Experimental research on pedestrian lower leg impact

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Abstract. The present paper is centred on the research of deceleration measured at the level of the lower leg during a pedestrian impact in multiple load cases. Basically, the used methodology for physical test setup is similar to EuroNCAP and European Union regulatory requirements. Due cost reduction reasons, it was not used a pneumatic system in order to launch the lower leg impactor in the direction of the vehicle front-end. During the test it was used an opposite solution, namely the vehicle being in motion, aiming the standstill lower leg impactor. The impactor has similar specifications to those at EU level, i.e. dimensions, materials, and principle of measurement of the deceleration magnitude. Therefore, all the results obtained during the study comply with the requirements of both EU regulation and EuroNCAP. As a limitation, due to unavailability of proper sensors in the equipment of the lower leg impactor, that could provide precise results, the bending angle, the shearing and the detailed data at the level of knee ligaments were not evaluated. The knee joint should be improved for future studies as some bending angles observed during the post processing of several impact video files were too high comparing to other studies. The paper highlights the first pedestrian impact physical test conducted by the author, following an extensive research in the field. Deceleration at the level of pedestrian knee can be substantially improved by providing enough volume between the bumper fascia and the front-end structure and by using pedestrian friendly materials for shock absorbers, such as foams.

1. Introduction
The European Union has had impressive success in achieving the highest pedestrian protection level on the globe. In 2013, 5,712 pedestrians were killed in road accidents in the EU, which is 22% of all fatalities. In the last decade, in the European Union, pedestrian fatalities were reduced by 37%, while the total number of fatalities were also reduced by almost 45%. The rate of pedestrian deaths in European countries varies from 3 pedestrian fatalities per million population in the Netherlands to more than 35 pedestrian fatalities per million population in Romania, a rate about 12 times higher. [2]

The present paper is focused on the research and development of an easier, cost-effective and more user-friendly tibia impact solution, for an overview analysis of decelerations at pedestrian knee joint level. The physical test results will be used in an advanced study for developing a method that can be used in the upstream stage of the vehicle project in order to predict the pedestrian impact performance and optimize the front bumper area.

2. Pedestrian regulations
A pedestrian crash can usually be divided into 4 stages: the vehicle initiates the contact with the pedestrian by touching his leg (tibia) with the front bumper, the front edge of the bonnet or headlight hits the upper leg (pelvis), the head of the pedestrian hits the bonnet or the windshield and finally the
pedestrian is projected in the air and hits the ground. The first three types of load cases are described in the European Commission Regulation, each using different sub-systems impactors to represent the main phases of a car-to-pedestrian impact. The three types of impactors are: a leg form impactor representing the adult lower limb to indicate lateral knee-joint shear displacement, bending angle and tibia acceleration, caused by the contact with the bumper; an upper leg form impactor representing the adult pelvis, in order to record bending moments and forces caused by the contact of the bonnet leading edge (BLE); child and adult head form impactors, recording head accelerations caused by the contact with the bonnet.

Figure 1. The sub-system tests used in EC Directive [1]

Additionally, vehicles are tested by specialized programs, like EuroNCAP (for Europe), JNCAP (for Japan), KNCAP (for Korea), etc., that publish the results, being a main tool for each customer who wants to buy a new vehicle to guide himself over the official reports in order to make a decision over the purchase. The exigencies for each of the programs mentioned above can be observed in table 1, and therefore it can be easily concluded that the most demanding in the lower leg impact case is EuroNCAP.

| Test method                  | Parameter          | EEVC lower leg form impactor (TRL) | EuroNCAP | JNCAP | KNCAP |
|------------------------------|--------------------|------------------------------------|----------|-------|-------|
|                              | Velocity          | 40km/h                             | 40km/h   | -     | 40km/h |
| Impact angle                 | 0°                | 170g                               | 150g     | 0°    | 150g   |
| Acceleration                 | 19°               | 6mm                                | 6mm      | 6mm   | 6mm    |
| Bending                      | 15°               | 7mm                                | 7mm      | 7mm   | 7mm    |
| Shearing                     | 20°               | 19°                                | 19°      | 19°   | 19°    |
| Shearing                     | 5mm               | 6mm                                | 6mm      | 6mm   | 6mm    |
| Tibia bending                | 282Nm             | 340Nm                              | 224Nm    | 388Nm | 340Nm  |
| MCL elongation               | 19mm              | 22mm                               | 16.4mm   | 22mm  | 22mm   |
| ACL/PCL elong.               | 10mm              | 10mm                               | 0mm      | 13mm  | 13mm   |

The trial for lower leg impact, the case analyzed in this study, may be conducted with two types of impactors: the rigid one (TRL) and the optimized flexible one (FlexPLI).

The difference between the two impactors is that the first one does not allow the two leg segments to deform, thus to simulate the flexibility of the human bone. Also, it cannot predict neither the fracture of the bone, nor the breaking of the knee ligaments. In this situation, the new developed FlexPLI impactor was created, with four flexible sections for each segment of the leg, that can provide results for torques read at the level of the tibia and three displacements read at the level of the knee that can give an overview of the risk associated with ligament breakage.

The rigid specification of the impactor was used in the pedestrian impact research, the analysed parameter, the deceleration at knee joint level being predicted more accurate in this configuration. Also, the development of this specification is less expensive and faster to build and calibrate.
3. Experimental research on pedestrian lower leg impact

A Renault Clio 2 vehicle, manufactured in 2005, with modifications conducted to the front bumper and front cross member in order to accommodate an EPP absorber specification, was used as test stand.

The impactor used was developed in the same way as described by the specifications in Regulation EC631/2009 [1], consisting of two circular cross sections (bars) of Ø70mm in diameter and 500mm in length, a simplified rotational knee joint at the intersection of the two segments, three 15mm thick foam layers made of 80% NBR (rubber butadiene rubber) and 20% PVC (polyvinyl chloride) and an exterior layer 1.5mm thick made of self-adhesive neoprene. The impactor was equipped with an X200-4 accelerometer (figure 2), produced by Gulf Coast Data Concepts, with 3-axis measurement capabilities and ± 200g range, which can be used with a sampling rate of up to 3200Hz. In the study, sampling rates of 400Hz, 800Hz, 1600Hz and 3200Hz were used for initial tests and trials. In these cases, it can be assumed that at a value of 400Hz, an acceleration value will be read at about 2.5ms; for a 800Hz sampling value, an acceleration value will be read at about 1.2ms; for a value of 1600Hz will be read an acceleration value at about 0.6ms and for a value of 3200Hz, an acceleration value will be read at each 0.3ms. Each line of the output file will contain 4 columns: in the first column the time will be found, in the second column the acceleration in the direction of the X axis, in the third column the acceleration along the Y axis, and in the last column the acceleration along the Z axis.

Figure 2. Gulf Coast Data Concepts X200-4 accelerometer [8]

The boundary conditions proposed for the physical impact test, were different from those specified in actual regulations. In the absence of a pneumatic system that launches the impactor in vehicle direction, it was chosen the reverted condition, the impactor being aimed by the vehicle. This configuration is closer to real accident conditions, but also has a number of limitations that need to be closely monitored during the tests in order to validate the results. The surface on which the car is running during the tests, shall be approximately flat, without unevenness, and the vehicle speed shall be measured and stabilized at least 3 seconds before the impact is produced. It has been chosen for instantaneous speed readings, vehicle OBD data, being one of the most accurate and simple methods. Additionally, speed measurement was carried out using a professional measuring system based on GPS satellite vehicle positioning, with an accuracy of 0.1km/h. The ambient temperature should be within the range of 23°C, ±3°C. At the time of the trials, on April 13th 2017, in the location where the tests took place, Bucharest, the outside temperature fluctuated between 20°C and 22°C. The zone where the impact has been achieved, should be evaluated and measured as soon as it’s completed. The impactor must be positioned appropriately (the accelerometer positioning in the direction of impact can be tracked as a reference) and must not be affected by any external environmental factors.

Impact kinematics were captured on digital support, similar to the one used in the EuroNCAP impact tests. This allows to record a large amount of information, which are captured in a very short time, with camcorders capable of recording high-speed images. Using this process, the images were captured at a rate of 240 frames per second, with the help of a GoPro Hero 4 Black Edition video camera, later being played back by slow motion. This process slows down the rate of photogram playback at a perceptible speed by the human eye, or even by "freezing" a single instant frame, which allows extracting as much information as possible.

The analysed data from physical tests, are the deceleration curves read at the knee joint of the impactor.
The configurations used in the simulations are described in the list below:
1. Standard vehicle configuration – vehicle speed 42.6km/h
2. Modified vehicle configuration, with EPP pedestrian absorber – vehicle speed 38.4km/h
3. Modified vehicle configuration, with EPP pedestrian absorber – vehicle speed 39.1km/h
4. Configuration 2/3, without front bumper fascia – vehicle speed 38.7km/h
5. Configuration 2/3, without front bumper fascia – vehicle speed 39.3km/h

Below in figure 3, the impact test setup can be observed, in 4th and 5th configuration.

The first test was carried out using the vehicle's standard configuration, in order to assess the test conditions and initial vehicle impact performance. Two other impact tests were carried out in a modified EPP absorber configuration, Renault reference 62090JZ00B, modified accordingly to the volume available in the interior of the front bumper. The last two attempts were derived from the previous configuration, but without a front bumper fascia, in order to better observe the deformations and kinematics of the impact. After each test, the shock absorber used was replaced with a new one.

Following the pedestrian impact tests, there were observed two areas where the impactor slightly deformed the bonnet outer panel. In the first area, marked with the number 1 in figure 4, the impactor deformed the hood near the 225mm Y coordinate. The bonnet leading edge (BLE) was not affected and the effects on the pedestrian will not have a considerable magnitude, the local rigidity of the bonnet in that area being reduced. In the second area, marked with number 2 in figure 4, the impactor hasn’t deformed the hood, but left visible traces of contact friction at the 135mm Y coordinate. The bonnet leading edge has not been deformed in this case either. During the impact tests, a single absorber was broken, in test configuration number 5, in which it was in direct contact with the lower leg impactor. The rupture was identified in the perpendicular direction of impact and propagated along the longitudinal axis of the vehicle. (figure 5)
The kinematics of the impact can be observed in figure 6. The chronology is similar to other physical tests conducted in the automotive field.

![Figure 6. Pedestrian impact chronology](image)

Decelerations obtained from the physical tests can be observed in figures 7-11, that contain the curve data. In the first load case, corresponding to the standard equipment of the vehicle, it can be noticed the ramp that the curve follows immediately after the initiation of the impact. This is most likely determined by the very rigid construction of the front bumper assembly, with a plastic honeycomb absorber and the presence of the three decorative elements, disposed integrally across the width of the front crossmember.

![Test no. 1](image)

![Figure 7. Deceleration curve – physical pedestrian impact test - configuration no.1](image)
The following two test cases were carried out starting from the standard configuration of the test vehicle, modified by replacing the absorber with a specification of EPP material, adapted to be mounted in the volume between the bumper fascia and the cross member. In these two cases, the maximum deceleration value recorded during impact may be reduced by approximately 25g. The difference between the shapes of the curves can be given in this case by the differences between vehicle speed values at impact initiation and impact section positioning along the lateral axis of the vehicle.

![Test no. 2](image1.png)

**Figure 8. Deceleration curve – physical pedestrian impact test - configuration no.2**

![Test no. 3](image2.png)

**Figure 9. Deceleration curve – physical pedestrian impact test - configuration no.3**

In order to better observe the deformations during the impact, and also to evaluate the influence in rigidity of the bumper fascia, the last two tests were launched and show a reduction of about 5-10 g in terms of the maximum values of the resulting decelerations, due to the more available volume for the absorber along the longitudinal axis of the vehicle.
Figure 10. Deceleration curve – physical pedestrian impact test - configuration no.4

Figure 11. Deceleration curve – physical pedestrian impact test - configuration no.5

The maximal deceleration values obtained from the physical pedestrian impact test can be analyzed in table no.2 below.

| Test configuration | Maximal deceleration (g) |
|--------------------|--------------------------|
| TEST 1             | 151.5                    |
| TEST 2             | 126.5                    |
| TEST 3             | 127.8                    |
| TEST 4             | 118.5                    |
| TEST 5             | 106.1                    |
| EuroNCAP limit     | 150                      |

Table 2. Pedestrian lower leg impact test deceleration test results
4. Conclusions

The field of passive safety, although set in the spotlight in recent decades, alongside other development directions in automotive industry and the number of road accident victims in the European Union, falling by about 25%, despite the significant increase in car fleets, some 40,000 people still lose their lives in traffic events, most of them pedestrians. Due to the continuous and very rapid evolution of motor vehicles, the variation in the intervals of the worldwide population anthropological parameters, the numerous scenarios of load cases that may be encountered in real life, the difficult manufacturing of devices that can precisely reproduce the biomechanical behavior of the human body and the limits to which human body can survive an impact, pedestrian protection will still be one of the most challenging research fields.

As the present study shows, the decelerations comply with the requirements of EuroNCAP. Using pedestrian friendly materials such as EPP foams, the decelerations measured during the impact are reduced by approximately 45g, compared to vehicle’s standard absorber specification, calculating a gain up to 30%. The EPP material offers great advantages for fast and cost-effective modification of a vehicle. Most likely scenario might be the adaptation of existing vehicles according to new regulations or new market requirements. In this case, an opportunity can be identified for vehicles currently sold in developing countries without exigent regulatory requirements, to implement the proper solutions already existing and applied in Europe or North America, therefore to reduce the highest number of pedestrian fatalities worldwide, registered in low and medium income countries.

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