# Stochastic Automotive Crash Simulation: A New Frontier in Virtual Prototyping

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**Abstract**

The paper reports on a recent and successful meta-computing exercise in which a large-scale automotive crash simulation has been approached from a stochastic point of view. The experiment, probably the first of its kind in terms of complexity and size, has involved the execution of 128 parallel PAM-CRASH simulations on the 512-node Cray T3E Supercomputer at the HWW in Stuttgart. The motivation behind the work may be found in the statistical flavor of the crash phenomenon due to the scatter of parameters of both the vehicle and the initial and boundary impact conditions. The analysis addressed in the paper could have easily been classified as a problem of the Grand Challenge class only a few years ago. Today, stochastic crash analysis on industrial scale is a reality and is expected to lead to results of high scientific and technical relevance.

## 1 Introduction

Modern mechanical design and analysis is almost exclusively based on Finite Element codes. These codes have reached today a considerable level of sophistication and versatility. However, one increasingly important aspect of analysis that these codes are unable to address is that of scatter, or uncertainty, in structural parameters, loading and boundary conditions. The parallel development of FE codes and the advent of High Performance Computing architectures is rapidly increasing the size and complexity of problems that may be addressed, but, unfortunately, on a purely deterministic basis. It is a well known fact that deterministic single-point evaluation of the response may under many circumstances produce an over-designed and excessively conservative system if the presence of parameter scatter is not taken into account. There are numerous classes of mechanical problems where the influence of scatter of structural parameters, initial and boundary conditions, and, last but not least, algorithm performance, naturally dictate a stochastic approach. One such problem, namely crash, is the subject of this paper.

Monte Carlo simulation techniques, due to their intrinsic parallelism, lend themselves ideally to the solution of complex Stochastic Mechanics problems, especially in a Meta-Computing perspective. A broad overview of industrial applications of these techniques have

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been reported in [1], [3] and [4] while in [5] the first known stochastic crash simulation is addressed.

It is clear that from a purely engineering point of view no two vehicles are identical. Therefore, from a statistical standpoint the problem of crash simulation should not be approached by considering a single deterministic vehicle, but rather by talking of a population of vehicles. Manufacturing and assembly tolerances account for the majority of scatter in vehicle properties. At the same time, however, car body engineers have to find structural designs that are robust enough so that given safety requirements are met, see [2]. The need for increased performance, very often at the limits of technology, naturally pushes engineering into non-deterministic grounds. With this spirit in mind, the authors have performed a large-scale stochastic crash simulation with the intention of verifying if Monte Carlo simulation techniques can indeed offer a promising and realistic platform for improving crashworthiness design and analysis.

The scatter of properties in an automobile may be found basically in the following:

1. Uncertainty in the quality (stiffness, ultimate stress) of the weldpoints.
2. Uncertainty in the characteristics of the various materials (yield and ultimate stress, strain-rate parameters, etc.).
3. Uncertainty in the local characteristics of the stamped parts (e.g local thickness and stiffness fluctuations, residual stresses, etc.).
4. Imperfections due to the actual assembly process.

The paper reports the results of a Monte Carlo crash experiment performed by the international PROMENVIR Consortium in collaboration with BMW, ESI and SGI GmbH in the framework of the PROMENVIR Project (ESPRIT 20189).

## 2 Stochastic Formulation of the Crash Problem

In generic mathematical terms, crash is a dynamic phenomenon that may be formally described by a set of nonlinear first-order vector differential equations

$$\dot{x} = f(x, F, p) \tag{1}$$

$$y = g(x, p) \tag{2}$$

where $x \in R^N$ is the state vector of displacements and velocities, $F \in R^p$ represents the stochastic external forcing terms, $p \in R^n$ is a vector of stochastic structural parameters and $y \in R^q$ the measurement vector (e.g. accelerations, strains, etc.). A classical problem in stochastic mechanics is the computation of the Probability Distribution Functions (PDFs) of the output variables given the PDFs of the external forces and of the structural parameters. Once these PDFs, normally approximated by histograms, are available, their examination can yield the following type of information

1. Take into account the scatter present in crash phenomena.

2. Yield the most likely system behaviour (i.e. most probable failure mode, most safe states, etc.).
3. Furnish global stochastic sensitivity information on the system, i.e. $\frac{\partial f}{\partial p_i}$
4. Help to identify the important system variables and establish transfer function-type and correlation relationships between the input and output random variables.

The concept of a stochastic crash simulation is illustrated in figure 1. One may observe that the problem comprises a set of stochastic structural parameters, stochastic external forces and boundary conditions and, finally, the stochastic output variables such as displacements, accelerations and internal energies. The stochastic crash problem may be stated, in general terms as follows: *Given the Probability Density Functions (PDFs) of the stochastic structural parameters, external forces, boundary and initial conditions, determine the corresponding PDFs of the output variables.* One straightforward way of approaching the problem is via the Monte Carlo technique which has been implemented in the PROMENVIR system. PROMENVIR is a generic solver-independent meta-application which enables to attack large stochastic problems in a heterogeneous and distributed computing environment. The adoption of modern Monte Carlo sampling techniques enables to solve Computational Stochastic Mechanics (CSM) problems with approximately 100-200 solver calls. Therefore, the solution of industrial-size problems can be envisaged even with a relatively small Local Area Network (LAN) of workstations. Crash is of course a problem that belongs to a class of its own, in particular due to the size of todays models (around 200000-250000 elements) and requires formidable computational resources even for a traditional deterministic analysis. It is therefore not surprising that approaching crash in a stochastic context is an exercise accessible exclusively to a restricted group of industries.

The scheme adopted in PROMENVIR for the solution of CSM problems may be summarised as follows:

1. Establish the input and output random variables of the problem, together with the corresponding PDFs.
2. Select randomly the values of each input parameter according to its PDF and from a predefined interval.
3. Replace the nominal values of the input parameters with the random values obtained at point 2. This process is known as cloning.
4. Execute a deterministic simulation with the cloned input-deck.
5. Extract from the corresponding output file(s) the random variables of interest.
6. Store the input and corresponding random variables.
7. Compute the statistical moments (mean, standard deviation, etc.) and check for convergence. [1] If convergence has not been reached, go to step 2, otherwise, go to step 8.

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[1] In the context of statistical analysis, convergence is reached if the confidence intervals of the random variables reach the desired amplitude.

8. Once the statistical descriptors have stabilised (or if the corresponding confidence intervals have been attained) one may proceed with the full statistical analysis of the results. This normally includes:
   - Ant-hill plots (i.e. point plots of one variable versus another).
   - Statistical moments (mean, standard deviation, skewness, kurtosis, etc.)
   - Cumulative Distribution Functions (CDFs).
   - Cluster analysis (i.e. separation).
   - Histograms (i.e. PDFs) and frequency plots.
   - Correlation analysis (linear, nonlinear).
   - Linear, nonlinear regression modelling.
   - Reliability assessment (i.e. computation of probability of failure).

The PAM-CRASH model of the vehicle adopted in the experiment may be seen in figure 2 and consists of approximately 60000 elements. The stochastic structural parameters, such as thicknesses and failure mechanisms of certain structural members in the engine compartments may be seen in figure 3 while the boundary and initial conditions (overlap, impact angle and velocity) are reported in figure 4. Intrusions of the footwell, the firewall and the A-pillar, have been chosen as the output variables together with accelerations and internal energies of selected groups of materials. The nominal PAM-CRASH input file has been cloned (replicated) by PROMENVIR 128 times adopting the Descriptive Sampling Monte Carlo technique. The parallel Cray T3E $\beta$-version of PAM-CRASH that has been used for the experiment has enabled to complete the analysis in the time of 3 days and accumulating approximately 8000 hours of CPU.

## 3 T3E Port of PAM-CRASH

The porting of the PAM-CRASH solver to the T3E machine was in many ways simplified by previous experience acquired during the T3D shallow port. In a first step, the standard CRAY T90 code version was compiled on the T3E processor using the CRAY F90 compiler. Basic tuning was performed in order to improve cache memory usage, which, in spite of the new L2 cache, proved to be very sensitive, as had been observed already on the T3D. Next, the distributed-memory version was built on top of this sequential code library, using the standard host/node programming model of the code and the PVM communication interface from the CRAY Message Passing Toolkit. The host/node scheme was found to lack stability because of task scheduling limitations of the system and because of the slow, socked-based communication between the node processes and the host process. Consequently, the code was converted into a single executable (SPMD style), which better fits the architecture and also delivers superior parallel performance. The experiment itself was run using 16 PE's per run, but during separate tests, successful simulations were performed with as many as 180 processors.

## 4 Technical Description of the Cray T3E

The experiment was run on the massively parallel CRAY T3E supercomputer of the HWW (Hoechstleistungsrechner fuer Wissenschaft und Wirtschaft Betriebs GmbH) which is located in Stuttgart Untertuerkheim and connected via ATM to RUS. With its 512 application PEs (PE: Processing Elements), a Peak-Performance of 307 GFLOP/s and a Main Memory of 65 GB it is the admiral of the HWW. Likewise its predecessor Cray T3D, the T3E the memory is physically distributed but logically global. In contrast to the T3D, the T3E does not require an additional front end.

### 4.1 The T3E-Architecture

Like in other systems containing distributed memory, the most important part of the architecture is the connection network between the nodes. The designers of the T3E set a great store on the fact that this network has in principal no scaling limits (there are systems with up to 2048 PEs) and provides excellent communication parameters which guarantee the full performance for each parallel application. Similarly to the T3D, the connection network of the T3E is a threedimensional torus, but in contrast to the T3D each PE contains its own router. All links are bidirectional and have a performance of 500 MB/s. The partitioning of the machine is very flexible since the number of nodes can be freely defined, only the form of the partition must be contiguous.

### 4.2 The Nodes

Each PE has a DEC 21164ev5 with 300 MHz and a main memory of 128 MB. Due to two floating-point pipes the peak performance of one node is 600 MFLOP/s and the bandwidth of the data bus is 1.2 GB/s.

The cache is in relation to the floating point performance quite small: 8kB L1 and 96kB L2 cache memory. To avoid an additional off-chip cache Cray introduced a stream buffer concept to speed up the vector access.

### 4.3 Input/Output

In additional to the message passing network each node is embedded into an I/O-network. This network is the so called Gigaring which incorporates doubled bidirectional SCI-technology (SCI: Scalable Coherent Interface, IEEE-Standard) Each Gigaring has a bidirectional bandwidth of 600 MB/s. During the experiment 10 of these Gigarings were available and via extra I/O-nodes disks (507 GB) and networks (HiPPI, ATM, FDDI etc.) were connected to the machine.

## 5 Analysis of Results

Practically any structural problem when viewed from a stochastic perspective yields information that a deterministic approach will very rarely deliver. The "injection" of noise (i.e. parameter scatter) into a system, enables it to develop and reveal response mechanisms and information otherwise "trapped" by a forcedly deterministic approach. With scatter in the loop, one quickly realises that much more may be understood about the system and its behaviour than a single-shot deterministic simulation can provide. This is not surprising, one is in fact consuming more than two orders of magnitude more CPU and, logically, expects more information in return. Crash is no exception.

Figure 5 reports how the scatter of the intrusions relates to the deterministic values. Only in the case of the firewall intrusion is the deterministic value close to the mean as obtained via Monte Carlo analysis. The other two intrusions, on the other hand, denote lower values with respect to the means. Moreover, given the character of the corresponding PDFs, the nominal values of the intrusions do not correspond to the most likely values that the stochastic analysis indicates. [2]

Interesting conclusions may be drawn from figure 6. Examining the ant-hill plots one observes that the firewall and A-pillar intrusions are highly sensitive to the angle of impact (bifurcation). Moreover, the deterministic values of the intrusions, indicated by "•", are situated on the frontiers of the respective ant-hill plots while the most likely values are evidently higher. Also, the shapes of the clusters of points reflect a chaotic relationship between the impact angle and the intrusions. In practice this means that it is impossible to effectively control the magnitude of the intrusion while controlling the impact angle. Similar conclusions may be drawn from the other numerous ant-hill plots which have not reported in the paper but which possess similar chaotic attributes. [3]

In summary, the study has prompted the following conclusions:

- The effect of the stochastic boundary conditions (impact angle and offset) dominate the response.
- This domination is reflected in the fact that it was practically impossible to determine structural parameters that controlled significantly the response.
- The above points suggest that the structure, in the given configuration, has little potential for significant improvement. This is supported by the fact that the CAMAS model, although not corresponding to any "real" vehicle, has been extensively optimized and improved in previous studies.
- Two basic classes of ant-hill plots have been observed: chaotic and linear. This leads to a surprising conclusion, namley that certain pairs of input and output parameters (e.g. thickness of a plate and acceleration at a certain point) may be approximated by a linear regression model. This fact, apparently in contrast with the fact that crash is a strongly nonlinear phenomenon, is evident if one views it at an appropriate level of scale. Many phenomena are nonlinear at, say, meso-scale and linear at macro-scale.

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[2] It is important to acknowledge that in stochastic mechanics the most probable response of the system never corresponds to the nominal values of its parameters (this happens only under exceptionally simple conditions). Although not at all intuitive, this fact is of fundamental importance in structural design and is due to nonlinearities that govern the input and output relationships. Consider, as an example, a linear single degree-of-freedom mass and spring system. The natural frequency of such a system is given by $f = \frac{1}{2\pi}\sqrt{k/m}$. Imagine that $k$ is random and follows a Gaussian distribution. Although the system is linear, the dependance of $f$ on $k$ is nonlinear, namely $f \sim \sqrt{k}$. This nonlinearity breaks the symmetry of the Gaussian distribution and is responsible for the fact that the most likely frequency (i.e. the one with the highest peak in the PDF) does not correspond to the nominal value of $k$.

[3] The number of ant-hill plots one obtains via Monte Carlo analysis is, evidently, equal to $n \times m$, where $n$ and $m$ are, respectively, the number of input and output stochastic variables. In the present case, this number was in the hundreds range.

In the case of vehicle crash, the nonlinearities due to contacts, friction, material yield, etc., dominate locally (over characterstic distances of centimeters) giving, however, a linear-like behaviour when viewed from a global perspective. In the case of the CAMAS model, the existence of these linear "global" input-output relationships confirms, once again, that the current design is almost optimal.

## 6 Conclusions and Future Developments

The study has been driven by two major objectives. First of all, emphasis has been placed on the practical demonstration that full stochastic crash simulation is possible with todays hardware and that results of industrial relevance can be obtained in engineering reasonable times. This is indeed the case and especially if the problem is approached with Monte Carlo techniques. Monte Carlo simulation, due to its intrinsically parallel nature, is an example of "meta-aplication" which guarantees very high effectiveness of use of the available computational resources. The PROMENVIR environment, which to the authors best knowledge is the first and only CSM-dedicated industrial meta-computing tool, has proved to be an efficient platform for the solution of problems as complex as stochastic crash.

Secondly, from a more scientific perspective, the objective has been to investigate whether Monte Carlo simulation can indeed yield interesting and useful engineering information when applied to crash. This objective has been effectively reached and the results of the T3E experiment have prompted a second similar analysis. In fact, a second run of 100 simulations has been executed on a 64 processor SGI Origin 2000 platform at the Polytechnic University of Catalunya in Barcelona. The results of this run are currently being processed. Finally, a third major-scale experiment is being planned with a model of approximately 200000 elements. This analysis shall be performed at the BMW installations in Munich during the month of December.

## Acknowledgements

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## References

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## Illustrations

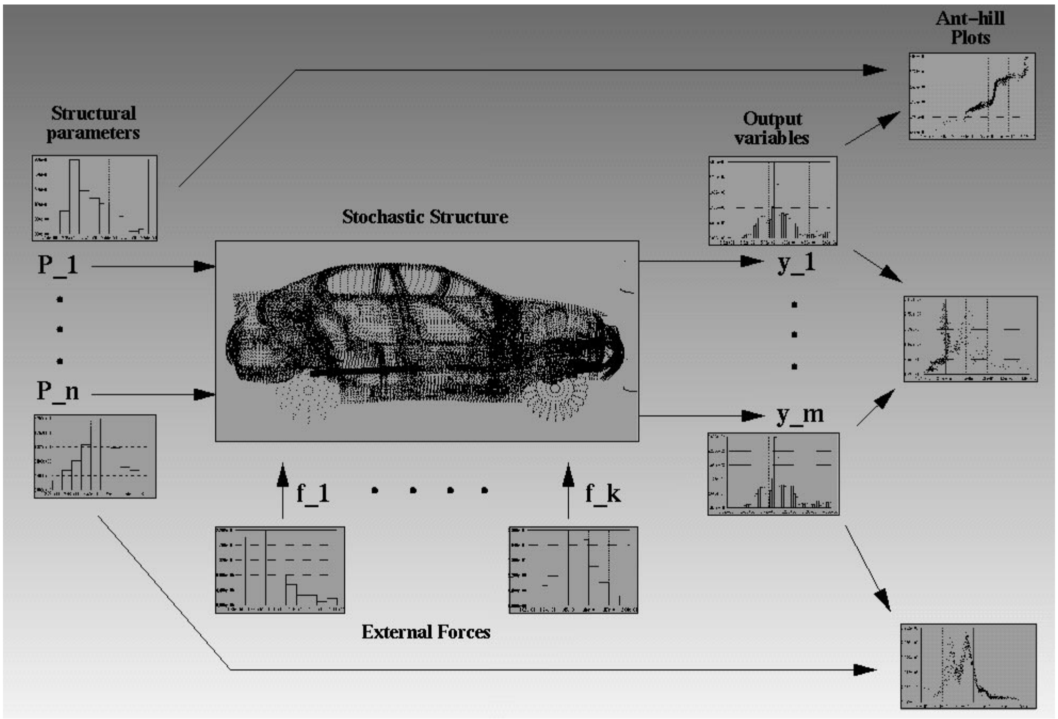
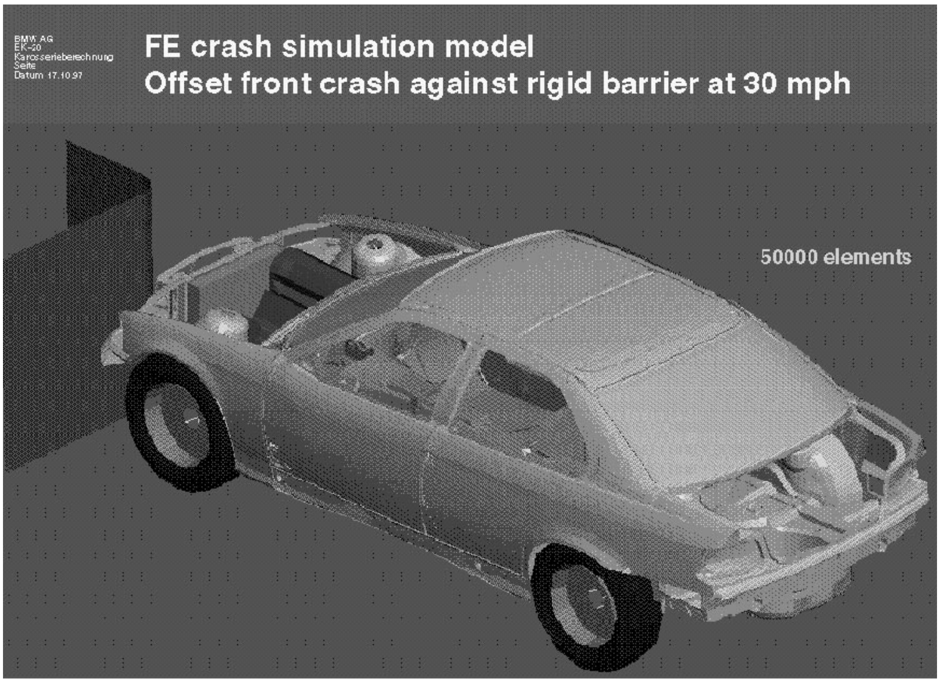


Figure 1: The stochastic crash problem.



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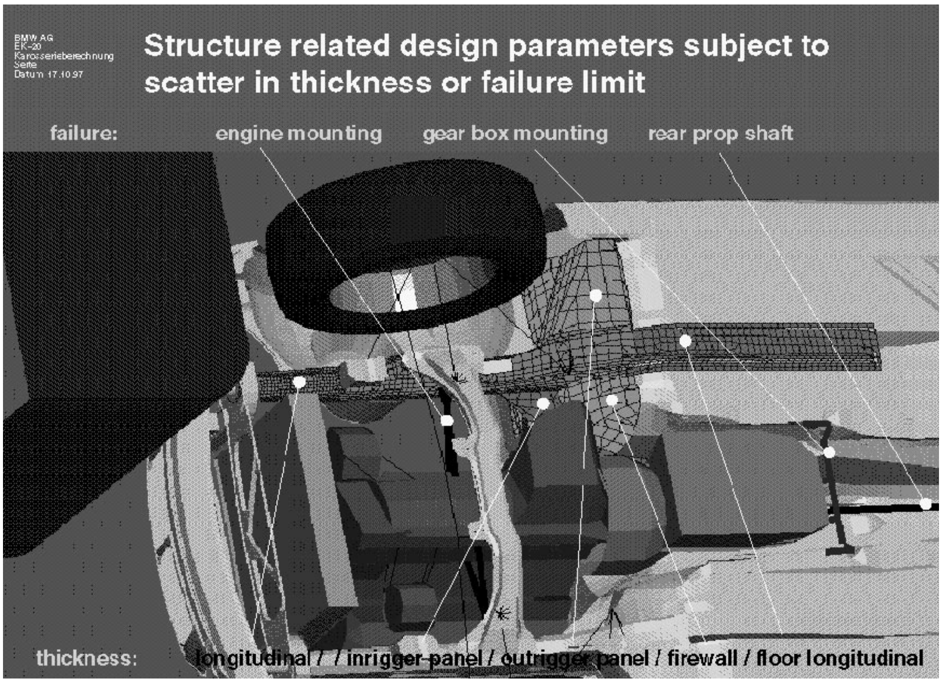
**FE crash simulation model**
**Offset front crash against rigid barrier at 30 mph**

Figure 2: The CAMAS model and crash scenario.



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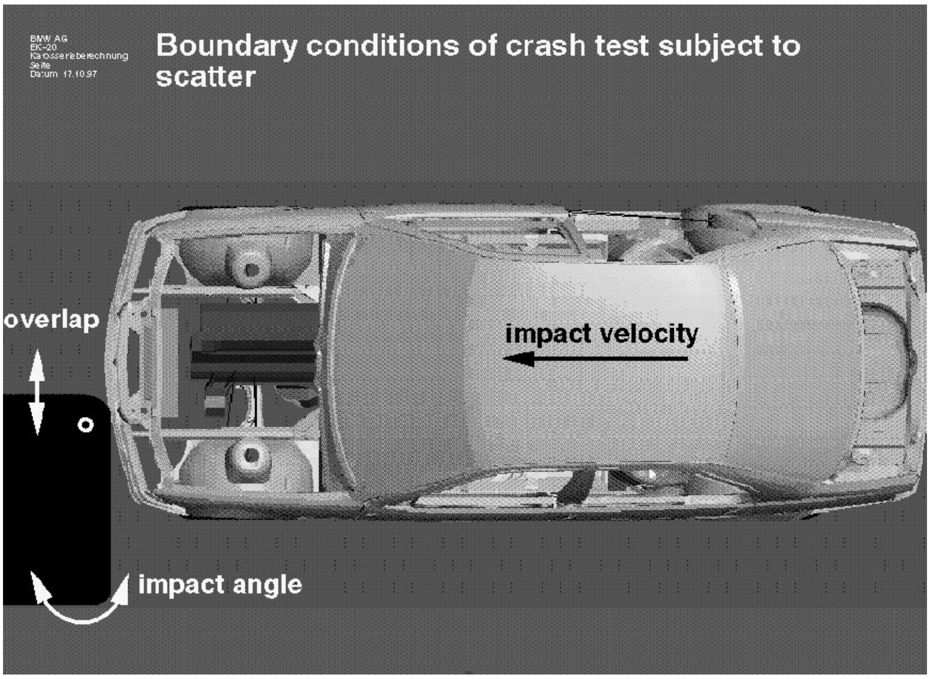
**Structure related design parameters subject to scatter in thickness or failure limit**

Figure 3: Location of the stochastic structural parameters.



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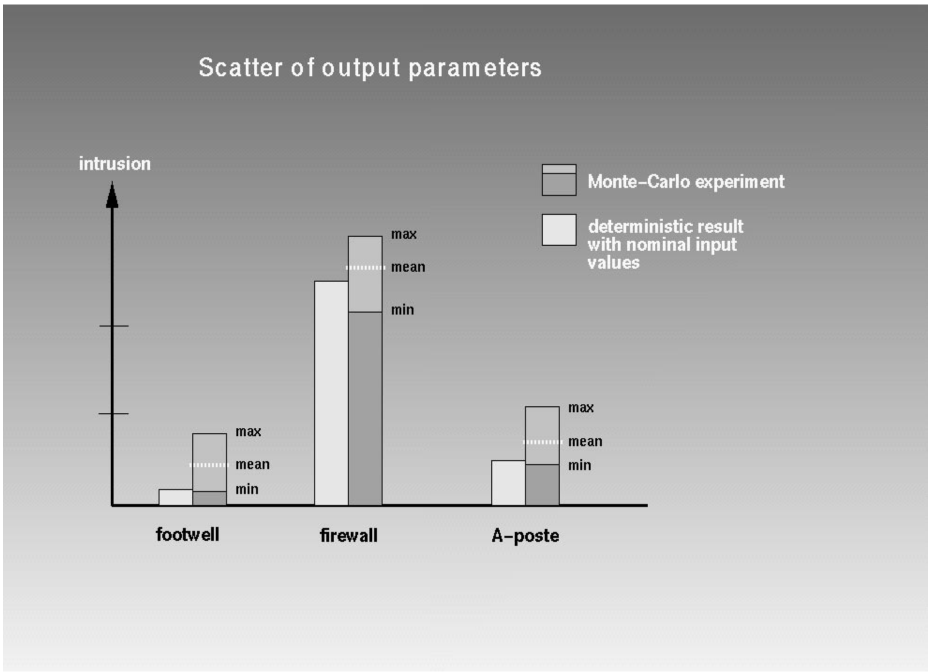
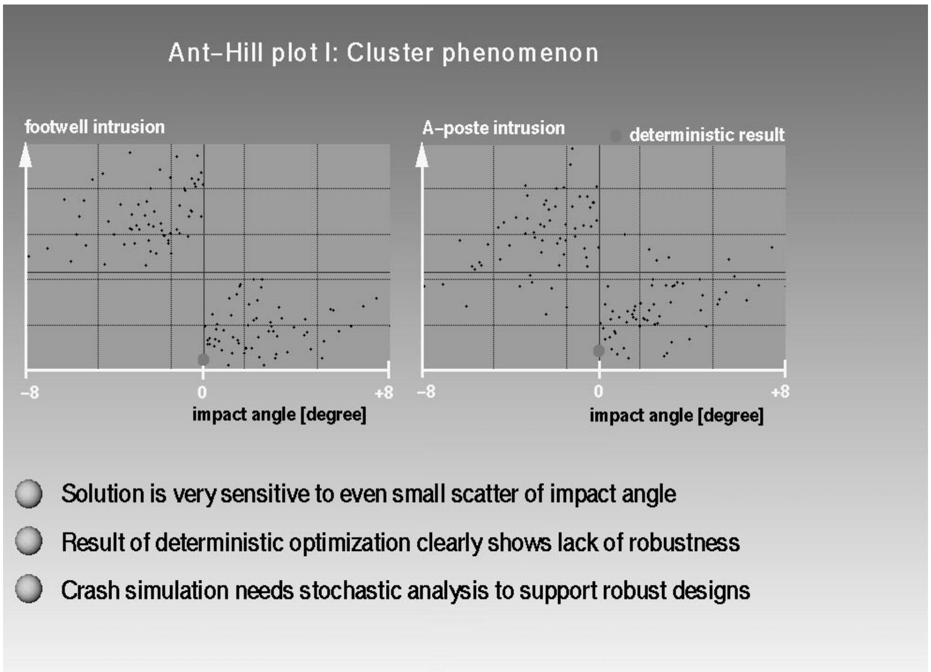
Boundary conditions of crash test subject to scatter

Figure 4: Definition of the stochastic boundary conditions.



Scatter of output parameters

Figure 5: Scatter of the intrusion parameters versus deterministic simulation.



Ant-Hill plot I: Cluster phenomenon

- Solution is very sensitive to even small scatter of impact angle
- Result of deterministic optimization clearly shows lack of robustness
- Crash simulation needs stochastic analysis to support robust designs

Figure 6: Scatter of the firewall and A-beam intrusions versus impact angle.