DEMONSTRATOR FOR VIRTUAL TESTING PROCEDURE. APPLICATION TO PEDESTRIAN ADULT HEAD IMPACTS

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ABSTRACT

The research activities presented in this paper were carried out within Sub-Project 7 of APROSYS (Advanced PROtection SYStems), a European Integrated Project implemented within the 6th Framework Programme which main objective is the development and introduction of critical technologies that improve passive safety for all European road users in all relevant accident types and accident severities. Furthermore, this IP aims to increase the level of competitiveness of the European industry by developing new safety technologies (safety is a proven selling point) and by developing design tools and evaluation methods that will increase the efficiency of the development process of the involved industries.

SP7 (Virtual Testing) deals with the development of knowledge and tools to facilitate the design and evaluation of advanced crash protection systems by virtual testing (numerical simulation). Within SP7 a Virtual Testing (VT) demonstrator based on a combination of simulations and physical tests for pedestrian protection (head impact) was delivered. Where VT has proven to be predictive and where benefits in terms of increasing safety are expected.

In a first approach, experimental adult head form impacts against bonnet structures were performed. Besides, a series of virtual tests with standard adult head form numerical model and numerical model of the test rig were performed. VT was performed with limited data (only initial conditions) from physical test and no validation results were provided to adjust the nominal simulation model. Finally, a study of experimental testing variation using stochastic models was performed. The effects of these variations were quantified using stochastic analysis.

INTRODUCTION

Pedestrian protection has been identified as one of the fields with greatest potential for improvement. It can be asserted that numerical simulation is meanwhile highly predictive for pedestrian protection testing. Moreover, studies carried out in current EC projects such as APROSYS [1][2] conclude also that the implementation of virtual testing in homologation/regulation with regards to pedestrian protection directives, could lead to tangible benefits in terms of injury reduction and cost reduction in vehicle design. Pedestrian regulation has a medium degree of complexity in comparison with a full scale crash, as impactors are used for the assessment, and only the front part of the vehicle is significantly affected. Nevertheless, unfortunately not a high number of cars reach the maximum level on pedestrian protection. Thus, the potential impact of improving pedestrian protection will be very worthy since the number of pedestrian fatalities is still high like mentioned above.

Within APROSYS SP7 a Virtual Testing (VT) demonstrator based on a combination of simulations and physical tests for pedestrian protection (head impact) was delivered. The goal of these activities is to show the feasibility of the simulation models as well as the accuracy of the virtual and physical tests.

In a first approach, experimental adult head form impacts against bonnet structures were performed. The test matrix was defined covering following characteristics:

- Extended instrumentation (additional instrumentation to measure 3D deformation contours)
- Sensitivity analysis testing (level of results variation due to slight variations in testing configuration)
- Repeatability ranges (level of repeatability for same testing configuration).

Besides, a series of virtual tests with standard adult head form numerical model and numerical model of the test rig were performed. VT was performed with limited data (only initial conditions) from physical test and no validation results were provided to adjust the nominal simulation model. Finally, a study of experimental testing variation using stochastic models was performed. The effects of these variations were quantified using stochastic analysis.

ADULT HEAD IMPACT TESTS

Test bench

A bonnet test bench was built (Figure 1). The design of the test bench is adaptive so it can be

used for testing different kinds of bonnets by only performing minor modifications. The bonnet is mounted on rigid crossbeams placed in correspondence of its hinges, front lock and rubber mountings/grommets. Furthermore, a plate for representation of the motor block was placed.

Figure 1. Bonnet test bench.

The adult head form as specified in Directive 2003/102/EC, phase II [3] was used to record head accelerations caused by contact with the bonnet top. Additionally, a system for measuring three-dimensional deformations has been employed in order to provide additional data about the mechanical behaviour of the bonnet and the positioning and kinematics of the head form. The base of this system is software that computes the deformations of a surface based on the stereoscopic analysis of pictures registered with two high speed video cameras [5]. These results allow to achieve a more complete validation of the results of the numerical simulations, as well as to check the correct positioning of the head form at the contact time.

Test conditions

Four different impact locations were investigated (Figure 2). These locations were selected to represent the most frequent occurred impact points:

1. close to the front lock
2. close to the hinges
3. close to the rubber mountings
4. close to the motor block highest point

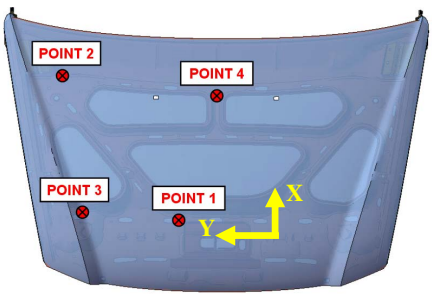

Figure 2. Impact locations.

The objectives of performing these tests were to analyse the level of results variations due to slight variation in testing configuration (sensitivity analysis testing) as well as the level of repeatability for same testing configuration. According to these objectives the test matrix was define.

Initially four reference tests were performed (one in each point). These tests were launched according to the Directive 2003/102/EC [3], phase II. Test conditions for the adult head form impactor are as following:

- Angle of impact: 65º±2º to the ground reference level
- The point of first contact: within ±10mm of tolerance to the selected impact location
- Impact velocity: 11.1±0.2m/s

Then, variations of the impact variables were taken into account. These variations were carried out only in points 1, 2 and 3 whereas point 4 was used to perform the repeatability analysis. Thus, three tests were performed at this point with the same impact conditions (reference boundary conditions according to the standard). At points 2 and 3 the reference test was also repeated so repeatability could be checked also in different points of impact. The test matrix is shown in the next table:

Table 1. Tests matrix.

Point 1 (front lock)			Point 2 (hinge)		
v [m/s]	Ang. [º]	Pos. [mm]	v [m/s]	Ang. [º]	Pos. [mm]
11.1	65	0	11.1	65	0
10.6	65	0	11.1	65	0
11.6	65	0	10.6	65	0
12.1	65	0	11.6	65	0
11.1	60	0	11.1	60	0
11.1	70	0	11.1	70	0
11.1	65	y-10	11.1	65	y-10
11.1	65	y+10	11.1	65	y+10
Point 3 (supports)			**Point 4 (motor highest point)**		
v [m/s]	Ang. [º]	Pos. [mm]	v [m/s]	Ang. [º]	Pos. [mm]
11.1	65	0	11.1	65	0
11.1	65	0	11.1	65	0
10.6	65	0	11.1	65	0
11.6	65	0			
11.1	65	y-10			
11.1	65	y+10			
11.1	65	x-10			
11.1	65	x+10			

BLIND VALIDATION

Series of virtual tests with standard adult head form numerical model and numerical model of the test rig were performed. VT was performed with limited data from physical test. The FE model was built starting from the CAD, material data

properties, description of the connections among the different parts of the bonnet (adhesives, spot-welds…) and test conditions (test set-up) but no validation results were provided to adjust the nominal simulation model.

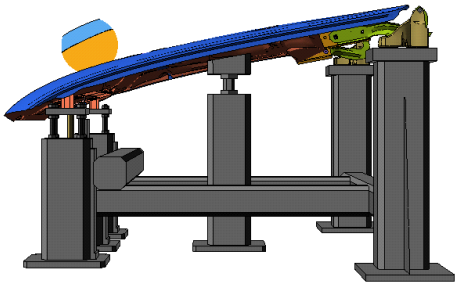

Figure 3. Numerical model.

In order to check the accuracy of the simulation model, a comparison between the simulation results and the test results were performed. This model was not tuned once the comparison with the test results was done.

First of all the four reference tests were considered. The curves obtained are depicted in the following images:

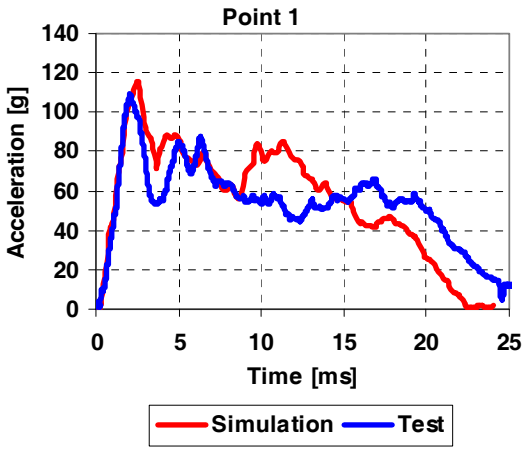

Figure 4. Acceleration pulses (point1).

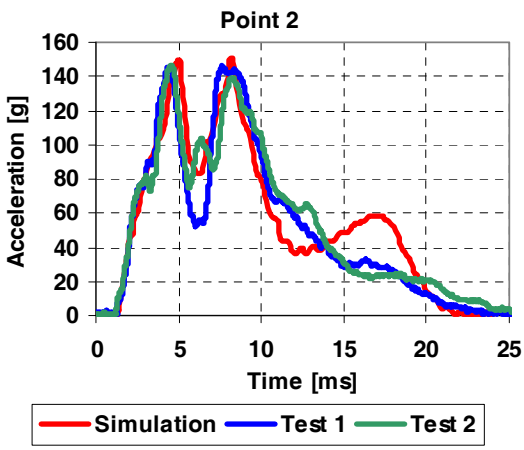

Figure 5. Acceleration pulses (point2).

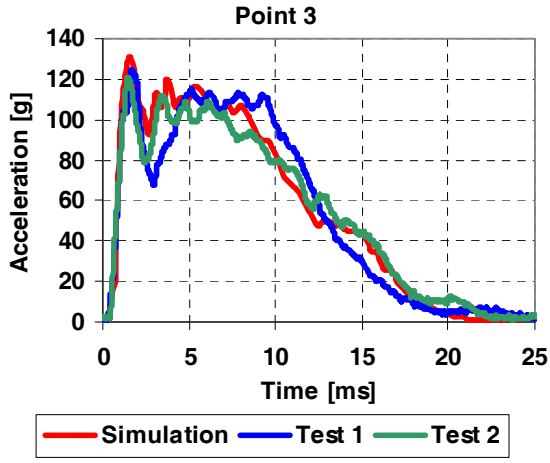

Figure 6. Acceleration pulses (point3).

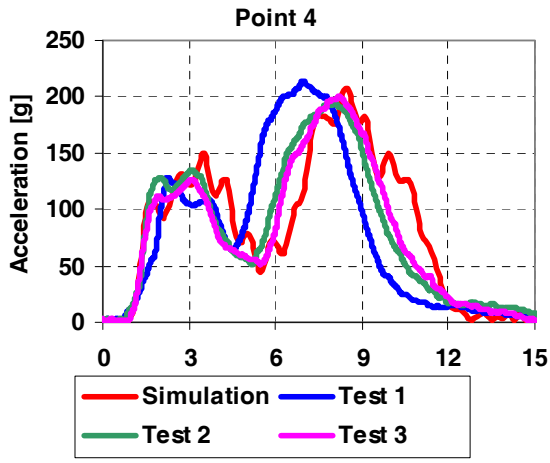

Figure 7. Acceleration pulses (point4).

In the case of the first point there is not repetition of the test, so only one test result is available. Nevertheless, the results presented in all cases show a good correspondence between the output signals of both, simulation model and tests, in shape as well as in absolute peak values.

As it was explained above, a system for measuring three-dimensional deformations has been employed in order to provide additional data about the mechanical behaviour of the bonnet and the positioning and kinematics of the head form impactor.

This system allows measuring of displacements and three-dimensional deformations by two cameras simultaneously recording. A previous calibration process is required. This process consists on taking series of images of several points from a panel which exact distances are known. Then, the program is provided with information about the specific spatial position of the cameras and then it is able to interpret correctly the images obtained

during the tests. On the other hand, the test's object (bonnet and headform impactor in this case) has to be painted with a random mottled (see Figure 8) which provide reference points in order to work out deformations in consecutive images.

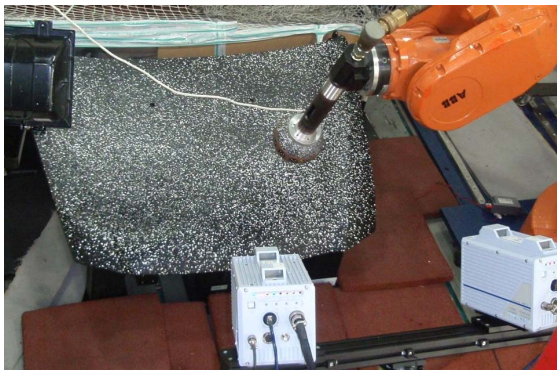

Figure 8. Cameras location and random mottle of the bonnet and headform impactor.

As far as the behaviour of the bonnet is concerned, the kinematics observed in the simulations correlate well with the one registered with the stereoscopic analysis of the high speed images. Some examples can be seen in the next figures. In the upper images (in a white background) the simulation contour is depicted whereas in the lower ones (in a grey background) the contour obtained from the stereoscopic analysis is shown.

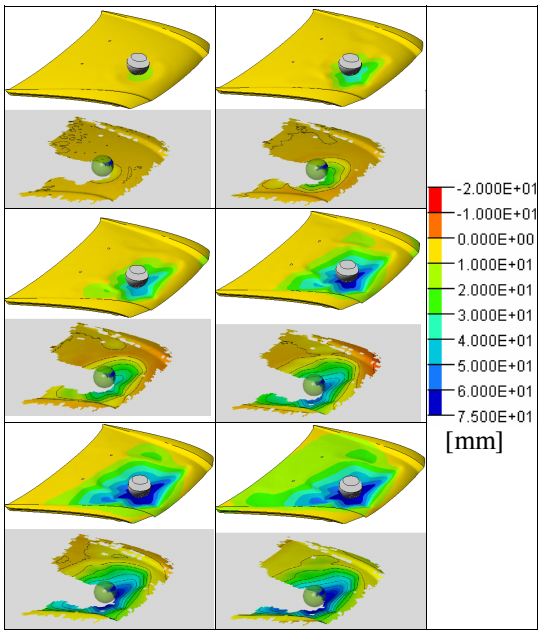

Figure 9. Displacement contours (point1).

Displacement contours of the bonnet as well as the absolute displacement values are very close in all cases for both, virtual tests and real tests (stereoscopic analysis of the high speed images).

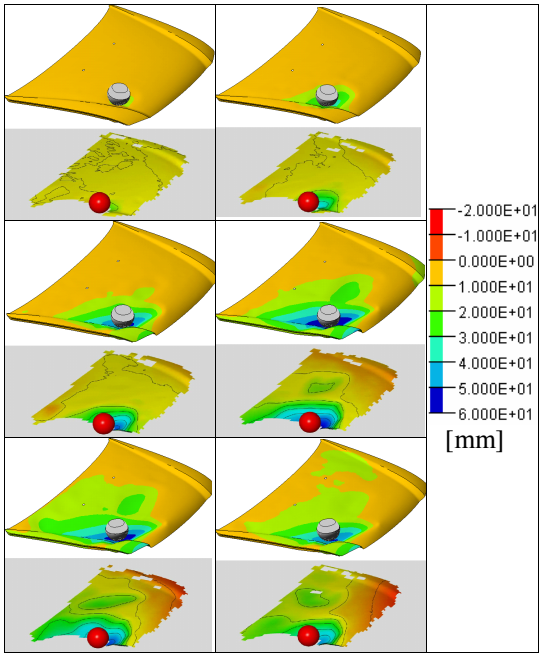

Figure 10. Displacement contours (point3).

Once the results of the reference cases were compared, the analysis was extended to all the test cases with the variations in the input conditions (see Table 1). The results obtained are shown in following tables:

Table 2. Experimental - Simulation results point 1.

Point 1 (front lock)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang °	Pos. mm	Test	Sim.	Test	Sim.
11.1	11.06	65	0	109.3	115.4	487.2	703.7
10.6	10.48	65	0	80.5	109.9	487.6	643.6
11.6	11.73	65	0	109.8	121.0	562.2	799.3
12.1	-	65	0	-	126.4	-	914.8
11.1	11.08	60	0	110.8	127.7	559.1	726.6
11.1	10.97	70	0	92.8	116.6	603.4	660.1
11.1	11.15	65	y-10	101.6	121.1	533.0	667.6
11.1	11.15	65	y+10	110.9	117.2	481.4	534.2

The system that launches the head form impactor against the bonnet allows reaching velocities higher than 12.1m/s. Nevertheless, when the system works close to this maximum threshold it is possible to have problems during the test. These problems appeared in this case. The system was out of control and then, it was not possible to know the real velocity achieved. Thus, it was decided not to use this test results. This problem only appeared in the point 1 since in the other cases the maximum velocity was 11.6m/s.

Table 3. Experimental - Simulation results point 2.

Point 2 (hinge)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang º	Pos. mm	Test	Sim.	Test	Sim.
11.1	10.98	65	0	146.6	151.0	988.9	955.3
11.1	11.19	65	0	146.4		937.1	
10.6	10.78	65	0	142.2	141.6	1038	838.8
11.6	11.8	65	0	157.4	159.5	1042.6	1080.1
11.1	10.96	60	0	143.8	146.3	1209.2	904
11.1	11.00	70	0	161.4	151.1	1142.3	972.7
11.1	11.11	65	y-10	129.7	148.1	883.4	896.8
11.1	11.10	65	y+10	152.8	164.6	1189.4	1000.1

Table 4. Experimental - Simulation results point 3.

Point 3 (supports)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang º	Pos. mm	Test	Sim.	Test	Sim.
11.1	10.91	65	0	124.1	130.6	1095	1087.5
11.1	11.13	65	0	120.5		937.5	
10.6	10.61	65	0	103.6	125.4	777.9	1013.7
11.6	11.47	65	0	132.6	137.4	1130.5	1158.8
11.1	11.16	65	y-10	121.0	138.8	954.4	1091.1
11.1	11.05	65	y+10	114.0	166.9	866	1181.7
11.1	10.93	65	x-10	126.0	157.7	1034.2	1405
11.1	11.17	65	x+10	146.6	127.1	989.2	987.1

Table 5. Experimental - Simulation results point 4.

Point 4 (motor)							
Input Parameters				Output parameters			
				Max. Acc [g]		HPC	
v m/s	v_{real} m/s	Ang º	Pos. mm	Test	Sim.	Test	Sim.
11.1	11.03	65	0	194.2	207.2	1485.3	1627.8
11.1	10.97	65	0	200.2		1696.9	
11.1	11.22	65	0	213.8		1686.2	

The correlation (similar trends are seen for experiment and simulation results) is very good for point 2 and point 4 in both maximum acceleration and HPC and good for point 3, whereas the simulation results are overestimated in case of point 1. This point is close to the lock of the bonnet. In the blind simulation model, the lock system was modelled as a rigid body, this fact makes that the acceleration peaks and the HPC values were higher than the obtained in the physical tests.

These results leads to conclude that more information regarding the bonnets and the test rig would be needed to build the nominal simulation model. For instance, it is very important to know the material cards so material characterizations would be required.

STOCHASTIC ANALYSIS

The target of the study is the generation of knowledge about the influence on the pedestrian adult head criteria responses (according to the Directive 2003/102/EC [3], phase II) regarding slight experimental testing variations such as impact velocity, impact angle and relative impact position.

In the above sections, a deterministic approach has been shown. Simulations with the same experimental conditions have been performed and results of corresponding simulations and tests results have been compared. This study consisted in one simulation results vs. one physical test results comparison. With the stochastic approach, the level of results variations due to slight variation in testing configuration (sensitivity analysis) can be study. Correlation between experimental and simulation clouds can be checked as well as the robustness and accuracy of the simulation models.

Stochastic pre-processing: stochastic modelling and sampling

Four stochastic analysis were performed, one per point of impact. The values of dispersion considered for the impact conditions covers the ones used in the experimental tests at each point. Thus, the next tables show the set of input parameters as well as the considered variability:

Table 6. Stochastic variables - Point 1 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±1m/s	11.1m/s	[10.1,12.1]	Veloc
Impact angle	±5º	65º	[60º,70º]	Ang
Impact point position X	± 10 mm	0 mm	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm	[-10,10]	Pos_Y

Table 7. Stochastic variables - Point 2 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±0.5m/s	11.1m/s	[10.6,11.6]	Veloc
Impact angle	±5º	65º	[60º,70º]	Ang
Impact point position X	± 10 mm	0 mm.	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm.	[-10,10]	Pos_Y

Table 8. Stochastic variables - Point 3 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±0.5m/s	11.1m/s	[10.6,11.6]	Veloc
Impact angle	±2º	65º	[63º,67º]	Ang
Impact point position X	± 10 mm	0 mm.	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm.	[-10,10]	Pos_Y

Table 9. Stochastic variables - Point 4 study.

Stochastic variables	Range	Numerical variable		
		Nominal value	Range	Name
Impact velocity	±0.2m/s	11.1m/s	[10.9,11.3]	Veloc
Impact angle	±2º	65º	[63º,67º]	Ang
Impact point position X	± 10 mm	0 mm.	[-10,10]	Pos_X
Impact point position Y	± 10 mm	0 mm.	[-10,10]	Pos_Y

In this last case (point 4), the variability of the input variables considered matches with the allowed range of tolerances established by the standard [3] for the tests. Thus, the variability obtained in the tests results at point 4, which were performed with the same impact conditions can be analyse through this study. For the study the reference model built by a blind validation presented above was used.

Once the stochastic variables were identified in the reference model, the next step was to get a set of simulation cases in accordance with one of the sampling methods available [6]. The "Optimal Latin Hypercube" method was chosen in order to provide better coverage of the multivariate space with less simulation runs (30 per point of impact, total 120 simulations cases). Uniform distributions for the ranges established in the table above were defined to account for the estimated variability.

Before starting the set of simulation runs, the resultant values to be extracted and analysed were defined. As the main interest was to know the sensitivity of pedestrian adult head criteria, evaluation files .sto and .crit were built in order to get the maximum acceleration pick, time at this maximum acceleration pick and the HPC value.

Stochastic post-processing: sensitivity analysis

The results were analysed with several approaches, and valuable conclusions resulted from the different analysis carried out.

Following tables show the main statistics of the outputs or properties, resulting from the different clone model runs at each point:

Table 10. Stochastic results statistics - Point 1.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	9.77866E+01	1.30101E+02	1.15357E+02
HPC	30	5.53438E+02	8.81923E+02	7.03893E+02
TIME_ MAX-ACC	30	3.00047E+00	4.20028E+00	3.69039E+00
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	6.94042E+00	8.31786E+00	0.0721056
HPC	30	8.33078E+01	9.73500E+01	0.138302
TIME_ MAX-ACC	30	3.19323E-01	3.88878E-01	0.105376

Table 11. Stochastic results statistics - Point 2.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	1.40797E+02	1.68239E+02	1.52388E+02
HPC	30	8.03288E+02	1.14861E+03	9.46985E+02
TIME_ MAX-ACC	30	5.30068E+00	9.20039E+00	7.33040E+00
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	6.32505E+00	7.82325E+00	0.0513376
HPC	30	7.43241E+01	8.94827E+01	0.0944922
TIME_ MAX-ACC	30	1.56135E+00	1.60564E+00	0.219039

Table 12. Stochastic results statistics - Point 3.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	1.23533E+02	1.67693E+02	1.41284E+02
HPC	30	9.59821E+02	1.43727E+03	1.14476E+03
TIME_ MAX-ACC	30	2.10027E+00	4.70008E+00	2.99370E+00
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	1.29068E+01	1.47524E+01	0.104416
HPC	30	1.02722E+02	1.34482E+02	0.117476
TIME_ MAX-ACC	30	7.23537E-01	8.65761E-01	0.289194

Table 13. Stochastic results statistics - Point 4.

Property	Points	Min. mum	Max. mum	Mean
MAX-ACC	30	1.80371E+02	3.18280E+02	2.54933E+02
HPC	30	1.42373E+03	2.41783E+03	1.89340E+03
TIME_ MAX-ACC	30	1.02005E+01	1.08004E+01	1.03638E+01
Property	**Points**	**Ave Deviation**	**Std Deviation**	**|SDev/Mean|**
MAX-ACC	30	3.37991E+01	3.99696E+01	0.156785
HPC	30	2.18702E+02	2.68302E+02	0.141704
TIME_ MAX-ACC	30	8.32636E-02	1.15837E-01	0.0111771

From the tables, some results are concluded by looking at the [standard deviation/mean] ratio. This ratio is an estimation of the sensitivity of the parameters in terms of ratio variability. Values of around 1, present a percentage of sensitivity from the mean of 100%. Different behaviours can be observed at the different points of impact.

Not so high sensitivities can be seen. At point 2 (close to the hinges) and point 3 (close to the supports - rubber mountings) the most sensitive parameter is the time at the maximum acceleration (>20%). This variation can be produced due to a second impact of the head form owing to the input variations. At point 1 (close to the lock) no major variations can be seen (maximum ≈13% in the case of HPC). And finally, at point 4 (close to the motor block) the most sensitive parameters are the acceleration pick and the HPC value (≈15%).

Then, the next stage is looking for the input variables whose scatter is responsible for this output variability.

The correlation matrix is one of the outputs offered by ADVISER [6] to the user, showing relationships between the problem parameters. The linear correlation matrices can be seen in the following figures:

	Point 1				Point 2			
	vel	ang	posX	posY	vel	ang	posX	posY
MAX-ACC	0.84	0.099	0.47	-0.2	0.6	0.18	0.29	0.67
HPC	0.92	-0.22	-0.091	-0.28	0.86	0.21	0.28	0.37
TIME_MAX-ACC	-0.32	-0.11	-0.87	0.21	-0.075	0.26	-0.16	0.75

	Point 3				Point 4			
	vel	ang	posX	posY	vel	ang	posX	posY
MAX-ACC	0.18	-0.15	-0.52	0.6	0.45	0.25	-0.76	-0.23
HPC	0.4	-0.0057	-0.81	0.25	0.48	0.31	-0.78	-0.12
TIME_MAX-ACC	-0.12	0.03	0.25	-0.68	-0.39	-0.038	-0.15	0.083

Figure 11. Linear correlation matrices.

Looking at the correlations higher than 0.5 (in absolute value), the stochastic input variables more clearly related (linearly) to the variability of the output parameters are different at each point of impact.

At point1 the most influence variable is the velocity on the maximum acceleration and the HPC value. The variation of x position is the following influencing factor, but in this case the influence is on the time at the maximum acceleration. This effect is due to a second impact of the head form as results of the variation of the x position.

Similar effect can be seen at point 2. The most influence variable is the velocity on both the maximum acceleration and the HPC value and the variation of the y position on the maximum acceleration and the time at this maximum acceleration. This point 2 is closed to the hinges. The variation of the y position has two effects. One is that the first impact point is closer to the hinge so the acceleration peak is increased. And the other effect is the opposite; the first impact point is farther to the hinge and the acceleration peak is later in time.

This last effect appears again at point 3; the variation of the y position has a big influence in the maximum acceleration and the time at this maximum acceleration. But also the variation of the x position has a big influence in the HPC value.

Finally at point 4, the most influence variable is the variation of the x position on the maximum acceleration and the HPC value. The x position variations makes that the point of impact is closer or farther to the motor block highest point and then has a direct effect on the acceleration peak and then in the HPC. As closer is the impact point to the motor block highest point, higher is the acceleration peak.

Another calculation can be done in terms of the norm of the regression coefficients, for the input variables. Using the stochastic post processing of ADVISER [6], is presented the next **Error! Reference source not found.**, that represent the global relative influence in the variability of the model of each one of the input variables taken into account in the study.

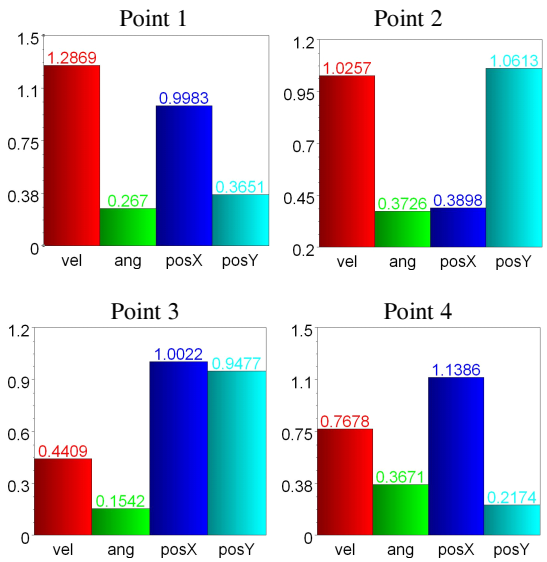

Figure 12. Global sensitivity rating. Point 1.

Input parameters like velocity of impact and impact position (in X or Y direction depending on the point of impact) are the most sensitivity variables whereas the angle of impact has not so much influence in the responses for all the points of impact.

All the results (test, simulation and stochastic results) are plotted on scatter plots to highlight relationships between responses and variables. Only scatter plots of variables with a correlation value higher than 0.5 in absolute value (see Figure 11) are shown since lower values do not show a clear relation. Blue dots are used for simulation results, red dots for experimental results and black triangles for stochastic results.

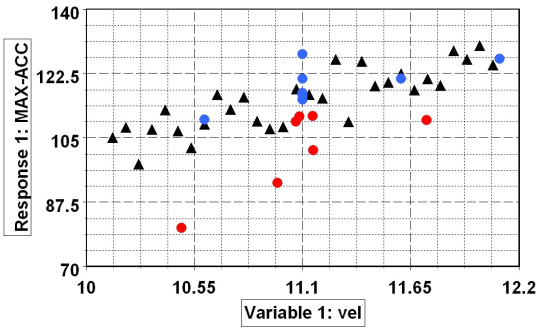

Figure 13. Scatter plot; Point 1 – Acceleration peak [g] vs. Velocity [m/s]

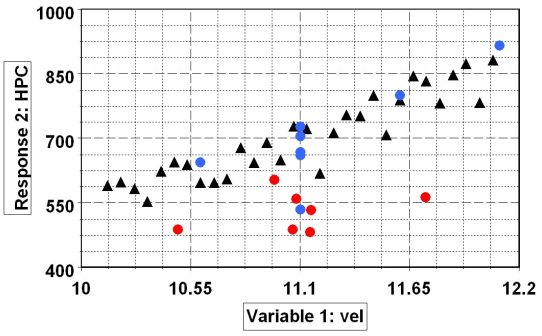

Figure 14. Scatter plot; Point 1 – HPC vs. Velocity [m/s]

As it was advanced in the linear correlation matrices (Figure 11) at point 1, only the velocity has a very high influence on the maximum acceleration and the HPC value in a direct and positive correlation. This means that increasing the impact velocity affects in an increasing of these values.

At point 2, not only the velocity shows a high influence on the maximum acceleration and the HPC value (Figure 15 and Figure 16) but also variations in the y-position lead to high variations on the maximum acceleration value.
This effect is due to the location of point 2 (close to the hinge). Small variations of y-position lead to an impact position closer to the hinge, a very rigid area, so the acceleration peak (first contact between the headform impactor and the bonnet) is increased.

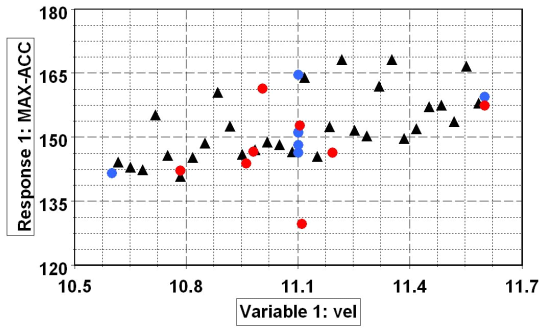

Figure 15. Scatter plot; Point 2 – Acceleration peak [g] vs. Velocity [m/s]

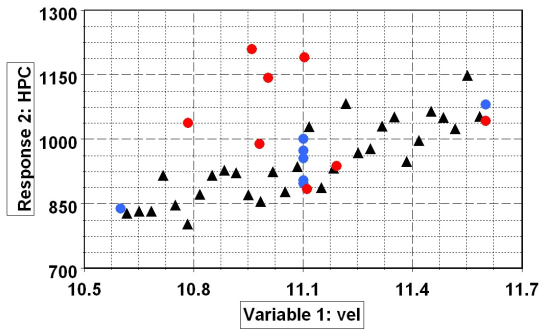

Figure 16. Scatter plot; Point 2 – HPC vs. Velocity [m/s]

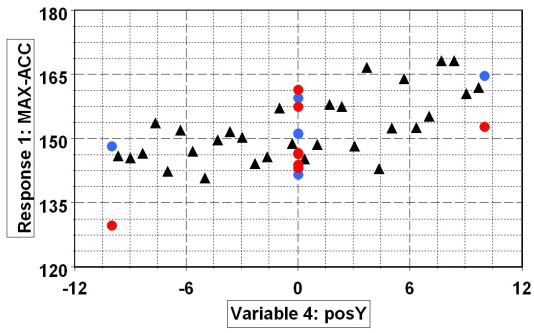

Figure 17. Scatter plot; Point 2 – Acceleration peak [g] vs. y-Position [mm]

The influence of the velocity in the HPC is higher than in the maximum acceleration. This is due to the fact that the variation of the velocity does not only increase the severity of the impact (increase the acceleration peak) but also modify the shape of the acceleration curve leading to higher increments of HPC than maximum accelerations. The formula used to calculate the HPC is identical to that used to calculate the Head Injury Criterion (HIC):

$$\mathbf{HPC} = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a\,dt \right]^{2.5} (t_2 - t_1) \qquad (1).$$

where ‘a’ is the resultant acceleration as a multiple of ‘g’, and t1 and t2 are the two instants (expressed in seconds) during the impact, defining the beginning and the end of the recording for which the value of HPC is a maximum. The difference between HPC and HIC is that for HPC, values which the time interval (t1 - t2) is greater than 15ms are ignored for the purposes of calculating the maximum value.

Looking at the linear correlation matrix related to point 3, the velocity is not the variable with more influence in the output parameters but the position.

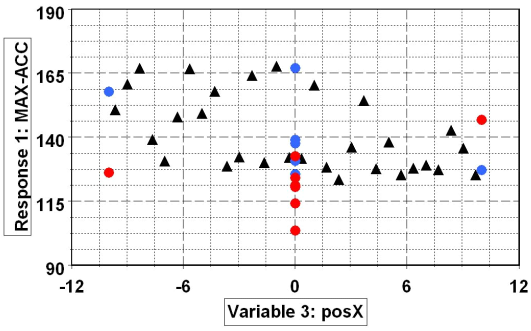

Figure 18. Scatter plot; Point 3 – Acceleration peak [g] vs. x-Position [mm]

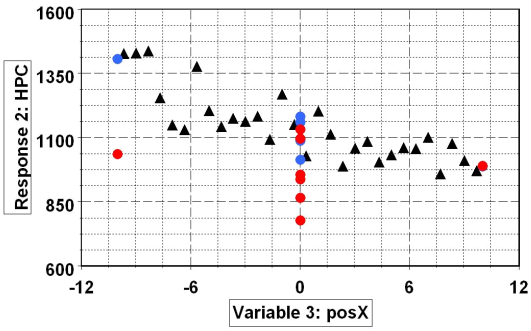

Figure 19. Scatter plot; Point 3 – HPC vs. x-Position [mm]

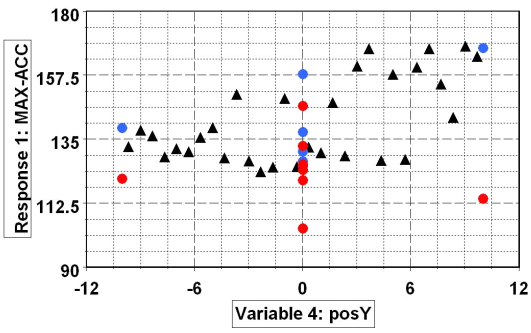

Figure 20. Scatter plot; Point 3 – Acceleration peak [g] vs. y-Position [mm]

At point 3, contrary to what append in the other points, the velocity has not clear influence in the maximum acceleration and the HPC value whereas the position variation presents a direct correlation. This point of impact is close to the rubber mountings, positive increments of the impact position in x direction leads to move away the impact point from the stiffer point that are the rubber mountings. Thus, the acceleration peak as well as the HPC value decreases.

In the case of impact point 4, variations of the input variables taken into account (velocity of impact, angle of impact and position of impact – x and y directions) match with the allowed range of tolerances established in the standards [3].

Variations of the velocity and the impact position in x direction are the ones with more influence in the maximum acceleration and the HPC value in a direct and positive correlation in case of the velocity (Figure 21 and Figure 22) and in a direct and negative correlation in case of x position (Figure 23 and Figure 24).

Looking at the results obtained, e.g. in the case of HPC, it can be observed that small variations of these input variables ($\Delta V=\pm 0.2$m/s and $\Delta X=\pm 10$mm) lead to differences in the HPC value of even 1000 (from HPC≈1400 to HPC≈2400). These variations (allowed range of tolerances established in the standards [3]) can not be detected by experimental tests since the testing system are not allowed performing variations within these ranges under control.

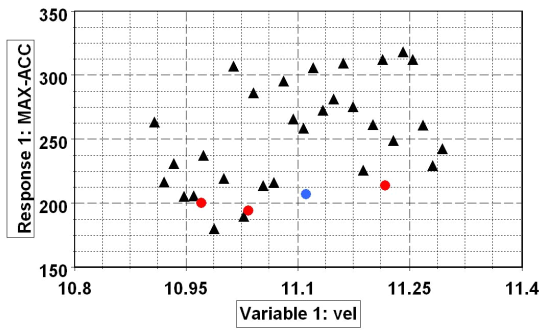

Figure 21. Scatter plot; Point 4 – Acceleration peak [g] vs. Velocity [m/s]

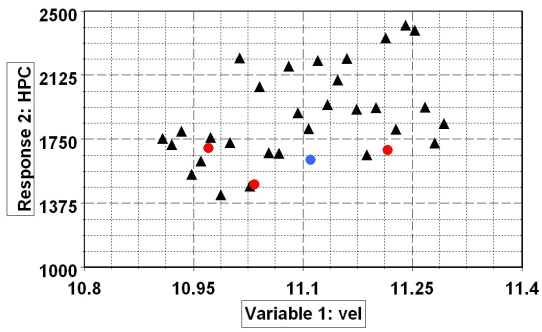

Figure 22. Scatter plot; Point 4 – HPC vs. Velocity [m/s]

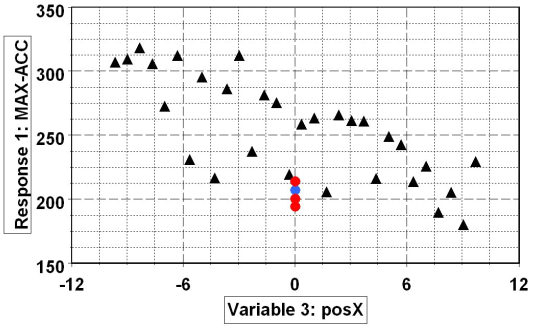

Figure 23. Scatter plot; Point 4 – Acceleration peak [g] vs. x-Position [mm]

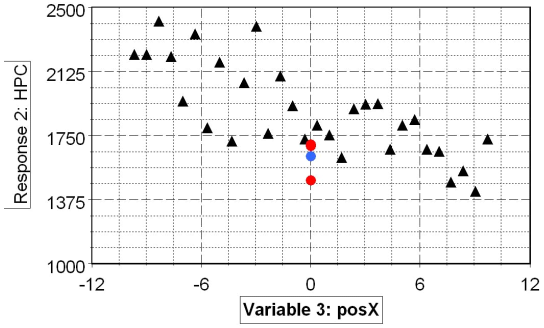

Figure 24. Scatter plot; Point 4 – HPC vs. x-Position [mm]

In this specific case, all HPC values are higher than 1000 so this point would not pass the standards. But there are other cases where this HPC variability is around 1000. So it would be a good point or a bad point depending of the different tolerances achieved in the experimental conditions. Even performing sensitivity analysis via physical tests is not possible to cover a wide range of parameter variations since it would mean among others, high costs and time.

CONCLUSIONS

The pedestrian subsystem tests were chosen in APROSYS SP7 as demonstrator for a Virtual Testing procedure, because virtual testing turned out to be predictive for the pedestrian head form assessment using accurate material and CAD data.

Experimental adult head form impacts against bonnet structures were performed. The test matrix was defined so the level of results variations due to slight variation in testing configuration (sensitivity analysis testing) as well as the level of repeatability for same testing configuration could be analysed. Slight variations in the velocity and angle of impact as well as the impact positions (in x and y directions) were taken into account (Table 1) and their effects on the maximum acceleration and HPC values were studied. On the other hand, four different points of impact were considered (Figure 2) so it was possible to analyse the effects of the variations of the input parameters on the outputs in different impact situations.

At the same time, blind simulations according to the tests carried out were performed. When performing blind simulations the need to provide as much information as possible is essential. But limited data (material, boundary conditions…) from physical test can be provided and no validation results to adjust the nominal simulation model are available.

In order to check if the simulation model predicts closely enough the physical tests, simulation and test results were compared for all cases. Very good correlations were obtained for the reference cases (test conditions according to the Directive 2003/102/EC [1], phase II) in terms of the shape of the acceleration curves as well as absolute peak values (see Figure 4 to Figure 7). This analysis was extended to all the test cases with the variations in the input conditions. For these cases, the accuracy of the models was not so high like in the reference cases. The correlation is very good for the points of impact 2 and 3 but in the case of point 1 the simulation results were overestimated (see Table 2 to Table 4).

In order to provide additional data about the mechanical behaviour of the bonnet and the positioning and kinematics of the head form a new system for measuring three-dimensional deformations was employed. Thanks to this system, deformation contours as well as maximum deformations of the bonnet during the physical tests could be measured and compared with the ones obtained by the simulation model (Figure 9 and Figure 10).

Results of these comparisons (acceleration vs. time curves, HPC values and deformations) pointed out the capability of the simulation model to reproduce the physical tests. It is important to remark that this simulation model was not validated. It was not tuned after comparison with the test results.

Next step was to perform a study of experimental testing variation using stochastic models. The effects of these variations were quantified using stochastic analysis. Four stochastic analysis were performed, one per point of impact. The values of dispersion considered for the impact conditions covers the ones used in the experimental tests at each point.

The stochastic variables more clearly related (linearly and quadratically) to the variability or sensitivity of the responses are clearly the impact

velocity and the position (in x and y directions) being the less related the impact angle in the ranges studied. This has been confirmed by the correlation matrix, scatter plots and global sensitivity rating. Again, this effect is different for the different points of impact selected. Thus, the most relatively sensitive input parameters with global sensitivity rating greater than 0.7 are:

- Point 1: velocity and x-position
- Point 2: velocity and y-position
- Point 3: x and y-position
- Point 4: velocity and x-position

It is very interesting the analysis of the results obtained at point of impact 4. In this case, variations of the input variables taken into account (velocity of impact, angle of impact and position of impact – x and y directions) match with the allowed range of tolerances established in the standards [3]. These variations are allowed when physical tests are performed. Within this study three tests were carried out. The required velocity (according with the standards) is 11.1±0.2m/s and the achieved ones were: 11.03m/s, 10.97m/s and 11.22m/s. These variations in the achieved velocity led to slight variations in the HPC values (see Table 5). Nonetheless, though the stochastic analysis where variations of all the input variables were taken into account, it can be seen that the variability of the results is higher (variations in the HPC value of even 1000 were obtained, see Figure 22 and Figure 24).

Even performing sensitivity analysis via physical tests is not possible to cover a wide range of parameter variations since it would mean among others, high costs and time. Virtual testing covers a wider range of vehicles and boundary conditions not yet available for real testing.

Nowadays, minds are changing progressively towards virtual testing and simulation is already state of the art technology within the automotive industry. Nevertheless, relationship between real testing and virtual testing is globally seen as a necessary coupled approach. Real testing is still needed to demonstrate virtual testing capabilities by comparison to real testing with a necessary feedback. And also virtual testing provide an added value for real testing as it induce improvements of experimental testing.

An important issue for further studies would be to analyse how virtual testing could result in cost reductions and increase competitiveness for European car manufacturers by substituting a range of real tests by virtual testing. And in a step by step process, to study the possibility of a higher content of virtual testing within the existing or within future homologation procedures.

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