DEVELOPMENT OF VALIDATED FINITE ELEMENT MODEL OF A PASSENGER CAR SUITABLE TO SIMULATE COLLISIONS AGAINST ROAD SAFETY BARRIER

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ABSTRACT

The effectiveness of the FEM (Finite element method) approach to improve crashworthiness, both from the vehicle viewpoint and from the road safety hardware one has been plainly demonstrated in literature. Of course, this is possible only when models calibrated in a wide range of impact conditions are available.

In this work, a multipurpose finite element model of a light weight passenger car is presented. The model has been set up through an extensive comparison between full-scale and simulated outputs of four different experiments: the frontal and oblique collisions against a concrete wall and the impacts against two types of steel barrier with different containment energy level (127kJ and 724kJ). The differences between these impacts are related to (i) the stiffness of the safety devices and to (ii) the height where the vehicle collides against the barriers. Therefore, the considered situations are representative of a wide range of impact conditions

The fundamental steps of the modelling process will be described along with all the particulars needed to reproduce the four full scale tests. Data comparison between full-scale and FE simulation concerns time histories of longitudinal and transversal acceleration of CG's vehicle, ASI, THIV, PHD, pitch and roll angle, velocity variation in the vehicle direction and residual displacements of the barrier.

The excellent agreement attained when simulating the abovementioned impacts, characterized by noticeably different nature, demonstrates that the modelling processes of vehicle and devices were accurate and that, in particular, the FE model of the passenger car is suitable for a wide range of impact conditions. As a conclusion, the validated model is reliable to foresee the impact behaviour without needing expensive crash tests.

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Keywords: Passenger Car, Nonlinear Finite Element Analysis, Road Vehicle Crashworthiness, Road Safety Steel Barrier, Concrete Wall

1. INTRODUCTION

In Italy, run off the road is the fourth type of accident causing about 19 %of the mortalities and 9.0% of the injuries, with a ratio between fatality and frequency twice as high as the overall accidents [1].

The standards which fix guidelines for the execution of crash tests to assess the effectiveness of safety barriers in USA and Europe, define an experiment with a low weight passenger car [2-4]. Such an investigation's aim is to evaluate risks for vehicle's occupants in case of impact against the tested device. The congruence of this approach with the philosophy of testing at "the practical worst condition", has been widely demonstrated in literature [5-6].

During years, crash tests prescribed in the European standards demonstrated to have a huge importance to improve crashworthiness. On the other hand, this kind of tests is really expensive and many parameters are hard to control and measure. Due to the aforementioned reasons, numerical analysis of vehicles collisions against safety barriers has become a convenient methodology that supports and integrates the previous one, especially considering the continuous technological hardware/software progress[7-10]. Besides, the chance of controlling and evaluating each factor which influences full scale crash tests, makes such a methodology an important tool to perform parametric studies to assess the influence of different factors on crashworthiness [11-12].

Of course this is possible only when available models are validated in a wide range of impact conditions.

This research, carried out through FEM (finite element method), was intended to develop a well defined multipurpose finite element model of a low weight passenger car. The model has been set up through an extensive comparison between full-scale and simulated outputs of four different experiments: the frontal and oblique collisions against a concrete wall and the impacts against two types of steel barrier with different containment energy level (127kJ and 724kJ). The differences between the aforementioned impacts are related to (i) the stiffness of the safety devices and to (ii) the height at which the vehicle collides the barriers. Due to these reasons, the considered situations are representative for a wide range of impact conditions

In the following, the fundamental steps of the modelling process are described along with the requirements needed to reproduce the full scale tests - suspensions, tires, steering system, longerons, subframe, rocker, A-pillar, B-pillar, etc. Afterwards, the comparison between full-scale and simulated test outputs is presented, concerning time histories of longitudinal and transversal acceleration of CG's vehicle, ASI, THIV, PHD, pitch and roll angle, velocity variation in the vehicle direction and residual displacements of the barrier.

The results obtained simulating the four impacts, demonstrate that the modelling processes of vehicle and safety devices were accurate and that, in particular, the passenger car FE model is suitable for a wide range of impact conditions. As a conclusion, the validated model is reliable to foresee the impact behaviour without needing expensive crash tests. Similar investigations regarding a rigid and an articulated truck are provided in another contribution by the same authors [13-14].

2. FINITE ELEMENT MODEL OF PASSENGER CAR

The vehicle model represents a GEO METRO. It was developed by EASi Engineering for the National Highway Traffic Safety Administration (NHTSA).

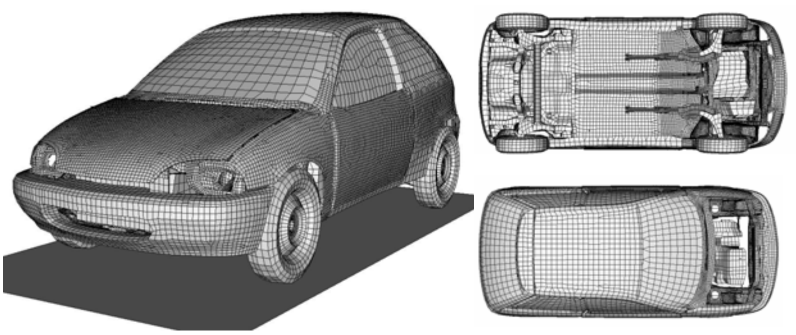


Figure 1: FE model of the light weight passenger car

Compared with the model available on the web, many improvements were introduced in the present release performed in our laboratories. The most relevant problems which were pointed out analyzing the behaviour in some preliminary crashes against safety barriers and when running on a road with bumps (all of these problems were resolved in the improvement activities carried out), are:

- Poor mesh quality: in the initial model, many elements are too undersized causing a dangerous increasing of mass (shooting nodes) or a too small time-step. On the other hand, many elements are characterized by large warpage, skew ratios and high aspect ratio with dangerous consequences on computational stability. All parts being exposed to large deformations, i.e. longerons, subframe, rocker, A-pillar, B-pillar, etc, were modelled performing a stress state convergence analysis in order to select the most convenient mesh[15]
- Wrong merge of many parts: during impacts' simulations against several barriers, unjustified division of vehicle's structural part were registered. Using a process of reverse engineering and the wide literature [16-17] about this topic, the right position of spotweld was identified.
- Wide initial penetration
- Inadequate characterization of some important shapes
- Wrong geometry of wheels: the new model of the wheels includes both tires and rims: in particular, to describe the rubber material, the #27 one embedded in Ls-Dyna was adopted[18]. Moreover, in order to properly describe the friction between wheels and pavement, a pre-processing simulation only accounting for the gravity force on the loaded weights vehicle was performed, which allowed achieving the actual wheels configuration and their tensional stress state (*INTERFACE_SPRINGBACK_LSDYNA).
- Suspensions: the suspensions' system didn't permit the right kinematical behaviour of the system tire-limb and didn't allow vehicle weight to act on wheels only through suspensions. These problems have been solved by

modifying the geometry and the mechanical characteristics of the suspension system and by changing the links between wheels and vehicle coachwork.

- Torsion bar: the vehicle model available on the web didn't include any torsion bar which is useful to moderate rolling . It was introduced in the release performed in our laboratory .
- Steering system

The global model, in the release performed in our laboratory, is composed of 65000 elements and 68000 degree of freedom. The elements used for the regions experiencing large deformations are "fully integrated Hughes-Liu" shells with 5 integration points through-the-thickness. For a shell element with 5 integration points through-the-thickness, fully integrated Hughes-Liu formulation requires 35367 mathematical operations compared to the 725 ones for Belytschko-Lin-Tsay formulation. This choice, despite an increase of simulation time, drastically reduces the deformations in the zero energy modes (hourglass effect). For the other portions of the model, the Belytschko-Lin-Tsay formulation has been chosen [19]. The modelling process has been properly carried out to limit in every portion of the vehicle the hourglass energy below the 5% of the deformation energy. The steel material characterized by using the elastic piecewise linear plasticity material model of Ls-Dyna with a specific curve stress/strain. Failure criteria based on maximum plastic strain were considered.

All of the previous enhancements to the original finite model available on the web allowed to obtain a well detailed model useful to reproduce real crash tests of light weight passenger cars. The good agreement with the results obtained in full scale tests will be shown in the following paragraphs.

3. VEHICLE MODEL VALIDATION

3.1 Effectiveness of adopted strategy for the model validation

The potential of Finite Element Method both from the design of new safety devices point of view and from the parametric analysis of collisions one, was clearly inferred from the proposed reference literature. However, also a refined FE model of vehicle like the one described above, needs to be validated in a wide range of impact condition, through an extensive comparison between full scale and simulated outputs. Due to the aforementioned reason four collisions have been chosen, the frontal collision and three oblique one: against a concrete wall, a H1-type barrier, with a containment energy level of 127kJ and a three rail steel bridge barrier, with a containment energy level of 724kJ [2].Full scale results in all four cases are available allowing the evaluation of simulation outputs. These collisions represent four situations extremely different considering parts undergoing large deformations. Indeed during the frontal crash the most collapsed parts are longerons and subframes while during an oblique collision the most relevant deformations are registered in the rocker and in the A, B and C-pillar. Besides, concerning with oblique collisions, the actions on the vehicle during the impact against a concrete wall are very severe, impulsive and essentially concentrated on a confined portion of the vehicle, while during a collisions against a steel barrier the actions are less significant and more distributed. In this case, however, the impact against posts of tires, axles and suspensions in more severe.

To perform the simulations of the two collision, the Ls-Dyna 970 code version MPP on 8 bi-processors has been employed. A preliminary optimization to share the simulation run on 16 processors was performed. Such an operation allowed to reach an optimum value for the Grind Time (the averaged elapsed time for computing one element at a single step) and the speed up (the ratio between the elapsed time for a simulation executed on one processor and that for a simulation on n-processors) [20 - 21].

3.2 Comparison methodology for collisions of passengers car against road safety barriers

The finite element model has been set up to develop a reliable tool to estimate the results of a real crash test. Nevertheless, the time histories of acceleration, velocity and displacement collected during the simulation and the same registered during the full scale test will be not exactly matchable.

The reasons of this circumstance are:

1. The vehicles used in the simulation, even though very detailed, is an approximation of a real vehicle.
2. The FE model of the vehicle differs from the real vehicles used in full-scale crash tests. In Europe at the moment Fiat Uno, Peugeot 205, Opel Corsa etc are used.
3. The vehicle used in the crash tests often are quite old and so they could hide structural defects and/or corroded parts.
4. The instrumentation used to collect data could be fixed in a different way and also the position could be different
5. The pavement surface and the tires conditions could be different
6. The friction between vehicle and barrier could be different.

With the exception of the first, the abovementioned aspects inducing differences between a simulation and a real crash tests are the same that produce differences among results of crash tests carried out in different test houses against the same barrier. Taking this consideration into account a simulation could be considered reliable if the differences in the results with the real test are lower than the maximum differences among crash tests carried out in different laboratories at the same nominal conditions. At the moment this is matter of study. A criterion that could be applied to establish how a simulation reproduces a test, relies on the residuals of the signals collected. In particular the residual at the sampling time i from the signal collected in the simulation and the one collected in the real test is evaluated as follows:

$$res_i = x_i^{sim} - x_i^{test} \quad \text{(Eq.1)}$$

The compliance of the simulation can be evaluated through the following indices, which have to be calculated for acceleration, velocity and displacement of the center of gravity:

1. The absolute value of the mean value of residuals:

$$Index1 = \left| \sum_{i=1}^{n} \frac{res_i}{n} \right| = |resmean|$$

(Eq.2)

2. The standard deviation of residuals:

$$Index2 = \sqrt{\sum_{i=1}^{n} \frac{(res_i - resmean)^2}{n-1}} = stdev\_res \qquad \text{(Eq.3)}$$

Where **n** is the number of sampling point during the collision phase, not including the pre or post collision phases.

The first index can be considered as an “end” collision index: it represents a measure of the difference between the integer of the signal of the simulation and the integer of the same signal in the real test at the “end” of the collision period. So when it’s applied to the transversal acceleration it is a measure of the difference in the transversal speed at the end of the contact

The second index can be considered as a “during” collision index: it represents a measure of the difference between the two signals during the collision period.

A simulation can be considered reliable if the previous indices evaluated for the acceleration, velocity and displacement are lower then the ones evaluated for the same nominal test carried out in different laboratories. At the moment the data of the real crash tests carried out in different laboratories are confidential. However in all of the following simulations of oblique impacts the values of the abovementioned indices are always lower then the maximum values arising from the comparison of the same nominal test performed in different laboratories.

3.3 Frontal impact

The first considered full-scale test is the frontal impact, carried out in accordance with US-NCAP instructions: the vehicle, with a mass of about 1000kg and an initial velocity of about 56km/h, collides against a rigid barrier (about 100.000 lib), engaging the whole frontal part.

	BX*		AX*		ΔX			BX*		AX*		ΔX	
	Full-scale	FEM	Full-scale	FEM	Full-scale	FEM		Full-scale	FEM	Full-scale	FEM	Full-scale	FEM
1	3790	3757	3173	3078	617	679	12	2458	2484	2425	2435	33	49
2	3285	3283	2962	2918	323	365	13	2438	2484	2414	2440	24	44
3	2806	2793	2725	2697	81	96	14	2781	2762	2622	2601	159	161
4	2488	2475	2475	2464	13	11	15	2808	2762	2635	2599	173	163
5	2484	2475	2485	2467	2	8	19	3740	3681	3156	3111	584	570
6	2496	2497	2490	2489	6	8	20	3740	3681	3137	3112	603	569
7	2487	2497	2485	2491	2	6	21	128	140	131	140	-3	0

table 1: measurements in mm

***BX: Pre-test vehicle measurements data **AX: Post-test measurements data**

In table1, pre and post test measurements are reported. The indices used refer to: 1. the total length of vehicle; 2. the rear surface at the front of the engine block; 3. the rear surface of the front at the fire-wall; 4. /5. the rear surface of the front superior part of the right / left front door; 6. /7. the rear surface of the front inferior part of the right / left front door; 12. /13. the rear surface of the rear inferior part of the right / left pillar “A”; 14. /15. the rear surface of the right side of the fire-wall; 19. /20. the rear surface of the vehicle at the right corner of the front bumper; 21. the length of the engine block.
In figure 2 and 3 the accelerometers outputs and the comparison between full-scale and simulated data are presented. Signals have been filtered using a 60 Hz Butterworth 4-pole phaseless digital filter, according to US-NCAP instructions. As can be observed, an excellent agreement between full-scale and simulated outputs is achieved.

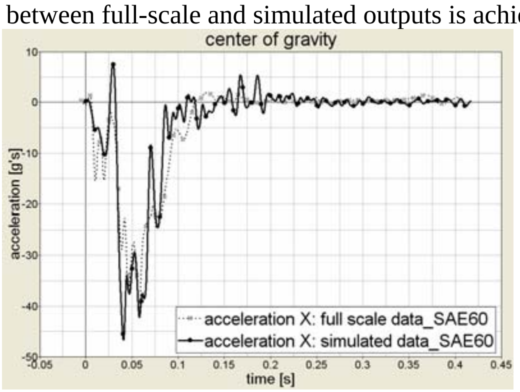
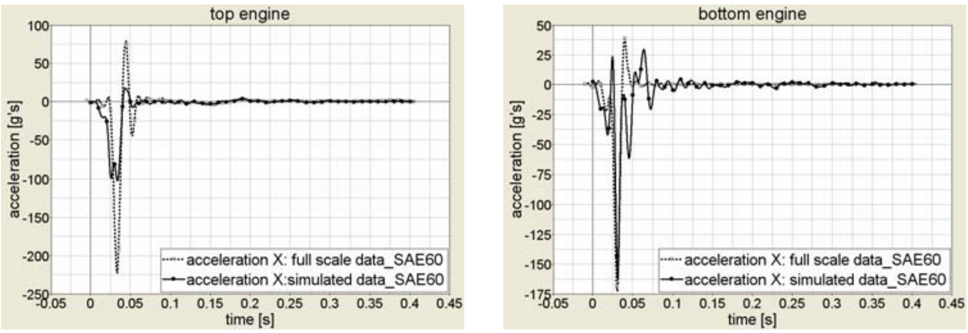
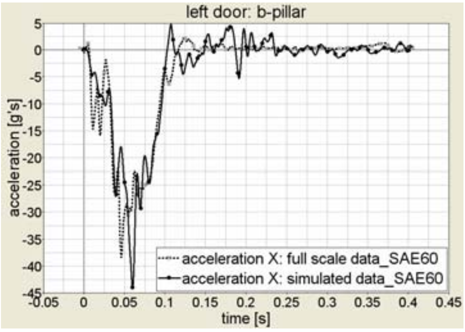


Figure 2: centre of gravity acceleration [g’s] in the longitudinal direction filtered CFC60





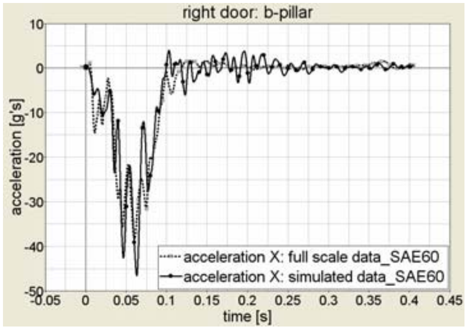


Figure 3: longitudinal acceleration [g's] in 4 different point filtered CFC60

3.4 Oblique impacts

As said above three different oblique impacts ware simulated, the first against a concrete wall, the second against a H1-type barrier, with a containment energy level of 127kJ according to EN 1317-1/2 standard for the test TB11 and the third against a three rail steel bridge barrier, with a containment energy level of 724kJ. In all three cases, the vehicle mass is about 1000kg, the velocity is 100km/h and the impact angle is 20 degree. All the abovementioned oblique impacts can be split in four parts:

- **STAGE1**: The impact of the front corner, which causes a strong transversal force and in addition a considerable moment on the yaw axis which lead to reduction of the impact angle
- **STAGE2**: The lateral scraping of the vehicle, where the interaction between vehicle and barrier is low
- **STAGE3**:The impact of the rear corner, which causes the end of the yaw motion
- **STAGE4**:The end of the impact

Concerning the comparison between full-scale and simulated test, the occupant impact severity indices, included in the standard En 1317, will be pointed out, i.e. the Acceleration Severity Index (ASI), the Theoretical Head Velocity (THIV) and Post-Impact Head Deceleration (PHD).

3.4.1 Impact against concrete wall

A. Barrier description

The concrete wall is a very rigid barrier, which could be used, equipped with a flexible protection on the side exposed to the car collisions, in situations where areas beside roads have to be particularly protected against vehicle penetration i.e., bridge crossings high speed railways, areas used to store very dangerous substances, etc

The FE model represents a reinforced concrete wall having an elastic modulus of 28500 N/mm^2 and a density equal to 2.5e-9 ton/mm^3. Its geometrical characteristics are: length 27m, height 3m and thickness equal to 0.3m. The wall has been modelled by shell elements 75 mm x 75 mm. Such values were defined through an optimization process in which the convergence of the element stress state was accounted for. The material has been assumed as indefinitely elastic and resistant. The wall is fully constrained at the lower edge.

B. Comparison between full-scale and simulated outputs

	Index1	Index2
a_y [g] filtered cfc12	0,033	2,198
v_y [m/sec]	0,055	0,048
s_y [m]	0,013	0,016

table 2: statistical indices

	Full-scale test	Simulated test
ASI	1,94	1,94
THIV	32,1	31,5
PHD	14,8	19,8

table 3: impact severity indices

3.4.2 Impact against H1 barrier

A. Barrier description

The model represents an H1-type barrier (see EN 1317-1/2) , with a containment energy level of 127kJ (H1). This device consists of:

- C120x80x4 posts, 1.70m long, embedded into the ground and spaced every 2.00m
- W beam 3mm thick (length: 4.32m, top height: 0.75m)
- European spacer
- Rear plate (65x5mm, length:4.14m) connected to the back side of posts

Two different steel materials were used for the barrier (S275 JR and S235 JR) which behaviour was reproduced by (the) Material #24 in Ls-Dyna with the definition of a stress-strain curve for the plastic yield. The force-displacement relationship of the posts embedded in the soil has been obtained by real pull out tests and simulated by using spring elements with elasto-viscoplatic characteristic [22].

B. Comparison between full-scale and simulated outputs

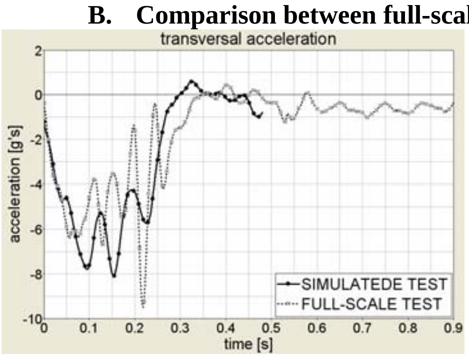


Figure 4: transversal acceleration [g's] filtered CFC12

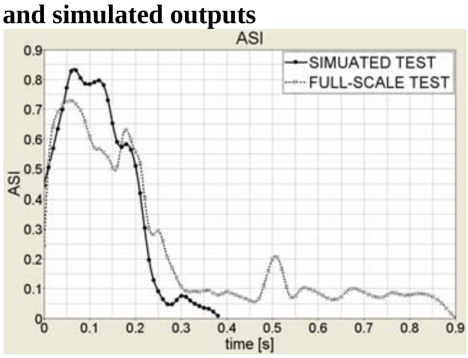


Figure 5: Acceleration Severity Index (ASI)

	Index1	Index2
a_y [g] filtered cfc12	0,134	1,492
v_y [m/sec]	0.594	0.678
s_y [m]	0.077	0.077

table 4: statistical indices

	Full-scale test	Simulated test
ASI	0.764	0.873
THIV	23.7	24.5
PHD	16.5	10.4

table 5: impact severity indices

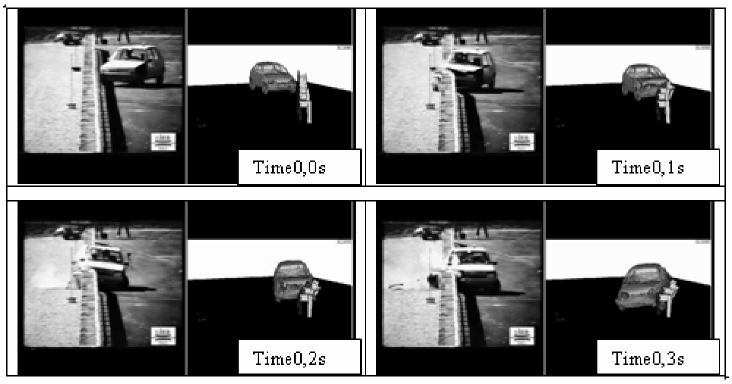


figure 6: scratch images of the impact (front camera)

3.4.3 Impact against H4b barrier

A. Barrier description

The model represents a three rail steel bridge barrier, with a containment energy level of 724kJ (H4b - see EN 1317-1/2). This device consists of:

- HE posts .
- Upper 2-wave and 3-wave rails whose length is 4820mm
- Upper and 3-wave rail spacers, made with 2 symmetrical steel parts
- Raised concrete beam whose height is 125mm.

The steel material behaviour was reproduced by the Material #24 in Ls-Dyna with the definition of stress-strain curve for the plastic yield.

To achieve accuracy in the FE simulation of the collision between the passenger car and the considered steel barrier, preliminary tests on the post and the spacer are essential. The outputs of these tests are provided in another contribution by the same authors [14]. For both tests, the comparison between full-scale and simulated test outputs is shown and both the model of the post and the spacer are able to describe the real behaviour of the correspondent structures with a high rate of confidence.

B. Comparison between full-scale and simulated test

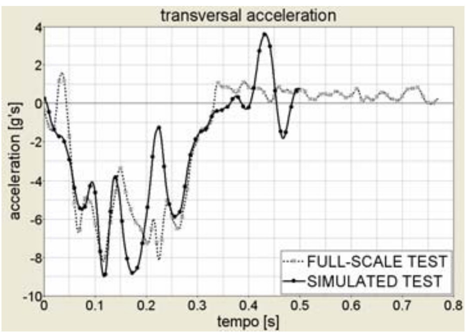


Figure 7: transversal acceleration [g's] filtered CFC12

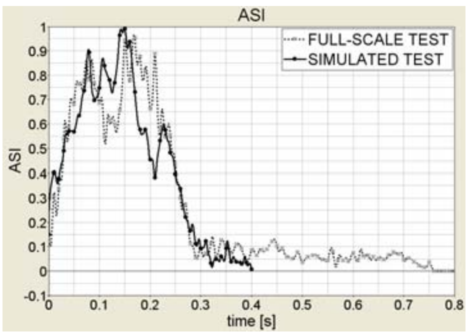


Figure 8: Acceleration Severity Index (ASI)

	Index1	Index2
a_y [g] filtered cfc12	0,12	1,52
v_y [m/sec]	0,22	0,41
s_y [m]	0,056	0,055

table 6: statistical indices

	Full-scale test	Simulated test
ASI	0.95	0.97
THIV	25	23
PHD	17.3	11

table 7: impact severity indices

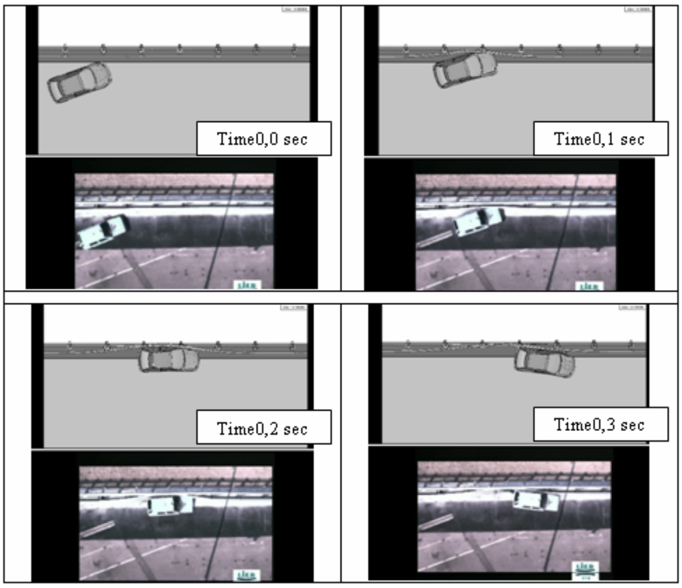


figure 9: scratch images of the impact (top camera)

4. CONCLUSIONS

The developed passenger car FE model was aimed to be (i) a support to design novel devices and (ii) a tool to perform parametric studies to assess the influence of different factors. Due to this, each part of the vehicle has been modelled with particular attention. The model has been set up through an extensive comparison between full-scale and simulated outputs of four different experiments: the frontal and oblique collisions against a concrete wall and the impacts against two types of steel barrier with different containment energy level (127kJ and 724kJ). The excellent agreement attained when simulating the abovementioned impacts, characterized by noticeably different nature, demonstrates that the model of the light weight passenger car is suitable for a wide range of impact conditions. As a conclusion, the validated model is reliable to predict the impact behaviour without needing expensive crash tests.

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