# FLEXIBLE VEHICLE MODEL FOR PLANAR COLLISIONS ANALYSIS

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***Abstract.*** *A procedure for two dimensions direct simulations of flexible ground vehicles collisions is presented, which uses the conditions at the instant just before the impact as input variables and the evolution of the dynamic variables during the collision as output. The algorithm was implemented using Simulink/Matlab software and used the same structure of the other programs under development in this area. The dynamic model developed intends to avoid the use of sophisticated and particular Finite Elements models in cases where the needs of precision, like accident reconstruction, are not so demanding. Besides, it gives a time history of the collision variables and deformations, which is not available at Momentum Conservation model.*

***Keywords****: Vehicle Dynamics, Accidents Reconstruction, Bidimensional Collisions Time History, Crashworthiness*

## 1. Introduction

Nowadays the ground vehicles are a large-scale tool for the economic development and social utility, which results in a great number of accidents throughout the whole world, where the human factor is the main cause. Although techniques for the correction of human fails have been introduced on modern vehicles, like ABS and stability control, it is still not possible to avoid accidents caused by imprudence or unskillfulness, making it necessary the use of passive security systems, like airbags and protection bars.

One of the main fields in the study of automobile passive security is the optimization of the vehicle's behavior during the collision (crashworthiness). Aiming to achieve higher levels of security, the great factories study accidents and perform innumerous crashtests, despite of the high costs. Crashtests have already forced some factories to review entire projects. These tests are basically forced collisions against normalized obstacles under controlled conditions, where one can extract important data for the analysis of vehicle and occupants behavior.

The costs of the crashtests, justify the development of computational models to analyze the collision problem. Another factor that sustains the creation of computational vehicle collision models is the law contentions originated by accidents, which claim, added to the physical data, a graphic representation. The most common models used in collision analysis and accidents reconstruction are described in Carvalho et al. (2003) and Carvalho (2004) and make use of radial vectors, used in SMAC simulation programs, quantity of movement conservation, used in CRASH simulation programs, or deformable discrete elastoplastic elements, used in SINRAT program.

To analyze a collision there are two possible approaches: one considering rigid vehicles, where the evolution of the properties during the shock are not evaluated and the collision is considered as being instantaneous; and another one with deformable vehicles, where the shock is considered a dynamic event and the forces and strengths are evaluating during the contact. This paper presents a routine for the simulation of different collisions among flexible vehicles, based on deformable elastoplastic elements, which aims to integrate the vehicular simulators under construction at PUC-Rio, having as input the conditions at the instant just before the impact and giving as outputs to the same simulators the conditions just after the lost of contact. These modules are intended to allow the simulation of a variety of ground vehicle accidents, together with graphic pre and post processors. The platform used for the development of the exposed model was *MatLab/Simulink*, following the line presented in Carvalho (2004) and it fits the structure shown on the Fig. 1, which describes in a simplified way the main elements of the analysis. This diagram shows some paths to be followed inside an impact simulation that depend on the event to be modeled.

## 2. The Vehicle Model

The elastoplasticity model developed was based on a spring and a damper arranged in series (Fig. 2) placed on each discrete element of the vehicles. This arrangement is known as Maxell Model (Huang, 2002). The mathematical model for this system is,

$$\begin{cases} \dot{v} = -\dfrac{1}{M} F_K \\ \dot{F}_K = K\left(v - \dfrac{1}{C} F_K - V_0\right) \end{cases} \tag{1}$$

where $v$ is the vehicle velocity, $M$ is its mass, $F_k$ is the spring force, $K$ is the spring constant, and $C$ is the damper coefficient, and $V_0$ is the base velocity, due to the other vehicle. Note that the vehicle has also an initial velocity $v(0)$.

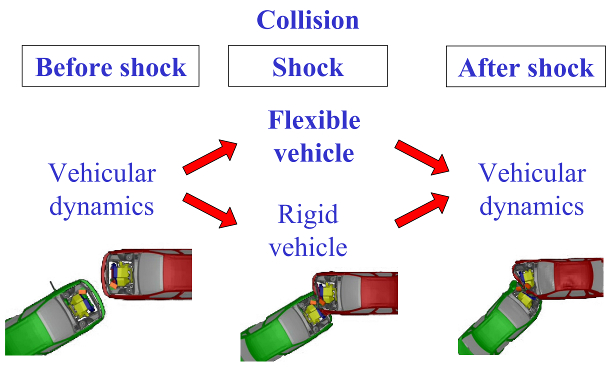



Figure 1. Scheme of the proposed structure for the vehicular simulation programs integration.

In order to improve the representation of the vehicle structure, and the plasticity effects, the damper coefficient is not constant and depends on the deformation by the Eq. (2) (Lozano, 1998).

$$C = \begin{cases} 1{,}2C_o - \frac{C_o}{2}\delta^2, \ F_K > 3000N \\ \infty \ (10^7 \text{ inside the program}), F_K \leq 3000N \end{cases} \tag{2}$$

where $C_o$ is a coefficient here called "plasticity coefficient", due to its nature and use, and $\delta$ is the total deformation, given by

$$\delta = \int (v - V_0)dt \tag{3}$$

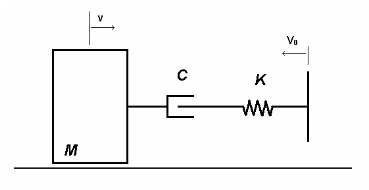



Figure 2. Vehicle Model.

Thus, Figure 2 then represent a simplified physical model for a one-dimension collision of a vehicle, and the Eqs. (1) to (3) can be implemented as blocks diagram in *Simulink* as shown on Fig.3, where the damper function evaluates the velocity of the damper, determines $C$ and divides the force by it, as in Eqs. (2) and (3). The vehicle is represented by the first expression in Eq. (1) and the geometry function evaluates de distance between the front of the undeformed vehicle and the element that collides with it (another vehicle or a rigid barrier).

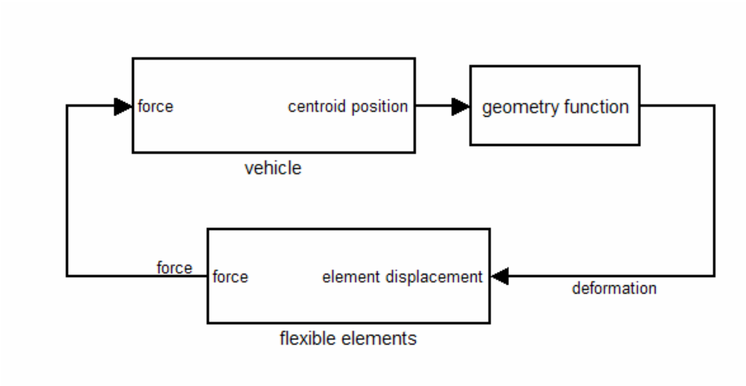
## 3. Bidimensional Model

A bidimensional model for the collision of two vehicles was built by the discretization of their contour. Over each divisor point, two spring-damper elements described above were placed orthogonally, one on the longitudinal and the other on the transversal direction as shown on Fig. 4 (a). The geometric position of this contour points of each vehicle are saved and monitored on matrixes P1 and P2, as shown in Eq.(4) and Fig. 4(b),

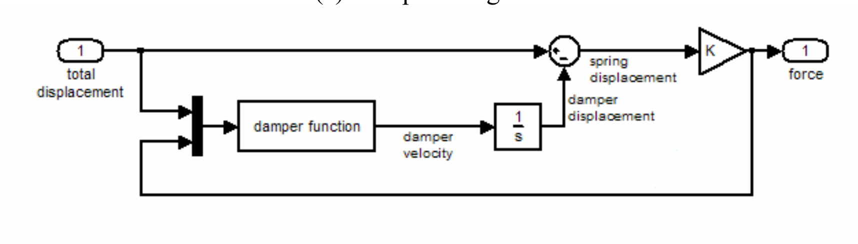
$$P1=[A\ B\ C\ p_1\ p_2\ \ldots\ p_{nd-2}\ D]$$
$$P2=[A\ B\ C\ p_2\ p_3\ \ldots\ p_{nd-1}\ C\ p_{nd+1}\ p_{nd+2}\ \ldots\ p_{2nd-1}\ D] \tag{4}$$

where the components A, B… are two dimensional vector with the first dimension representing the x coordinates and the second the y coordinates.

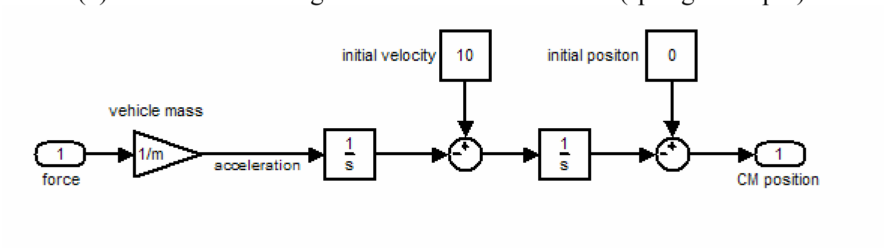
According to the physical representation of the bidimensional model, shown on Fig. 5, the contact between points of distinct vehicles deforms the corresponding flexible elements causing a force and a moment acting on each vehicle. The forces and moments of all contour points of a vehicle are summed generating a resultant effort over it.




(a) Compact diagram

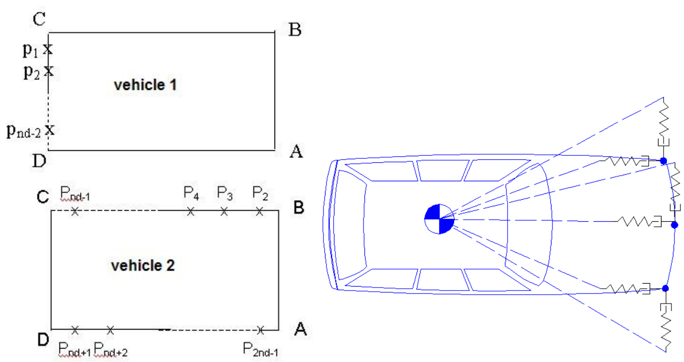



(b) Detailed block diagram of the flexible element (spring - damper).




(c) Detailed block diagram of the vehicle element.

Figure 3. *Simulink* block diagram for one flexible vehicle.




(a) (b)

Figure 4. (a) Discretization of a vehicle contour and respective flexible elements.
(b) Position matrixes generated by the discretization of the geometry.

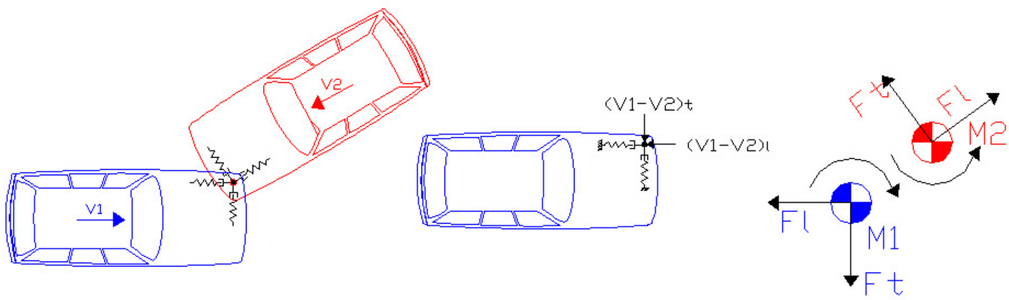



Figure 5. Application of forces generated by the flexible elements.

The modeling of the contact problem is made through the use of the deformation index, which is considered equal through all the contact area, that is, if at an instant three flexible elements of vehicle 1 are in contact with vehicle 2, all of them have the same displacement index while the others have no displacement. The displacement indexes are calculated by the difference of the centroids velocities and the contact area velocity, which is calculated applying the sum of both resultant forces over a massless point. This procedure uses a simplified model, as it does not consider the linear velocity of the contour points due to the rotational movement of the vehicle. The discretized elements are independent too, not having a stiffness link among them. In order to determine which points are part of the contact area, the model makes use of a geometric test that returns a matrix of ones and zeros corresponding to the contour points, that multiplied by a vector of displacement index *vr* generates a matrix with the deformation indexes of all contour points. This procedure is exemplified on Eq. (5) and Fig. 6, where the contact test returns the ones – zeros matrix *teste1* that is multiplied by the relative velocity vector.

$$\text{If teste1} = [011000], \textit{ with } \text{vr} = \begin{bmatrix} \text{vr}_l \\ \text{vr}_t \end{bmatrix}, \textit{ so } \text{v} \times \text{teste} = \begin{bmatrix} 0\,\text{vr}_l\,000 \\ 0\,\text{vr}_t\,000 \end{bmatrix} \tag{5}$$

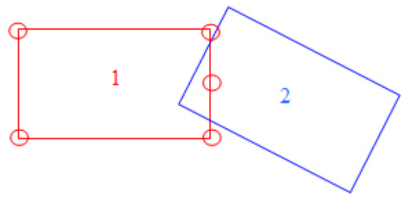



Figure 6. Determination of the displacement indexes of the contour points.

The Fig. 7 describes a fluxogram of the program created, inside which each of its phases corresponds to a *MatLab* routine or a *Simulink* model called by a main routine named “colisao”. The *Simulink* file *choque.mdl*, shown on Fig. 8, is executed from the main file *colisao.m* just after the data input, as shown on the Fig. 7. Inside this file the blocks named *veiculo1* e *veiculo2*, shown on Fig. 9, receive the efforts from the impact as vectors (**Fl** –longitudinal force, **Ft** – transversal force, **M** - moment). These efforts are divided by the mass (forces) and by the moment of inertia (moments), resulting the acceleration vector, which is integrated and then summed to the initial velocity in order to obtain the velocity vector (**vl –** longitudinal velocity, **vt –** transversal velocity, **w –** angular velocity). As it is not used in the evaluation of the deformation, the angular velocity is excluded on the output. The output is then converted to the global coordinate system and then integrated and summed to the initial position of the vehicle, generating the centroid position. The elastoplastic elements model is shown on Fig. 10.

**4. Simulations**

Simulations similar to the ones found on the literature were made aiming to qualitatively validate the developed model through some cases of collisions.

**4. 1. Frontal collision of a light truck against a rigid pole**

A collision similar to the vehicle – pole presented by York (1999) was analyzed. A fixed small vehicle represents the pole with high stiffness. Both the simulated vehicles had their frontal area divided by 50 points and their characteristics are listed on Tab. 1. The plastic and total deformations versus time graphics generated by the simulation are presented on Fig. 11 and the graphic output of the vehicle contour at the end of contact is shown on Fig. 12, where the penetration of the pole into the vehicle structure can be seen. The behavior of the variables is similar to the one presented by York (1999), although the acceleration is smaller and so the impact is shorter. At the performed simulation a maximum acceleration of 15g was achieved, while in York, 1999 a value of 25g was found during an impact of 8ms. This can be explained by the absence of the drag force and by the vehicle data imprecision. From the graphic of displacement x time, on Fig. 11, one can observe the presence of the restitution and a maximum displacement around 42 cm, which is a reasonable value for a 35 km/h collision against a pole.

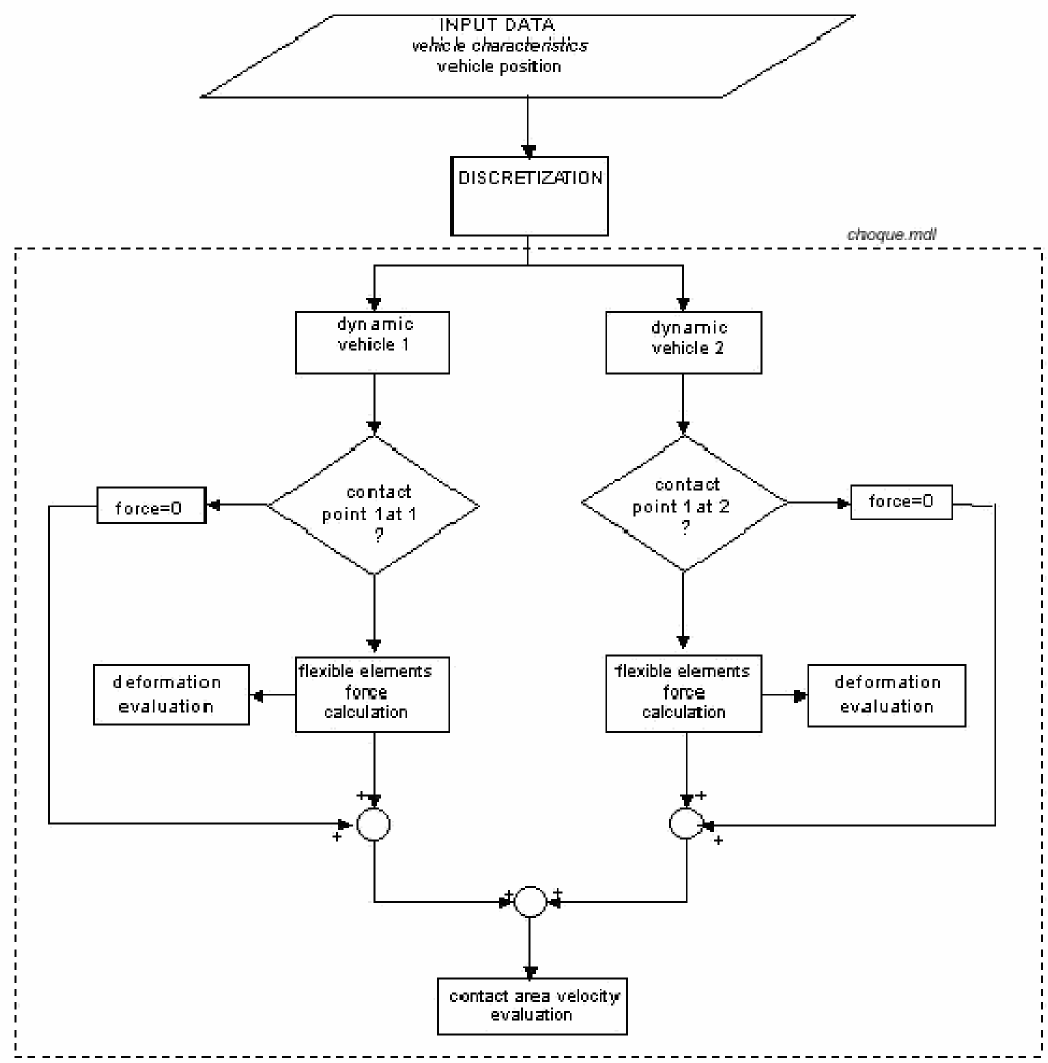



Figure 7. The bidimensional vehicle collision program.

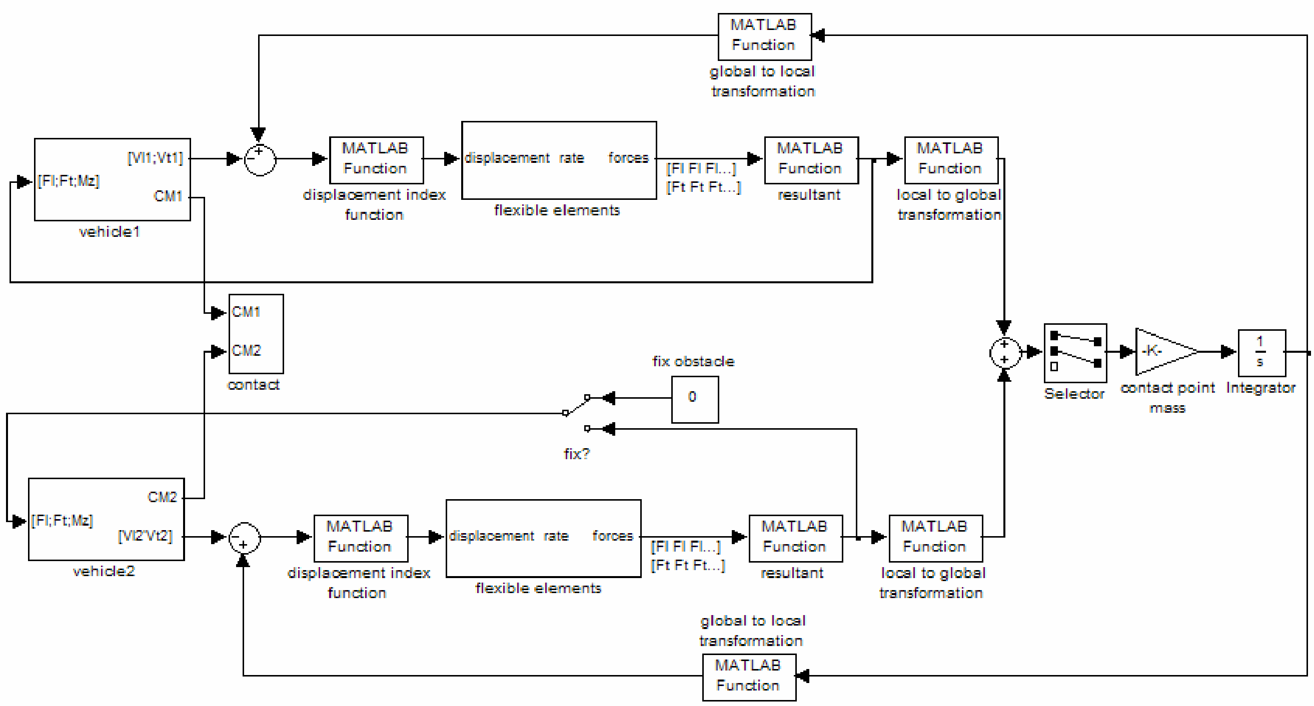



Figure 8. *Simulink* diagram for the two vehicles bidimensional collision model.

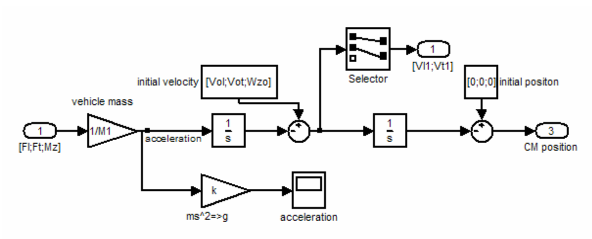



Figure 9. Vehicle model for bidimensional collision.

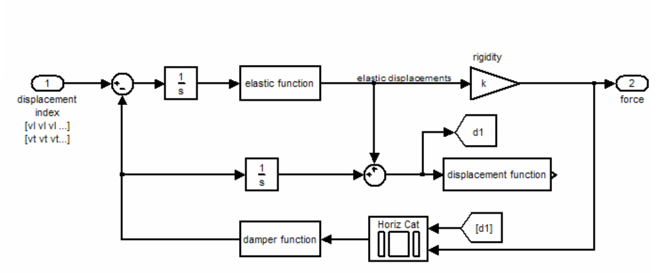



Figure 10. Elastoplastic model for the bidimensional collision.

Table 1: Characteristics of the simulated vehicles.

| **Characteristic** | **vehicle 1** | **vehicle 2** (pole) |
|---|---|---|
| Mass (kg) | 900 | - |
| Initial velocity (m/s) | 9 | 0 |
| Plasticity Coefficient $C_o$ (N/m/s) | 5,946 x $10^4$ | $10^7$ |
| Stiffness (N/m) | 81,7X$C_o$ | 81,7X$C_o$ |
| Width (m) | 1,5 | 0,4 |

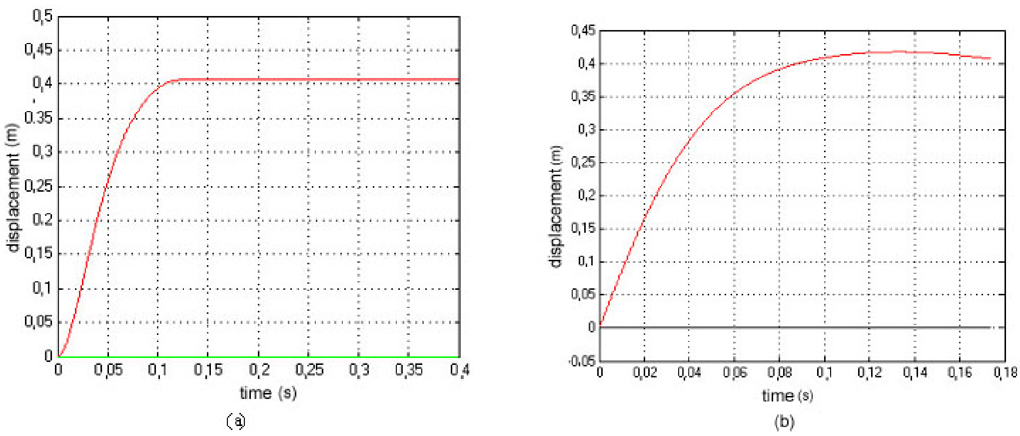



Figure 11. (a) Plastic deformation x time and (b) total deformation x time.

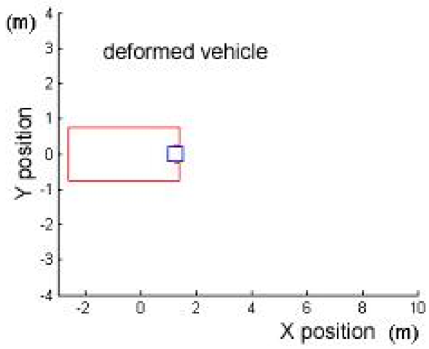



Figure 12. Displacement output at the end of the simulation.

**4. 2. Frontal offset collision between two vehicles**

A collision similar to the one presented at York and Day (1999) was made, using two identical light trucks with an initial velocity of 6,7 m/s and the characteristics listed on Tab.2. Each of the vehicles had its frontal and lateral areas divided in 10 contour points, which have their elastic displacements shown in the graphic of Fig. 13 where one can notice that these values do not vanish to zero after the lost of contact. That is because of the way the contact test is applied: after the end of impact the deformation index is zeroed but not the elastic deformation itself.

Comparing the literature results to the ones obtained in the simulation can be noticed a difference between the duration of the compression phase, while on the literature this phase lasts around 90 ms on the simulation it lasts around 200 ms. This difference can be owned to friction representation absence, stiffness parameters indetermination and difference between the contact area of the vehicles. From Fig. 14 we can follow the falling of the velocity of both vehicles to zero at the end of simulation as expected. A graphic comparison can be made between the two outputs at the end of the contact on Fig. 15.

Table 2: Characteristics of the simulated vehicles.

| **characteristic** | **vehicle 1** | **vehicle 2** |
|---|---|---|
| Mass (kg) | 1338 | 1338 |
| Inertia ($m^2$kg) | 2207 | 2207 |
| Centroid distance to the front (m) | 2 | 2 |
| Centroid distance to the back (m) | 3 | 3 |
| Initial velocity (m/s) | 6,7 | 6,7 |
| Plasticity Coeficient $C_o$ (N/m/s) | 3,580 x $10^4$ | 3,580 x $10^4$ |
| Stiffness (N/m) | 81,7X$C_o$ | 81,7X$C_o$ |

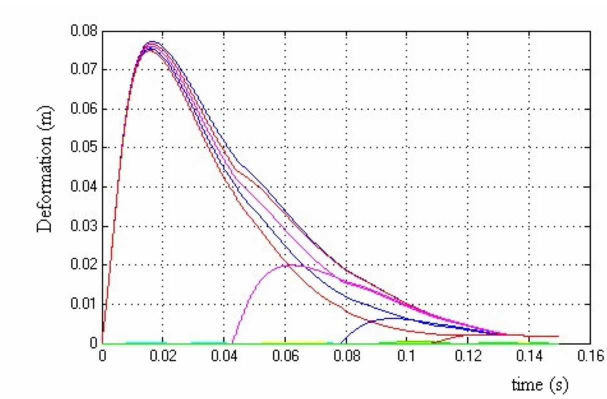


Figure13. Elastic deformation of one vehicle contour points.

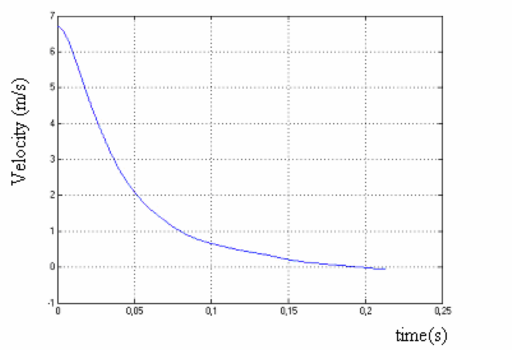


Figure 14. Velocity x time from the simulation.

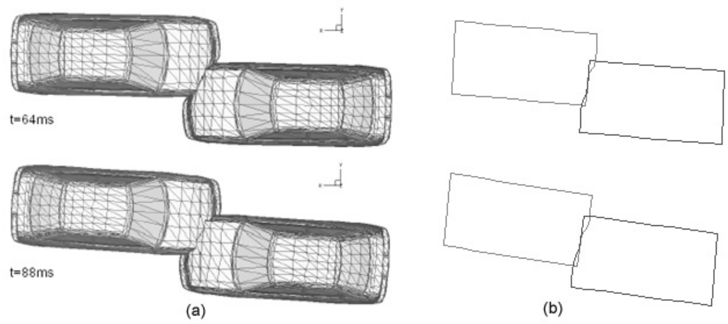


Figure 15. Graphic outputs at the end of contact from (a) literature and (b) simulation performed.

### 4. 3. Frontal oblique collision light truck – rigid barrier

A 30° oblique collision between a vehicle at 13 m/s and a rigid barrier similar to the one presented by Day and York (2000) was performed. The velocity x time graphic generated shown on Fig. 16 provides a follow-up of the vehicle velocity and it is similar to the one presented on the literature and the values' differences can be explained by the imprecision of parameters and friction absence.

A graphic evolution of the vehicle position was compared to the one presented on the literature on Fig. 17. It can be seen that the vehicle spins clockwise on the literature model and counterclockwise on the developed model. This can de explained by the center of mass' position, witch is not provided at the referenced article and was guessed at the presented model.

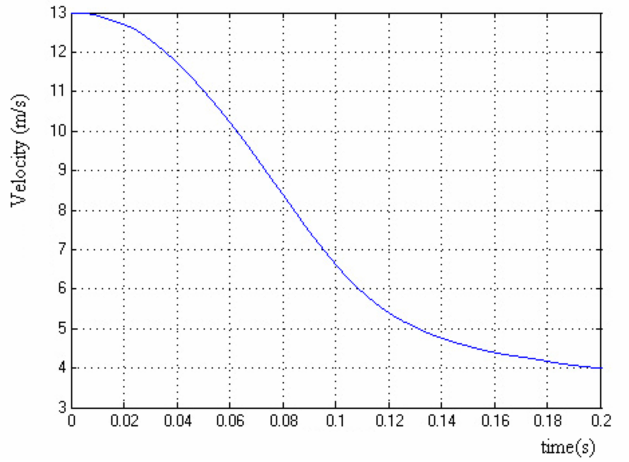



Figure 16. Velocity x time from the simulation performed.

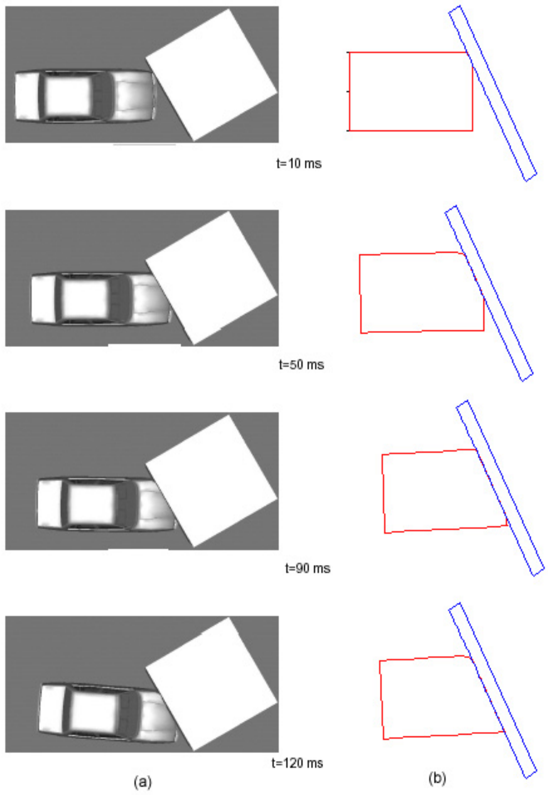



Figure 17: Evolution of the vehicle's position.
(a) From the literature and (b) from the simulation.

## 5. Conclusion

Comparing the results to the ones available on the referenced literature can be concluded that the model created has a qualitatively similar behavior, although there is a need of improvement of the vehicle data, of the friction modeling and of the contact test application.

It must be emphasize that the model and its platform, *Simulink/MatLab*, allows the input of any external forces, like friction and traction efforts, as the vehicle mass is an independent block and the contour of the vehicles can be changed to any shape by the user, as it is saved on a matrix with coordinate of the discretization points. This modular structure allows the further integration with complementary models, as described in the introduction chapter.

It is important to determine precisely the stiffness parameters to be simulated in order to obtain a validation of the model. The mass of the contact point used between the vehicles is a very important factor because of the singularity it can cause in the model making it numerically unstable.

## 6. References

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## 7. Responsibility notice

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