Santos, S., Álvarez-Caldas, C. & San Román, J. L. (2016, 1 noviembre). Is the Virtual Homologation for Pedestrian Protection Viable? CONAT 2016 International Congress of Automotive and Transport Engineering, 836-843.

DOI: 10.1007/978-3-319-45447-4_92

Is the virtual homologation for pedestrian protection viable?

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Abstract. One out of five deceased in traffic accidents is a pedestrian. In addition, pedestrians represent the 20% of the hospitalized injured people. The deadliness rate of a pedestrian crash is significantly greater than for the rest of accidents. Thus, pedestrian crash is one of the more lethal traffic accidents and, consequently, pedestrians are the most vulnerable road users. Vehicle´s design can influence immensely in the risk of seriousness of the accident. Regulations are the legal instruments in order to establish if a vehicle achieves the minimum safety requirements. Nevertheless, homologation implies costly and destructive tests. This problem could be solved by simulation techniques. Analyzing the viability of a virtual homologation is the main goal of this article. After studying pedestrian crash biomechanics, virtual tests will be performed using Finite Element software (Ls-Dyna) to assess the influence of the design of vehicle and the effect of a safety system (active bonnet). Comparison between virtual tests results and real tests allows deducing if the virtual homologation for pedestrian protection is viable.

1 Pedestrian safety systems

The 22% of global deaths from traffic accidents are pedestrians, so-called vulnerable road users together with cyclists and motorcyclists. The pedestrian is the weakest element of the road because above 55 km/h, 95% of pedestrian crashes are fatal. Among pedestrian passive safety systems, airbags and active bonnet highlight. With the airbags displayed from the top of the hood on the windshield it is intended to prevent the pedestrian's head striking the windshield glass, and by means of the airbags deployed on the front of vehicle to reduce the force of impact of the bumper against lower limbs. Also there are actuators that lift the hood at its rear edge to increase the distance between hood and engine components in order to the passerby's head does not hit extremely hard elements and decrease the severity of brain injury and thus the risk of death. For its part, among the ADAS (Advanced Driver Assistance Systems), which keep a thin line with active safety, image recognition highlights allowing some systems recognize autonomously a pedestrian between the different obstacles that precede the vehicle and calculate by the electronic control unit if there is danger of collision and the distance and time to prevent it. These systems can automatically brake the vehicle and even act on the power steering to avoid pedestrians. Thermal or infrared cameras improve these systems allowing night vision.

2 Pedestrian crash dynamics

The sequence of events that happens in a pedestrian crash, in most cases, follows a pattern that only in unusual circumstances will be modified significantly. Depending on the point of impact between the vehicle and the pedestrian and, specifically, the position of the center of gravity of the passerby respect to the bumper and the prior edge of hood, we can distinguish five basic typologies of pedestrian crashes [1, 2]:

- Wrap projection. The torso and head bend over the vehicle by contacting the hood and sliding over it. When vehicle decelerates, the body is separated from it and is thrown down to the floor. Usually it occurs at about 30 km/h, while the contact head-windshield is commonly seen over 40 km/h.
- Forward projection. It is typical when it comes to a short pedestrian or child who is hit by a passenger car, or when an adult pedestrian collides with a vehicle type SUV or industrial, that is, when the center of gravity impacts at the height or below the top of the car front. Habitually it occurs at about 20 km/h.
- Fender vault. It normally takes place when pedestrian is hit near the front corner of vehicle, in such a way that passerby is moved outwardly by the sideways of the hood. Usually it occurs around 40 km/h.
- Roof vault. It is characteristic when the pedestrian's center of gravity remains high relative to the hood, so that he is turned in the air as a result of the impact speed and/or vehicle design. It often occurs at high speed, lower than 60 km/h, and not usually to less than 30 km/h.
- Somersault. It requires high-speed impact (50-60 km/h) so that energy is such that it causes the pedestrian spins around him in the air before falling to the ground, usually in front of the vehicle.

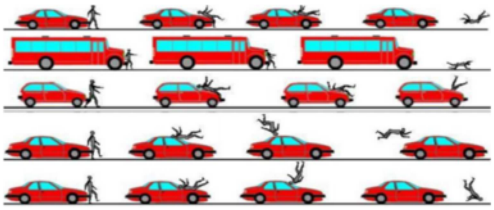

Fig. 1. Pedestrian crash typologies: wrap projection, forward projection, fender vault, roof vault and somersault [3].

3 Pedestrian injury biomechanics

Factors that influence the distribution of injuries in the run over pedestrians are many. Among influential factors in the distribution of injuries spotlight impact velocity, vehicle type, stiffness and frontal geometry, pedestrian's age and size and his position with respect to the front of the vehicle at the impact moment. The most frequent injuries due to pedestrian crashes are located in the head and lower extremities. Those placed in head are the fatal injuries more frequent. Not only are important cranial fractures, but also the acceleration experienced by the brain mass. The Head Injury Criteria (HIC) measures the risk of suffering brain injury. This criterion does not take into account the influence of rotational acceleration of the head nor any effect on the location of impact on the head. But even so, it is used universally in injuries research in collisions. Regulation assigns a maximum value of 1000 which corresponds to a 16% risk of brain injury with an AIS (Abbreviated Injury Scale) value equal or higher than 4, equivalent to a serious injury. There are other criteria for assessing the damage suffered by pedestrians such as the Neck Injury Criteria (NIC), or the Thoracic Trauma Index (TTI). Another of the most affected areas is the pelvis, in which the most common injuries are caused by external rotation, lateral compression and shear. The impact with the vehicle front and subsequent acceleration transmitted to the lower extremities result in injury mechanisms, emphasizing the lateral shear and lateral bending of lower extremities. The most common lower extremities injuries are long bone fractures (femur, tibia and fibula), knee injuries and sprains or fractures of ankle or foot. Loads on the lower extremities are typically applied laterally [4].

4 Pedestrian protection homologation tests

Regulation imposes and harmonizes the minimum requirements that must meet vehicles to ensure the safety of both occupants and pedestrians. Investigations conducted by the European Enhanced Vehicle-Safety Committee (EEVC) led to the drafting of directives and regulations concerning pedestrian protection systems homologation. Unlike legislation, which only uses impactors simulating the legs and head in physical testing, the European New Car Assessment Programme (Euro NCAP) performs tests with anthropomorphic dummies. The disadvantage of the latter is the need for more infrastructure, greater complexity in data collection, and not knowing the exact point where the head hits the vehicle. The European Regulation (EC) 78/2009 collects the homologation requirements for vehicles in protection to pedestrians and other vulnerable road users [5]. Specifically in its annex I are the maximum allowable limits (HIC factor, displacement and bending angle of the knee, tibia acceleration, impact forces, etc.) that can be achieved in the trials. The implementing rules of tests are described in Annex I of European Regulation (EC) 631/2009 [6]. These approval tests are perfectly summarized in figure 2, and they consist of the throw of a lower legform impactor to bumper and upper legform impactor against the prior edge hood, both trials at 40 km/h, a child/small adult headform towards the top of the hood and adult headform impactor against the windshield at 35 km/h.

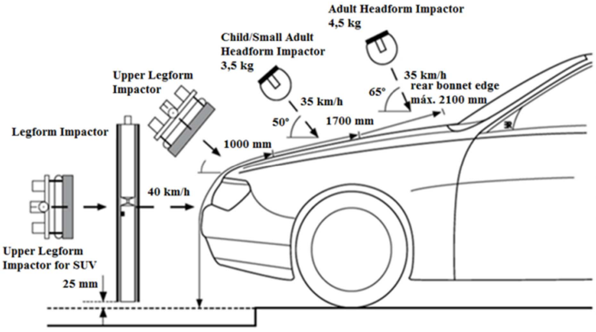

Fig. 2. Pedestrian protection homologation tests.

5 Virtual test of a pedestrian crash

Homologation tests are, in most cases, destructive, besides too expensive both in time and economically. It should be noted then the power of computers tools in the industry. Nowadays, it is unthinkable to design a vehicle without the presence of virtual testing. These virtual labs are becoming increasingly important both from lawmakers and car manufacturers. This type of tests can be a future alternative to actual tests in the approval of vehicles. The IMVITER European project (Implementation of virtual testing in safety regulations), which intended to settle virtual testing in the field of safety legislation, concluded that although the simulation technique is not able to replace the physical tests to date, virtual testing provide clear benefits in cases where repetitive tests are carried out.

In order to establish a first hypothesis about the reliability of virtual testing, it is decided to perform the simulation of pedestrian crashes by the finite element software LS-DYNA using a Crash Test Dummy with percentile 50. The virtual tests results will be compared with actual results of trials conducted by Euro NCAP, for the purpose of checking whether what is observed in the simulations corresponds to what happens in reality. For this, two car models completely opposite concerning pedestrian protection will be used; the sedan Citroën C6, equipped with one of the more notable pedestrian safety systems, the active bonnet and was also a pioneer in obtaining four stars in pedestrian protection in Euro NCAP, and, on the other hand, the SUV Mercedes Benz ML with only one star. The particularity of this second model is a defense located on the frontal area of car which in case of collision with another vehicle is beneficial but if it does against a person injuries increase significantly [7]. On modeling of the vehicle front it has been used Solid Edge CAD software. The rear of the car and wheels have been ignored in the model since they are not significant in the study of a pedestrian crash. This simplification reduces the complexity and time simulation. Furthermore, the visualization of car deformation caused by the dummy is omitted, not being useful information in this study. The inner structure engine can be critical in the injury result of pedestrian. Thus, in order to supply the lack of internal structure definition, the mechanical strength of the car front was increased.

Fig. 3. Real and virtual pedestrian and vehicle models for simulation.

Virtual tests are performed to study the influence of the safety of these vehicles. They consist of a frontal pedestrian crash caused by the Citroën C6 with and without active bonnet at 40 km/h and, on the other side, a frontal pedestrian crash caused by Mercedes Benz ML with and without its front defense at 40 km/h. The reason why this value of speed is because the percentage of pedestrian crashes increases considerably in urban roads, where 48% of deceased in traffic accidents are due to a pedestrian crash. In these roads the limit is usually 50 km/h. A close and lower value is selected in order to take into account the possible previous braking conducted by the driver.

6 Results

In the simulation of pedestrian crash caused by the Citroën C6 without active bonnet, it is observed a roof vault post-impact trajectory, as a result of the high impact speed and the high position of the pedestrian's center of gravity with regard to the impact point with the vehicle front. Some studies affirm that this typology is not observed below 32 km/h or above 60 km/h, so apparently this simulation may reflect what would happen in reality. The HIC criterion shows the severity head injury by measuring the acceleration in the nodes of the virtual dummy's head. In this case, it reaches a maximum value of 4828. However, when in the test the active bonnet is applied, the HIC decreased approximately 45% up to a value of 2136. It is proved in this way what would be expected in reality happens, i.e. the active bonnet reduces significantly the severity of brain injury, preventing the pedestrian's head impacts with extremely hard areas which stay under the hood, such as engine, increasing the separation distance between these hard elements and the hood veneer. That is why Euro NCAP awards such a high score to this car model. Results from neck, chest and hip severity injury pedestrian have been also obtained. They are reflected in Table 1 by the NIC (Neck Injury Criteria), CSI (Chest Severity Index) and LEC (Lower Ext. Criteria) factors respectively.

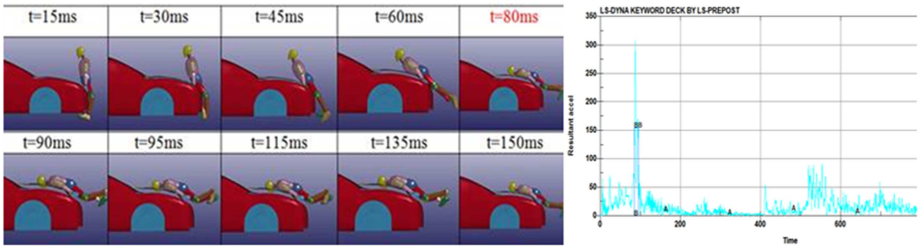

Fig. 4. Simulation sequence of frontal pedestrian crash by Citroën C6 at 40 km/h with active bonnet and HIC results.

On the other hand, in the simulation of pedestrian crash by Mercedes Benz ML without front defense, it is observed a wrap projection post-impact trajectory. In order to study the severity of this accident it is used again the HIC criterion, reaching a value of 2836. When the front defense is adding in the test, it is surprising that the HIC value is almost constant, so it is decided to analyze the global injury in the pedestrian by means of the Injury Severity Score (ISS) which takes into account the three highest values achieved among the various factors that evaluate the different parts of the body. These three factors considered by the ISS, in this simulation, are the HIC (head), the CSI (chest) and the LEC (hip). In Table 1, it can be seen that by including the front defense the chest injury is 4 times greater and the hip injury is 5 times greater. Thus, this defense increases significantly the pedestrian injury severity and can be cause his death due to internal bleeding and other injuries. For this reason, Euro NCAP penalizes this car model in its pedestrian protection score.

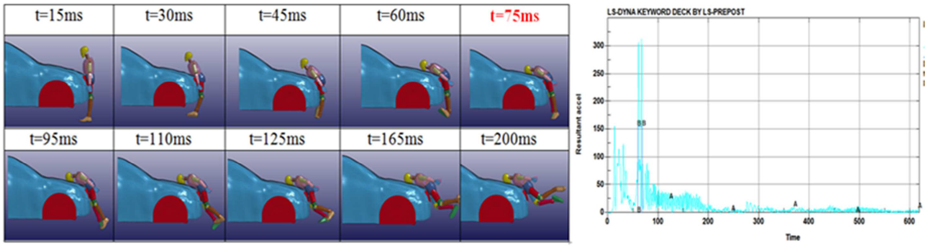

Fig. 5. Simulation sequence of frontal pedestrian crash by Mercedes Benz ML at 40 km/h without front defense and HIC results.

Table 1 shows the numerical results of the factors that assess the severity of the injuries suffered by the virtual dummy in the head, neck, chest and hip. It displays a comparison of the values obtained without safety systems in both models (the active bonnet in Citroën C6 and a front defense in Mercedes Benz ML) versus those obtained when these systems are included. Reference values based on data extracted from cadavers, actual tests and traffic accident data, have been also include in order to reflect the maximum tolerance injury for these body parts.

Table 1. Head (HIC), neck (NIC), chest (CSI) and hip injury simulation results with and without safety systems.

Without safety systems	**HIC**	**Neck**	**Chest**	**Hip (kN)**
Citroën C6	4828	3,925	525,5	-7
Mercedes Benz ML	2836	5,55	2058	- 21
With safety systems	**HIC**	**Neck**	**Chest**	**Hip (kN)**
Citroën C6	2136	-	362	-6,5
Mercedes Benz ML	2864	-	8231	-110
Reference values	700-1000	1,20	700-1000	-10,9

7 Conclusion

Although pedestrians were forgotten for decades by automotive designers with respect to their protection, it exists lately a tendency in safety systems focused on them. Some systems have demonstrated that they are very effective in the survival of the pedestrian, such as the active bonnet, and they begin to be incorporated as standard on new vehicles. Nevertheless, homologation tests for these systems are destructive and so greatly costly. Thus, finding a viable alternative to physical tests would minimize enormously the costs. Virtual labs could become in the best option to achieve this aim.

After analyzing the simulations performed and comparing their results of injuries severity suffered by the pedestrian with the score awarded by Euro NCAP to these car models, it is verified that finite element software (and, specifically in this case, LS-DYNA behaves as a tool able to reflect the actual behavior of pedestrian protection systems. Undoubtedly, these virtual representations leave many factors without intervening or studying together, while they do in real life. Nonetheless, there is no doubt that virtual tests represent a trend or a reliable quick overview of the immediate consequences of certain factors such as speed, front height, position or pedestrian safety measures in the car design without having to resort to costly and time-consuming full-scale tests. Thus, they can reflect what factors are the most influential in a pedestrian crash, in such a way that they can lead the efforts in the development of safety measures or in the vehicle design to protect increasingly in an effective way to pedestrians.

In the simulations of the pedestrian crash caused by the Citroën C6, it has been possible to quantify the importance of incorporating a pedestrian safety system as significant as it is the active bonnet. It has to be noted the reduction of 45% in the HIC value corresponding to the risk of suffering a serious brain injury. These values are consistent with those provided by Euro NCAP for this car model based on physical tests, assigning a high score in pedestrian protection with four stars. There have also been reductions in the injuries severity of chest and hip but to a lesser extent by using the active bonnet. On the other side, in the simulations of pedestrian crash by the SUV model Mercedes Benz ML, it is surprising finding out that the risk of serious injury brain does not change when the front defense is added to the vehicle. However, when making an overall assessment of the injury severity taking into account other hurt parts of the body as chest and hip, the severity degree increases significantly. When the front defense is added, chest injury severity is 4 times greater and hip values are 5 times greater. Hence, these virtual tests have behaved as expected according to physical tests performed by Euro NCAP, which emphasize that this model is extremely lacking in pedestrian protection. This front defense is a protection system in case of collision with another vehicle, but if it impacts with a pedestrian increases greatly the risk of dying.

Although virtual tests conducted in this study have reached the same conclusion as actual tests performed by Euro NCAP, it is considered that there is still a long way to go in research of virtual laboratories and set up which simplifications and limitations are acceptable to consider the results drawn from these virtual models as true repre-representative of reality.

One of the most decisive factors to accept a virtual test is as reliable validation and justification of the virtual model. However, in this research field there is a need to collect enough test and actual accidents data in order to compare and verify the accuracy and reliability of these virtual tests. This information is not generally available or its access is extremely limited. Therefore, in this study we have not been able to simulate the homologation tests by using legform and headform impactors, since no actual data were available with which to compare the results of virtual tests. Hence the decision to consult the physical tests provided publicly by Euro NCAP to check the veracity of virtual labs and establish some first assumptions on the viability of substituting the real approval tests with regard to pedestrian protection or at least to reduce them in number by virtual tests. Virtual labs could reduce enormously both temporal and economic cost of tests. Moreover, accepting as valid and reliable virtual tests would allow vehicle manufacturers to reduce time to market of their models and so increase their competitiveness.

As a final conclusion, to date, it is considered that the physical tests cannot be replaced completely by virtual tests, but virtual labs can provide great benefits in repetitive tests, such as in the case of homologation tests of pedestrian protection systems in which the impactor must be thrown several times in the same conditions. Although virtual tests are able to simulate the reality considering a large number of variables and, therefore, each time with minor differences between real and virtual model, it will be always necessary to have real data in order to validate the models.

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