Stochastic Analysis of Vehicle Models for Sensitivity Analysis and Optimization

STOCHASTIC CRASH ANALYSIS OF VEHICLE MODELS FOR SENSITIVITY ANALYSIS AND OPTIMIZATION

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ABSTRACT

Within the 6th Framework Programme EU project APROSYS, the Sub-project 7 is fully devoted to virtual testing. The aim is to improve the quality of the crash simulation in order to be able to come to rating and qualification by virtual analysis.

One of the main issues lies in the evaluation of scatter sources and the consequences of scatter on the results of the analysis. Therefore, great effort was devoted in the project to identify and quantify sources of dispersions, and to assess their relevance.

To evaluate the influence of scatter on crash responses a series of stochastic models has been developed. Within the APROSYS project a series of generic car models was developed to perform this task. Generic car models are virtual vehicles, derived from the geometry, layout, and characteristics of the best-in-class models currently available on the market according to EuroNCAP ratings, generated to have commonly shared models to work out towards improvement in crash simulations.

In this work a stochastic analysis developed by using one of these generic car model, called GCM4, a multi-purpose vehicle, will be reported. The stochastic model was generated by considering the stochastic variation of some parameters. In particular, the steel sheet properties were used as stochastic variables (input). Moreover, to evaluate the structure influence on the passenger behavior, a simpler stochastic passenger compartment model was developed.

The simulation runs were managed by a specific tool, called ADVISER, developed within the APROSYS project and its antecedent ADVANCE. The results were analyzed by means of the post-processor included in the same ADVISER tool.

The results give further insight in the problem of the improvement of simulations for passive safety applications.

1. INTRODUCTION

Besides improvement in quality and performance of cars, a major requirement in automotive industry is the reduction of costs by reducing time-to-market. To achieve this goal the use of advanced design methodologies and tools is mandatory. By using improved simulation tools in design, it is possible not only to speed up the project but also to improve it, because many different alternative solutions can be easily analyzed and compared, and it is possible to limit the number of expensive experimental tests, or avoid them at all. Strictly speaking, experiments are not eliminated: physical experiments are replaced by virtual tests. Therefore, this method has been called *virtual testing* (VT) [1].

The greatest advantages of VT in automotive design are certainly in the field of passive safety due to the complexity of crash analyses and the costs implicated with it. In the 5th Framework Programme of the European Union, two projects introduced VT: VITES (VIrtual TESting, [2]) and ADVANCE (ADvanced Virtual ANalysis of Crash Environments [3]). The authors were involved in both projects. In VITES the basic methodologies to develop VT were developed, whereas ADVANCE was mainly focused on the tools to achieve VT.

Further improvements are being obtained within the 6th European Framework Programme APROSYS (Advanced PROtection SYStems), and in particular, in a subproject (SP7) just named *Virtual Testing*.

Final aim, besides developing VT methods and tools, and demonstrating the validity and convenience in using VT methods, is to go towards the use of VT in Regulations [4].

One of the greatest problems in developing VT methods is how to deal with the large number of simulations required to check numerical codes and models, and which models can be used to do this. Car manufacturers are very reluctant, for justified and comprehensible reasons, to share their finite element (FE) models for research purposes. Even developing by scratch a real car model is not accepted by everybody. For that reason, it was decided to create virtual models of virtual cars, that is of cars that do not actually exists, but are like real cars with the best, top-in-their-class, performances in the rating tests like EuroNCAP. These Generic Car Models (GCM) were shared among the APROSYS partners to develop passive safety parametric [5] and stochastic analysis [6], design of advanced passive safety [7] and active safety [8] devices, studies in the protection of pedestrian, cyclists and motor bikers [9-10], and biomechanical investigations [11].

In this work a full vehicle stochastic analysis of a GCM is reported. The aim of this work was to develop and apply a tool for stochastic analysis (ADVISER), examine the feasibility of full vehicle stochastic analysis, and the advantages from using this kind of analysis in car crash design for safety.

Final objective of these research activities is to demonstrate the possibility of using VT in regulations also. There is, in fact, one case of certification that can be already made by simulation, namely ECE R44 regarding bus rollover. In the authors' opinion, VT can be further extended and cover many other possible certification schemes, as it will be developed as a final task of APROSYS Subproject 7 on Virtual Testing.

2. GENERIC CAR MODELS

In APROSYS four generic vehicle models were developed, namely:

- **GCM1** a small city car, like EuroNCAP *superminis* (Fiat 600 and Punto, Renault Clio, Citroën C2 and C3 etc.).
- **GCM2** a small family car, like in EuroNCAP classification (Renault Mégane, Fiat Stilo, Audi A3…).
- **GCM3** a large family car (such as Mercedes C class, BMW Series 5, Audi A4…)
- **GCM4** a multipurpose vehicle (MPV) (such as Renault Espace, Citroën C8, Peugeot 807, Fiat Ulysse, Lancia Phedra…).

The first three GCMs were developed by Centro Ricerche Fiat, whereas GCM4 was developed by Politecnico di Torino. Besides, a heavy truck generic model was developed by the Technical University of Graz. All these are finite elements models, developed both in Radioss from Altair (formerly Mecalog) and LS-Dyna, but the same car models were converted to multibody in the Madymo code from TNO.

Figure 1 shows some snapshots of the four GCMs.

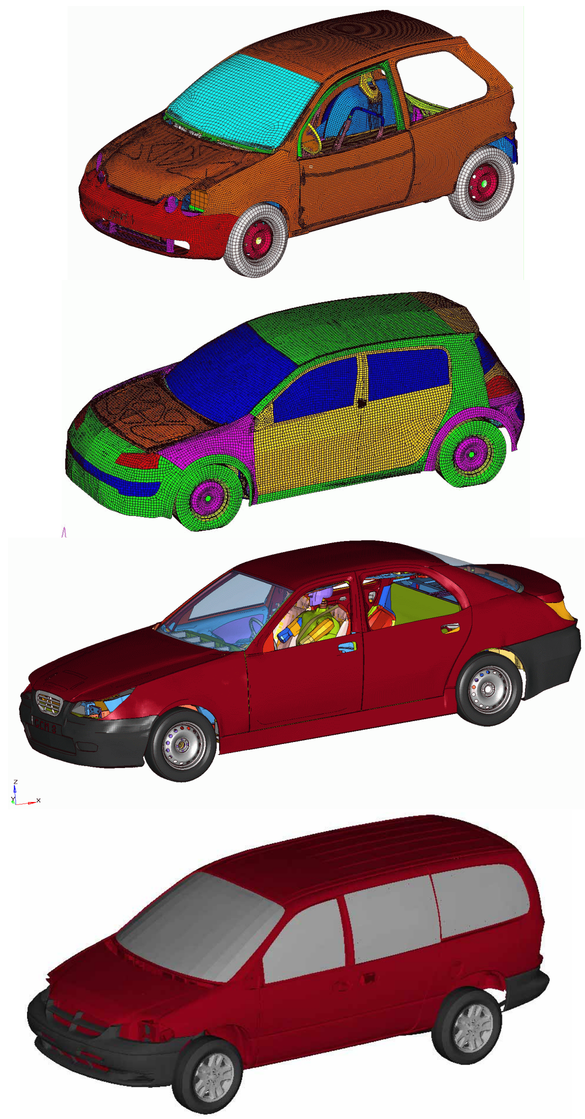


Figure 1. The virtual fleet: the GCMs developed within the APROSYS project.

2.1 The generic car model 4 (GCM4)

The generic MPV model was not started from scratch, but was developed starting from a public domain model of the Dodge Caravan, sold in Europe as Chrysler Voyager, made by the George Washington University and FHWA/NHTSA National Crash Analysis Center (NCAC), and available through the NCAC web site. This initial LS-Dyna model has no crash environment defined, but a rigid barrier and a US-NCAP frontal crash test environment defined are available. The model includes the whole chassis and body with engine and wheels, but does not include steering system and suspension and also does not include dummies, seats, seatbelts, airbags, nor any other restraint system.

The model was first converted to Radioss with some automatic tools:

- Hypermesh translator for “LS-Dyna Key” to “Radioss block format ver.44”.
- M-Crash translator from LS-Dyna to Radioss (under development, performed by Mecalog Italia)

Both translators have some limitations (especially the Hyperworks one when defining material laws and element types). By mixing together the translated files and adding a great amount of manual editing work, a good initial translation of the model was obtained.

However, the model generation did not stopped there for a series of reason. It was decided to have a car model mostly close to the best-in-class models according to EuroNCAP tests. These 5 stars vehicles were, in 2004 when this work begun, the Citroën C8, the Peugeot 807, the Fiat Ulysse, and the Lancia Phedra (that are built on the same platform and are structurally very similar), and the Renault Espace.

Therefore, a series of modifications were made on the virtual model to make it more resembling to these real cars. Modifications include:

- overall external size
- basewheel reduction to 2850 and forward translation of the front wheels and slight rearward translation of the back wheels to match the more usual current styling of European cars
- mass reduction of the body-in-weight to 1271 kg
- many structural modifications to improve impact strength by reinforcement of structural parts, especially in the front area

The front rails were straightened and sheet thickness was increased. Figure 2 show front rail modifications. Fenders were also modified.

Then, the steering line, the front suspensions, the seats, the dashboard, the interior panels were added to obtain the full vehicle model shown in figure 3.

Figure 4 show an example of a simple AMUS crash test against a rigid barrier.

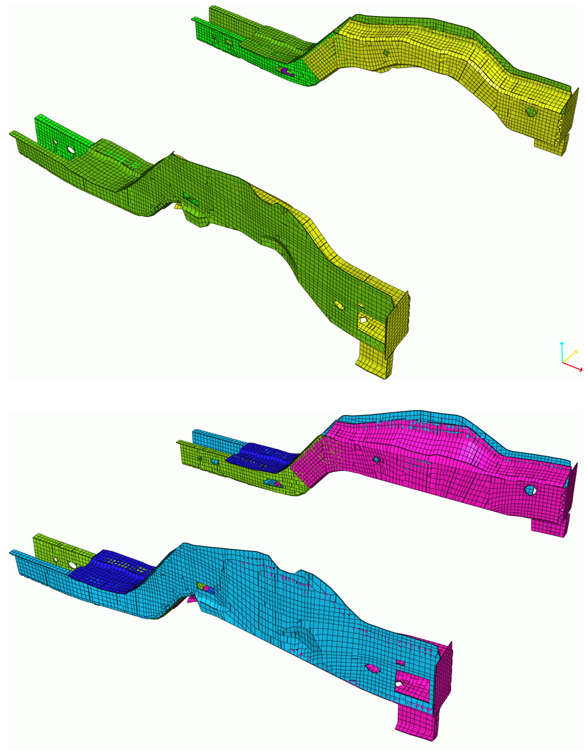


Figure 2. Front rails modifications, above original, below the improved version.

2.1 Validation of the GCM4

An important issue in the development of the GCMs was model validation.

Validation in its usual technical connotation is the process that tries to demonstrate the validity of a numerical (or also theoretical or analytical) model. The most widely accepted validation process comes from the comparison of a series of experimental test results (numerical values of some chosen physical quantity or specific index, characteristic curves, time histories or spectra of some definite signal, and so on) with the equivalent results from the numerical model. Usually validation is considered at the global system level, also including interactions with the external environment (boundary conditions in the most general sense, in the case of a car crash barriers and interaction with the soil, in the case of some simple mechanical test the interaction with environment and the external constraints) but it can be at the component level also [4]. In some cases validation of a series of components at their component level can be accepted for validation of the assembly also: this bottom-top validation process is not without inconvenient and must be used with careful attention, but is acceptable under cautious examination.

However, other forms of validation can be foreseen and are sometimes used and accepted: for example the validation of a numerical model from a former theoretical analysis (typically the comparison of numerical results with the results from widely accepted mechanical theories like Saint Venant's beam model or thick shell theory, that were previously experimentally verified; this is like Nafems process).

Figure 3. The GCM4 exterior and, below, a view of the interior parts (seats are not shown but are included in the model).

The difficulty in the case of GCMs comes from the fact that there is no physical sample to compare with. Since GCMs are fully virtual cars, there are not and there will not be a physical system nor component at all. Therefore, no experimental test will be available to check. Besides the costs involved with the production of such a prototype, it is not sure that the unique or almost unique sample will be significant and useful.

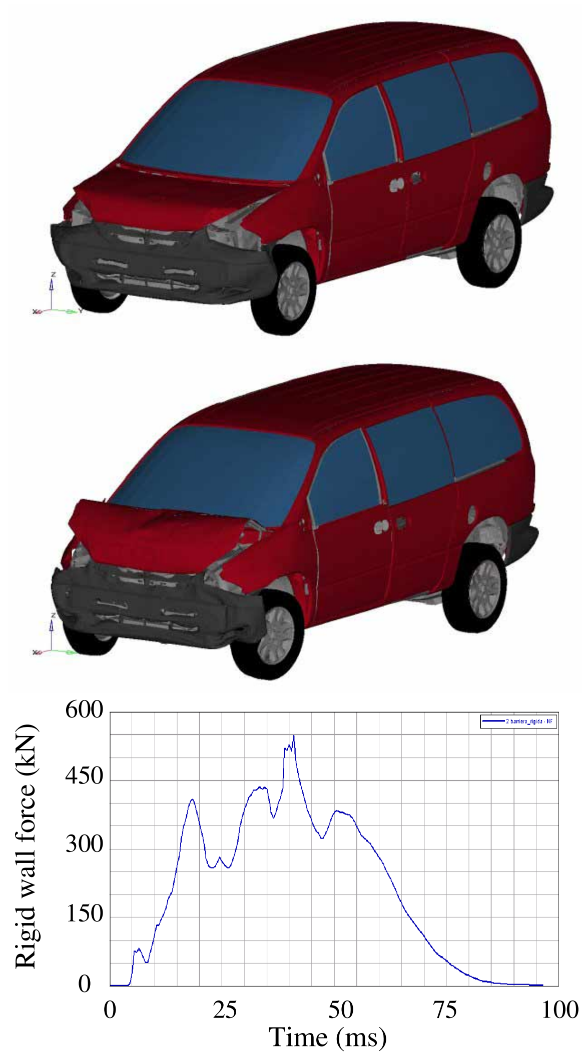


Figure 4. Crash test of the GCM4 against a rigid barrier, deformed structure after 50 ms and 100 ms, and the associated force time history.

However, some validation criteria was to be defined in the most efficient and convincing way. The most acceptable approach to validate the GCMs was agreed to be the comparison with the most wide number of experimental tests coming from external independent sources.

Such a comparison can be done with recent results from EuroNCAP tests of cars of the same class, that for the GCM4 is MPVs, as shown for example by Huibers and de Beer [12].

The GCMs were then tested in various conditions. The results from the EuroNCAP 60% offset crash test on deformable barrier [13] are shown in figure 5. The structural deformation is reasonable, and there are not serious critical deformations.

Figure 6 show the comparison in terms of forces exchanged with the barrier. The reference curves are from [12].

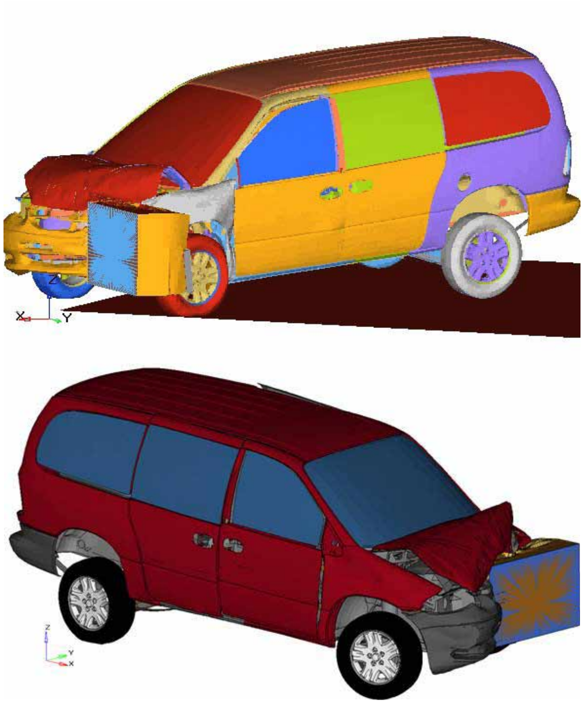


Figure 5. Crash test of the according to EuroNCAP standard for offset impact against deformable barrier [13].

In figure 6, below, the comparison is also shown in terms of a corridor defined from the envelope of all the seven reference curves. The force-displacement curve of the GCM4 is about 86% of the time inside the corridor (strictly inside is 70%; this discrepancy is partly related to uncertainty at the first impact and the shorter length at the end of the impact). The final displacement is slightly less than the average, but this is justified by the fact that the vehicle was without dummies: therefore the overall mass was smaller than the average, even if the body-in-white mass of the GCM4 compares well with the other cars of the class.

Therefore, the GCM4 can be considered validated and acceptable.

It is worth noticing that this validation is important and sufficient for the scope of the APROSYS project to have numerical models available for research purpose, to develop advanced protection systems and the virtual testing methodology and protocols.

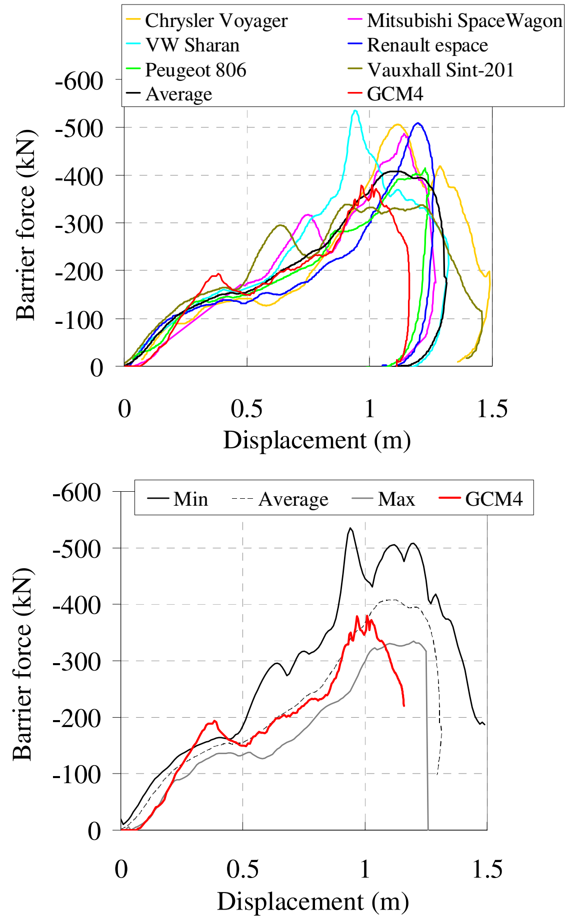


Figure 6. Comparison of the force-displacement curves from EuroNCAP experimental tests on similar cars of the same class (MPVs) with GCM4. Below, the curve is compared with the corridor obtained from the envelope of all the test curves.

3. STOCHASTIC MODEL

A probabilistic approach can be used to evaluate the uncertainties in simulated responses of a system [14-15]. This is extremely important to evaluate the results coming from virtual models. There are, in fact, uncertainties coming from modeling material behavior, material data, geometrical parameters, contact definition, but also uncertainties due to the numerical tools as for example validity limits of the elements formulation. Boundary conditions are also known with a certain degree of uncertainty.

Stochastic analyses give also much information on the influence of the various parameters of influence and their relative importance. These results can be used for optimization and robustness analysis of the vehicle in the design process.

In the following sections the results from a stochastic analysis carried out on the GCM4 are described. The results are analyzed by means of the ADVISER [16-17] software, developed jointly by Mecalog (now Altair Development France) and TNO during the ADVANCE project.

Stochastic variables and analyzed responses

A stochastic model is based on the analysis of the distribution of some output response due to the stochastic variations of some input variable, affected by random variations.

The material properties and the sheet thickness are among the main sources of dispersion that affect the structural behavior of the vehicle body. The thickness variation is typically very small and has an effect analogous to a variation in the stress-strain curve of the material. Therefore, it has been chosen to examine the variation of the material characteristics. The range of variation accounts for both the natural material variations and the thickness dispersion.

Two variables were then defined, one for the variation of the properties of the material of the front rails and the other for the variation of the material properties of the remaining GCM4 body.

The range of variation is reported in table 1, whereas figure 7 gives a graphical representation of the variability of the stress-strain characteristic.

Table 1.
Steel properties and range of variation

Stochastic variables	*RailsYieldStress*	*CabinYieldStress*
Nominal value (GPa)	0.365	0.250
Standard deviation (GPa)	0.035	0.040
Upper value (GPa)	0.40	0.29
Lower value (GPa)	0.33	0.21

The two variables were considered with a normal distribution. The samples for the simulations were generated by ADVISER, by using the Optimal Latin Hypercube algorithm. The experimental plan is shown in figure 8.

The responses used in the analysis are acceleration curves from selected characteristic points within the passenger compartment (figure 9), the force transmitted by the car to the barrier, and the intrusion on the vital space of the driver (figure 10), as follows:

- Maximum value of the acceleration on the base of the left B-pillar;
- Mean value of the acceleration on the base of the left B-pillar;
- Maximum value of the acceleration on the centre of the passenger compartment between the front seats;
- Mean value of the acceleration on the centre of the passenger compartment between the front seats;
- Maximum value of the normal contact interface force between car and barrier;
- Mean value of the normal contact interface force between car and barrier;
- Maximum value of the X component of the normal contact interface force between car and barrier;
- Mean value of the X component of the normal contact interface force between car and barrier;
- Total displacement of the centre of the passenger compartment between the front seats;
- X component of Displacement on the base of the left B-pillar;
- Intrusion on the vital space of the driver; measured as the reduction of the distance between the base of the B-pillar and the knee of the A-pillar.

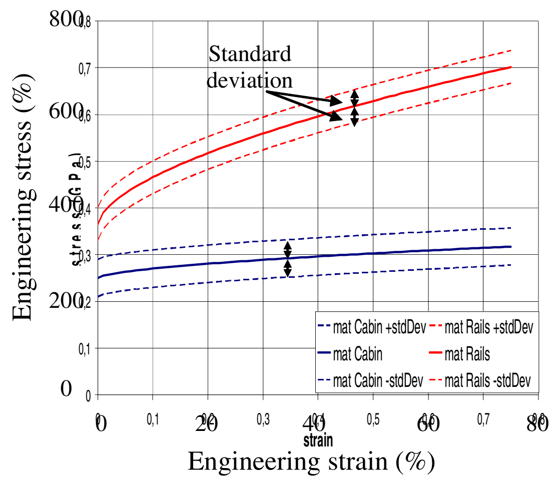


Figure 7. Material characteristic of the steel of the front rails and the GCM body overall, with the range of variation.

Figure 8. Scatter plot of the two analyzed variables.

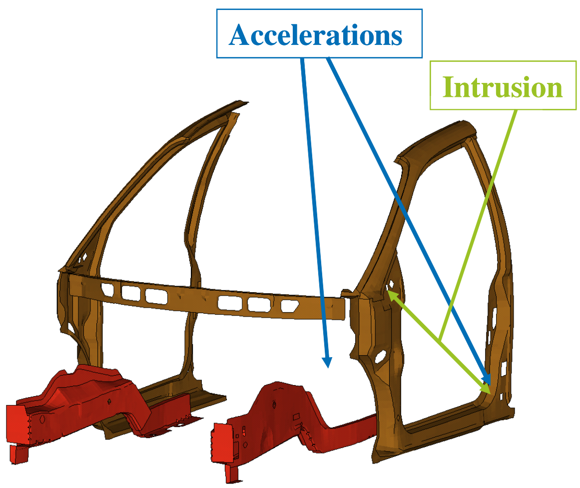
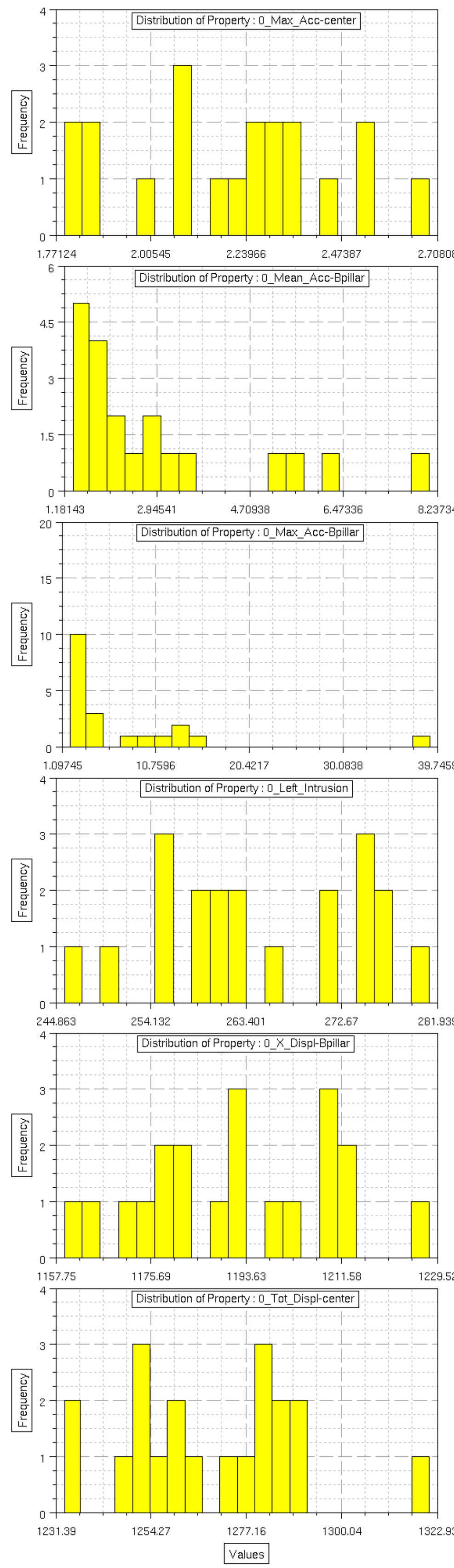


Figure 9. Measurement points of the acceleration and of the intrusion.

Stochastic analysis

The results from the simulation runs were analyzed by means of the ADVISER software. The results are put in the form of tables. Each run (row) is associated to a series of responses (columns) as described above. Some statistical descriptor useful for the analysis can be calculated (mean value, relative range of variation, standard deviation, variance, skewness, and kurtosis).

A graphical representation of the raw figures is shown in figure 10. Some simple consideration can be drawn from the observation of these charts. The responses linked to the acceleration of the B-pillar, and especially its maximum values, have a wide range of variation and seem to be quite sensitive to the variables variation. Moreover, the maximum value can not be considered to have a normal distribution and its histogram shows a possible bifurcation of the response.



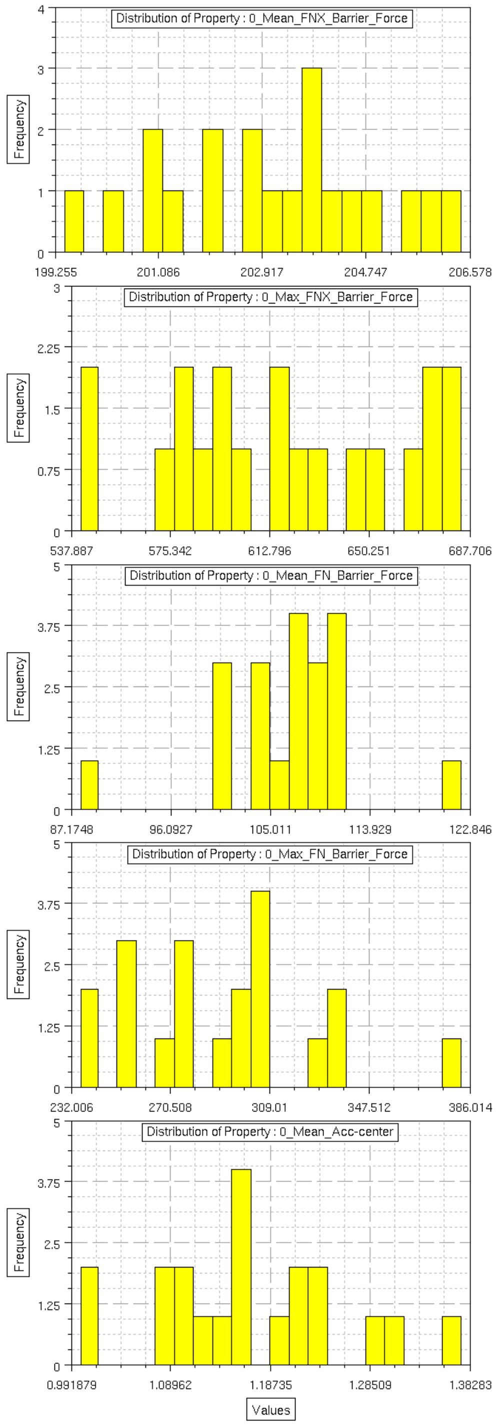


Figure 10. Histograms of the distribution of the responses.

The analysis of the scatter in the responses highlights how a relatively small variation of the input, in the order of magnitude of 10%, can produce greater effects, up to some 20%. This is a very critical issue, to be considered even for physical crash tests which have very few or no repetitions. Scatter in experimental crash it is not known, as sources of dispersion cannot be taken into account.

Further insight in the parametric response of the system is given by the linear and quadratic correlation matrices (figure 11) [18-19]. It appears that the variable yield stress of the steel has high direct correlation with the intrusion on the left side, and high inverse correlation with the maximum and mean values of the acceleration in the centre of the passenger compartment. The variable yield stress of the steel of the rails has only a moderate direct correlation with the responses related to the contact interface force. The maximum and mean values of the B-pillar acceleration, instead, are the only responses with a quite low correlation with both input variables. Finally, it has to be noted that most quadratic correlation coefficients are higher than the corresponding linear ones.

The linear correlation coefficient of the various parameters can also be computed [18].

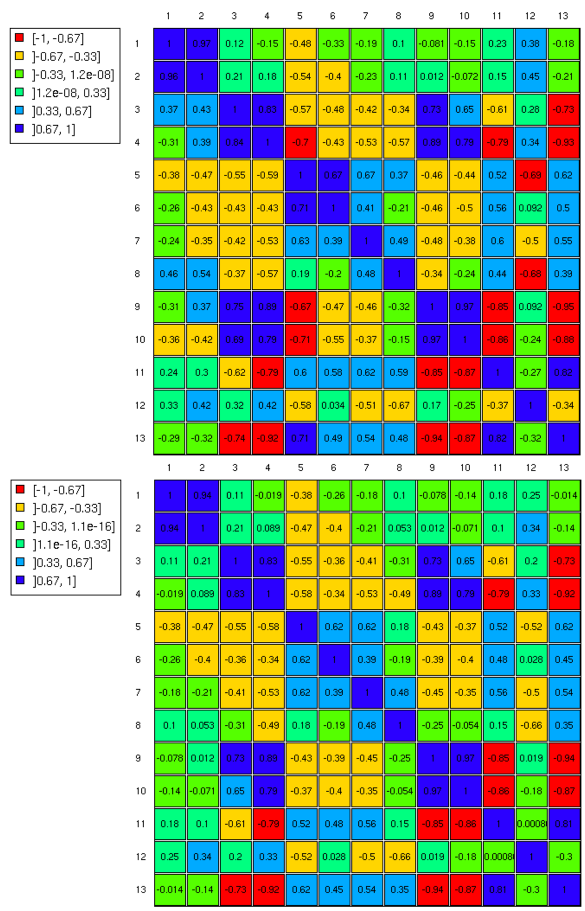


Figure 11. Linear and quadratic correlation matrices for the stochastic parametric problem analyzed.

Confirmation of the results from the correlation matrices comes from the principal component analysis (PCA). It was performed with ADVISER and shown in terms of the distance bi-plot (figure 12) and of the correlation bi-plot (figure 13). Both are representations of variables and responses in the plane of the first two principal components and confirm the previous observations. In this plots direct correlation corresponds to parallel vectors in the same direction, inverse correlation corresponds to parallel vectors in the opposite direction. Perpendicular directions mean lack of correlation. In the distance bi-plot the main role of the *CabinYieldStress* variable is shown: its vector is almost coincident to the first principal axis. The correlation bi-plot shows the high direct or inverse correlation of a lot of responses with the *CabinYieldStress* variable, and highlights that the only response which have a quite good inverse correlation with the *RailsYieldStress* variable is the mean X component of the contact interface force. The absence of correlations for the maximum and mean values of the B-pillar acceleration is also visible and the uncertain correlations of the maximum values of the total and X contact force can be revealed.

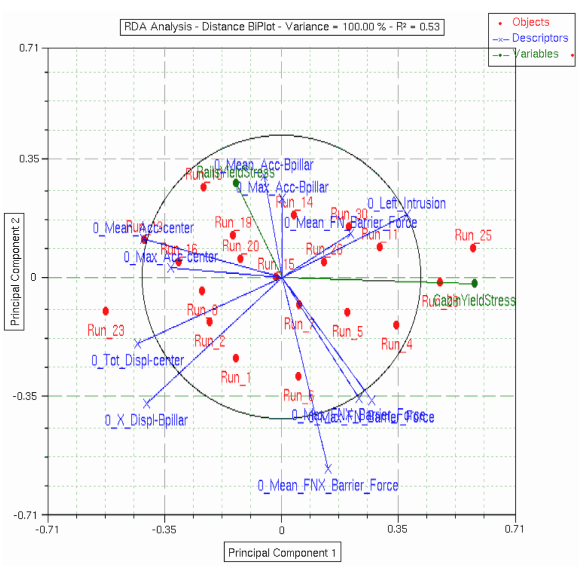


Figure 12. Distance bi-plot: the yield stress of the cabin steel shows high inverse correlation with the mean and maximum acceleration in the centre of the passenger compartment (the related vectors are almost parallel, but in opposite directions). The front rail steel yield stress has direct and inverse correlation with many outputs.

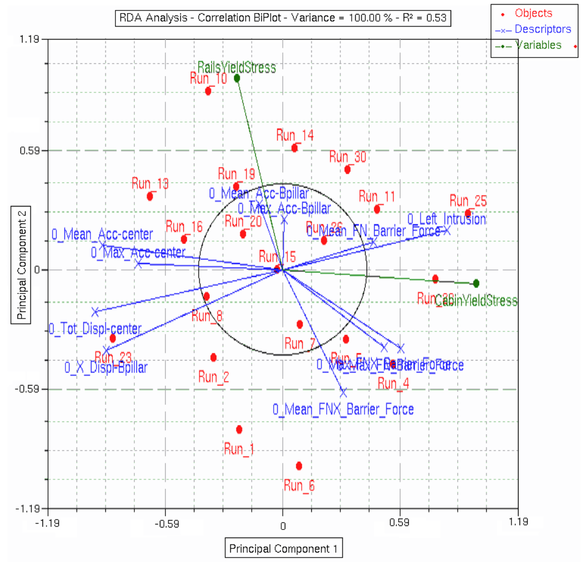


Figure 13. Correlation bi-plot: the results are similar to the distance bi-plot, but it gives also a quantitative measure of the correlations.

From the analysis of the correlation matrices and correlation bi-plots, the main results can be summarized as follows:

- All responses can be considered to have a normal distribution with the exception of the maximum and mean B-pillar accelerations, which have quite high ranges of variation and seem to present bifurcated behaviors.
- From both the linear and quadratic correlation matrices, high correlations of a lot of responses with the yield stress of the passenger compartment steel were found, while the yield stress of the frontal rails steel is only moderately correlated with some responses related to the interface contact force.
- The coefficients of the linear regression confirm the correlations revealed by means of the correlation matrices. Furthermore the first order interaction coefficients are quite low for all responses, except for the left side intrusion which is affected by a strong interaction of the two variables.

Finally the principal component analysis (PCA), by means of the distance bi-plot and of the correlation bi-plot, confirms the main importance of the yield stress of the passenger compartment steel and its high direct or inverse correlation with a lot of responses.

To identify what are the main influences and how they are grouped together, the cluster analysis can be performed. The cluster analysis by means of a single linkage grouping of response variables is shown in figure 14.

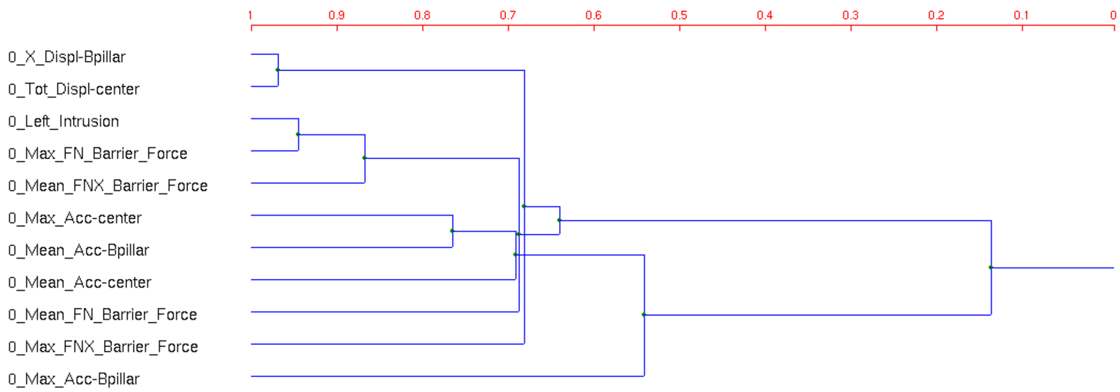


Figure 14. Cluster analysis: it helps to identify how the influence on the various responses can be grouped together.

5. CONCLUSIONS

One of the important topics addressed in the 5th and 6th European FP projects ADVANCE, VITES, and APROSYS is the development of the virtual testing (VT). Validated and fully reliable virtual testing methods and tools have been improved, and the use of virtual testing will not be restricted to the design of vehicles for crash, but it is possible to foresee its utilization, hopefully, also in regulations.

An essential tool to build validated and safe VT models is based on the stochastic analysis. Stochastic analysis allows examining the sources of influence and the correlation with the structural responses. It can help identifying correlations, but also their relative influence, the distributions of the outputs and their statistical parameters, and even show whether there are unpredictable behavior. For example, bi-modal distribution of a response can be related to bifurcations.

A numerical example has been used to demonstrate this approach. The example used a generic car model (GCM) developed within the APROSYS project. The GCMs are virtual cars specifically developed to be used for advanced researches, to be shared among the APROSYS partners to address all the necessary studies for VT. The GCM4, a multipurpose vehicle, developed by Politecnico di Torino was used.

The analysis was carried out by means of the ADVISER software, developed by Mecalog and TNO, during the above mentioned projects.

The effectiveness of the provided tools has been demonstrated. The correlation matrices, both linear and quadratic, give a first glimpse to the main factor of influence, by ranking in a scale from 0 to 1.

Direct and inverse correlations can be made clear with the use of the correlation and distance bi-plots. These are graphical tools that represent the correlations of a couple of input parameters with the output responses. When many input parameters are considered, several correlation bi-plots will be created, even if this will complicate the analysis of the results.

To help the analysis, in the case of multiple input and output, the cluster analysis help in identifying the main mutual connections between responses and will point the analysis in the right direction.

The availability and the continuous improvement of these tools is an important contribution to the assessment of up-to-date analysis methodologies to improve the passive safety of vehicles of any type.

ACKNOWLEDGEMENTS

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