# The kinematic behaviour of the driver and the degree of injuries in vehicle frontal collision

Oana V. Oţăt, Nicolae Dumitru, and Victor Oţăt

***Abstract –*** The research study carried out within the present paper aims at determining the kinematic behaviour of the driver in vehicle frontal collision. The opening sections of the study put forward the overview of a statistical analysis on road accidents casuistry, so as to identify those specific types of collision leading to severe injuries. To achieve virtual testing we have used Virtual Crash software, thus simulating a frontal collision between a vehicle and a rigid wall at a 100% overlapping degree. The kinematic analysis of driver's behaviour was completed by means of numerical modelling performed in the LS-DYNA software package. Under the circumstance, the influence of the vehicles' passive safety has been considered in order to establish the injury degree. Hence, we have analysed four different situations: initially the driver is anchored with the seatbelt and the vehicle is equipped with airbags. Then, the passive safety elements were deactivated in turns, first the seatbelt and then the airbag. Subsequently, the forth situation will investigate the case in which the driver is not secured with any retaining system and the vehicle is not equipped with an airbag.

***Keywords—*** passive safety, frontal impact, dummy kinematics, head injury criteria.

## I. Introduction

The ever increasing necessity for road transportation development, both for freight and for passenger transport, in the context of a road infrastructure that has not undergone much change in the last decades, has led to an increased density of flow traffic. Admittedly, the main negative effect of road congestion is the steady growth of the number of accidents, particularly those with serious consequences.

Current research studies undertaken within the field of safe transportation throw spotlight on a series of methods to reduce road congestion. By means of the application developed by Vincenzo Barrile in [1], real-time information on traffic congestion and road accidents are conveyed, thus facilitating route reconfigurations through applications on mobile telephony.

Another method to fluidize road traffic is put forward by Hamza Toulni et al., in [2]. The paper sheds light on the impact of intelligent transport systems (ITS) integration in dedicated traffic management programmes.

In order to reduce both the number of traffic overcrowdings as well as the injuries' severity, in case of an accident, among the most actual solutions adopted by vehicle manufacturers was a large-scale implementation of active and passive safety systems in order to increase their effectiveness. Thus, the airbag system is a well-known example of passive safety systems, already integrated in the mass production, and closely related to the seatbelt, the widely acknowledged safety system element, which has been the subject matter of a series of recent research studies within this field of investigation.

A close and critical reading of mainstream literature indicates that a series of scientific research studies analyses the casuistry occurrence of traffic accidents, as well as the type and the severity of the injuries suffered by of the occupants of the vehicle.

A contemporary approach regarding the study of road accidents is endorsed by Filippo Carollo, in [3]. The investigations carried out by the authors aim at improving the passive safety measures for the vehicle occupants. Also, special attention was paid to the vulnerable category of traffic participants, i.e. pedestrians and cyclists.

An essential research study on the analysis of the driver's kinematic behaviour is indicated in [4], aiming at quantifying the whole-body kinematic response of the post mortem human surrogates (PMHS) tested in the same frontal impact condition. Within this research study the three-dimensional displacement corridors development has been introduced in order to quantify the whole-body kinematic response of restrained PMHS for a frontal impact conducted in a controlled laboratory environment.

In terms of development and optimization of the active safety systems, K. Preston White et al. describe in [5] recent enhancements of a software which enables the use of vehicle and occupant simulation models in order to determine the design and the restraint systems meant to increase the occupant impact protection, being also applied to establish the optimal design of a passenger vehicle involved in frontal collisions.

A method to develop injury prediction algorithms by statistical analysis of numerical crash reconstructions using dummy models is presented in [6]. The normal or out of position of the occupants correlated with the operating mode of the airbag system leads to a further research topic.

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In [7] Louden indicates, how the air bags are affecting the occupants (Hybrid III 3-year-old, 6-year-old and SID-IIs - 5th percentile adult female side impact dummy) in different OOP test modes for all rows in the vehicle. In [8] some recommended procedures are envisaged in order to evaluate the occupant injury risk due to side airbags deploying. An overview of the actual status with regard to the simulation methods for the deployment process of an airbag is provided in [9], a research paper entitled *On the simulation of out-of-position load cases with the ale-method*. By means of the case-control study of real-world crashed vehicles conducted in [8], the reduction in number of head, face, chest and neck injuries in airbag-equipped vehicles is being highlighted, although the numbers of upper extremity injuries increased.

According to [10], frontal impacts have been defined as follows: non-rollover and principal direction of force (DOF1) = 11, 12, or 1 o'clock positions or DOF1 = 10 or 2 o'clock positions with the crash damage forward of the A-pillar.

The salient regulations in force, which establish the prerequisites of vehicle testing in frontal impact simulations, are the Federal Motor Vehicle Safety Standards (FMVSS208) and the ECE (UN Economic Commission for Europe).

According to the USA FMVSS 208 and the CMVSS 208 Canada, frontal impact testing shall be conducted at a vehicle velocity of 48 km / h, with a rigid barrier and a 100% overlapping. However, according to the European regulations ECE / 96/79, [11] the front velocity on frontal impact shall be between 48.3 km / h and 53.1 km / h.

## II. Road Accidents Statistics

### 2.1 The dynamics of road accidents rate in Europe

In order to establish the type of collision that generates serious injury and even the death of a vehicle occupant, a statistical assessment of road traffic accidents has been carried out. Thus, for this study the following criteria have been taken into consideration: the type of collision, the human body parts exposed to the most severe injuries as well as the type of the driver.

Prior to this case study, in order to determine the most vulnerable road user, statistical data on road accidents have been thoroughly analysed. This study was divided into four main categories, as follows:

Figure 1 [12] indicates a comparison of the male and female fatality distribution by road user type for four age groups. Accordingly, it can be observed that regardless age and sex classification, most of the victims are the occupants of vehicles, at the rate of over 40% in all cases.

In order to select the most appropriate type of dummy that will be used within this case study, we have first analyzed the statistical data in Figure 2. As shown in Figure 2, the highest death rate is registered among male vehicle drivers, i.e. 35% of all fatalities recorded.

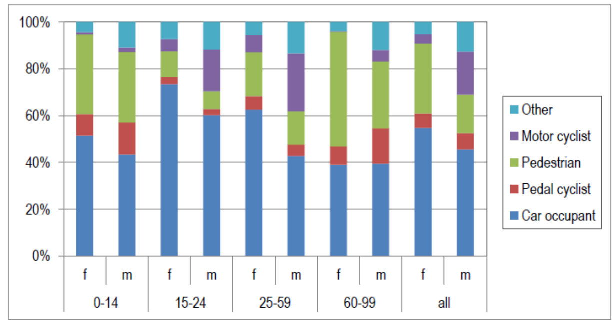


Fig.1. Distribution of fatalities by road user type [12]

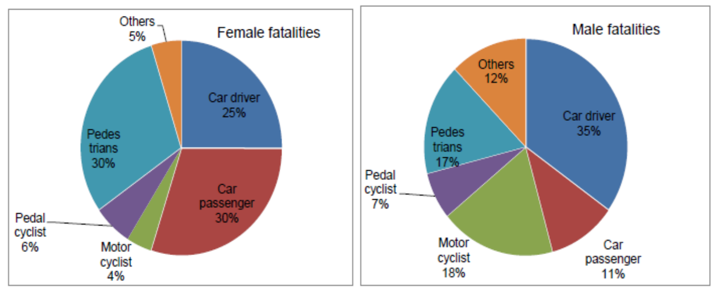


Fig.2. Distribution of male and female fatalities by means of transport [12]

Figure 3 [12] indicated the proportion of fatalities by road user type on three types of road. Thus, regardless of the road type, vehicles' rivers have been reported as the most frequently encountered road traffic victims.

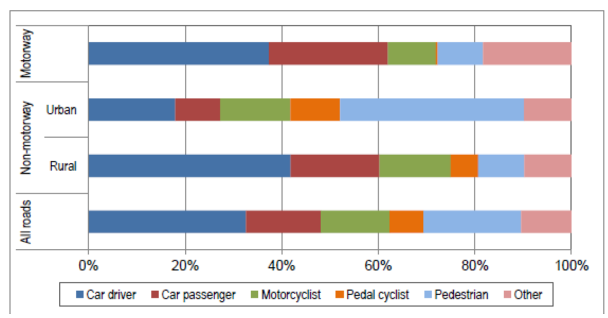


Fig.3. Distribution of fatalities by road user type [12]

Figure 4 [12] illustrates the distribution of the injured body parts with various road user types. As indicated below, the ratio of head injuries as well as the ratio of neck and thorax injuries is most frequently recorded among car occupants, presumably linked to the incidence of whip-lash.

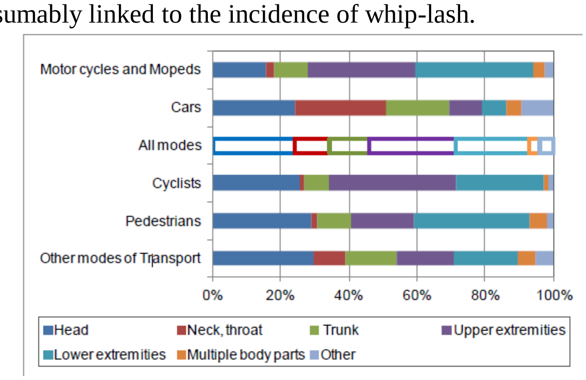


Fig.4. Body part injured by mode of transport [12]

2.2 Traffic accidents statistics in Dolj County, Romania

In the context of an ever increasing number of road accidents with severe consequences we sought to develop a statistical analysis regarding road accidentology, paying special attention to both the increased number of accidents and the their causes in Dolj county, within the period 01.01.2012 - 31.12.2014.

According to the data provided by the Police Inspectorate Traffic Department of Dolj county, over the last three years, there have been recorded an average of 800 accidents per year, of which about 260 had serious consequences. Figure 5 below illustrates the total number of accidents within this period, and the frequency rate of severe and moderate accidents.

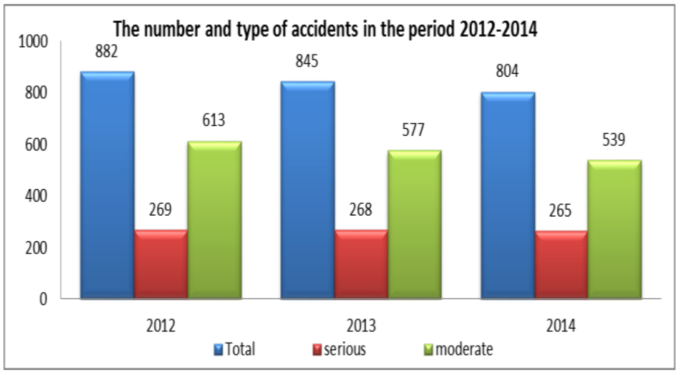


Fig.5. The number of accidents within the period 2012 – 2014

Another important criterion in road accident classification refers to the type of collision. The most common types of collisions are: front – rear collisions, frontal collisions, lateral collisions, slidings, vehicle-pedestrian collisions, rollovers, and the collisions with obstacles.

A considerable frequecy rate in the total number of accidents occurred within the period 2012 - 2014 in Dolj county inicates the occurrence of vehicle – pedestrian collisions. The second place is occupied by latteral collisions, followed by front – rear collisions.

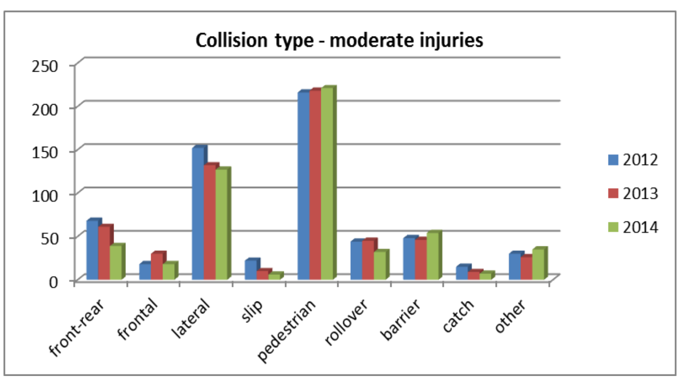


Fig.6. Type of collision for moderate accidents within the period 2012 – 2014

Regarding the category of road users involved in road accidents in Dolj county, the undertaken statistical analysis indicates that a considerable frequency rate of fatalities was recorded among drivers. Thus, throughout the considered period, namely the years 2012- 2014, over 1,100 deaths assigned to the category of drivers have been recorded annually.

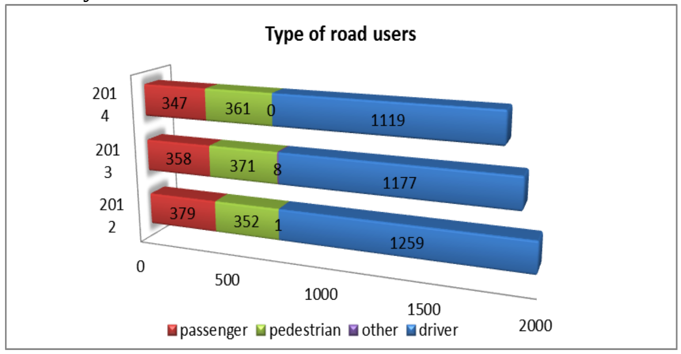


Fig.7. Type of road users within the period 2012 – 2014

The next step in the proposed statistical analysis was to investigate the frequency rate of safe systems used by road accidents victims recorded in 2014 in Dolj county. Thus, Figure 8 illustates the use of safety systems used by traffic accident victims. According to the figure below, the frequency rate of safety systems in 2014 is extreemly low, for as in most of the registered road accidents the occupants did not use any passive safety system.

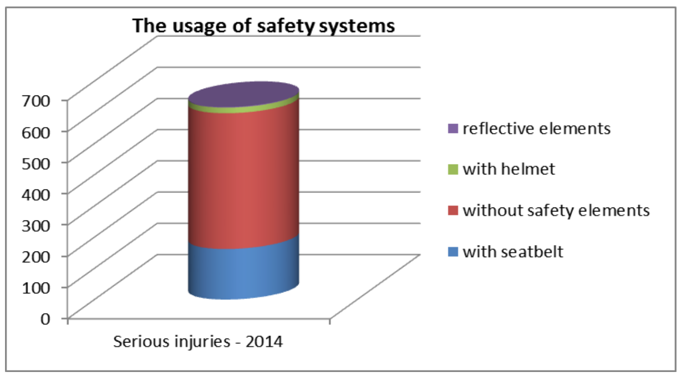


Fig.8.The rate of passive safety systems used in 2014

Also, according to our statistical analysis, the percentage of male victims within the considered time interval is over 70% of the total number of injured persons (Figure 9). One possible explanation concerning the results of the statistical analysis with a view to the rate of victims in relation to their gender is based on the fact that in Dolj county the number of male drivers is significantly higher than the number of female drivers.

Based on the above-indicated statistical analysis, it has been established that the highest amount of injuries and fatalities caused by road accidents was recorded among male car drivers. The most commonly affected body part due to road accidents is the upper part of the human body, i.e. the head, neck and thorax regions.

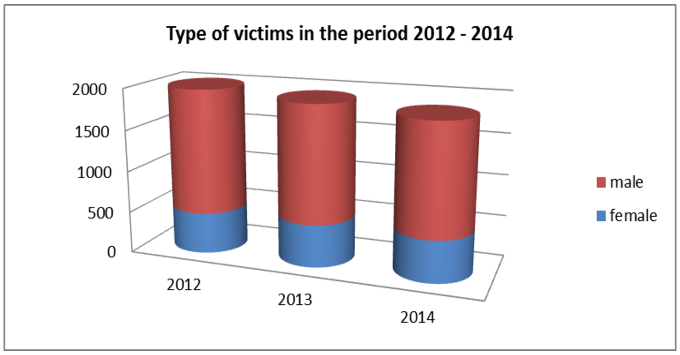


Fig.9. Victims' frequency rate by gender

## III. Dummy Positioning

### 3.1 The dummy-type used

In line with the above illustrated statistics, the study of the influence of passive safety systems in a frontal crash test shall be performed on a Hybrid III dummy-type - 50th percentile male, which was placed on the driver's seat.

Figure 10 indicates the geometry of the Hybrid III-type dummy to be used throughout the proposed study.

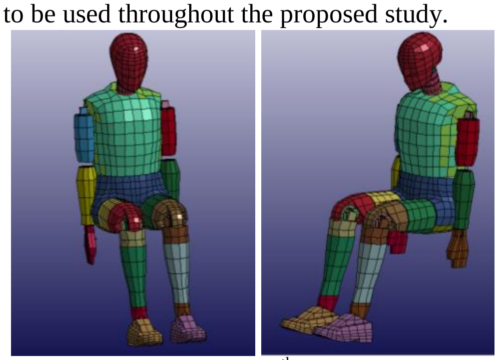

Fig.10. Hybrid III – 50$^{th}$ percentile male

### 3.2 Dummy positioning

The following step in implementing the numerical simulations of the driver's kinematic and dynamic behaviour during frontal impacts consisted in the design of the seat-steering wheel-dashboard assembly. Once this assembly was designed, the dummy was also positioned.

The normal position of the dummy was considered and the dummy Hybrid III 50$^{th}$ percentile male - was placed in the centred thorax position in relation to the steering wheel, at a distance of 350 mm.

The joints of the upper and lower limb(s) of the dummy were positioned as indicated below, in relation to the global coordinating system:

- the full arm up down joint was set at an angle of -40˚
- the elbow joint at an angle of -70˚
- the hands were placed on the wheel at an angle of -10˚
- the knee joint was set at an angle of -40˚
- the foot joint was set at an angle of -3˚

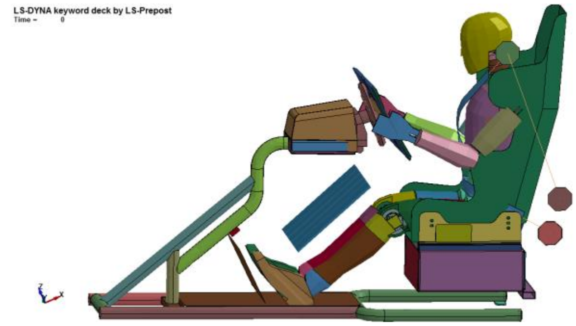


Fig.11. Normal position belted dummy

## IV. Passive Safety Systems

The present research study aims therefore to provide a comparative analysis with regard to the influence of the passive safety systems upon the behaviour and the injuries caused to the vehicle driver in the head region during a frontal collision.

In addition, it is necessary to define and to fix the seatbelt at the level of the dummy's body components. The contact between the seatbelt and the dummy is of a node – area type, and it has been defined in the dummy's torso and pelvis region, as shown in Figure 12.

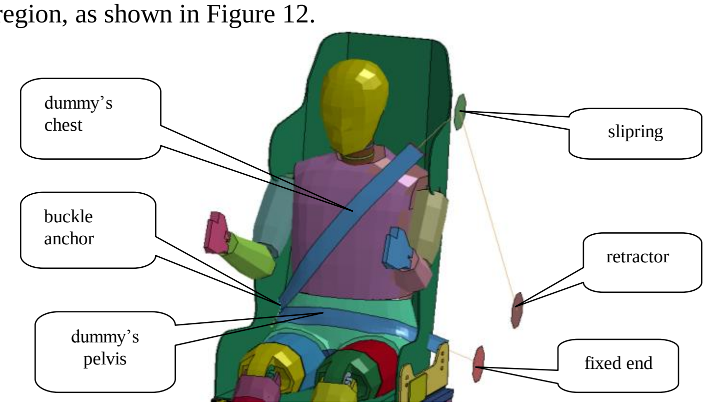


Fig.12. Seatbelt fitting

The second passive safety system that has been defined during the simulation was the airbag, positioned on the steering wheel assembly.

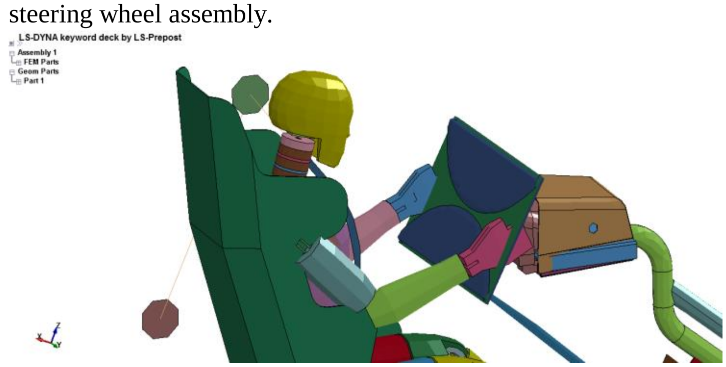


Fig.13. Airbag positioning

The airbag inflator follows the curve for mass flow rate, indicated in Figure 14.

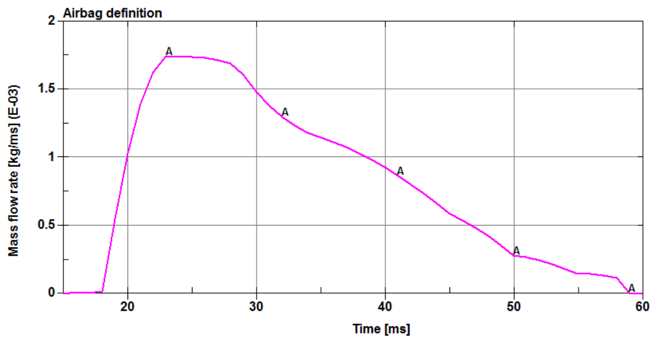


Fig.14. Airbag inflator

## V. Collision type and prescribed motion

In order to determine the motion curve of the vehicle during the pre-crash, crash and post-crash phase and to determine the kinematic parameters required for the dynamic impact analysis, a frontal-type collision simulation was obtained by means of the software Virtual Crash.

Thus, a frontal impact between a mid-size sedan vehicle and a rigid wall has been considered, where the main force direction (PDoF) has been oriented in a 12 o'clock position and a 100% overlapping degree.

The initial vehicle velocity during the pre-crash phase has been set at 50 km / h.

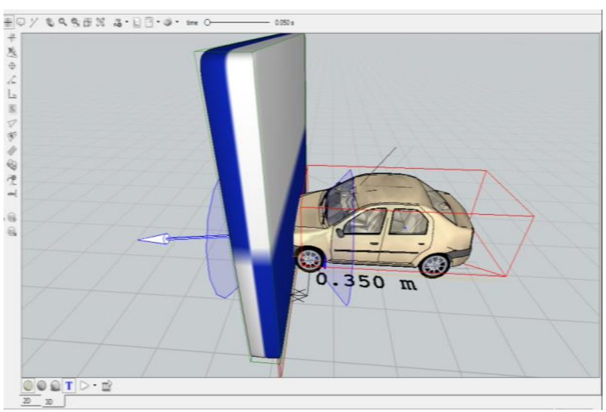


Fig.15. Frontal collision between a vehicle and a rigid wall in Virtual Crash

According to the velocity diagram in relation to time, the highest velocity variation was obtained within a time interval of 110 ms, during which the velocity rate ranged from the 0 [mm/ms] baseline and reached the maximum value vmax = 13,686 [mm/ms] at the final moment of tf=110 ms.

Based on the simulation performed by means of Virtual Crash we have established the velocity time variation diagram, as a prerequisite for the simulation used by the LS-DYNA software package as indicated in Figure 16.

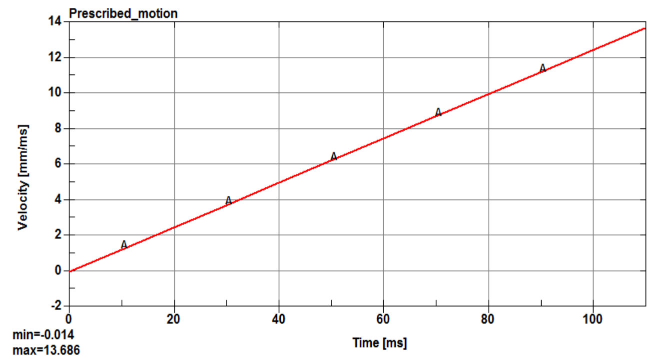


Fig.16.The velocity variation curve for vehicle's movement

## VI. The analysed situations

In order to establish the major influence on the driver's behaviour as well as the most severe injury degree, four different situations concerning the position of the dummy have been analysed during the impact moment, as follows:

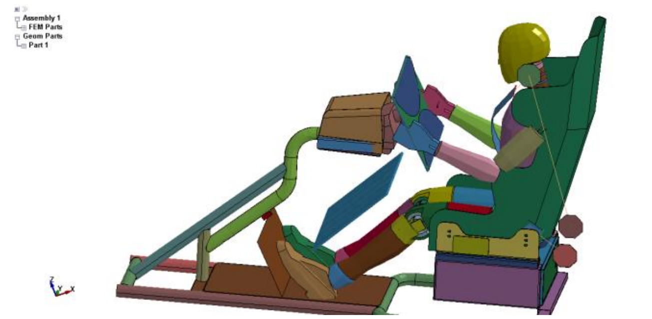

Fig.17. Test A - normal position with seatbelt and airbag systems

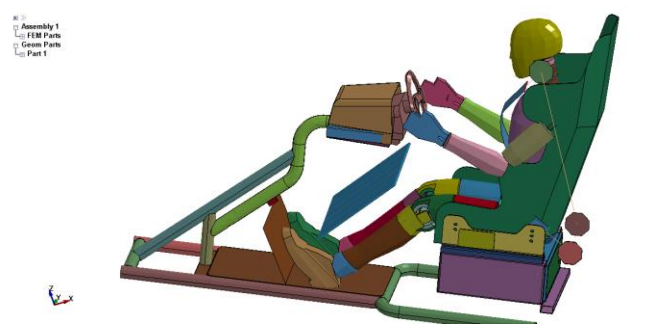

Fig.18. Test B - normal position with seatbelt, without an airbag system

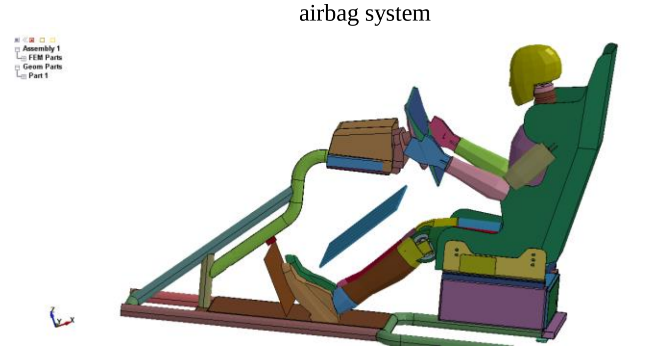

Fig.19. Test C - normal position without seatbelt and airbag system

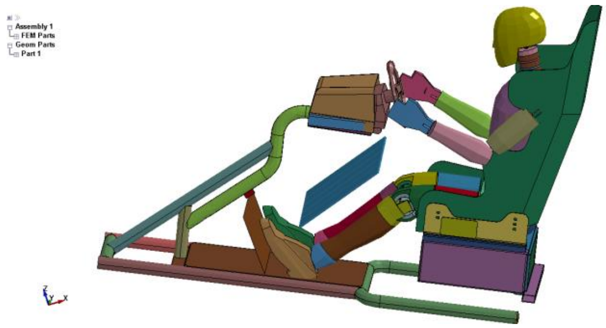

Fig.20. Test D - normal position without seatbelt and airbag system

The analysis carried out in all the above mentioned situations focused on the kinematic and the dynamic behaviour of the mechanism.

## VII. RESULTS AND DISCUSSION

### 7.1 Determining injuries at the head level

The assessment of the driver's injury degree in the head region at the moment of the frontal impact can be completed by means of two parameters:

- the *head acceleration*

According to the FMVSS 208 Regulation, the maximum acceleration in the head region is 80 [g].

- *HIC (head injury criteria)*

The Head Injury Criteria has been applied as determining factor to establish the head injury in relation to the complex curve of acceleration, based on the resulting acceleration of the centre of gravity of the dummy head, on an interval of maxim 36 ms, HIC 36 [3].

Where t1 and t2 indicate the initial and the time (in seconds) and a (t) is the acceleration resulted (in g), measured in the centre of gravity of the head region.

$$HIC = \left\{ (t_2 - t_1) \left[ \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)dt \right]^{2.5} \right\} max \quad (1)$$

According to FMVSS 208 and CMVSS 208 Regulations in case of frontal collision, the maximal values of HIC, compatible with the driver's survival are as follows:

HIC 15 (throughout a 15 ms interval) < 700

HIC 36 (throughout a 36 interval ms) < 1000

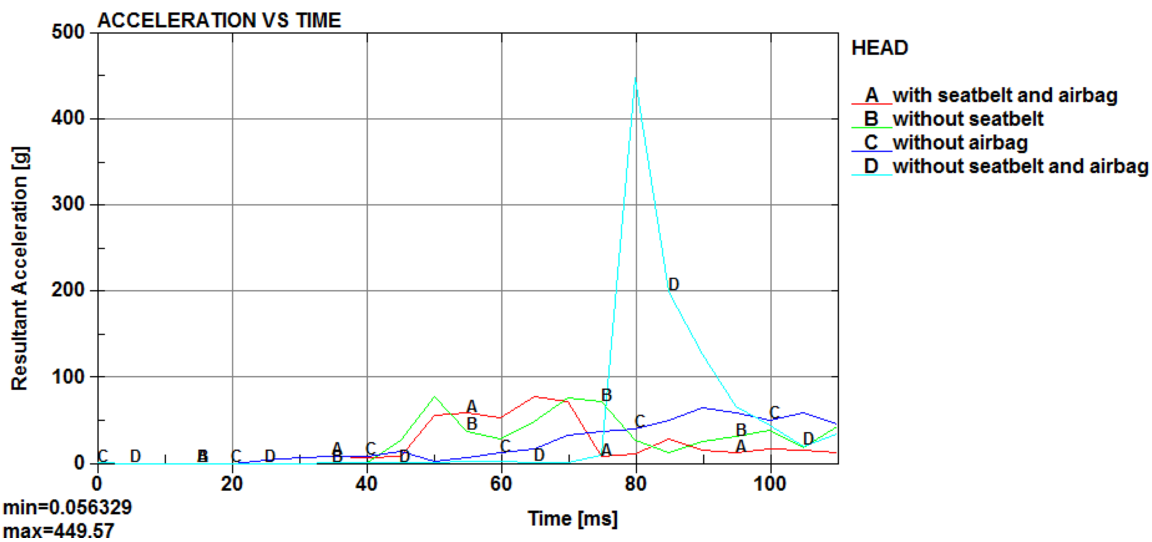


Fig.21. Head acceleration

According to the variation of acceleration over time, as in Figure 21, we have registered that the acceleration highest value in the head region is recorded in situation D, i.e. the driver's normal position without restraint and airbag system.

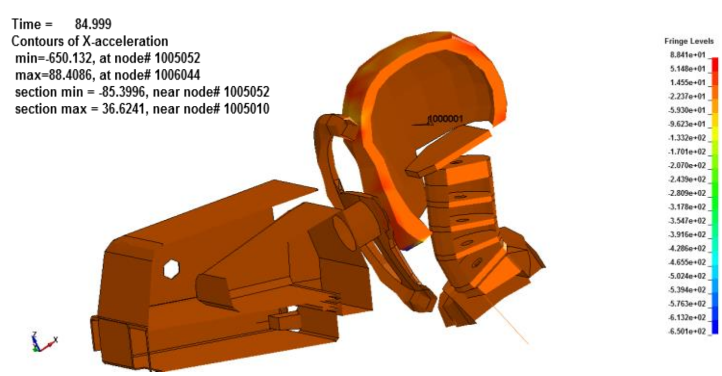


Fig.22. Contours of head acceleration – test D

As indicated in Table 1, the lowest acceleration value in the head region was registered in that situation when the driver is restrained by a seatbelt while a frontal airbag system is missing, i.e. test C. In this situation the maximum value of the acceleration recorded does not exceed the limit of 80 g, which is compatible with the driver's survival. During the simulation, we could notice that due to the restraint system, the dummy's head moves longitudinally, according to the X axis direction, though it does not get in contact with the steering wheel, while the missing airbag prevents any impact in the head region of the dummy. Also in this situation, the maximum recorded acceleration value does not exceed the acceleration limit, thus the injuries suffered are compatible with the driver's as well.

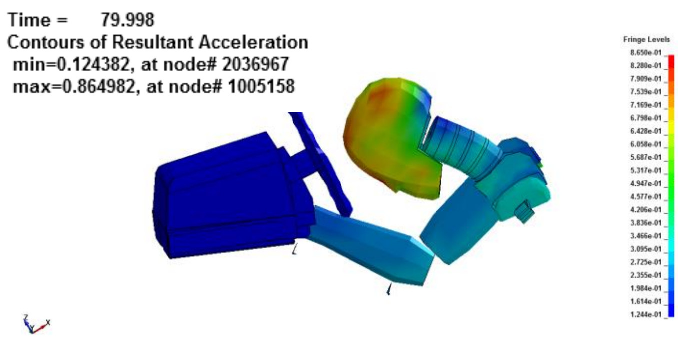


Fig.23. Contours of head acceleration – test C

The close values of the acceleration in the dummy's head region obtained in A (with restraint and airbag system) and in B (without restraint system, but with an airbag system), indicate that the degree of injury is primarily influenced by the existence of the frontal airbag system. Thus, in B, that at the impact moment, the entire body, having not been retained by the seatbelt, moves freely not only in the head region, subsequently indicating lower acceleration values in the head region.

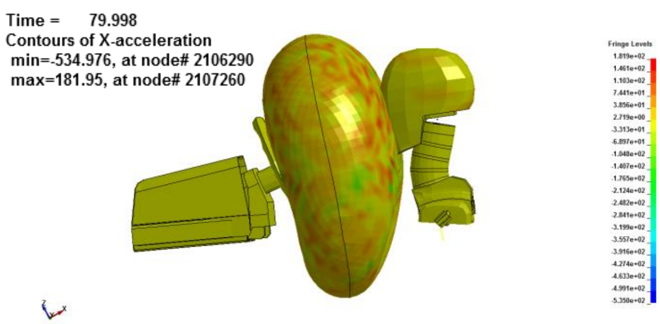


Fig.24. Contours of head acceleration – test B

The results obtained following the analysis of the above-illustrated situations are indicated in Table 1.

Table 1 – Resultant acceleration and HIC

| Parameter / Nr. test | Max resultant acceleration [g] | HIC 36 |
|---|---|---|
| Test A | 79 | 714 |
| Test B | 70 | 600 |
| Test C | 64 | 626 |
| Test D | 449 | 1566 |

Comparing the values obtained in the situation where the driver has not been restrained with a seatbelt and the vehicle has not been equipped with an airbag system, we have drown the conclusion that the maximum values as established by the CMVSS 208 and FMVSS 208 regulations are outdated . Thus, in situation D, the driver's injuries degree in the head region is not compatible with the driver's survival.

Figure 25 indicates the acceleration variation and the head injury criteria for the situations when the driver is secured by a restraint system and the vehicle is equipped with an airbag system.

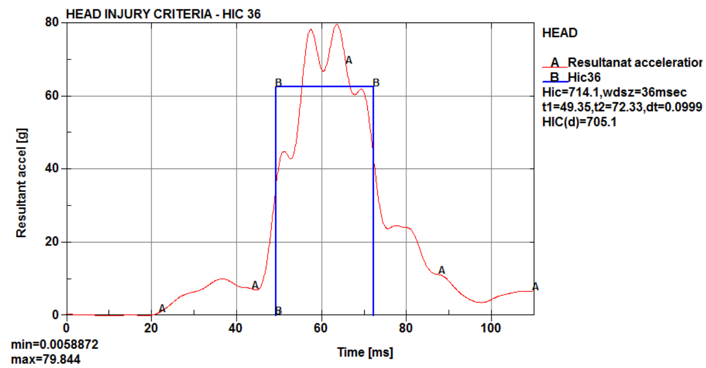


Fig.25. Head injury criteria – test A

7.2 Determining injuries at the thorax level

As previously described, in the statistical analysis on the most common injuries in road accidents, the next stage of the study was to establish the influence of passive safety use and lack of use on the driver's thorax

Thus, four situations have been considered, i.e.:

- Test A - normal position with seatbelt and airbag systems
- Test B - normal position with seatbelt, without an airbag system
- Test C - normal position without seatbelt and airbag system
- Test D - normal position without seatbelt and airbag system

As in the case when the head injuries were established, the injuries in the thorax area can be determined and quantified by means of two parameters:

- the *thorax acceleration*

In compliance with FMVSS 208 and ADR 69/00 regulations, the maximal acceleration in the thorax area must be below 60 [g].

- *CSI (chest severity index)*

The accelerations variations in the thorax area, determined in the collision simulation, are summarized by a standardized measure of injury [5].

The factor used in crash tests to assess the degree of injury in the thorax area is the Chest Severity Index – CSI, calculated on a 3 [ms] interval and defined as follows [5]:

$$CSI = \left[\int_{t_1}^{t_2} a_c(t)^{2.5}\,dt\right] \tag{2}$$

where:

$a_c$ – is the acceleration in the thorax area [g]

$t_1$ – the collision initial moment

$t_2$ - the collision final moment

In compliance with FMVSS 208 and CMVSS 208 regulations, in case of a frontal impact, the maximum value of CSI, compatible with the survival is:

CSI < 1000

The results obtained for the accelerations determined in the driver's thorax area and the CSI value is indicated in Table 2.

Table 2 – Resultant thorax acceleration and CSI

| Parameter / Nr. test | Max resultant acceleration [g] | CSI |
|---|---|---|
| Test A | 36.5 | 191.5 |
| Test B | 33.1 | 146.3 |
| Test C | 38.1 | 173.9 |
| Test D | 121.5 | 575.2 |

According to data obtained from the 4-types simulations, the lower values of acceleration and of the CSI factor were recorded in test B – unbelted.

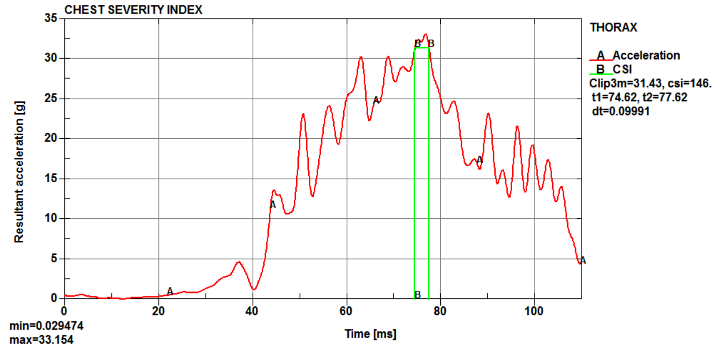


Fig.26. Chest Severity Index – test B

Figure 26 illustrates the acceleration curve, reaching a maximal value of 33.1 g at moment of time of 75 ms.

The CSI value is illustrated in the same graphic, for as it has been recorded on a 3 ms interval during the maximal acceleration level.

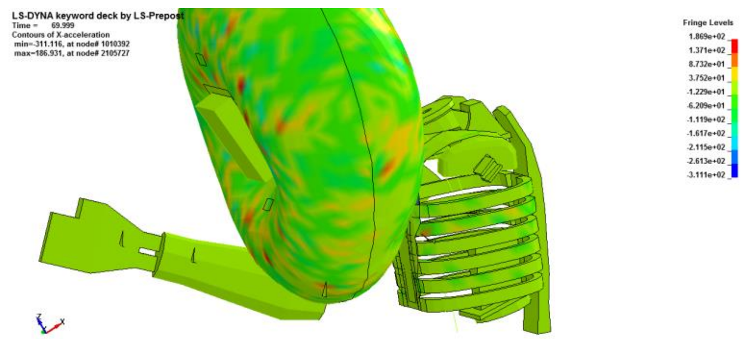


Fig.27. Contours of thorax acceleration – test B

The lack of seatbelt, and consequently the lack of the contact between the seatbelt and the driver's head and thorax determine a free movement, without stress upon the thorax which may lead to the thorax deformation.

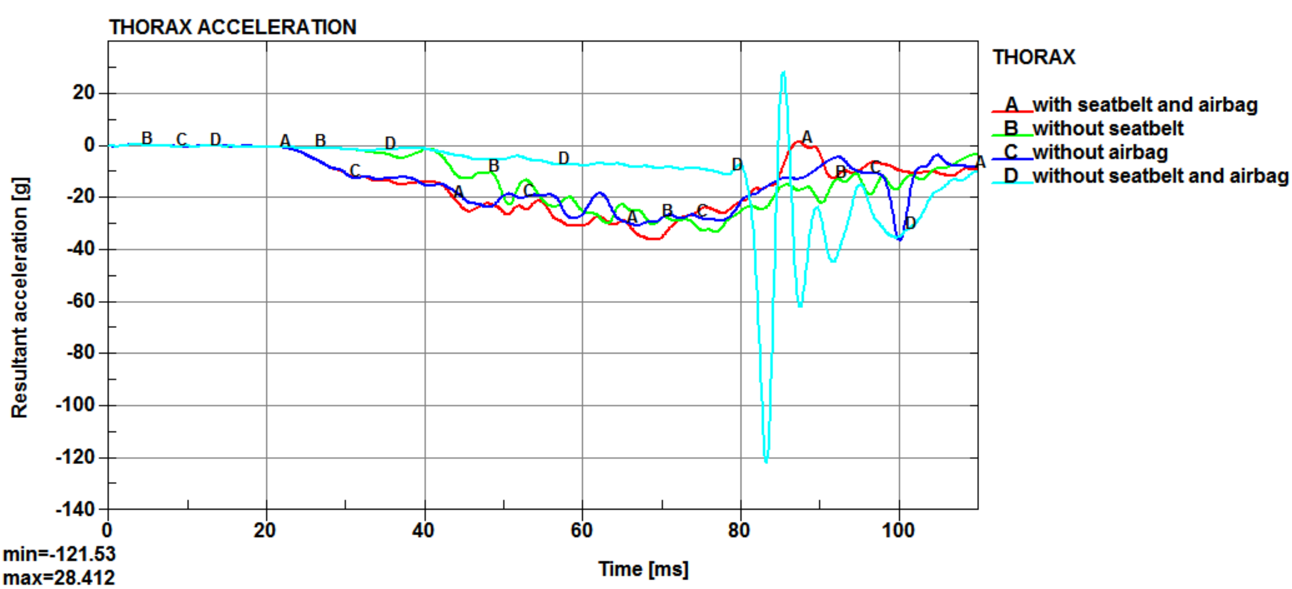


Fig.28. Thorax acceleration

In test A - the situation with safety belt and airbag, the values obtained are below the maximum limits imposed by the crash regulations in force. If compared to test B, both the acceleration and the CSI value are lower.

The maximum acceleration value, i.e. 36.5 g, has been registered in the interval 66-69 ms, simultaneous with the time period of 3 ms, when we have established the CSI value of 191.5.

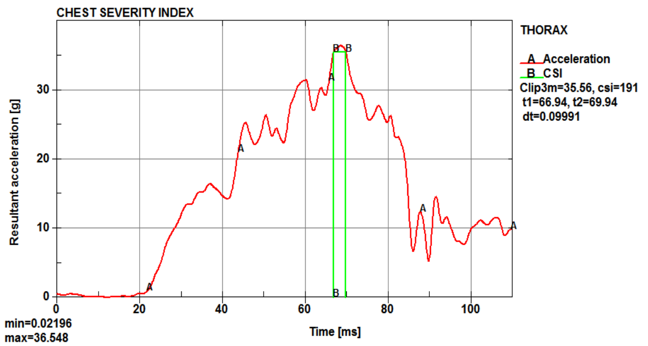


Fig.29. Chest Severity Index – test A

Figure 30 illustrates the accelerations contour for the thorax-airbag-seatbelt complex. Thus, the highest values are obtained in the upper area of the thorax during the interaction with the airbag and the ventral section of the seatbelt.

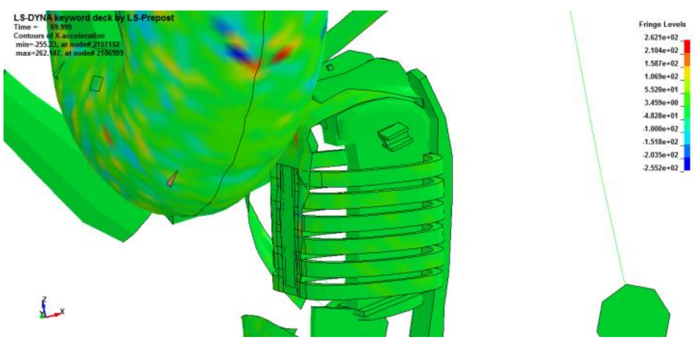


Fig.30. Contours of thorax acceleration – test A

Based on the graphical representation of the data obtained, we have extracted the value that actuates at the interaction of the driver's thorax with the seatbelt.

Figure 31 indicates that the maximum value of the contact force is 2.4 kN, the force that is exerted by the ventral belt upon the thorax when the driver is secured on his seat.


Fig.31. Contact seatbelt to thorax force – test A

The values obtained in C - seat belted, but without airbags are below the maximum limits established by FMVSS 208 and CMVSS 2018 directives. In comparison with the test in A, the maximum acceleration obtained is 38.1 g, this higher than in A. However, with regard to the CSI factor, we have registered a lower value, situated below the CSI value established when both the airbag system and seatbelt were activated.

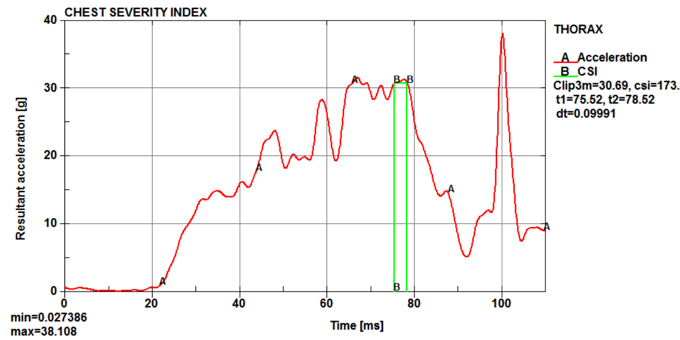


Fig.32. Chest Severity Index – test C

According to the graphic shown in Figure 32, the maximal CSI value is registered in the 75-78 ms interval. The maximum value of the thorax acceleration is recorded at time t = 100 ms, but for a short period of time, thus the value of CSI is calculated for the another value of acceleration, which remains constant over a period of 3 ms. This is also the explanation according to which the maximum acceleration is higher than in A, though the CSI factor is lower.

The acceleration contour in the thorax area for the situation in C is shown in Figure 33. We can identify the area where the maximum acceleration is recorded, i.e. in the lower right contact area with the seatbelt.

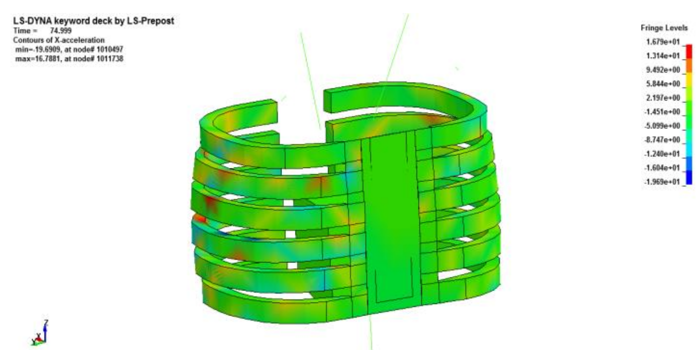


Fig.33. Contours of thorax acceleration – test C

As regards the fourth situation analysed in D – where the airbag system is not active, and the driver is not secured with the seatbelt, it can be seen, as illustrated in Table 2 and Figure 28, that the maximum acceleration value of exceeds is by far considerable higher, doubled in comparison to the limit of 60 g, imposed by FMVSS 208 and ADR 69/00 regulations. Also, the CSI value is much higher compared to the previously presented three situations, though it remains below the 1000 limit, as imposed by FMVSS 208 and CMVSS 208 regulations.

The variation curve of the acceleration and value of the CSI factor, in case the passive safety systems are not active, i.e. airbags and seatbelts, are shown in figure 34:

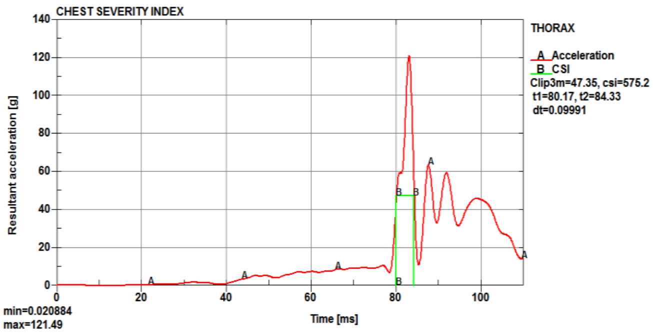


Fig.34. Chest Severity Index – test D

The accelerations contour at time t = 85 ms, when the maximum acceleration value was registered and of the CSI factor alike, is illustrated in Fig. 35. Thus, according to the figure below, the maximum acceleration values are distributed mainly in the upper area of the thorax, at the level of the first pairs of ribs, both on the front and on the back sides.

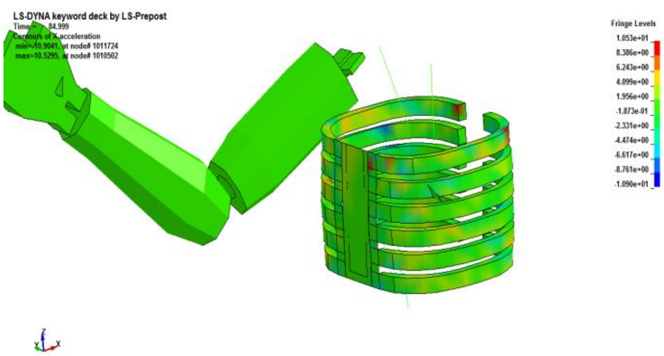


Fig.35. Contours of thorax acceleration – test D

Compared to the previously described situations, in case neither of the two passive safety elements are activated, the obtained injuries degree in the thorax area as a result of a frontal road accident exceed the limits crash tests required by the regulations, the injuries are not always compatible with the victim's survival.

## VII. Conclusion

To put in a nutshell, according to the results obtained following the analysis of the above-mentioned situations, during a frontal collision against a rigid wall at a speed of 50 km/h, the passive safety systems point out a considerable influence upon the driver's degree of injury, both in the thorax and the head area The most severe injuries are to be registered in such situations when the driver is not secured by a retention system and the vehicle is not provided with an airbag system.

The influence of at least one passive safety system (be it a retention seatbelt system or an airbag system) triggers acceleration values, in the thorax and the head area, head injury criteria and chest severity index, which are situated below the maximum limit established according to crash tests regulations.

## Acknowledgment

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