Theoretical and Experimental Approaches to Motor Vehicle – Pedestrian Collision

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Abstract: The motor vehicle has raised new problems that had not been encountered until its creation. Statistics show that at the world level more people die in road traffic accidents than in armed conflicts. The researches carried out in view of reducing the number of victims as well as in view of diminishing the degree of injuries in pedestrians have been numerous in the last decade. EURONCAP association has proposed the car manufacturers, through the EEVCWG17 directive, a partial solution with regard to the changes that must be brought to the front end of the vehicle. Through the present paper the authors have built a dummy, have made experimental tests and have theoretically analyzed some aspects regarding the frontal collision between motor vehicles and pedestrians, emphasizing certain constructive factors on which the severity of injury in pedestrians depends. Likewise, theoretical results were compared with the experimental ones in view of improving programs and calculation models.

Key-Words: - Automotive, Pedestrian, Accident Simulation, Accident Reconstruction

1 Introduction

The study of injuries suffered by persons involved in road traffic accidents represent, for motor vehicles designers, a good method to obtain data that contribute to improving road safety, particularly passive safety. This process develops directly (the results of mixed analyses – medical and engineering-oriented – of the frequency of body injuries as well as of their causes are transposed in adequate designing solutions for different parts of the motor vehicle) or indirectly (when these analyses are used to simulate real accidents in laboratory).

During collisions, the human body is subjected to extreme loads that are mainly due to high accelerations and decelerations (at severe collisions they reach values of more than 30 g) which generate great forces of inertia. Another factor that determines injuries of the human body are the deforming elements of the motor vehicle's body. During collision, these elements act upon the various anatomical parts, causing serious injuries.

In Romania, road traffic accidents cause more than 2800 deaths and more than 7700 serious injuries every year; these figures, considering the dimensions of the country, are high. The mean value between traffic values and number of accidents is six times higher in Romania than that recorded in the European Community. Bone and internal organ injuries require large funds from the budgets of each country.

In this paper, the authors compared the values related to the kinematics of body segments experimentally obtained and the values related to the multimass mathematical model of the pedestrian.

The criteria used in order to estimate the traumas of the human body are head and thorax decelerations as well as impact speeds of these human body segments with motor vehicle's parts.

2 Testing scenarios and mathematical model proposed

The basic principle when it comes to protect life of both pedestrians and motor vehicle occupants is to reduce the potentially injurious forces by absorbing a part of the motor vehicle's kinetic energy. This may be achieved by deforming or by destroying certain parts of the motor vehicle the pedestrian comes into contact with.

Provided that, while in motion, the pedestrian's body hits certain objects, these objects absorb part of the kinetic energy and the impact forces decrease. The issues to be raised make reference to the energy a deforming body can absorb and the force needed for the deformation to be produced.

A simplified relation of the connection between the kinetic energy of the body and the space needed for energy absorption is:

$$F \cdot d = \frac{m \cdot v^2}{2} \quad (1)$$

where ***d*** stands for the distance required to stop the body, ***F*** stands for the average force occurring during the impact, ***v*** stands for the body's speed before the impact. It is easy to understand that head protection calls for lowest possible values of ***F*** and greatest possible deformations of the motor vehicle's parts.

The study of phenomena occurring during the motor vehicle-human being interaction entailed the use of various computer-based mathematical models, based on the dynamics of rigid bodies, in order to simulate the motor vehicle-pedestrian impact. Therefore, the specialist literature provides analyses that used commercial software as well as specific models. Other researchers investigated the efficacy of bi-dimensional models with different complexity degrees. The commercial program MADYMO was used to create bi-dimensional models of the pedestrian with two, five and seven rigid body segments as well as a tri-dimensional model whose body is made up of fifteen segments, figure 1. [4]

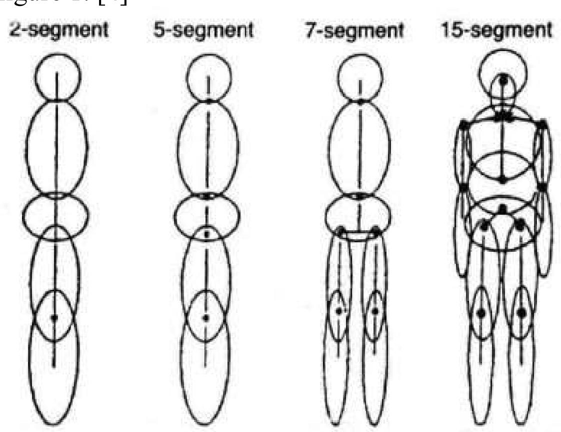


Fig 1. Dummies with different complexity degrees

Tests results were compared with those obtained following the experiments with dummies.

In order to define the tests the following two situations were considered representative for the motor vehicle-pedestrian accidents.

- ➢ Pedestrian in lateral position (crossing the street) hit with the front end area of the braking vehicle - scenario (a);
- ➢ Pedestrian in frontal position, coming into a frontal collision with the vehicle traveling at constant speed – scenario (b);

Fig 2. The pedestrian dummy crossing the street

The motor vehicle used for tests was towed on the test road and accelerated to a speed of 30 km/h. Just before the moment of impact the motor vehicle was braked. In order to find out the average deceleration of the motor vehicle, the braking marks were measured. Statistical data showed that most of the road traffic accidents involving pedestrians occur at speed of up to 30 km/h, in most cases the motor vehicles being in braking operation.

2.1 Multimass mathematical model of the pedestrian

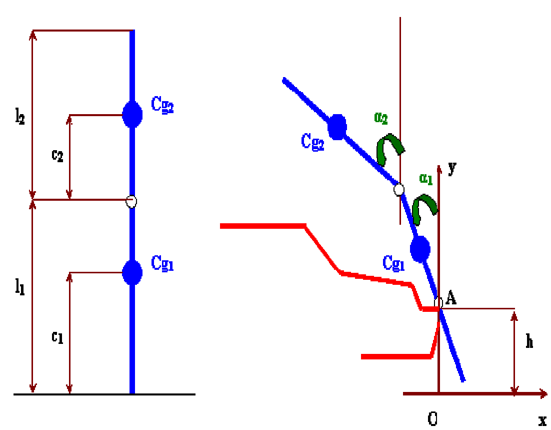


Fig 3. Mathematical model – general diagram

To generate equations the model used was the two-mass mathematical model of the pedestrian, this model being easily modified by adding additional masses.

At time $t \neq t_0 = 0$, after the motor vehicle has acted upon the pedestrian's knee, the contact point being A, in the impact configuration of the pedestrian in lateral position with the front end of the vehicle, the pedestrian is found in the position presented in figure 2. In this first stage of the impact it is considered that the instantaneous center of rotation of mass one of the pedestrian is at the contact point with the vehicle's bumper, mass two rotating around the hip joint. The hip joint is considered a cylindrical joint, when solving the plane problem, having a rigidity coefficient k_{21}, which stimulates the muscular tonus.

The coordinates of the centers of mass, on X and Y axes, of the two body segments are displayed according to the diagram in figure 3.

Through derivation, there are to be obtained the speeds on the two axes of the XOY system, corresponding to the centers of mass of the two segments of the pedestrian's body

$$\begin{cases} x_{cg1} = -(c1-h)\cdot\sin(\alpha_1) \\ y_{cg1} = h + (c1-h)\cdot\cos(\alpha_1) \end{cases} \quad (2)$$

$$\begin{cases} x_{cg2} = -(l1-h)\cdot\sin(\alpha_1) - c2\cdot\sin(\alpha_2) \\ y_{cg2} = h + (l1-h)\cdot\cos(\alpha_1) + c2\cdot\cos(\alpha_2) \end{cases}$$

$$\begin{cases} \dot{x}_{cg1} = -\dot{\alpha}_1\cdot(c1-h)\cdot\cos(\alpha_1) \\ \dot{y}_{cg1} = -\dot{\alpha}_1\cdot(c1-h)\cdot\sin(\alpha_1) \end{cases} \quad (3)$$

$$\begin{cases} \dot{x}_{cg2} = -\dot{\alpha}_1\cdot(l1-h)\cdot\cos(\alpha_1) - \dot{\alpha}_2\cdot c2\cdot\cos(\alpha_2) \\ \dot{y}_{cg2} = -\dot{\alpha}_1\cdot(l1-h)\cdot\sin(\alpha) - \dot{\alpha}_2\cdot c2\cdot\sin(\alpha_2) \end{cases}$$

Lagrage method is to be approached in order to find out the unknown

$$\frac{\partial}{dt}\left(\frac{\partial Ec}{\partial \dot{q}_i}\right) - \frac{\partial Ec}{\partial q_i} + \frac{\partial V}{\partial q_i} = 0\,, \quad (4)$$

where for our case i=1,n, and q_i are angles α_1 and α_2 for the case presented

$$Ec = \sum_i Ec_i \quad (5)$$

$$Ec_i = \frac{m_i\cdot vcg_i^{\,2}}{2} + \frac{J_i\cdot\dot{\alpha}_i}{2} \quad (6)$$

$$vcg_i^{\,2} = \dot{x}_{cgi}^{\,2} + \dot{y}_{cgi}^{\,2} \quad (7)$$

$$V = \sum_i\left(m_i\cdot g\cdot y_{cgi}\right) + \sum_i\frac{k_{i,i-1}\cdot(\alpha_i-\alpha_{i-1})^2}{2} \quad (8)$$

Where:

Ec – kinetic energy;
V – potential energy
m_i – masses of the body segments making up the pedestrian;
J_i – moments of inertia of the pedestrian masses;
Vcg_i – speeds of center of masses of pedestrian masses;
k_i – rigidity coefficients in the joints of the pedestrian body;

Through replacement process in relation (4) and through its differentiation, a system of differential equations is to be obtained in unknown α_1 and α_2.

3 Theoretical results

Statistics drawn up in hospitals show that the probabilities for the anatomical parts to suffer injuries during an accident are different. The head is the anatomical part which is most likely to be injured. This may be explained through the multitude of factors acting upon the head during collision. The most dangerous situations (head injury) are the frontal impact (the head is submitted to a secondary impact, hitting the windshield, the hood or the wheel, depending on the position of either pedestrian or vehicle occupant) and those involving front-end and rear-end collisions (when loads are mainly due to the relative motion between the head and the body).

On the basis of the mathematical model presented in the previous section, simulations were carried out with regard to the collision presented in scenario (a) motor-vehicle – pedestrian crossing the street. The simulations were made with the PC Crash 8.0 program, choosing a dummy with a height of 1,83 m and a weight of 73 kg. In head-neck and hip-thorax joints there were introduced moments of resistance variable in time, according to the relative angle between the body segments mentioned.

The initial speed of the motor vehicle was of 30 km/h, just like in real situation; at the moment of impact a braking deceleration of 3,5 m/s^2 was applied upon the rear axle wheels.

The head and thorax accelerations were recorded and are subsequently presented in figure 4. Just like in the case of experimental researches, the impact covered two main stages. The first stage approached in the present paper, starts at the moment of the first contact between the bumper and the pedestrian's leg and ends at the moment the pedestrian hits the motor vehicle's windshield or hood with the head. In theoretical simulations this interval lasts for about 0,225 seconds, slightly more increased than in experimental researches. The maximum value of pedestrian's head deceleration is of 70 g. The maximum level of the deceleration obtained is not as important as the period covered by the maximum level admitted, this being in fact a criterion to establish the head traumas, the HIC criterion.

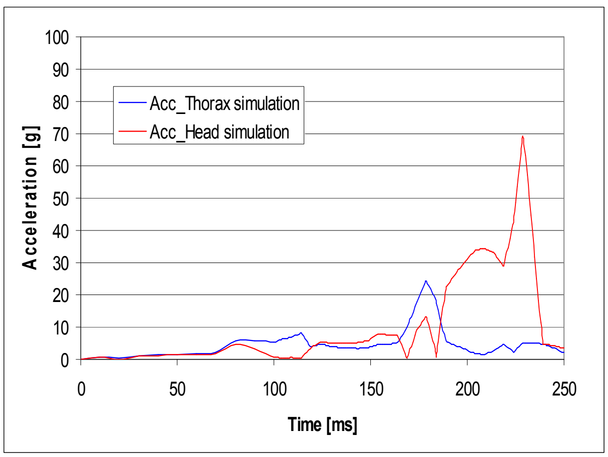


Fig 4. Theoretical results obtained.

4 Experimental tests

The experimental tests used a dummy built by the authors, figure 5. The weight of the dummy skeleton is 10 kg distributed as follows: 4,9 kg - the body together with the head, without hip joint, and 5,1 kg - lower limbs together with hip joint. The total weight of the dummy is 73 kg, the dummy being linked with elastic elements made of rubber as muscles. The dimensions of the dummy and the masses of the main regions of the body are given in tables 1 and 2.

Table 1

Dimension of the body segment	**[cm]**
Head circumference	59
Chest circumference (dressed)	108
Hip circumference (dressed)	89
Height of the head + neck	29
Distance from shoulder to elbow	28
Distance from elbow to arm wrist	25
Height to which the knee is placed, from the soil	47
Distance from hip to knee	49
Height of the body	58

Table 2

Body segment	**Mass [kg]**
Head + Neck	5
Body + arms	40
Legs + hip	28
Total body	**73**

Dummy instrumentation includes two triaxial accelerometers set in the head and in the thorax. Optionally, displacement transducers may be assembled to measure the deflection of the ribcage and strain gauges may be set on bones to measure the forces occurring during the impact.

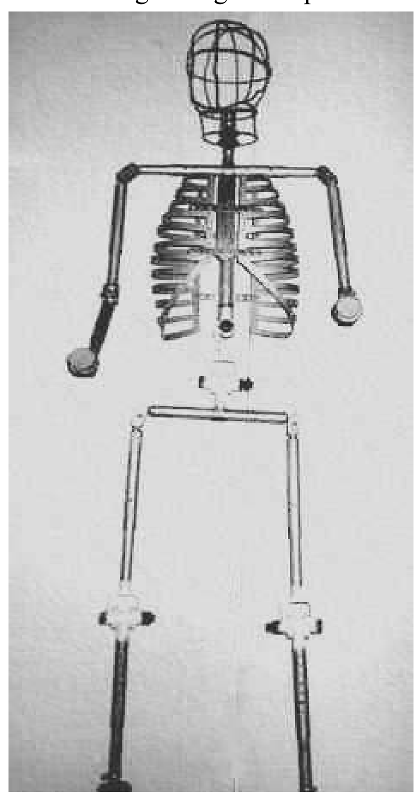


Fig 5. Bone structure of the dummy

A moment of resistance in joints is achieved by diminishing the clamping force in the respective joint and by assembling elastic rubber elements between the body segments linked through that joint.

By clamping or by loosening the joints a mono-mass or multi-mass dummy may be obtained. The maximum number of the masses of the model built is 11, figure 5.

The dummy was instrumented with two Bell & Howell accelerometers of type 4-204-0001, assembled in the center of gravity of both head and thorax. In view of a better adjustment of the dummy's head, changes were made in order to fix it in three points placed on shoulders and on the vertebral column. In order to measure the thorax accelerations, a second accelerometer of the same type was assembled on the vertebral column. The accelerometers were assembled with axles parallel to the three anatomic planes of the body (coronal, sagittal, transversal). X and Y axes, on which the accelerations were recorded, are contained in the sagittal and coronal plane, and Z axes are parallel to the transversal plane.

The values obtained following the tests are presented in figure 6.

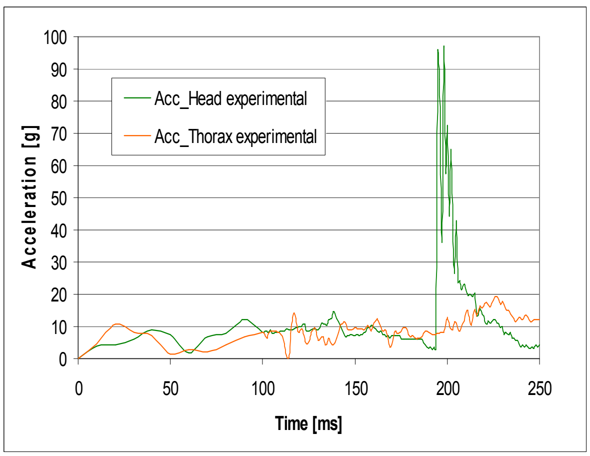


Fig. 6. Experimental results

4.1 Preparing the motor vehicle

The motor vehicle used was Dacia Nova. The vehicle was tested at a weight of 1024 kg, and empty fuel tank. The front end and the hood were dyed in order to trace the areas with different potential for injury of the pedestrian and to facilitate the image analyses with the FALCON Germany soft. Two dummies Hybrid II Fyrst Technology USA were set inside the vehicle as testing elements.

A special braking system with electrical triggering through cable, figure 7, was assembled in the motor vehicle's boot. The aim was to trigger the braking system at the moment of impact with a pedestrian dummy and to avoid its destruction during the impact with a fixed collision barrier (170 tonnes + metallic barrier for collision) placed at about 15 meters from the impact area. The vehicle was towed on the test road with a special installation, whose parameters may be modified with regard to the speed of tests development.

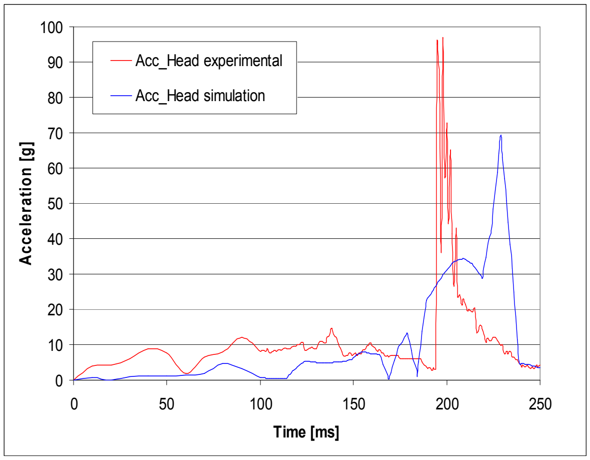
The speed at which the vehicle was towed on the collision-designated test road was 30 km/h; the vehicle was completely uncoupled from the pulling installation shortly before the impact, it rolled freely for a certain time and then it was braked on the rear axle with an average deceleration of 3,5 m-s^2 just before the impact.

Fig 7. Braking system of the motor vehicle

5 Conclusion

The analysis of the results obtained following the impacts suggests that despite the relatively low impact speeds, the head and thorax accelerations are significant; the duration at which these accelerations are present is added to these values. The injuries suffered by victims are serious and, most of the times, lethal. In the tests carried out, the values of the vertebral column accelerations were inferior to those given by the supportability limits of the human body. Therefore, during the experimental tests, at the initial impact between the motor vehicle and the lower limbs of the pedestrian, in the interval ranging from 0 to 60 ms, the mean value of the vertebral column acceleration was 9 g. In the interval ranging from 190 to 250 ms, when the pedestrian hit the windshield with the head, the mean value of the vertebral column acceleration is 12,75 g.

Between experimental tests and simulation there is a time lag of about 10% with regard to the moment the dummy's head hits the windshield. We believe that this difference results from the fact that on the real dummy the moments in the head-neck and hip-pelvis joints are constant during the tests, without having the possibility to modify these moments according to the relative angle between the body segments mentioned.



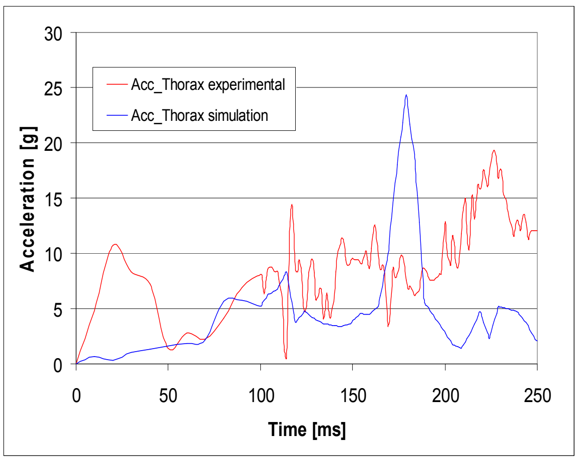


Fig. 8. Comparison between theoretical and experimental values

The maximum value of head deceleration is 95 g at 0,200 sec from the contact between the vehicle's bumper and the dummy's leg. Through the variation of moments of resistance in joints there was noticed an increase in the maximum values of head and thorax accelerations from the moment of the first contact until the moment the head hits the windshield or the hood.

By integrating the accelerations values obtained there are obtained the variation curves of speeds at which the pedestrian's head and thorax hit the vehicle's surface. The values obtained indicate a maximum level of the speed at which the head hits the windshield of 10,3 m/s at the moment of 0,2 sec from the beginning of the collision [2]. The values obtained are in concordance with the results obtained by other motor vehicles' manufacturers.

The secondary impact, with the soil, proved to be another important factor in generating severe traumas. Therefore, in the future, the efforts of motor vehicles' manufacturers should be oriented towards finding solutions that should diminish the effects of the collision with pedestrians, assuring, at the same time, protection to the vehicle's occupants.

In the last few years the EURONCAP Center - European New Car Assessment Program, a catalyst that encourages the design improvement for the new motor vehicles, has carried out tests whose aim is to analyze the degree of damage to pedestrians caused by all new models of motor vehicles. On the basis of EURO NCAP procedures new regulations regarding the protection for pedestrians are to be developed. Car manufacturers face a difficult problem because they must make a compromise between the protection for children and the protection for adults as the measures applicable for an adult are to be approached differently in case of children.

Another way to diminish the number of vehicle-pedestrian accidents is to create a road infrastructure that should meet the current requirements not only in urban areas but also outside urban areas (designing pedestrian walkway, avoiding the intersection of motor vehicle routes with the pedestrian ones, designing protection panels).

We also have to remind the fact that the road traffic education of each participant in traffic, driver or pedestrian, plays a major role in reducing the number of road traffic accidents.

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