MATHEMATICAL MODEL OF HUMAN BODY HEAD AND THORAX INJURY LEVEL SIMULATION FOLLOWING THE MOTOR VEHICLE - PEDESTRIANS COLLISIONS

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KEYWORDS - Vehicle, Pedestrian, Accident, Bumper, Injuries

ABSTRACT - The impact velocity and motor vehicle frontal structures, including geometry and rigidity, have proved to be important factors that produce trauma. The paper hereby analyzes the impact between the motor vehicle and the bidimensional pedestrian. The motor vehicle has a constructive configuration provided with a double bumper. The second bumper is positioned under the first bumper and it is withdrawn backwards to a certain degree. The bumpers positioning heights, the impact force distribution on the two bumpers will be varied whereas the total impact force remains constant, and the velocities imprinted at the pedestrian thorax and head will be calculated. The motor vehicle rolling condition does not consider pitch movements.

GENERALITIES

Traffic safety as well as the possibility to reduce the social costs of rehabilitation and the seriousness of injuries suffered by pedestrians present a particular complexity, being necessary to take a close approach to these issues.

In order to carry out developments concerning the traffic safety at low costs, there occurs the necessity to prioritize the interventions on the basis of „costs – advantages" analyses, by introducing the criterion of efficiency when drawing up working programs.

Various calculation methods may be used in order to calculate the average cost per accident.

$$C = GDP\,(31{,}48D + 3{,}75I + 0{,}15i) \tag{1}$$

where:

C = the cost of an accident, expressed in the same currency units in which the GDP is expressed; PIB= gross domestic product per inhabitant; D = number of dead persons in the accident; I = number of seriously injured persons in the road accident; i = number of slightly injured persons in the road accident.

In 2008 in Romania at a GDP of 6000 EURO/person and an average statistical number of 0,3018 dead persons/accident; 0,9135 persons seriously injured/accident and 0,025 slightly injured persons /accident, there results an average cost per accident in 2008: C = 77580 Euro. As related to these calculations, we can state, purely informative, that in France the material and human losses resulted from accidents in 1990 represented about 1,4% of the GNP, and in 1992 this percentage increased to 1,9%.

The statistics with regard to road traffic accidents indicate that a significant percentage of traffic victims are pedestrians and cyclists who are injured in an impact with a motor vehicle in motion. Most accidents take place in urban areas where serious or lethal injuries may occur at reduced speeds, especially in case of children. The general desire is to diminish the seriousness of injuries by improving the frontal structures of motor vehicles. From a certain speed the aim of reducing the number of injuries is limited; yet, at speeds below about 40 km/h it is likely to significantly reduce the levels of injuries caused to pedestrians involved in frontal impacts with motor vehicles. The impact velocity and the vehicle's frontal structures, including the geometry and the rigidity proved to be important factors to cause trauma.

Most of the fatal injuries among pedestrians are caused by head injuries. The major causes of serious head injuries are the bonnet and the A pillars. Otte also reported that in 1999 the windshield stood for a significant cause of head injuries. The modern vehicles have rigid components under the bonnet, with spaces even smaller than 20 mm. Thus, the deformation that is likely to occur is too small to allow the absorption of necessary energy. Theoretically, there is required a distance of about 55 mm at an impact with a velocity of 40 km/h in order to maintain the HIC value below 1 000 for an adult head.

The impact velocity has also a major influence upon the resulted trauma. The pedestrians hit with velocities reaching 25 km/h usually suffer minor injuries. More than 95% of the accidents involving pedestrians are produced at impact velocities below 60 km/h. The average velocity specific to serious accidents is about 40 km/h. A typical impact of the head in a vehicle-pedestrian collision at 40 km/h takes place at about 140...150 miliseconds after the first contact of the leg with the bumper. The shoulder hits the bonnet at about 120...130 ms in the same type of impact.Although there have been brought many improvements to the vehicles' frontal structures in view of reducing the pedestrians' injury potential, these improvements are not yet able to meet the more and more imperative requirements of the new passive safety regulations in force.

EuroNCAP has carried out collision tests in accordance with the EEVC WG 10 method on a big number of vehicles. 44 vehicles have been tested and none has met the imposed requirements so far. The researches into the mechanisms of pedestrians' injuries in accidents produced by vehicles have been conducted at a large scale; however, few improvements have been brought to vehicles with the aim of producing fewer traumas to pedestrians. It is necessary to develop safety systems based on the pedestrian's reactions and on the injury mechanisms occurring in road accidents.

MATHEMATICAL MODEL OF IMPACT

The hereby paper analyses the impact between the vehicle and pedestrian, the vehicle being in constructive configuration with double bumper. The second bumper is considered to be placed under the first one and a little withdrawn backwards.

The bumpers positioning heights will be varied, and the velocities imprinted at the pedestrian thorax and head will be calculated. For simplification there is considered:

- The pedestrian as single-mass, of constant height and mass throughout the several simulations;
- The impact model is only on X and Y axes;
- The impact upon the pedestrians' legs will be produced simultaneously by the two bumpers;
- The impact force will be distributed in two points corresponding to the bumpers' heights and it will vary on the upper and lower bumper, but the sum of the two values will be the same for each simulation. Practically, this is translated through a similar impact velocity for each simulation.
- The pedestrian is motionless in both longitudinal and transversal direction;
- The vehicle's running system does not manifest through the occurrence of pitching motions and, therefore, the height of impact points upon the leg will not vary within one simulation.

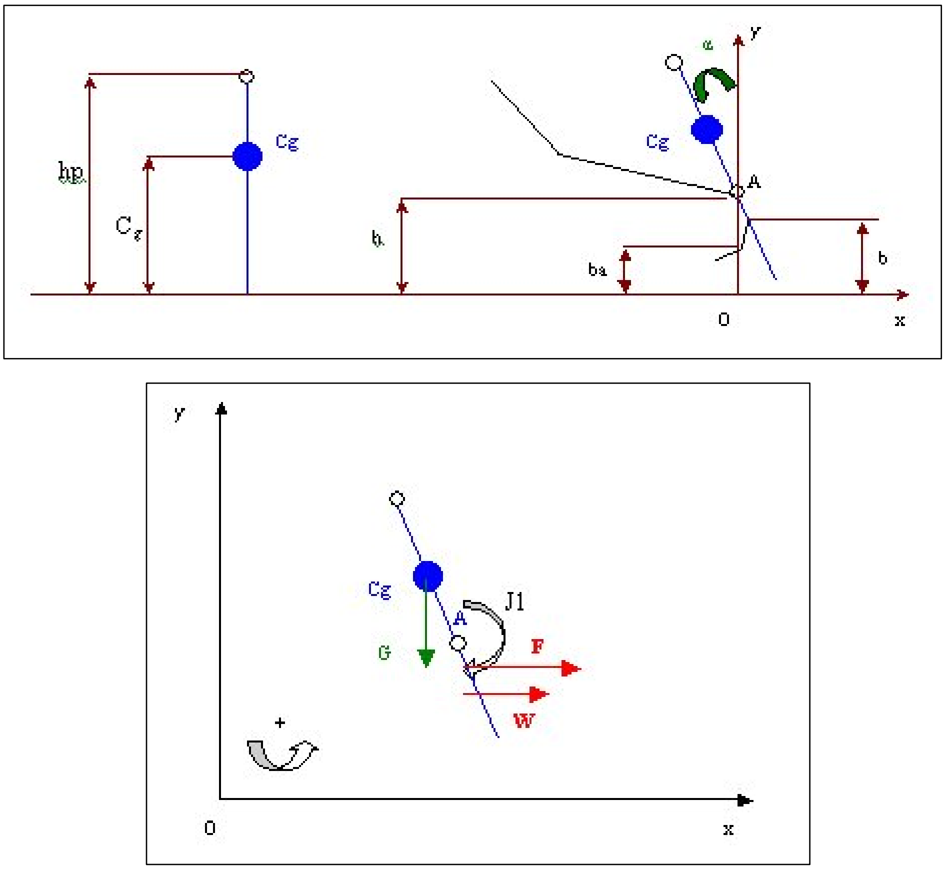


Figure 1. Impact schema

According to the figure 1 the coordinates of the pedestrian centre of gravity are as follows:

$$\begin{cases} x_{c1} = -(Cg - h)\cdot\sin(\alpha) \\ y_{c1} = h + (Cg - h)\cdot\cos(\alpha) \end{cases} \tag{2}$$

Following the successive derivations and transformations there is obtained the vector of the pedestrian translation and rotation accelerations:

$$\begin{cases} \dot{x}_c = -\dot{\alpha}\cdot(c1 - h)\cdot\cos(\alpha) \\ \dot{y}_c = -\dot{\alpha}\cdot(c1 - h)\cdot\sin(\alpha) \end{cases} \tag{3}$$

$$\begin{cases} \ddot{x}_c = -\ddot{\alpha}\cdot(c1 - h)\cdot\cos(\alpha) + \dot{\alpha}^2\cdot(c1 - h)\cdot\sin(\alpha) \\ \ddot{y}_c = -\ddot{\alpha}\cdot(c1 - h)\cdot\sin(\alpha) - \dot{\alpha}^2\cdot(c1 - h)\cdot\cos(\alpha) \end{cases} \tag{4}$$

$$\begin{Bmatrix} \ddot{x}_c \\ \ddot{y}_c \\ \ddot{\alpha} \end{Bmatrix} = \begin{bmatrix} -(c1 - h)\cdot\cos(\alpha) \\ -(c1 - h)\cdot\sin(\alpha) \\ 1 \end{bmatrix}\cdot\left\{\ddot{\alpha}\right\} + \begin{bmatrix} (c1 - h)\cdot\sin(\alpha) \\ -(c1 - h)\cdot\cos(\alpha) \\ 0 \end{bmatrix}\cdot\left\{\dot{\alpha}^2\right\} \tag{5}$$

$$\{a\} = [A]\cdot\left\{\ddot{\alpha}\right\} + [B]\cdot\left\{\dot{\alpha}^2\right\} \tag{6}$$

where [A] stands for the pedestrian’s angular acceleration coefficients matrix;

[B] stands for the pedestrian’s square angular acceleration coefficients matrix;

{a} stands for the vector of the body translation and rotation accelerations.

Out of the forces and moments equations of equilibrium, the matrixes are used in order to obtain:

$$\begin{bmatrix} m1 & 0 & 0 \\ 0 & m1 & 0 \\ 0 & 0 & J1 \end{bmatrix} \cdot \begin{Bmatrix} \ddot{x}_{c1} \\ \ddot{y}_{c1} \\ \ddot{\alpha} \end{Bmatrix} = \begin{Bmatrix} F + W \\ -G1 \\ -G \cdot (Cg - h) \cdot \sin(\alpha) - F \cdot (h - b) \cdot \cos(\alpha) - W \cdot (h - ba) \cdot \cos(\alpha) \end{Bmatrix} \quad (7)$$

that can be more simply written under the form:

$$[M] \cdot \{a\} = \{Q\} \quad (8)$$

where: [M] stands for the matrix of both the mass and pedestrian’s inertia moment;

[Q] stands for the matrix of the forces actuating upon the pedestrian;

{a} stands for the vector of the body translation and rotation accelerations.

Aiming at finding out the unknown out of the equations (6) and (8) by multiplying at the left with $[A]^T$ there will be obtained:

$$[A]^T \cdot [M] \cdot [A] \cdot \{\ddot{\alpha}\} + [A]^T \cdot [M] \cdot [B] \cdot \{\dot{\alpha}^2\} = \{Q_{ext}\} \quad (9)$$

where: $\{Q_{ext}\} = [A]^T \cdot \{Q\}$ *(10)*

The relation (9) may be written under the form:

$$[A1] \cdot \{\ddot{\alpha}\} + [B1] \cdot \{\dot{\alpha}^2\} = \{Q_{ext}\} \quad (11)$$

The relation (10) represents the simplified form of the differential equation in the unknown $\alpha = \alpha$ (t). By replacing it in the relation (1) the coordinates of the pedestrian’s body centre of mass can be found out.

The vehicle is considered to be equipped with a bumper the impact points of which will vary on height within the ranges limit 0,51 – 0,6 m for the upper bumper and 0,3 – 0,4 m for the lower one. The impact force added to the two impact forces is of 6 kN for each simulation. The bonnet’s frontal edge is situated at the constant height “h” during the simulations. The contact point between the bonnet’s edge and the pedestrian’s leg is considered to be a cylindrical articulation around which the pedestrian will pivot after the impact.

IMPACT SIMULATION

In order to answer the proposed problem a MathCad application was conceived to resolve the system by using the Runge Kutta method with the rkfixed function.

The steps to be pursued are as follows:

Define solver parameters:

$ic_0 := y0$ Vector of initial solution values.

$D(t,Y) := f(t,Y_0)$ Derivative function. The second argument must be a vector of unknown function values.

Establish Solution matrix:

$S := rkfixed(ic, t0, t1, N, D)$

$T := S^{\langle 0 \rangle}$ Independent variable values

$Y := S^{\langle 1 \rangle}$ Solution function values

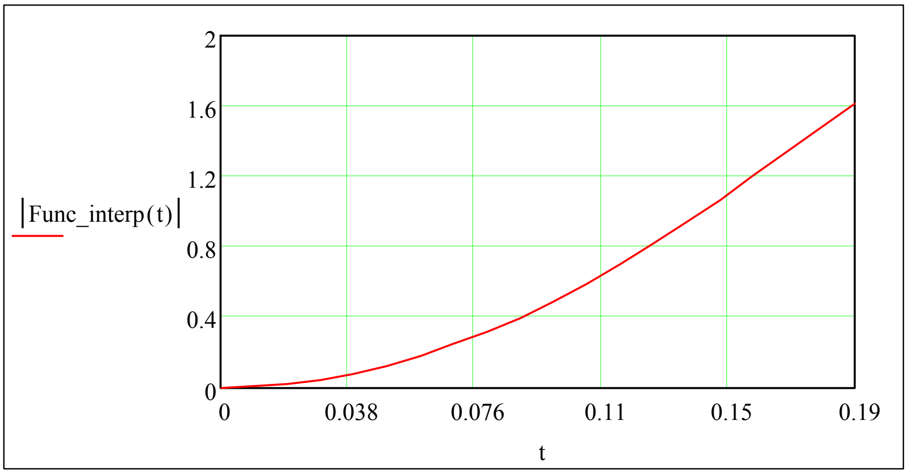


Figure 2. Time variation of the rotation angle of the body

Determining an interpolation function of the deformation values in view of determining the variation of both speed and rotational acceleration.

$t := t0, 0.01 .. tf$

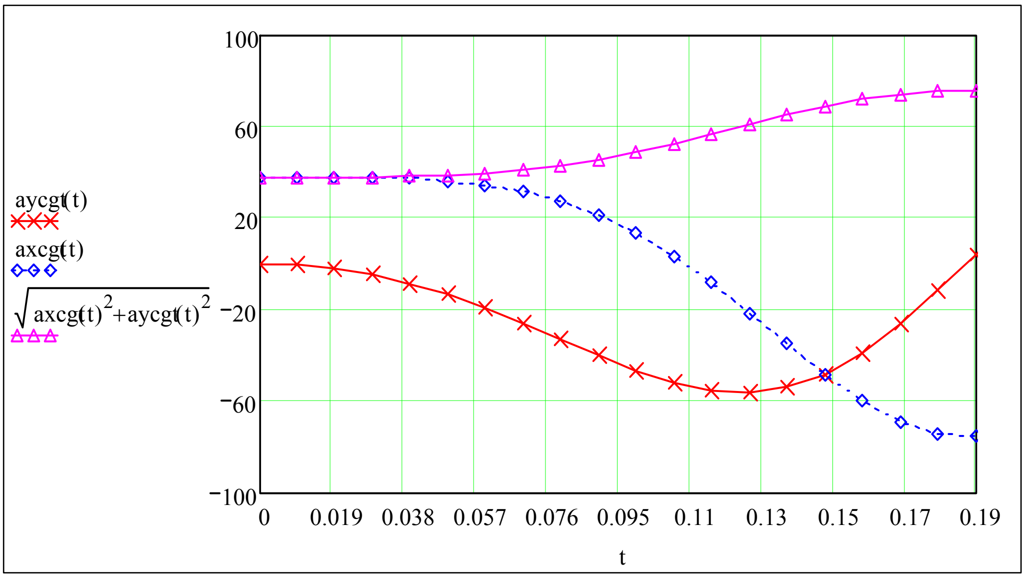
$\alpha(t) := Func\_interp(t)$

$Func\_interp(t) := interp(cspline(T, X), T, X, t)$

$$V(t) := \frac{d^1}{dt^1} Func\_interp(t)$$

$$acc(t) := \frac{d^2}{dt^2} Func\_interp(t)$$

The thorax and head speeds and acceleration are obtained on the basis of the rotation angle of the body generated by the impact force through replacement and particularization in relation (2).



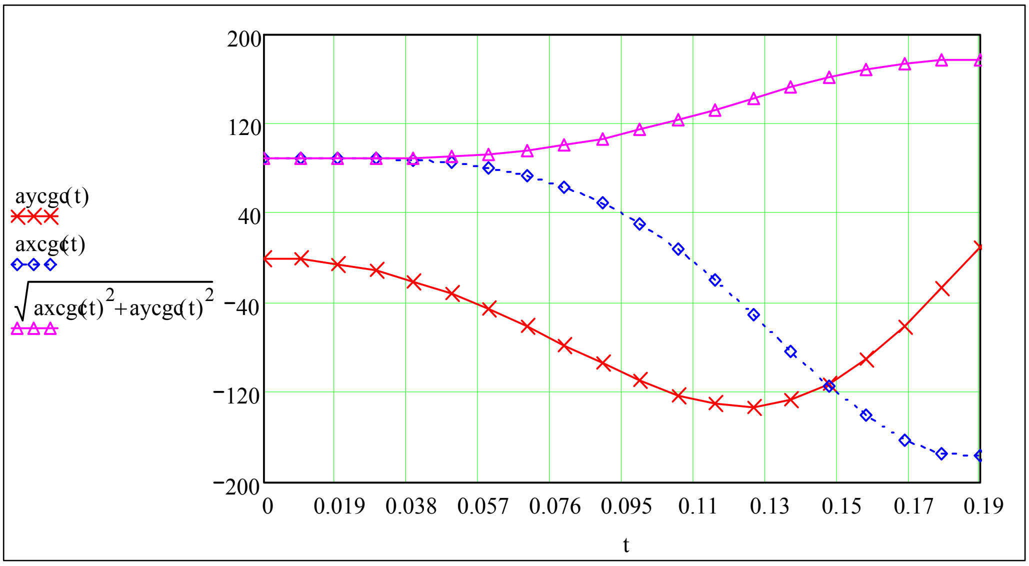


Figure 3. Sample of head and thorax acceleration

CONCLUSION

The results of the simulations conducted are briefly shown in tables 1, 2 and 3. The impact force was distributed on the two bumpers, the secondary bumper on a lower position and a little withdrawn backwards, actuating with lower or at most equal forces to the one on the main bumper. The length of impact was of maximum 0,19 seconds. The simulations enabled us to obtain the body's angles of rotation at the end of the impact, the maximum velocities of the thorax centre of mass and the maximum velocities of the pedestrian's head centre of mass.

Table 1

h = 0,7 m	**Simulation**	**b** [m]	**ba** [m]	**α** [°] at 0,19 s	**Max of $V_{cgthorax}$** [m/s]	**Max of V_{cghead}** [m/s]
F = 3 kN	**1**	0,51	0,30	100,1	6,399	14,872
	2	0,51	0,375	95,111	6,196	14,400
W = 3 kN	**3**	0,51	0,4	93,392	6,127	14,240
F = 3 kN	**4**	0,56	0,3	96,773	6,267	14,564
	5	0,56	0,375	91,673	6,062	14,089

W = 3 kN	**6**	0,56	0,4	89,897	5,994	13,930
F = 3 kN	**7**	0,6	0,3	94,08	6,152	14,298
	8	0,6	0,375	88,86	5,951	13,830
W = 3 kN	**9**	0,6	0,4	87,09	5,877	13,658

Table 2

h = 0,7 m	**Simulation**	**b**	**ba**	α	**Max of $V_{cgthorax}$**	**Max of V_{cghead}**
		[m]	**[m]**	**[°] at 0,19 s**	**[m/s]**	**[m/s]**
F = 4 kN	**1**	0,51	0,30	95,397	6,211	14,433
	2	0,51	0,375	92,017	6,076	14,120
W = 2 kN	**3**	0,51	0,4	90,871	6,031	14,016
F = 4 kN	**4**	0,56	0,3	90,871	6,031	14,016
	5	0,56	0,375	87,319	5,887	13,682
W = 2 kN	**6**	0,56	0,4	86,116	5,836	13,563
F = 4 kN	**7**	0,6	0,3	87,09	5,877	13,658
	8	0,6	0,375	83,48	5,718	13,287
W = 2 kN	**9**	0,6	0,4	82,219	5,661	13,156

Table 3

h = 0,7 m	**Simulation**	**b**	**ba**	α	**Max of $V_{cgthorax}$**	**Max of V_{cghead}**
		[m]	**[m]**	**[°] at 0,19 s**	**[m/s]**	**[m/s]**
F = 5 kN	**1**	0,51	0,30	90,585	6,022	13,995
	2	0,51	0,375	88,866	5,951	13,831
W = 1 kN	**3**	0,51	0,4	88,236	5,927	13,774
F = 5 kN	**4**	0,56	0,3	84,683	5,772	13,415
	5	0,56	0,375	82,85	5,69	13,222
W = 1 kN	**6**	0,56	0,4	82,219	5,661	13,156
F = 5 kN	**7**	0,6	0,3	79,756	5,543	12,882
	8	0,6	0,375	77,865	5,45	12,667
W = 1 kN	**9**	0,6	0,4	77,235	5,419	12,593

The data analysis leads to the following results:

- The rotation angles, respectively the lowest impact velocities of the pedestrian's thorax and head are obtained when the primary bumper takes a high percentage of the total impact force;
- The lowest impact velocities of both thorax and head are obtained by locating the bumpers at the highest possible height from the ground, the bonnet's edge remaining at the same standard height;
- The bigger the distance between the bumpers' impact points the higher the velocity the thorax and the head hit the vehicle with;
- The velocity the pedestrian's thorax hit the vehicle with rages from 5,42 to 6,4 m/s at a total impact force of 6 kN;
- The velocity the pedestrian's head hit the vehicle with rages from 14,9 to 12,6 m/s at a total impact force of 6 kN;
- The same impact velocities of the pedestrian's thorax and head can be obtained for different locating heights of the bumpers and for different percentages of repartition of the total impact force on the two bumpers. (ex Table 3, simulation 6 with Table 2, simulation 9; Table 3, simulation 2 with Table 1, simulation 8; Table 1, simulation 9 with Table 2, simulation 7.)

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