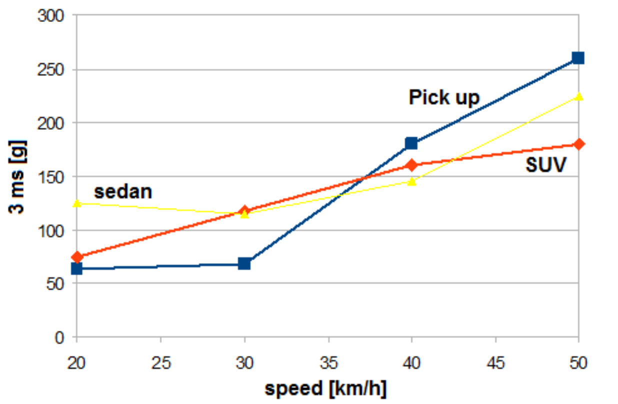

Figure 12: comparison Pick up – SUV and sedan in the frontal impact

Teenage cyclist is more likely to suffer an injury to the chest in rear impacts with the sedan as the values obtained by 3ms crterion remain above the values obtained with the SUV and Pick up. This is because the rider chest would project on the windshield of the sedan, the most rigid part of the vehicle. Unlike Pick up causes greater injury to the chest in the front and side impact because of greater height from the ground.

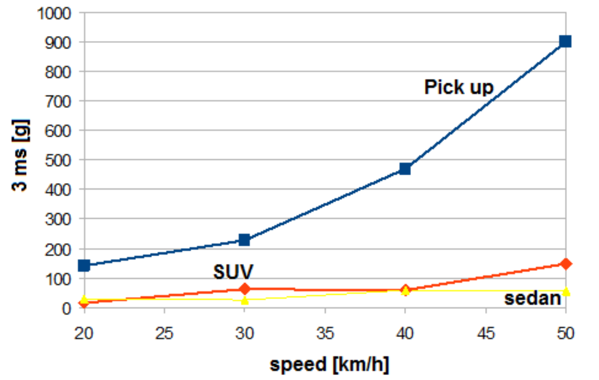

Figure 13: comparison Pick up – SUV and sedan in the side impact

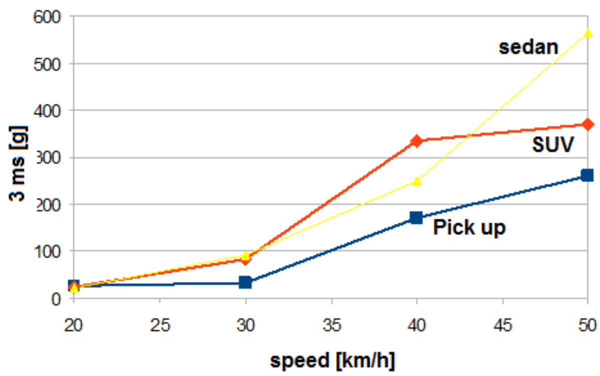

Figure 34: comparison Pick up – SUV and sedan in the telescoping

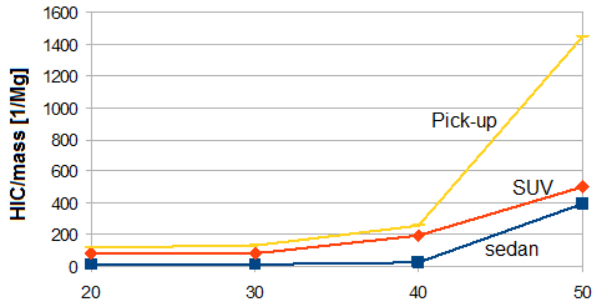

Figure 15: ratio HIC/mass in the frontal impact

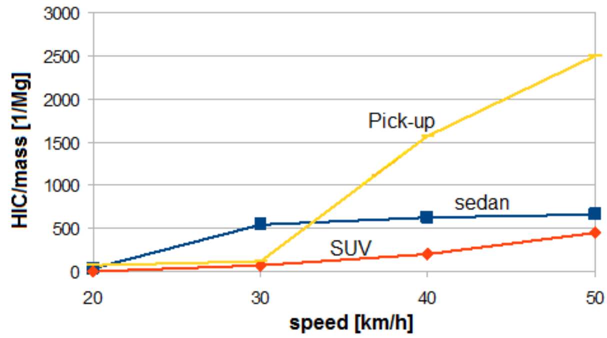

Figure 16: ratio HIC/mass in the side impact

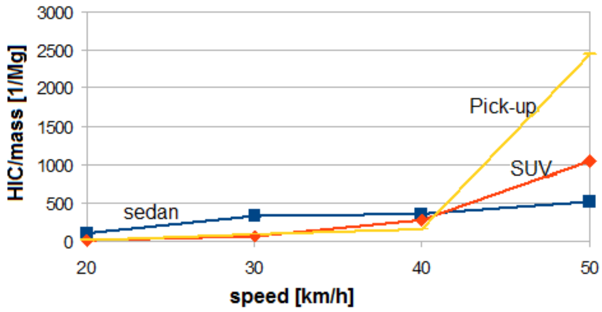

Figure 17: ratio HIC/mass in the telescoping

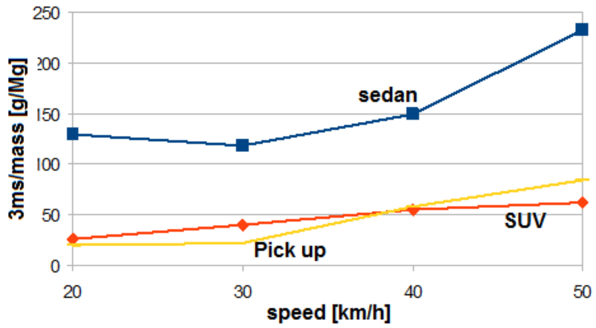

Figura 18: 3ms/mass ratio in the frontal impact (g=gravity acceleration).

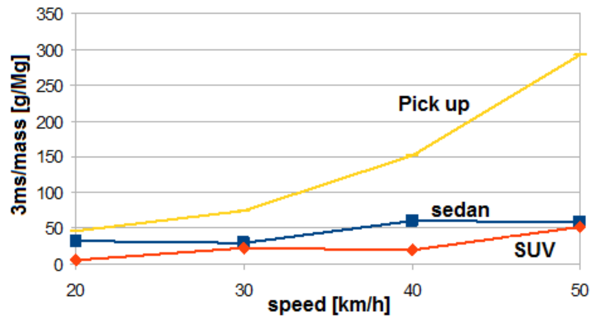

Figura 19: 3ms/mass ratio in the side impact (g=gravity acceleration).

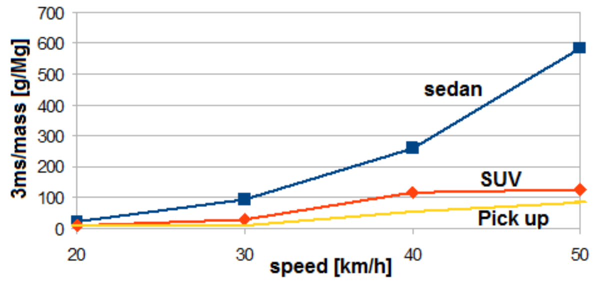

Figura 20: 3ms/mass ratio in the telescoping (g=gravity acceleration).

3.4 Influence of the vehicle mass.

Previous figures 7, 8 and 9 suggest that the mass of the vehicle can have importance on the HIC values in the impact with the cyclist. To try to understand better the importance of the mass, the following figures 15, 16 and 17 show the comparison HIC/mass versus the speed when the teenage cyclist is in front, side and rear position respectively, for the three vehicles tested: Pick-up (3084kg), SUV (2900kg) and sedan (968kg). The mass values are declared by the manufacturers.

A number of considerations can be made from this comparison:

- Examining the front and rear impacts at speeds of 40 km/h, values of HIC/mass ratio produce an almost coinciding or parallel graph, with increasing speed;
- The data in the same two cases show that 20 km/h is the speed causing minimum injury while the increase of this index see in 50 km/h maximum critical issues;
- During the side impact values are higher because the head of the rider immediately striking the bonnet of the vehicle that overwhelms him, and not the bike that could absorb the shock but does not happen;
- The mass of the investor vehicle has an influence definitely instrumental in the severity of injuries, at greater speed than 40 km/h.

Figures 18, 19 and 20 show analogous comparison for 3 ms criterion.

Examining the front and rear impacts the trends of 3ms/mass ratio of the SUV and Pick-up at higher speeds produce an almost coinciding graph or parallel trend. The side impact trends of the 3ms/mass ratio of Sedan and SUV with increasing speed produce an almost coinciding graph or parallel trend. At the front and rear impact the 3ms/mass ratio is higher for the sedan because the cyclist hits disastrously the windscreen of the vehicle.

Vehicle mass has negligible influence at low speed, but its influence is a few greater in side impacts.

3.5 Localization of the contact points and comparison.

Figures 21 and 22 show the bonnet area that is more involved when the rider head hits the Pick up front during the impact. The marking of the vehicle for identifying the same areas (WAD) occurs according to the EURONCAP directives.

Dispersion of the impact points is localized in the WAD area 1000 in all cases, except for impacts at 50 km/h (WAD 1000 - WAD 1500).

In the tests for side impact the dispersion of impact points concern a larger area than the front/rear case (fig. 21). Furthermore, the analysis of the contact points of both cases allows obtaining a new confirmation regarding the accuracy of values. The very intense acceleration peaks generally correspond to a collision against a rigid wall of the vehicle front (the windscreen is more rigid than the bonnet).

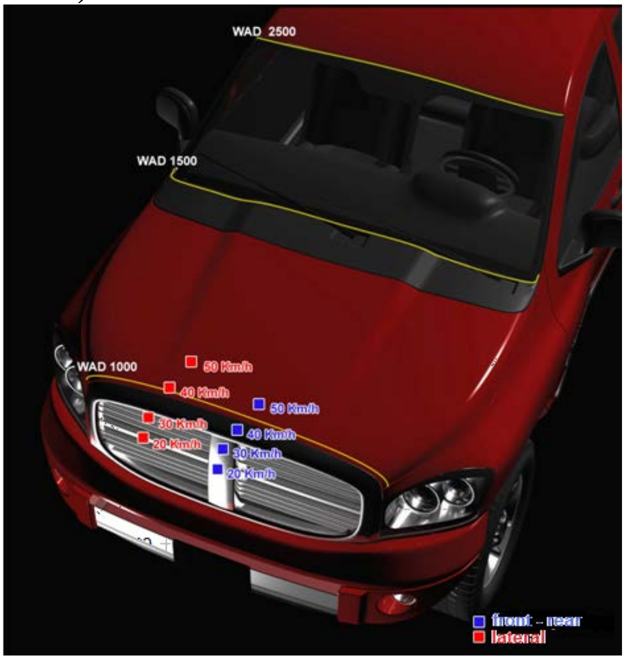

Figure 21: contact points head – Pick-up in the three series of tests.

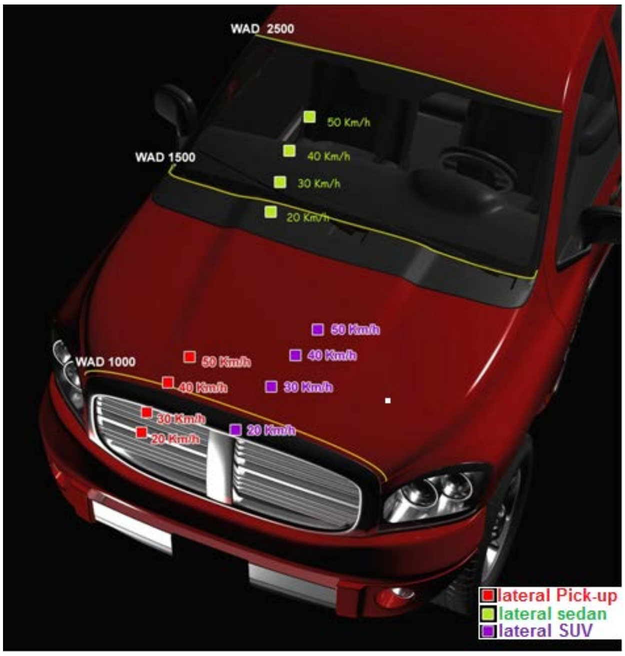

Figure 22: lateral crash tests; contact points of the head with sedan, SUV and Pick-up.

Impact points are highlighted in figure 29. Pick-up and SUV simulations stand out the same impact zones (WAD 1000) with a speed of 20 km/h. The rider hits the bonnet (areas between 1000 WAD and WAD 1500) with speeds of 40 to 50km/h. The teenager cyclist will end up in the impact area between WAD 1500 and 2500 in the event of impact with the sedan, with the exception of the 20km/h speed.

Results are in good agreement with the paper [39].

3.6 Throwing distance calculation

The calculation of throwing distances is a scope that has a certain professional interest, because it is useful to determine the vehicle speed at impact. In literature there are many works that deal with this topic [21] [22] [40] [41].

Table 7 shows a summary of the throwing distance values of teenage cyclist according to the vehicle, in the considered speed.

Table 7: throwing distance of the bicyclist regard to the vehicle and impact speed

vehicle	Speed [km/h]	Throwing dist. [m]			Mean value [m]
		front imp.	side imp.	rear imp.	
sedan	20	7.67	0.08	7.04	4.93
	30	12.75	0.30	9.85	7.63
	40	17.05	1.42	12.95	10.47
	50	20.05	2.00	14.85	12.30
SUV	20	6.55	0.54	2.85	3.31
	30	13.68	0.84	5.52	6.68
	40	17.37	3.15	13.35	11.29
	50	20.75	3.27	16.35	13.46
Pick up	20	7.10	0.56	5.65	4.44
	30	15.15	0.89	6.65	7.56
	40	17.85	3.35	13.65	11.62
	50	21.75	3.65	18.55	14.65

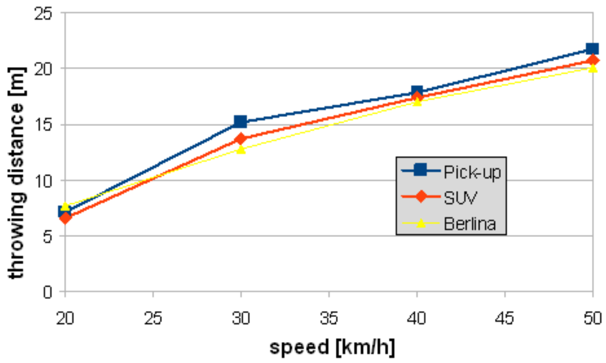

Figure 23: throwing distance for the frontal impact.

Figures 23, 24 and 25 show the trend of the throwing distance versus the impact speed.

Now a comparison is possible with the results presented in the paper [41]. Author interpolates numerous experimental data, obtaining the following regression curve:

$$d=0.1117v+0.003936v^2 \qquad (2)$$

Where d is the throwing distance and v is the impact speed expressed in km/h. Since no difference is done on the relative position between vehicle and bicyclist, the comparison is executed with the mean value of the three examined positions and reported in the last column of table 7.

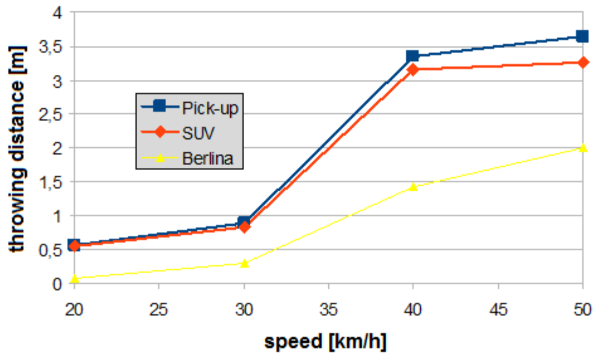

Figure 24: throwing distance for the lateral impact

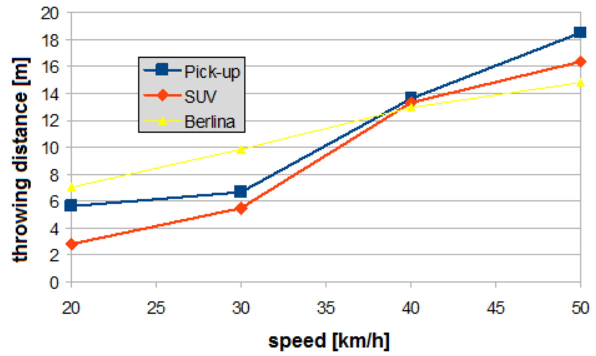

Figure 25: throwing distance for the telescoping

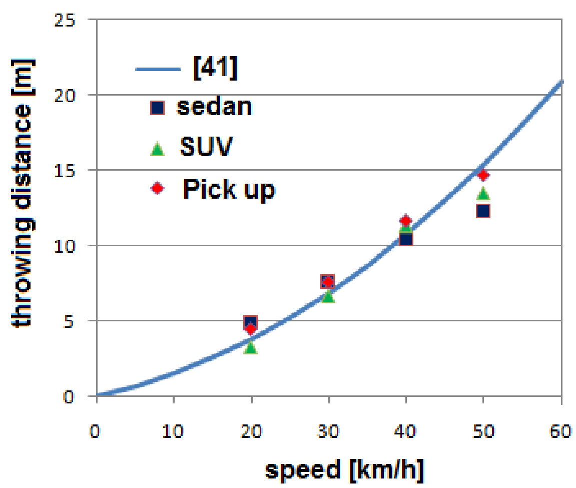

Figure 26 – throwing distance comparison with the values in literature

Visual comparison in Figure 26 shows that the results reported in this paper are in very good agreement with the literature results, but table 7 shows that the value of the projection distance can vary greatly depending on the relative position between the vehicle and the cyclist in the instant of impact.

4 Conclusions

Objective of this work is not only to assess the damage caused by an accident, by analyzing the impact dynamics between vehicle and bike, but, above all, to look for and suggest possible improvements and solutions to increase security, in order to limit the damage accused by the weakest subject.

The simulations show the importance of some key elements such as the rider height, and vehicle front profile and its minimum height from the ground, as well as the rigidity of those parts coming in contact with the cyclist at the moment of impact so jeopardize the outcome.

Cyclist position at the time of the accident can affect the outcome: the lateral position is more damaging than the front, in fact HIC values obtained by the simulations show that, during side impact, the values are higher since the head of the cyclist immediately strikes the bonnet of Pickup; it overwhelms him and not the bike that could absorb the shock, but it does not happen.

Different thing happens in the front and rear impact. In these cases the vehicle affects primarily the bike that absorbs the shock, the point of impact then is highlighted in the vicinity of the bumper and the cyclist falls in a different way, because he is located at a seemingly insignificant distance, but in reality more.

In the simulations, all HIC values fall within the value 1000; this is possible because good bump part is absorbed from the bicycle and not by the cyclist body. Moreover the simulations show that HIC values are much higher at 50 km/h which is the critical speed.

In the application of 3 ms criterion for the evaluation of chest injuries, the values are almost all higher than the limit 60g, higher than those resulting from the comparison with the pedestrian and with higher AIS + 4 parameter (i.e. fracture of the thoracic and aortic laceration). Also this time the reason is to be found in the gravity center position of the cyclist who is higher than that of the pedestrian, and upon impact sees the chest fall in the coldest areas of the Pick up.

The results also show that the mass of the vehicle has no decisive influence on the head and chest injury, but only if the vehicle speed is not very high. 40 km/h can be regarded as a threshold value. The mass influence is greater in the side impact.

The calculation of the throwing distance and the comparison with the available data in the literature shows the reliability of the results obtained by the

simulations in this paper, but also shows that the relative position between the vehicle and cyclist has significant importance.
The use of a virtual method as the multibody for the implementation of the simulations is beneficial; with it there were not a few adaptations, especially when one considers that the prototypes existed only as CAD drawings. In this way, the study of the accelerations transmitted by the vehicle is certainly easier and can lead to reliable results thus cutting also excessive costs.
This kind of simulation has not only an impact on the costs, but especially on security, thanks to the tests on the effectiveness of passive and active devices for a flawless and more efficient performance.
The front edge of the bonnet can be improved by eliminating all the unnecessary rigid structures. The ability to lift up the bonnet during impact improves the protection of the head of the rider and this result can be achieved by leaving greater space between the bonnet and the engine block.
Finally, making use of proximity sensors, the presence of a cyclist on the trajectory of the vehicle can be determined more effectively and rapidly, by communicating the data to a control unit that provides to implement a braking in less time than those obtainable by human reflexes.

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