Occupant Safety Simulation; Perspective of DOE, Optimisation and Stochastics in Restraint System Design.

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Abstract: Virtual testing has become an essential part of the vehicle design process. Supported by dedicated simulation tools, restraint system performance can be effectively evaluated and optimised for a large number of scenarios. Thus virtual testing enables efficient and robust design optimisation for regulated and consumer test procedures and provides ample scope for further safety improvement.

For challenging cases such as airbag out of position deployment, simulation technology is being enhanced continuously. Gasflow simulation in many cases provides more realistic airbag deployment and specific gasflow enhancements are being introduced to improve predictivity while limiting CPU demands.

Introduction

FMVSS 208 and European legislation force OEM's to develop restraint systems to work under an increased number of conditions. Consumer tests demand injury values below regulated levels, and new injury criteria are being introduced for instance for the neck and for the extremities.

Restraint system performance is to be evaluated for the mid size male and small female dummies, and the risk of airbag induced injury is to be evaluated with small female and child dummies. FMVSS 208 requires belted and unbelted evaluations and various speeds (16mph, 22mph, 25mph, 30mph, 35mph) and various level of deployment thresholds are generally considered for robust restraint performance in frontal impact. Meanwhile repeated laboratory testing under "identical" conditions often reveals a considerable scatter in restraint system performance. Thereby repeated testing is needed to prove robust restraint performance. While current restraint system design focuses on laboratory testing, there is a growing interest to evaluate restraint performance for real world accident scenarios (Hoof et al. 2003). Here the availability of well validated human models brings us one step closer to protection of real human beings in real world crash scenarios (Figure 1).

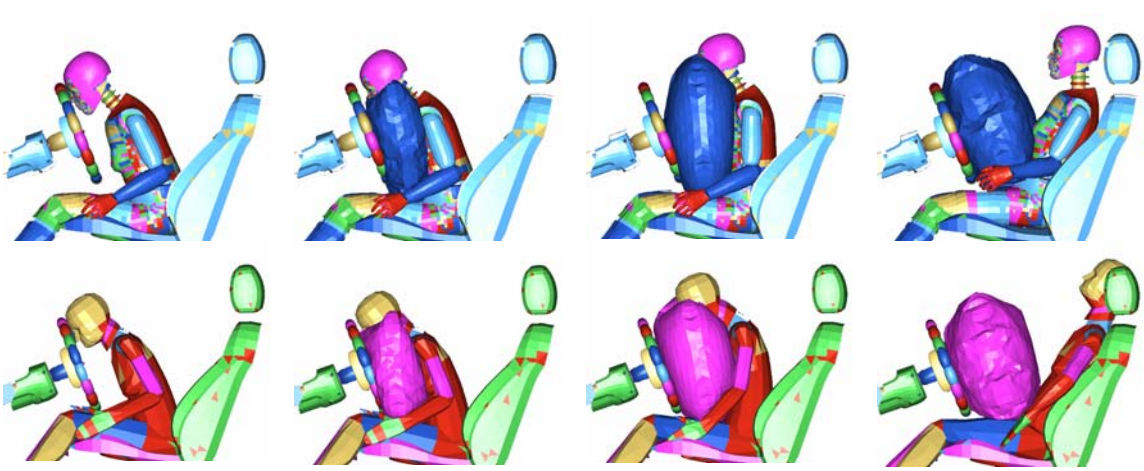

Figure 1: Small Female OOP Airbag loading (Bosch-Rekveldt et al. 2004) Dummy model (top) versus human model (bottom) at t = 0, 25, 50 and 100 ms respectively. Note that at time t = 100 ms, the dummy model already had its rebound whereas the human just reaches the rebound phase.

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The above trends in restraint system design create a need for evaluation of hundreds or even thousands of scenarios. Virtual testing enables such a comprehensive evaluation but also creates a need for specific tools supporting the simulation process:

- **Process Support Tools:** Restraint simulation models are increasingly complex, and contain components built by several engineers. In the safety evaluation & optimisation process only a limited set of model parameters needs to be adapted. Substitution of design components or dummies in a simulation model requires full knowledge of interactions defined in the model and takes major effort. Process support tools such as MADYMO/Exchange facilitate the model assembly and modification process.
- **Design of Experiments & Optimisation:** Well known techniques such as Design of Experiments (DOE) and optimisation enable systematic exploration of the design space and supply a basis for optimisation. A specific issue in restraint system design is that allowed maxima are specified for a large number of injury values for several loading scenarios. Dedicated graphical tools such as MADYMO/AutoDOE provide the designer direct insight in the effect of design parameters on multiple injury values in several scenarios. Numerically such requirements can be dealt with by defining multiple inequality constraints in the optimisation process.
- **Stochastic Simulation:** A related technique is stochastic simulation which enables verification of design robustness for scatter in the production process, for variations in testing (e.g. dummy position), for differences between dummies, and for numerical parameters (Hoof et al. 2003). The tool ADVISER/Stochastics enables verification of design robustness and in conjunction with this tool a stochastic Hybrid III model has been developed.
- **Evaluation and Rating:** Objective rating tools have been developed to quantitatively evaluate the validity of models (Jacob et al, 2000; Hoof et al. 2003). The tool ADVISER/Evaluation streamlines the process of model to experiment comparison using peak level comparison and signal comparison techniques. Subsequently model rating over multiple experiments and multiple signals can be presented as a matrix, or even as a single objective number.

The above tools supporting the restraint system design process are described in PART I of this paper. Such tools and methods rely on predictive airbag simulation techniques as discussed in PART II of this paper.

PART I - Simulation in the restraint system design process

Established products such a HyperWorks (www.altair.com) and Easi-Crash (www.easi.com) provide pre & post processing for a range of software tools. MADYMO provides the intelligent XML editor XMADgic which validates user input towards rules from the MADYMO type definition (Figure 2).

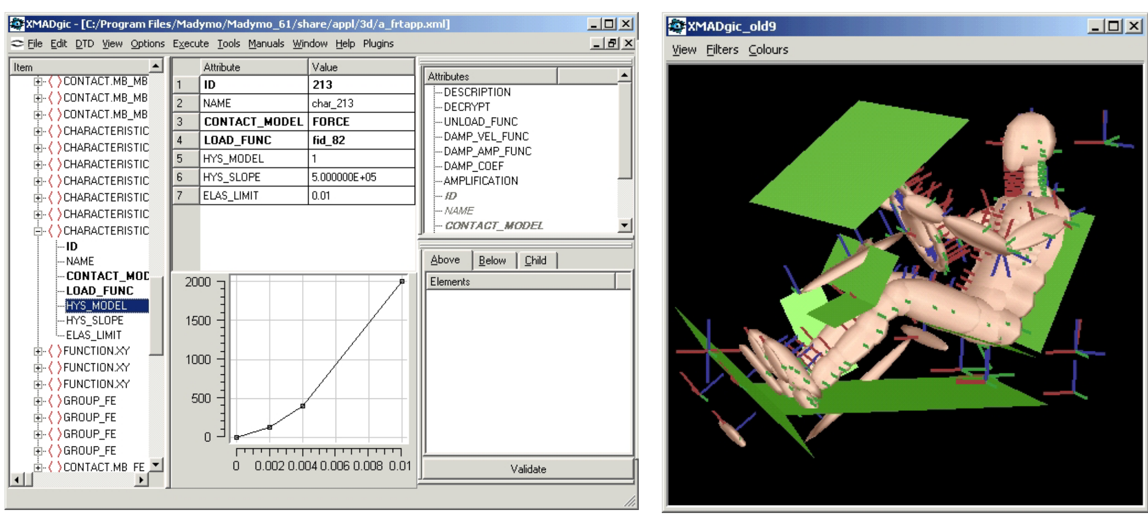


Figure 2. XMADgic dedicated XML editor with viewer for MADYMO pre-processing

Process Support Tools

MADYMO/Exchange is a tool to empower non-CAE experts with the benefits of MADYMO analysis. This is achieved by creating an environment wherein a release engineer (or super user) determines which components of a MADYMO model may be accessible through a graphical user interface. MADYMO/Exchange allows a user to navigate through an input deck; make changes to the occupant, vehicle and restraint system parameters; run modified simulation models and review results without having to know MADYMO code in detail. An example of the power of this tool would be replacing an airbag model with an alternate. During this exchange, model associations, such as contacts and supports will be automatically updated and maintained. The time to prepare an analysis is reduced from hours of work to minutes.

MADYMO/Exchange users can access base models and validated component models stored in a local or global database. Such databases are generated by experienced MADYMO users and stored in a central location.

Intelligent subroutines can be implemented in MADYMO/Exchange to permit better control over the model changes. These can be as simple as monitoring valid minimum and maximum ranges for a particular setting. More complex associations between interacting components can also be defined. For example, altering a seat's position can be configured to update the occupant's position. The overall effects of changes made to a model are graphically displayed to indicate if the model's validity is falling outside of acceptable boundaries.

DOE & Optimisation

MADYMO/AutoDOE is a software GUI that permits an engineer to study design changes in an efficient and controlled environment. It relieves the engineer of organising numerous model set-ups and provides practical statistical information to the modeller. The desire to know the significance of multiple design inputs on various MADYMO outputs has been highly effective for engineering of restraint systems.

For example, let us say a CAE engineer has correlated a model consisting of a crash sled with occupant and restraint and wants to investigate what parameters shall be modified to ensure that this occupant, as well as other classes of occupants, will be most effectively protected. The engineer may have several parameters in the seating system, vehicle interior and restraint. If each of these 3 systems has 3 variables with 3 settings apiece, then our engineer has 19,683 combinations of MADYMO models to run! (Seat's 3x3x3 combinations * interior's 3x3x3 combinations * restraint's 3x3x3 combinations). It is clear that implementation of these models would be a large task. It would take weeks to determine which combinations make a successful pool for analysis; edit a script to fill-in the decks with data; submit the tasks and extract. The MADYMO AutoDOE software, using D-Optimal tables, generates the runs; writes and submits the decks in a few hours. All the results can be compared in one table and plotted in 2D and 3D plots.

	With AutoDOE	*Without AutoDOE*
set-up	*15 minutes*	*~1 week*
run	*48 hours**	*48 hours**
post	*4 hours*	*1-2 days*
**MADYMO/AutoDOE doesn't make MADYMO run faster, but it can reduce the number of runs needed using concepts like D-tables*		

More importantly, all the simulations can be reduced to a single empirical meta-model or response surface model. The accuracy of this meta-model can be assessed by studying the goodness-of-fit and residuals (the difference of the meta-model's predicted vs. actual simulation values). If the goodness-of-fit and residuals are within acceptable tolerances, the engineer may then use AutoDOE's plots, graphs and optimisation tools to converge on the best design.

A special Graphical Optimisation Interface (GOI) provides the designer direct insight in the effect of design parameters on multiple injury values in several scenarios. Numerically such requirements can be dealt with by defining multiple inequality constraints in the optimisation process.

Stochastic Simulation

Where DOE is highly suitable to explore the design space, stochastic simulation is suited in particular to evaluates design robustness. Stochastic simulation enables verification of design robustness for scatter in the production process, for variations in testing (e.g. dummy position), for differences between dummies, and for numerical parameters (Hoof et al. 2003). Sensitivity analysis can be used to select the most influential design parameters.

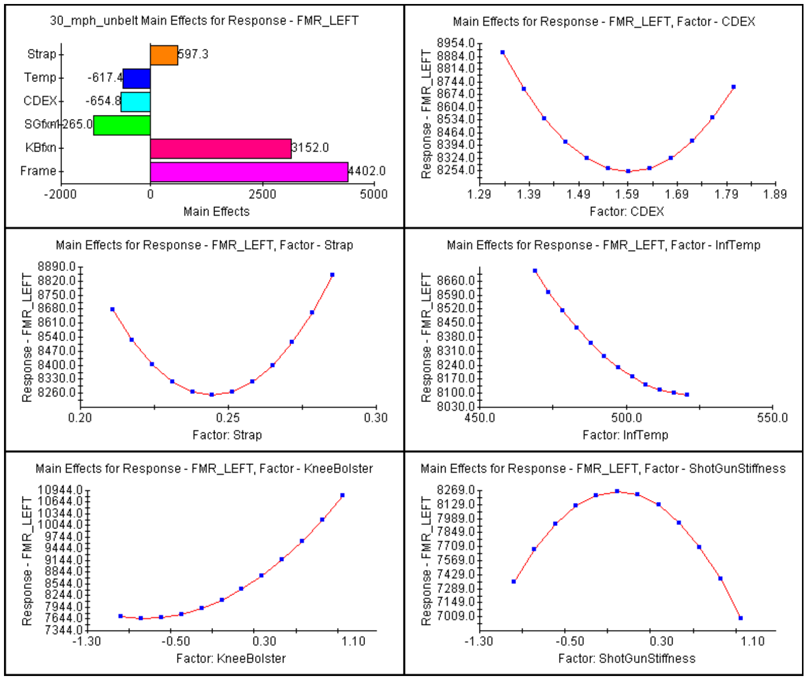


Figure 3. DOE result; main and detailed effects of an output (femur load) versus the model variables (inputs)

The EC-funded project SIDECAR has already demonstrated that the variability of crash dummies is a major source of scatter. More recent studies have also indicated a large effect of the scatter in the Hybrid-III thorax on the NCAP rating. The VITES project focused on the stochastic response of the Hybrid-III dummy in regulated crash scenarios caused by the scatter in the dummy and its immediate environment (restraint systems and vehicle interior). An inventory has been made of the main parameters causing scatter in the injury ratings obtained from the Hybrid-III and a numerical sensitivity study was performed to rank these scatter parameters (Hoof et al. 2003). The tool ADVISER/Stochastics[1] enables verification of design robustness and in conjunction with this tool a stochastic Hybrid III model is available.

Evaluation and Rating

A range of models with varying quality exists for all components involved in a car crash, including models of the occupant, restraint system, vehicle, and impactor. Of these components, the models of the regulated crash dummies are the most extensively validated. However, a user might not always be aware of the level of validation of these dummy models and can, therefore, inadvertently use the model beyond its validated range. Since vehicles and restraint systems are generally developed under high time pressure (within months), their numerical counterparts are mostly validated against a very limited number of impact conditions. Consequently, when these models are applied beyond their validated range, simulation and testing sometimes shows different trends. To make matters even more complicated, objective criteria to rate the correlation between numerical and experimental data are lacking, resulting in highly subjective 'validation' of models. Consequently, models that describe the same physical situation, but which have been developed and validated at different sites and/or with different tools cannot be compared directly. This situation greatly hinders the acceptance of virtual testing as part of occupant safety regulations and calls for the definition of general procedures to create validated models and objective criteria to rate the numerical results. The availability of such procedures and guidelines is an essential step towards the application of virtual testing in regulated crash safety assessments. The VITES project covers the various aspects related to the definition and application of procedures and criteria allowing an objective assessment of the quality of models and of the accuracy of the virtual test results obtained (Hoof et al., 2003). An extensive literature search into existing correlation methods and corresponding criteria was performed. The most suitable correlation criteria were evaluated in detail for their applicability in passive safety design and regulations. Those criteria that were found suitable were implemented in the software tool

[1] ADVISER stands for ADvance and VItes Simulation, Evaluation, and Rating and is a virtual testing tool developed in the EC projects ADVANCE and VITES.

ADVISER/EVALUATION. ADVISER/EVALUATION automatically correlates experimental and numerical data and based on this provides a quality rating for the numerical model. ADVISER/EVALUATION contains pre-defined correlation and rating procedures for the various numerical models typically used in car crash simulations, such as occupants (dummy and human), restraint systems, vehicles, and barriers. In addition, the evaluation tool provides the user with the ability to follow their own validation procedure by using existing or user-defined correlation criteria. ADVISER/EVALUATION currently interfaces with all codes commonly used in crash safety simulations, such as MADYMO, RADIOSS, LS-DYNA, and PAM-CRASH.

PART II - Airbag Simulation Technology

In order to meet current needs for predictive airbag simulation, the numerical methods are being improved and extended continuously. This section reviews developments for the following key ingredients for airbag simulation.

- Folding tools - providing an accurate representation of the folded airbag geometry.
- Initial Metric Methods providing realistic initial conditions for the deformed airbag, in particular when combined with relaxation methods to obtain static equilibrium.
- A robust, accurate and efficient finite element description of the airbag fabric and (self) contact.
- A numerical description of gasflow between the airbag layers, to account for non-uniform pressure effects that influence the deployment behaviour.
- Dummy models developed and validated aiming at side airbag and OOP loading conditions.

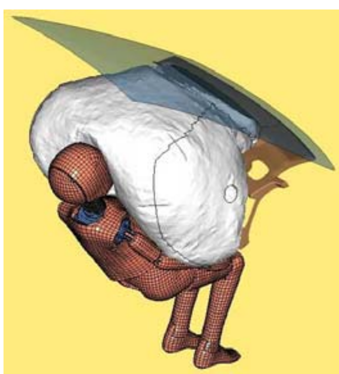


Figure 4. Hybrid III 6 year old FE model in OOP

Figure 5: Chaos fold.

Airbag Folding

An accurate representation of the folded geometry is critically important for detailed design and analysis of airbag deployment and occupant protection in OOP frontal and side impact analysis. In order to reduce injury risk for OOP occupants, fold patterns are changing from folds that cause 'frontal' unfolding towards folds that cause more radial oriented unfolding. An example of these 'new' fold patterns is the chaos fold. Tools such as the "MADYMO/Folder" enable rapid creation of folded airbag meshes with options such as "Zig-zag" or "accordion" folding up to the more complex Starfold-Origami fold. While standard options cover a range of folding patterns, dedicated solutions are needed for more irregular or chaos folds (Figure 5). Here standard folding options can be used as a first folding step, while further compression into the airbag container can be realised with dynamic simulation. Recent contact enhancements provide robust solutions even when the airbag is compressed into very small container volumes. Dynamic simulation has been used to create airbag meshes fitting into the known volume of the unfolded bag (Zhang and Cooper, 2003). Further development includes mesh independent folding, which is seen as a major step towards more efficient and better modelling of folded airbags.

Initial Metric Method & Relaxation

The finite element mesh of the airbag fabric must represent the airbag in the initial (folded) configuration, e.g. each node's initial coordinates must be specified. A second, separate mesh can be specified to represent the undeformed, design configuration. The Initial Metric Method (IMM) transforms the undeformed mesh into the folded configuration while detecting and calculating internal loads due to contact and element deformation. After the IMM, a relaxation phase is needed to obtain an equilibrium state before the airbag is triggered. In this way, the starting point of the airbag simulation is a quasi-static equilibrium state, but not necessarily free of strains and stresses. Relaxation can be simulated with standard options such as time-dependent Raleigh damping. However, the new relaxation option introduced with MADYMO 6.2 provides efficient static solutions while fewer parameters have to be set by the user.

Airbag Fabric and Self Contact

The material properties of technical fabrics that are used for airbag manufacturing are direction dependent. Usually two perpendicular principal material directions can be recognised that coincide with the warp and weft directions of the fabric. Due to the kinematic interaction between the warp and weft threads and their undulation in the unstressed state, non-linear stiffness is observed in uniaxial tension tests. This effect is small under bi-axial tension and therefore a linear isotropic material description is sufficiently accurate for many applications. However more advanced fabric descriptions are expected to contribute to physical accuracy in particular for special materials such as loosely woven fabrics. Therefore non-linear anisotropic material descriptions with hysteresis and rate dependency are now being evaluated.

During IMM, relaxation and unfolding the closely packed fabric layers unfold and slide. In this phase the contact algorithm has to robustly detect contact and minimise penetration with a realistic energy dissipation. Existing contact algorithms often require substantial user effort to find parameter settings in order to provide realistic airbag deployment. Therefore, edge-edge contact and other features contributing to robustness and accuracy have been added. Robust and realistic results have been found for realistic yet significant variations in contact friction, airbag inflation parameters and loading conditions. Hence *"one time right"* solutions are obtained when modelling guidelines are followed.

The optional edge-edge contact algorithm requires substantial additional CPU load, but time and reliability are gained by the "one time right" solutions. With the current SMP implementation, parallel computing enables runtime to be reduced by a factor of 5 with 8 CPUs (Figure 6). Even better performance is expected with MPP, which is in preparation.

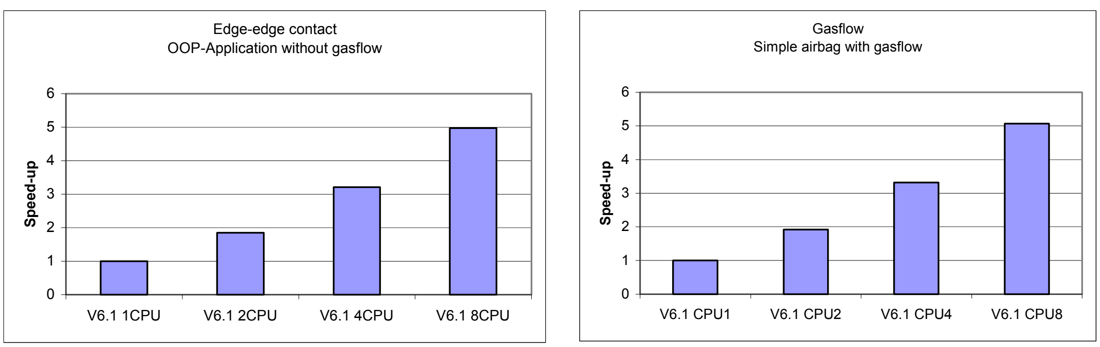


Figure 6: Speedup for edge-edge contact (left) and speedup for gasflow (right) using SMP.

Airbag Simulation and Gasflow

The airbag internal pressure can be calculated in several ways. The traditional scheme uses the assumption that the airbag internal pressure is uniform at any given time. This so-called *Uniform Pressure* (UP) method is very efficient and accurate for In-Position frontal impact scenarios, when the occupant-airbag interaction takes place after the airbag is almost fully deployed, and over a relatively long time-span. However, in Out-of-Position scenarios, there is strong interaction between occupant and airbag during the airbag deployment phase and during deployment, the airbag pressure is strongly non-uniform. In recent years, more complex gasflow models appeared on the market. They can be grouped into *Coupled Lagrangean-Eulerian (CLE) models* and *Mesh Free (MF) Methods.*

In CLE models, there are methods like ALE (Arbitrary Langrangean-Eulerian) in LS-DYNA, or the CFD (Coupled Fluid Dynamics) module in MADYMO. They no longer assume the pressure to be uniform; instead the volume inside and outside of the airbag is divided into an Euler mesh with a specific pressure, temperature and gas velocity to each element. The airbag fabric is modelled by a "normal" (Lagrangean) deformable mesh.

In MF models, like the FPM (Free Particle Method) in PAM Crash, or the SPH (Smooth particle Hydrodynamics) in RADIOSS or LS-DYNA, the gas is represented by freely moving nodes ("particles") rather than elements. These particles interact with each other and with the structure (the airbag is represented by Lagrangean elements) by a certain algorithm.

MADYMO CFD is based on the Flux Corrected Transport gasflow model which is well-established from the field of Explosion simulation. A direct integration of existing simulation techniques was accomplished through collaboration with Century Dynamics Ltd, UK (Steenbrink & Fairlie, 2000). The FCT method provides a strong theoretical basis for modelling effects of non-uniform pressure using an Eulerian description for compressible inviscid flow where effects of turbulence are neglected (Boris & Book, 1976; Zalesak S.T., 1979). The Euler grid is created and adjusted automatically and also the time step is controlled automatically in combination with the FE time step.

Verification of the gasflow method

Due to the complicated nature of airbag deployment it is difficult to measure and verify simulated pressure and gasflow using airbag experiments. Experimental repeatability is an issue in particular for pressures measured near the inflator. With relatively simple benchmark problems it is easier to check and validate individual items of the solution against analytical or experimental results. Happee et al (2003) show gasflow results matching an analytical reference with 0.25% for a shock tube while simulation of a frontal step is in good agreement with expected results.

Standard gasflow formulations provide some specific accuracy issues in airbag simulation. With standard formulations a very fine gasflow (Euler) grid is required to accurately simulate densely folded airbags. A coarse grid can result in a non-physical effects called "through flow" when Euler cells cross multiple fabric layers. In MADYMO 6.2 an enhanced formulation is introduced, which eliminates through flow while Euler cells may cross fabric layers (Figure 7). Thereby this formulation improves physical accuracy while limiting CPU demands.

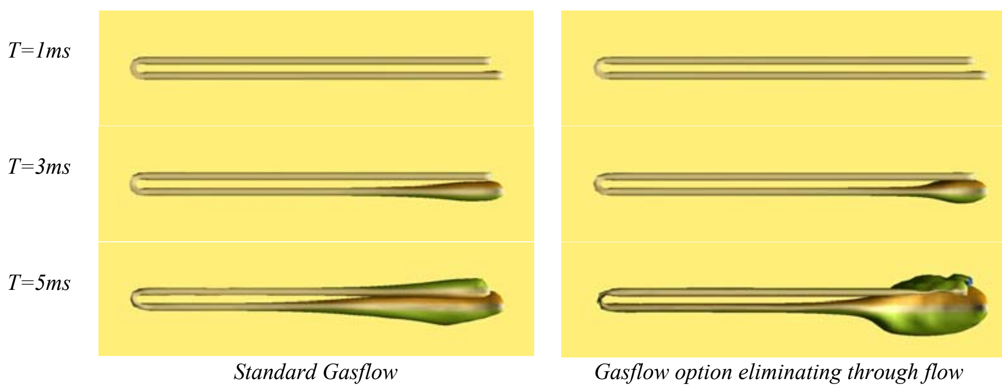
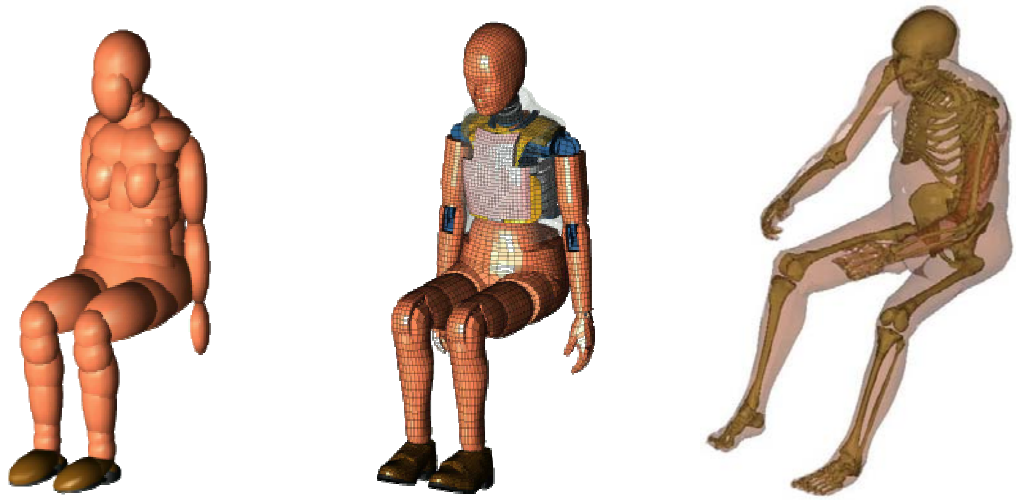


Figure 7. Effect of through flow: On the left it can be seen that gasflows from the lower tube to the upper tube through the contacting fabric. On the right it can be seen that the enhanced formulation eliminates through flow even though Euler cells cross both tubes.

Dummy & Human modelling

A full range of extensively validated models of crash dummies, crash barriers, and humans is available (see Figure 8 and the Annex).



Multibody Hybrid III *FE Hybrid III* *FE Human*

Figure 8: Typical MADYMO dummy & human models (see the Annex for an overview)

Since the introduction of OOP requirements, MADYMO introduced and upgraded models of the Hybrid III child dummies and the Hybrid III small female dummy. Development programs have been performed in co-operation with several industrial partners. Based on actual OOP applications, validation sets with representative loading severity and loading rate have been gathered. Detailed FE models have been developed of the Hybrid III 3 year old, 6 year old and small female while an FE model of the mid size male is under development. These new FE models have been extensively validated at all levels. The focus during development was on accurate prediction of chest and neck loading as these are the key values in the FMVSS208 regulations. An example of validation results for peak chest deflection is given in Figure 10. Also for simulation of side airbag deployment scenarios, a full range of (FE) side impact dummies is available.

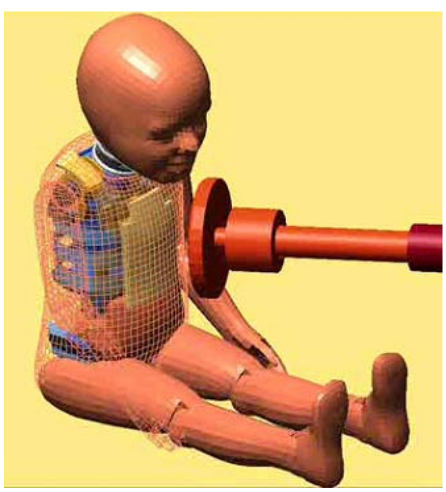


Figure 9. FE Hybrid III 3 year old dummy

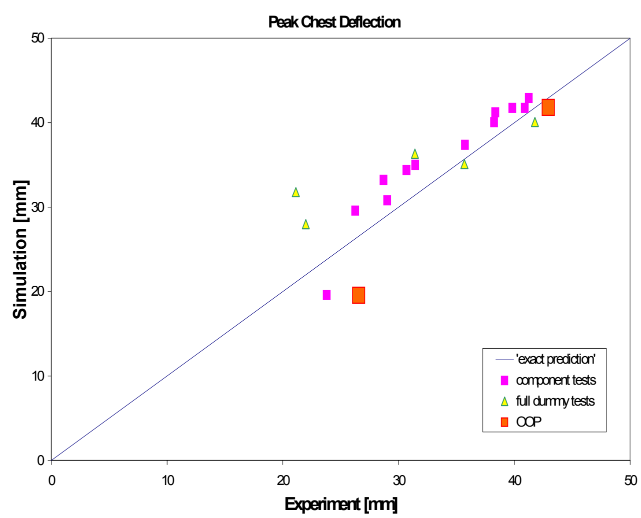


Figure 10. Correlation of peak chest deflection for the FE Hybrid III 3 year old

Summary & Discussion

Supported by dedicated simulation tools, restraint system performance can be effectively evaluated and optimised for a large number of scenarios. Thus virtual testing enables efficient and robust design optimisation for regulated and consumer test procedures and provides ample scope for further safety improvement for instance by evaluation of real life scenarios with real human models.

Techniques such as DOE, optimisation and stochastic analysis require great numbers of simulations, and it is impossible for the simulation engineer to check each simulation for validity of results. Therefore it is imperative that simulation technology not only provides a limited CPU load, but also provides robust and predictive results.

Stochastic analysis and objective rating enable evaluation of model robustness and predictivity. Tools and methods for stochastic analysis and for objective rating of model predictivity are currently introduced and in general it is concluded that restraint simulation is robust and predictive. Using multibody dummy models CPU loads are generally below one hour for in position frontal impact analysis, thereby allowing restraint optimisation studies to be completed within days. While the benefits of low runtimes are extensively exploited for frontal impact, comparable results can be achieved for side impact using Prescribed Structural Motion (PSM). Side airbags and door trim can be effectively optimised when the deformation of the side structure is prescribed based on a separate full FE analysis.

Simulation technology is being continuously enhanced for challenging cases such as airbag out of position deployment. Gasflow simulation in many cases provides more realistic airbag deployment and specific gasflow enhancements are being introduced for airbag simulation. In MADYMO 6.2 a new formulation is supplied, which eliminates through flow while Euler cells may cross fabric layers (Figure 7). Thereby this formulation improves physical accuracy while limiting CPU demands.

Current CPU loads for detailed OOP simulations with gasflow and edge-edge contact range from a few hours for pendulum loading to more than a day for dummy loading. There is still scope to improve CPU efficiency for gasflow, but it should be realised that a great amount of computing power will be needed to use simulation for OOP loading conditions. Techniques such as DOE and stochastic simulation may streamline this process by effective preparation and scheduling of a minimal number of simulations.

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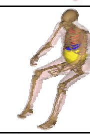
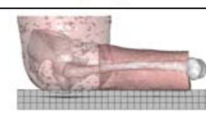
Annex: MADYMO dummy models, subsystem models, barrier models and human models

Frontal / Rear Impact dummies	***Side Impact dummies***	***Child dummies***
Hybrid-III 5^{th} female	EUROSID-I	Hybrid-III 3YO
Hybrid-III 50^{th}	ES-2	Hybrid-III 6YO
Hybrid-III 95^{th}	US DoT-SID	CRABI 12MO
Hybrid-III 50^{th} standing	SID-H3	Q3
Hybrid-III 50^{th} + thor lower legs	SID-IIs	P3/4
THOR	SID-IIs + airbag interaction arm	P1 1/2
Hybrid-II	BioSID	P3
Hybrid-III 50^{th} FAA (aircraft)	WorldSID (in preparation)	P6
Hybrid-III 50^{th} + TRID neck		P10
RID-II		
BioRID-II		
MATD (motorcycle dummy)		
Subsystems	***Barriers***	***Human models***
FMVSS 201 headform	Offset Deformable Barrier (ODB)	Occupant 5^{th} female & 50^{th} male
Pedestrian child headform	FMVSS-214 MDB	FE occupant model
Pedestrian adult headform	EEVC-WG13 MDB	Pedestrian 3y/6y/5/50/95%
Pedestrian ACEA headform 3.5kg	IIHS-SUV MDB	Facet neck model
Pedestrian legform	FMVSS-201 impact pole	FE arm model
Pedestrian upper legform		FE buttocks model
ECE-R12 Bodyblock		Facet leg model
H-Point Machine		FE brain skull model (on request)
		FE leg model (on request)

The following table provides a general overview of MADYMO human models and applications.

Human model	*Impact simulation*	*Comfort Simulation*	*General Biomechanics*	
Facet occupant models	Reference model for impact simulation	Prediction of vibration transmission from the seat through the human body	Simulation of voluntary motion using inverse or forward dynamics	
FE occupant model	Enables simulation of bone and soft tissue deformation			
Pedestrian models 3y/6y/ 5/50/95%	Extensively validated for pedestrian impact.			
Facet neck model	Enables detailed simulation of neck local loading. Active muscles included		Simulation of active motion by muscle activity	
FE arm model	Extensively validated for frontal and lateral loading to seated car occupants			
FE buttocks model	Validated for seat pressure as related to occupant sensing	Validated for seat pressure prediction		
Facet leg model	Enables detailed simulation of foot and lower leg local loading. Active muscles included		Simulation of active motion by muscle activity