Stochastic analysis of Frontal Crash Model

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Summary:

While working in the field of frontal crash simulation, a simulation engineer strives to build an accurate and a highly predictable model. Due to the very fact that automotive crash is highly non-linear and stochastic event, a purely deterministic approach is not appropriate to simulate such a crash. As uncertainties are always present in the properties of the physical system, in the boundary condition of the physical system and also in the nature in which the loading is applied to the system, the simulation engineer is forced to consider the scatter as an integral part of the model and subsequently the results.

The main motivation behind the stochastic simulation of a frontal crash model is to:
- Find the most likely behaviour of the system’s output parameters.
- Check the robustness, which includes check of stability, clustering and outliers.
- Identify relevant parameters, which drive the system behaviour.

This paper discusses various aspects of such a study including:
- The identification of the essential inputs and the degree of input scatter.
- Incorporation of this scatter in the frontal crash model.
- Analysis of the scatter in the results and subsequently stability analysis of the model.

Finally the paper presents a number of the promising outcomes of the study.

Keywords:

Stochastic analysis, Crash, MADYMO, ST-ORM, Robustness, Optimization

1 Introduction

The study was based on the TNO application model for a frontal crash (Ref. [1]). TNO application models are the example models which are supplied with the software MADYMO by TNO. The results that will be presented in this paper are the results from the TNO frontal application model and do not represent any BMW or other real car model.

In contemporary CAE, engineers usually work very often with simulation models based on the nominal design and load parameters. This often leads to an unnatural precision and accuracy which is not observed in a natural system. Due to the fact that the system under consideration is highly complex and non-linear, design criteria like robustness become crucial and cannot be omitted. Moreover, when looking for “real world behaviour”, scatter in system properties, in loads and in boundary conditions of the system cannot be neglected.
In this study an attempt is made to incorporate the scatter into the frontal crash application model for passenger restraint systems supplied by TNO and to investigate the effects on the results. After slight modifications in the restraint system properties, the TNO *model* proved to be a good basis for such a study. The model represents a US-NCAP (Ref. [2]) test with 56kmph and a rigid barrier. The most important criterion for the evaluation in this test is the 5-Star Rating procedure. Figure 1 shows the 5-Stars Rating of the model under investigation after a deterministic improvement study.

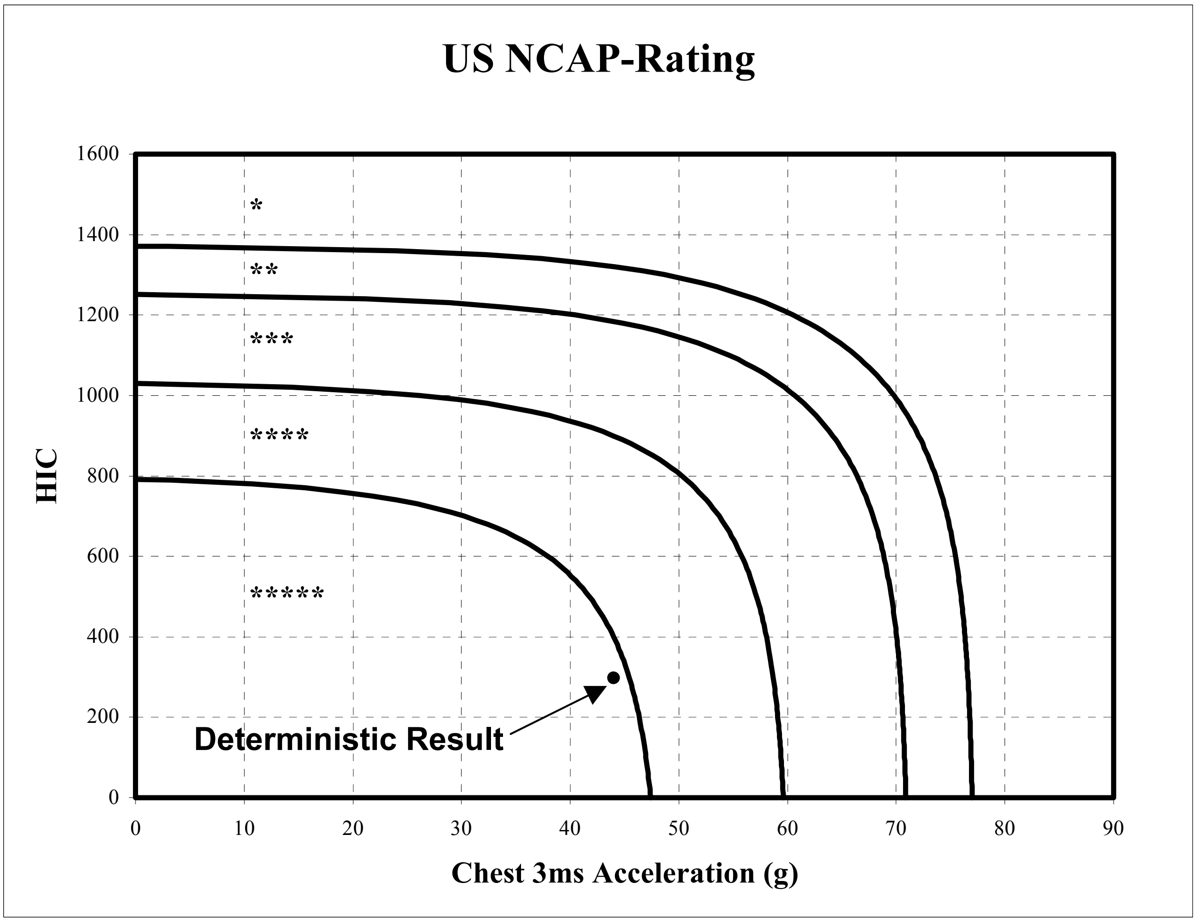

Fig. 1: 5 star rating of the model in a US-NCAP test.

The results suggest that the design target has been reached as a 5-Star Rating has been achieved. However it is not possible to answers some questions:

- How does the model react to uncertainties in material properties, tolerance in the manufacturing of the restraint systems and the scatter in the boundary conditions?
- Does the uncertainty and scatter in the input parameters cause a large output scatter? Is it large enough to reduce the US-NCAP rating to 4 stars or less?
- How large is the output scatter of the model? Is the model robust?
- With what confidence can the output be predicted?

To answer these questions a stochastic analysis of the model is performed. Input scatter is defined and stochastic simulations are run using the Monte Carlo Simulation method (see [3]). The results are finally analyzed to answer the above questions.

This paper discusses the stochastic study made on the model in detail. The paper starts with a brief introduction of Monte Carlo simulation method, further describes the procedure to identify and define input scatter. A concept for systematic check of robustness is proposed. It ends with a discussion on the results and their analysis. The paper also throws light on the improvement study using stochastic simulation on the same example model and mentions the limitations of the stochastic study.

2 Identification and definition of input scatter

The analysis of the restraint system behaviour is done using MADYMO, which is a coupled multi body and finite element code. Most of the physical systems like seat, instrument panel, steering wheel, etc are modeled by connected rigid bodies with attached contact surfaces.

An important role in Monte Carlo simulation is the identification and definition of inputs with proper statistical distributions. When doing a simulation of a real test configuration, which is the case here, they should be defined as realistic as possible.

2.1 Identification of input parameters

The uncertain parameters for input in the stochastic simulation are physical parameters as well as numerical parameters. The physical parameters reflect the scatter in material properties, load case parameters, boundary conditions, etc. Examples are:

- Positioning of the dummy: Dummy H-point, hands, legs, seat, seat belt, steering wheel
- Boundary Conditions: Initial velocity, angle of impact,
- Load case settings: the crash pulse[1], time to fire of the airbag (which in reality is a consequence of the pulse) , inflator fuel mass,
- Ambient conditions: Temperature, pressure.

The parameters of the simulation environment can also be a source of uncertainty. Some examples here are:

- numerical parameters,
- computer environment,
- bugs in the solver,
- peculiarities or errors in modeling.

What is seen here is the complementary characteristic of scatter to be investigated in CAE based simulation. In a physical test, only the scatter of first type is present. Therefore validation of a numerical model does not make sense without taking both types of scatter into account. In this paper we do not go into validation and assume that the numerical model is valid.

2.2 Definition of the input scatter

The input scatter definition is based on the type of the input parameters. The numerical parameters for example, are mainly to check the numerical stability of the model. Some examples for the numerical parameters within MADYMO are TIME STEP, IMM-DAMPING, CONTACT PENALTY.

The scatter in the physical parameters, like the H-point, the positioning of the hands and legs, the positioning of the seat and the seat belt etc. is defined in a realistic range, which reflects the uncertainty of a given test configuration with its procedure for setting it up. The table below shows typical ranges of input scatter for such parameters.

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[1] The crash pulse (overall acceleration of the body cell) is normally a result of the crash. In MADYMO analysis it is taken as a load condition coming from a previous structural crash analysis or from a physical test.

Physical Parameters	Range
H-point X	+5 / -5 mm
H-point Y	+5 / -5 mm
H-point angle @Y	+3 / -3 deg
Upper & lower Arms @X,@Y, @Z	+3 / -3 deg
Femurs, tibias & foot @X,@Y, @Z	+3 / -3 deg
Seat, Belt points	+5 / -5 mm

Table 1: Physical input parameters and their scatter.

The scatter in the load case parameters is also defined in the realistic ranges. Table 2 gives an idea of the scatter of load case parameters in this study.

Load Case Parameters	Range
TTF Airbag	+0.5 / -0.5 ms
TTF Pretensioner	+0.5 / -0.5 ms
Inflator Mass Flow scale factor	0.98 / 1.02
LL Level	+500 / -500 N
Pretensioner Level	+300 / -300 N
Vent Size	+2 / -2 mm

Table 2: Load case Input parameters and their scatter.

The type of statistical distribution, which these parameters follow should be based on the measurements from various physical tests see [4]. H-point for example, measured from different tests (FMVSS, USNCAP, etc. having the same theoretical H-point) should be statistically analyzed to determine the distribution it follows. The dummy positioning parameters, in the above mentioned small ranges tend to follow uniform distribution. The statistical distribution for the parameters like size of the hole in the airbag can be achieved by analyzing the data available form the quality control department where it is often checked. The scatter in these parameters, which come form the manufacturing tolerances often follow a normal distribution. The time to fire for the airbag and the pretensioner follow a uniform distribution. In case of absence of information of scatter of a parameter, an uniform distribution was applied for the stochastic simulations.

3 Stochastic Simulation using Monte Carlo Method

When doing Monte Carlo simulation for a given nominal model, clones of this model are produced, substituting the previously defined stochastic parameters of the model by random numbers that follow specified statistical distributions. Thus, a random sample of the model is created. Each cloned model differs slightly from the other. A number of such random samples of model are then run through the solver.

The results from all the calculations of the models are the data, which are then statistically assessed. The assessment includes the calculation of important statistical parameters (e.g. average value and standard deviation), the relationship between the variables using correlation analysis, as well as the graphic depiction of the data in the form of histograms or scatter diagrams.

For applications in mechanical engineering, a sample size for Monte Carlo simulation between 50-100 shots has proven to be sufficient. It is not worth chasing the decimals in the outputs, when the inputs scatter up to 20%. What is significant about this method is the fact that the size of sample taken does not depend on the number of variables, but simply on the type, precision and confidence of the desired statistical description of the event. Center point measurements, like average value and median, can actually be determined with precision using small samples. To predict rare events, however, larger sample ranges or specific Monte Carlo algorithms are necessary. The Figure 2 summarizes the principle of stochastic simulation schematically.

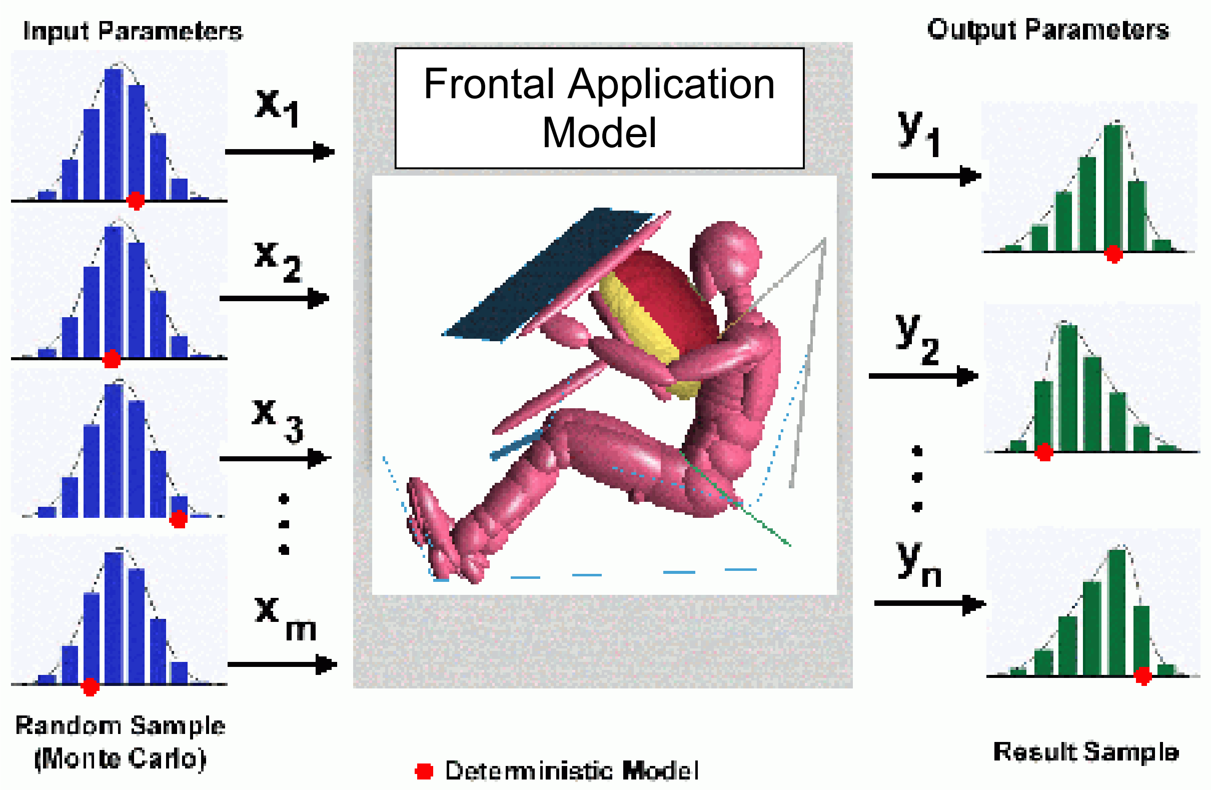

Fig. 2: Schematic diagram of a stochastic simulation.

4 Robustness

An important but not often analyzed design criterion is the robustness of the investigated system. Robustness cannot be checked directly by simulation with a kind of mathematical measure. There are numerous definitions for robustness (see [5]), which most of the time have the meaning of "*being safe against unexpected system behaviours*". But what "*expected"* or *"unexpected*" is can only be seen in the context of the applied project. In this sense, non-robustness can be proven by the occurrence of unexpected events. This is not possible without usage of a stochastic approach.

Non-robustness of a mechanical system can express itself in form of
- instabilities,
- bifurcations, clustering, or
- outliers

in the output parameters. These are discussed in the following.

4.1 Instability

When small disturbances in the input cause large changes in the output of a system, the system is considered to be instable. As illustrated in Figure 3, if the system amplifies the input scatter the system is considered to be instable. A simple way to check the stability is to compare the coefficient of variation for input variables with that for output variables from the stochastic simulations. The coefficient of variation is defined as the percentage of scatter (measured as the standard deviation) of a variable.

$$CV = \frac{\sigma}{\mu} = \frac{\text{Sample Standard Deviation}}{\text{Sample Mean}}$$

When interpreting CV, care has to be taken concerning the origin. Interpretation also depends on the context of the project. This means that a CV of 5% can be good in one case but unacceptable in another application, where there are different units.

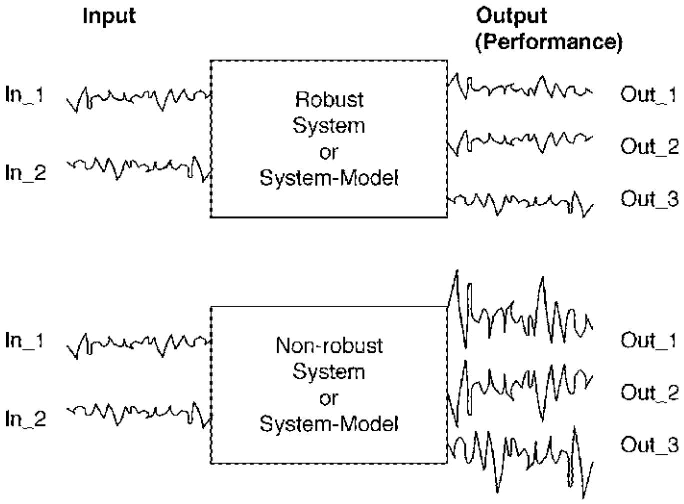

Fig 3: Stable vs. Unstable System.

In many cases the amplification originates in the simulation model itself and is due to numeric problems in the respective model and/or solver. This can be recognized by strongly scattered results that do not correlate to physical parameters. Often distinguishing between numerical and physical instabilities is only possible by “engineering judgment”. It is a hard work. Differentiating between both is necessary because of the different consequences. Numerical instabilities will force the simulation engineer to check his model again. Physical instabilities will force to change the design of the physical system.

4.2 Bifurcation and clustering

Bifurcations can lead to clustering in the output parameters. The danger about these is that one could feel too safe under “clean” nominal or laboratory conditions when unluckily only operating in one of the clusters during design phase and another cluster then appears under real conditions.

After running a stochastic simulation clustering can either be checked by
- visual inspection of anthill plots and histograms,
- check of Kolmogorov-Smirnov distance (ref. [6]) to normal distribution with same mean and standard deviation in the desired parameters,
- automatic cluster detection algorithms (ref. [4])

4.3 Outliers

Outliers are single events with outrageous bad (sometimes also good) system performance. Reasons are often a pathological unlucky combination of the system’s input parameters. An example could be the stimulation of a resonance in a very specific but rare load condition.
The check of outliers can be done by visual inspection of histograms and anthill plots. In case there are many parameters to investigate, outlier detection could also be done automatically. Background can be taken from [4].

5 Results

Although the main criteria for the US-NCAP evaluation are the HIC[2] and Chest 3ms[3], all other outputs from the stochastic study are analyzed in order to check the stability and robustness of the *model*. Peak accelerations, injury values and the accelerations for head, chest and pelvis over time are written out via ST-ORM (Ref. [4]) after every simulation. The result analysis becomes more complex as the number of outputs increase. Anthill plots, histograms and vector plots in ST-ORM help the simulation engineer to go through the output fast.

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[2] The HIC (Head Injury Criterion) is determined by tracing resultant acceleration signal of the head. Time frames of 15ms or 36ms are considered. See [7] for the HIC calculation.

[3] The Chest 3ms is computed by tracing the acceleration signal using a time window with a width of 3ms. The highest acceleration level with duration at least 3ms is value of the criterion.

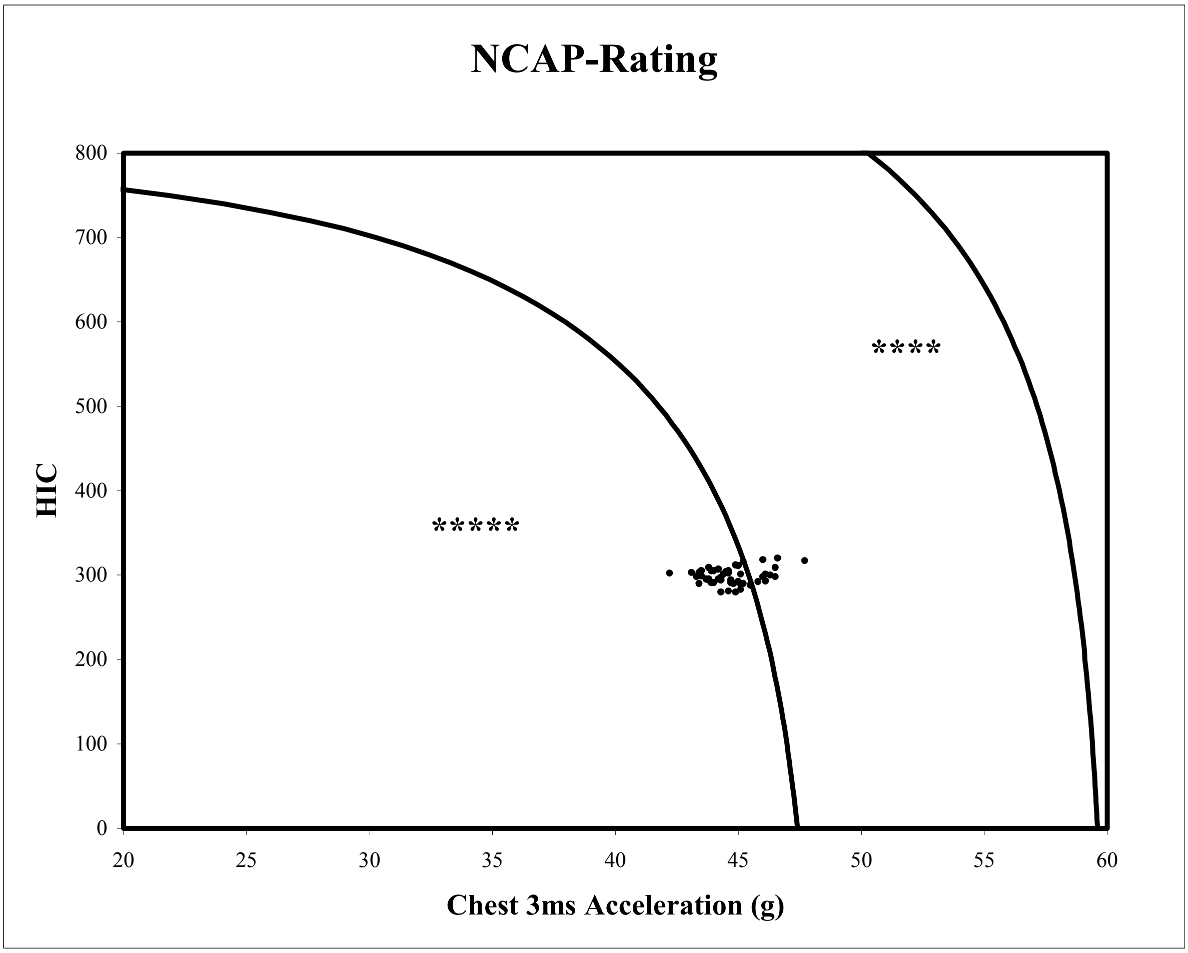

Fig 4: The output scatter on the 5 star plot. (Zoomed In)

The Star Rating plot of the resulting stochastic simulation is shown in Figure 4. Figure 5 and 6 show the histogram and vector plot for the chest acceleration. As seen in the histogram of figure 5, the chest acceleration shows a wide scatter. It is quite obvious that the 5th star is lost due to the Chest 3ms acceleration.

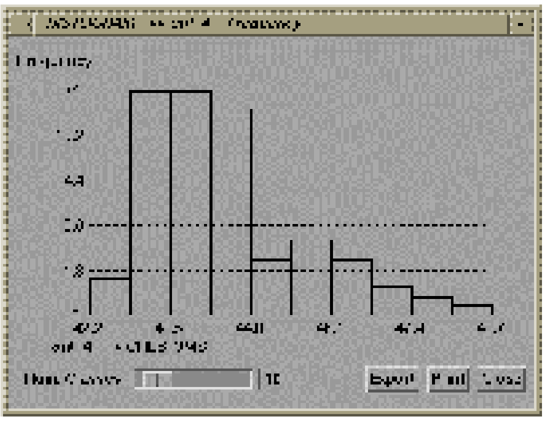

Fig 5: Histogram

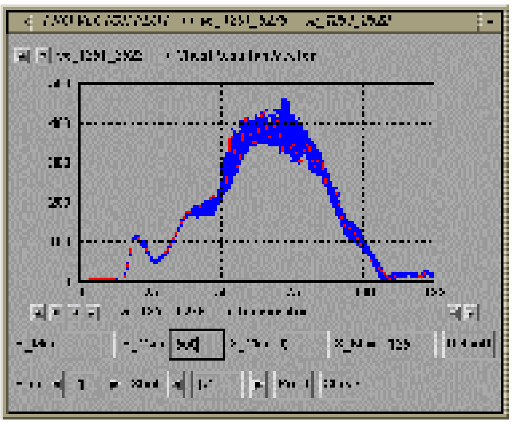

Fig 6: Two vector Plot.

The 5th star can be achieved with certainty either by reducing the scatter of the Chest 3ms in the models or by moving the entire scatter in the 5 star zone.

The statistical report of this study is shown in Table 3. As seen in the statistical report the coefficient of variation of most of the output variables is around 3-5%. This is of the same order as of the input variables. There are some exceptions like the femur forces, the chest VC, etc. which show a high coefficient of variation. This is due to the fact that the mean value of these variables is low and hence a slight variation of these parameters causes a high coefficient of variation. In general looking at the statistical report below the model can be seen as stable and the injury values can be predicted using mean and the CV(%). E.g. HIC = 300 (+/- 30).

An design improvement study is then performed in order to achieve a reliable 5-Star Rating.

Statistical Report				
Model	TNO Frontal application model			
Parameter	Output			
Description	**X_Min**	**X_Max**	**Mean**	**CV(%)**
HIC	280	325	300	3.0
HEAD_3MS (g)	40	48	43.6	4.0
CHES_3MS (g)	42	48	43.9	2.8
PELV_3MS(g)	52	54	53	1.0
FEMUR_L (N)	-398	-133	-166	31.4
FEMUR_R (N)	-1950	-1630	-1750	2.9
NECK_FX (N)	438	601	528	6.1
NECK_FZ (N)	1380	1650	1520	4.2
NECK_FLX (Nm)	31.8	44.8	38.7	7.6
NECK_EXT (Nm)	-29.4	-12.1	-15.7	25.2
CHEST_D (mm)	36	41	39	3.2
CHEST_VC	0.17	0.28	0.22	11.9

Table 3: Stochastic Study: USNCAP TNO Application model : Statistical Report (Output).

6 Improvement studies using stochastic methods

There are two methods of conducting the improvement study, (Ref. [3]). One approach is the direct method where the design variables are scattered across the full design interval by assigning these variables a uniform distribution within the limits of the design interval (Monte Carlo Search Method). This will scan the entire design space. An alternative approach is the design improvement in iterations, the so called the Return Mapping Method. (Ref. [6]). As the model runs for 10 minutes the first method is applied for the improvement study which can also show the system behaviour for the whole design space.

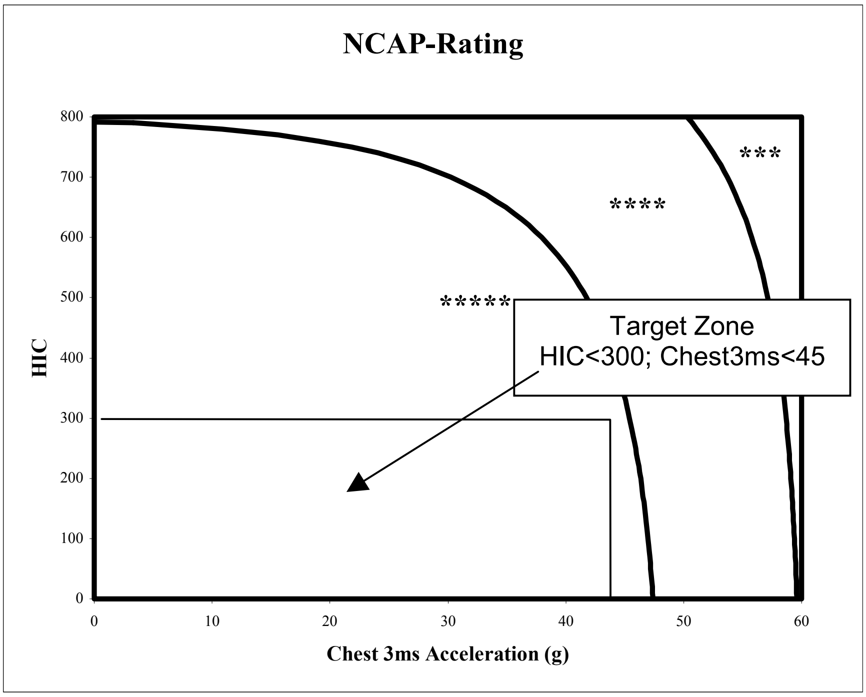

Fig. 7: Target zone

The aim of the improvement study is to move the whole scatter cloud into the 5 star zone, if at all it is possible, or to reduce the scatter of Chest 3ms values to fit the entire scatter in the 5 star zone or both.

The the design parameters are:

- the vent size in the airbag,
- the load limiter level in the belt,
- the airbag fire time

Their respective design ranges are given in Table 4. In addition the scatter on other input parameters like dummy positioning, boundary conditions, etc. are also defined in the model as background noise.

Design Parameters	Range
Load limiter level	2000-5000N
TTF Airbag	12 – 30 ms
CDEX (Equivalent vent size)	+/- 25 mm

Table 4: Design interval for improvement study.

The aim of the improvement study is to locate the result scatter cloud in a target zone which is defined by its boundaries with HIC < 300 and Chest 3ms acceleration < 45g, (see Figure 7). Around 50 simulations were sufficient to scan the entire range of the design variables using the Monte Carlo search method. It was observed that for CDEX (hole representation in MADYMO, Ref. [7]) value of 3.48 and the load limiter level at 3250N, the Chest 3ms was reduced to 39g. These values were taken as the new design point and a stochastic robustness study as discussed in the beginning of this paper, was again performed on the model. The output cloud was then plotted in the 5 Star Rating plot. The entire cloud is now within the target zone (Fig. 8). The statistical report of the stochastic study on the improved model (see Table 5) shows the improvement in the mean values of the Chest 3ms acceleration and the HIC. Despite the high coefficient of variation of the forces in the left femur and neck (X-component) and the neck extension moment, the system can still be considered robust in context of this project as their entire scatter is well below the respective Injury limit. (Ref. [2]). The coefficient of variation of neck force (X-component) is high due to the fact that the mean value tends to move towards zero and the minimum and the maximum values lie on different sides of the origin.

Statistical Report				
Model	TNO Frontal application model (IMPROVED)			
Parameters	Output			
Description	**X_Min**	**X_Max**	**Mean**	**CV(%)**
HIC	258	298	277	2.9
HEAD_3MS (g)	38	46	41	3.9
CHES_3MS (g)	37	41	39	2.6
PELV_3MS (g)	52	54	53	0.8
FEMUR_L (N)	-413	-132	-170	36.8
FEMUR_R (N)	-1820	-1630	-1730	2.4
NECK_FX (N)	-623	577	146	344.6
NECK_FZ (N)	1230	1640	1420	5.0
NECK_FLX (Nm)	31	45	37	7.7
NECK_EXT (Nm)	-36	-13	-22	27.5
CHEST_D (mm)	35	43	39	4.0
CHEST_VC	0.18	0.28	0.24	10.1

Table 5: Statistical Report (Improved model)

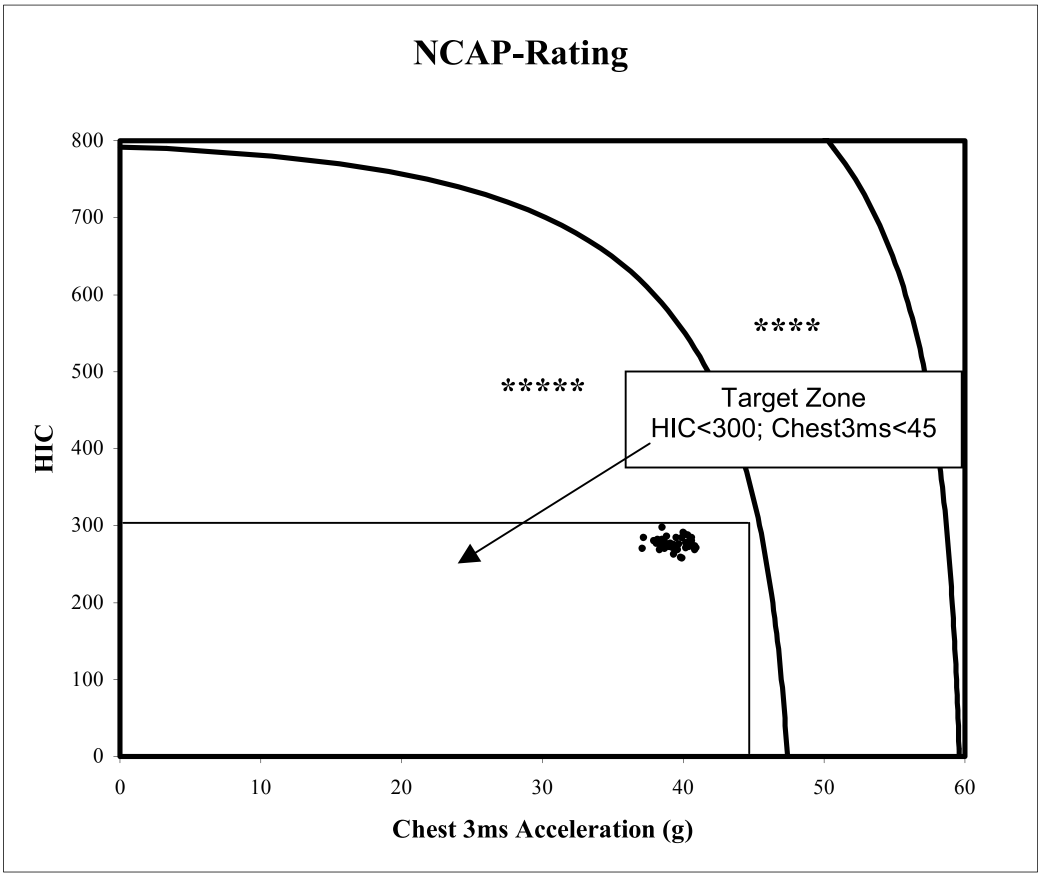

Fig. 8 : 5 Star plot with improved model scatter (Zoomed In).

7 Conclusion

In this study an approach was demonstrated to bring simulation one step closer to reality by introducing the physical scatter into the model. As expected the model showed output scatter. It was observed that the output scatter was too large to guarantee a reliable 5 Star Rating in the US-NCAP test. An improvement study was then conducted, which took into account the output scatter of the model. A design improvement was suggested. With the improved design, the entire output cloud is now located within the 5 Star zone. The design target of 5 Stars in the US-NCAP rating is now achieved with certainty. The output scatter of the model is determined and documented as a statistical report of the stochastic study. There were no bifurcation, clustering or outliers observed. In context of this project the model proved to be robust.

The demonstration example presented here is characterized by only two targets and only one load case. In a typical development scenario there can be as many as 7-8 load cases (EuroNCAP see [8], FMVSS 208, J-NCAP, etc.) and more than 10 critical objective parameters per load case. Also the number of design parameters is bigger. Such a study presents more challenges for the administration of all the load cases and proper combination of the objectives. However mathematically there is no additional complexity or extra effort involved. The process for such an multi-objective improvement study will be presented in an additional paper (9).

8 References

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