EEVC

EUROPEAN ENHANCED VEHICLE-SAFETY COMMITTEE

EEVC Working Group 22
Virtual testing

First mandate final report

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Contents

1 INTRODUCTION ... 6

2 TERMS OF REFERENCE ... 7

3 STATE OF THE ART OF VIRTUAL TESTING ... 7

3.1 SCOPE OF VIRTUAL TESTING AND TOOLS ... 7
3.2 FINITE ELEMENT SIMULATION IN CRASHWORTHINESS DESIGN ... 8
3.3 STATE-OF-THE-ART IN RELATED FIELDS ... 10
3.3.1 In railway domain ... 10
3.3.2 Virtual technology use in aircraft industry ... 11

4 EXPECTED BENEFITS ... 13

4.1 EXPECTED BENEFITS FOR THE INDUSTRY IN TERMS OF COMPETITIVENESS ... 13
4.2 EXPECTED BENEFITS FOR SOCIETY (EXTENSION OF SAFETY REGULATION SCOPE) ... 13
4.2.1 Welfare benefits by improvement of crash test reliability ... 14
4.2.2 Welfare benefits by increasing the number of current crash test configurations ... 14
4.2.3 Welfare benefits by the use of Human Models instead of Anthropomorphic Test Devices (Dummies) ... 14

5 VT FOR REGULATION ... 15

5.1 PURPOSE OF REGULATIONS ... 15
5.2 EXISTING REGULATION ALLOWING VIRTUAL TESTING ... 16
5.3 POTENTIAL EXTENSION OF REGULATIONS ACCEPTING VT ... 16
5.4 OBSTACLES TO THE INTRODUCTION OF VIRTUAL TESTING ... 16
5.4.1 Technical issues ... 17
5.4.2 Organisational issues ... 18
5.4.3 Legal issues ... 18

6 EU FUNDED PROJECTS ... 19

7 RELATIONSHIPS WITH OTHER GROUPS ... 19

7.1 ISO TC22/SC10-12/WG4 VALIDATION METHODOLOGIES OF MATHEMATICAL SIMULATIONS FOR SAFETY TESTS 19
7.2 CEN TC226/WG1/TG1/CME TASK GROUP ON COMPUTATIONAL MECHANICS IN ROAD FURNITURE ... 19
7.3 APROSYS SP7 ... 20

8 FUTURE WORK AND TERMS OF REFERENCE FOR A NEXT MANDATE ... 20

8.1 RATIONALE ... 20
8.2 OBJECTIVE ... 20
8.3 APPROACH ... 20

9 CONCLUSION ... 22

10 REFERENCES : ... 24

11 APPENDICES ... 26

11.1 CERTIFICATION SPECIFICATION IN AIRCRAFT INDUSTRY ALLOWING SIMULATION ... 26
11.2 APPENDIX 2 EC FUNDED PROJECT RELATED TO VIRTUAL TESTING ... 27
11.2.1 PROJECT VITES : VIrtual TESting for extended vehicle passive safety ... 27
11.2.2 PROJECT ADVANCE : ADvanced Virtual ANalysis of Crash Environments ... 28
11.2.3 PROJECT PRISM ... 31
11.2.4 PROJECT RISER ... 31
11.2.5 PROJECT ROBUST ... 33

11.2.6 PROJECT APROSYS 35
11.2.7 PROJECT APROSYS 36
11.2.8 PROJECT APROSYS 36
11.2.9 PROJECT APROSYS 38
11.2.10 PROJECT STORHY 39
11.2.11 PROJECT STREP HELISAFE TA 41
11.2.12 HUMOS (1 & 2) Human model for safety 42
11.3 APPENDIX 2 : REGULATIONS FOR WHICH VT COULD BE USED 44
11.3.1 R110 CNG tanks APPROVAL OF SPECIFIC COMPONENTS OF MOTOR VEHICLES USING COMPRESSED NATURAL GAS (CNG) IN THEIR PROPULSION SYSTEM 44
11.3.2 R66: Bus rollover (1/2) Annex 6 44
11.3.3 R21: impacts in dashboard Annex 8 : DETERMINATION OF A DYNAMICALLY DETERMINED HEAD IMPACT ZONE 45
11.3.4 R11 : door latches Annex 3 TEST PROCEDURE FOR THE DOOR LATCHES AND DOOR RETENTION COMPONENTS 46
11.3.5 R29: lorry cab deformation 46
11.3.6 2003/97(R46) : CAD for retrovision : Annex 6 REAR-VIEW MIRROR FIELDS OF VISION AT GROUND LEVEL 46
11.3.7 2001/192 : pedestrian test zone 47
11.3.8 78/549 : CAD for wheel arches : Allowed in France to present CAD instead of a car for type approval 47

Executive summary

The EEVC G22 was created in 2005 in view to explore the possibilities of introducing the virtual testing technology in the regulatory process. The terms of reference of its mandate were to provide :

- An overview of the current use of Virtual Testing for the assessment of vehicle and safety systems in the regulatory conditions.
- An analysis of the fields where benefits of Virtual Testing application are expected, and of the scope of these benefits.
- A summary of European projects related to virtual testing.
- A review of the work done by other international working groups (such as ISO).

Four meetings were held from March 2005 to March 2006. From the information that the group could compile, the following conclusion could be drawn.

Numerical simulation which constitutes the basis for the more general Computer aided engineering, is extensively used in industry for product development, including verification of crashworthiness performance in regulatory or consumer test conditions.

Benefits for the society and for the industry can be expected from the introduction of VT by widening the scope of protection and by reducing the number of physical tests for product approval. However, benefits for industry are not well defined so far.

The introduction of such virtual tests in the regulatory context faces several obstacles, of technical, legal and organisational nature. The main technical problem concerns model the validation criteria and the validation procedure.

A work program has been proposed for a next mandate in order to address these issues while working on the implementation of VT in a few simple cases.

Composition of the group

Name	*Organisation*	*Country*	*Function*
Jean-Pierre VERRIEST	INRETS		Chair
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Bob MORAN	Department for Transport	UK	National representative
François MINNE	UTAC	France	National representative
Benoît BESNAULT	PSA	France	Industry adviser
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1 INTRODUCTION

Despite considerable progress accomplished in the field of accident prevention, traffic-related accidents are still a major threat to life in the European Union. Illustrative in this respect is the annual road toll of more than 40,000 people killed in the EU25. This represents an unacceptably high burden on Europe's society and economy. This means that 1 in 80 European citizens will end their lives on average 40 years too early in a road accident and 1 in 3 will need hospital treatment during their lifetime as a result of a road accident. The social costs of these accidents are currently evaluated at some 160 billion Euro per year.

The regulatory tests and the consumer tests are a good means to improve the safety performances of vehicles released on the market in terms of protection of vehicle occupants and other road users.

Nowadays, the number and diversity of national, European and worldwide harmonized regulations on the one hand and the diversification of car models proposed by manufacturers on the other hand, lead to very a complex certification process which costs a lot of time and money to the automobile industry and hence to the customers.

One of the suggested ways to simplify the homologation of products and reduce the burden of regulatory tests is, as it was recently proposed by the "CARS 21" report, to introduce virtual tests in regulation (at least for 25 regulations to start with) and also to introduce the self certification instead of the type approval.

The concept of virtual testing is not synonymous of sophisticated numerical simulation. Virtual regulatory tests can be performed on the basis of simple technical drawings. However the fantastic development of computation power and available codes, especially finite element (FE) calculation codes, enabled to set design methodologies mainly based on the numerical simulation of all the functional features of a product. So, today when people talk about virtual testing, implicitly numerical simulation is meant.

Besides, one can think that the flexibility offered by the technology of numerical simulation allows, provided a numerical model is available and validated, to widen at a least cost the scope of protection by making easier the virtual examination of less frequent accident situations not taken into account by physical regulatory tests.

In order to explore the possibilities to introduce virtual testing in regulations and in order to estimate the potential benefits that could be derived, the WG22 was created. Its first mandate, according to its terms of reference, was to establish a state of the art in terms of available technology, to explore what was done in other related domains (railway, aircraft, …) where full scale physical tests are not possible due to the size of the vehicles and the cost of the facilities it would need, and propose a work plan for a further 3 year mandate.

The group started its work in March 2005 and held 4 meetings in March, June and October 2005 and in March 2006. The last meeting was held in conjunction with the APROSYS SP7 workshop on Virtual Testing.

The present report gives the main results of the work performed during this first mandate and proposes items to work on for a next mandate .

2 TERMS OF REFERENCE

The terms of reference for the first mandate were formulated as follows:

In the view of making proposals to extend the scope of regulatory tests by Virtual Testing application, this working group will provide, within a mandate on 12 months starting on the date of its first meeting :
- An overview of the current use of Virtual Testing for the assessment of vehicle and safety systems in the regulatory conditions.
- An analysis of the fields where benefits of Virtual Testing application are expected, and of the scope of these benefits.
- A summary of European projects related to virtual testing.
- A review of the work done by other international working groups (such as ISO).

A further 3-years mandate could be given subsequently with new terms of reference based on the work done during the first mandate.

3 STATE OF THE ART OF VIRTUAL TESTING

3.1 Scope of virtual testing and tools

The term "Virtual Testing" can range from analytical computation to full finite elements simulations. The first step of "Virtual Testing" is based on drawings. Then, there is simple calculation of resistance of materials, analytical dynamic, multi-body models and finite elements.
Numerical simulation is widely used for product development, covering a wide spectrum of physical domains (mechanical, electrical, optical, acoustical, thermal, …), part size (from a few mm to full scale ship), product features (vehicle handling, noise and vibrations, ride comfort, thermal behaviour, electronics, ….., crash response). The general objective is to support the timely development of vehicles with minimum prototype testing.

Within the group, communications were obtained from a few car makers on their use of numerical simulation in product development. Also, a few articles could be found on application of numerical simulation in product development. In particular, in the proceedings of code user meetings (such as LS-DYNA, MADYMO, PAM, and RADIOSS), one can find examples and illustrations of methods and procedures used in various industrial areas to assist product development and to help the evaluation of product performances, including in regulatory or consumer test conditions (see Figure 1).
The presentations made by several European and one American car makers allowed to understand the extent of effective application field, the interdependence of the various features addressed by the design process and also the diversity of the tools used. These presentations can be obtained from the EEVC WG22 web site; their references are given at the end of this document.

The general process is to use CAD, then simple multi-body models, and finally detailed finite element models. There are about ten kinds of softwares used by car makers (see for instance WD022) for the different fields concerned such as body structure, crash, chassis, thermal, proving ground, aerodynamics, fatigue, noise and vibration. For safety purposes, there are also different models depending of the test speed (15kph for reparability or 64kph for Euro NCAP). Even in the same field (explicit models for crash purpose) models can be different depending on the situation studied, pedestrian impact (at 40kph) or full wall crash test (at 50kph) (see WD015).

Figure 1 - Example of real and simulated frontal crash with up-to-date Finite Element simulation code
(http://www.esi-group.com/SimulationSoftware/NumericalSimulation/index_html)

3.2 Finite Element simulation in crashworthiness design

The development of Finite Element (FE) based simulation techniques has been a major step forward in improving the crashworthiness design of automotive structures, and today all major automotive manufacturers are using these techniques. The FE simulation is based on a so called first principle, i.e. the response will converge to the "true" response when the FE mesh density is increased, presuming that geometry and material modelling and boundary and initial conditions are correct. In general the results from the FE simulation are close to the corresponding test results, and the FE simulation is the best available prediction tool.

However, still there is a need for improving the accuracy. In particular there is a need for improving the material modelling, including failure modelling, of many new advanced materials found in a modern car.

Since the first complete car FE simulation was made in the middle of the 1980's, the simulations have been used in a trial-and-error fashion, i.e. an FE model has been created of the new design and the simulation results are then compared to the design criteria. If these criteria are not met, the design is modified, an updated FE model is made, and the new simulation results are checked. This process continues until all important design criteria are met. In recent years this process has been improved by the utilization of optimization, i.e. a mathematical optimization problem is set up, and the "optimal" solution is found from multiple sequential FE simulations. Recently, attempts are being made also to include real-life variations and uncertainties into this process, such that the response can be interpreted using statistical measures.

The utilization of FE simulation technology in the design process is continuously evolving, and the extent of its utilization varies among the OEMs. Many OEMs now have a design process driven by simulations, where obviously, the FE model of the car is of fundamental importance. The major merit of a design process driven by simulation is its potential in shortening the development time. Other OEMs are still using the traditional design process driven by testing. Since testing is time consuming and expensive, the trend is that all OEMs eventually will have a design process driven by simulations.

The quality of the FE model is of fundamental importance in order to get accurate simulation results. A more detailed FE model gives more accurate results, however at the expense of an increased computing effort. Thus, the FE modelling must be a balance between accuracy and efficiency. The development, both of the computer performance and the FE program algorithm efficiency, has resulted in a corresponding increase in the FE model level of detail and, consequently, model sizes. Today, the coupling between product definitions in CAD systems and the FE model is relatively tight, and a modified CAD design can quickly be transferred into a corresponding FE model modification. From an efficiency point of view, a balance must be made between one major detailed FE model of the complete car to be used for multiple load-cases, and multiple FE models developed for specific loading cases, e.g. the frontal, side and rear impact cases. It takes less time to continuously keep one complete FE model updated than many models, however at the expense of an increased computing effort. Another important FE modelling issue is crash dummy and safety system modelling. In order to make accurate prediction of the crash injury criteria, a vehicle model including interior details, safety systems and occupant models must be used, which fact further increases the size of the model.

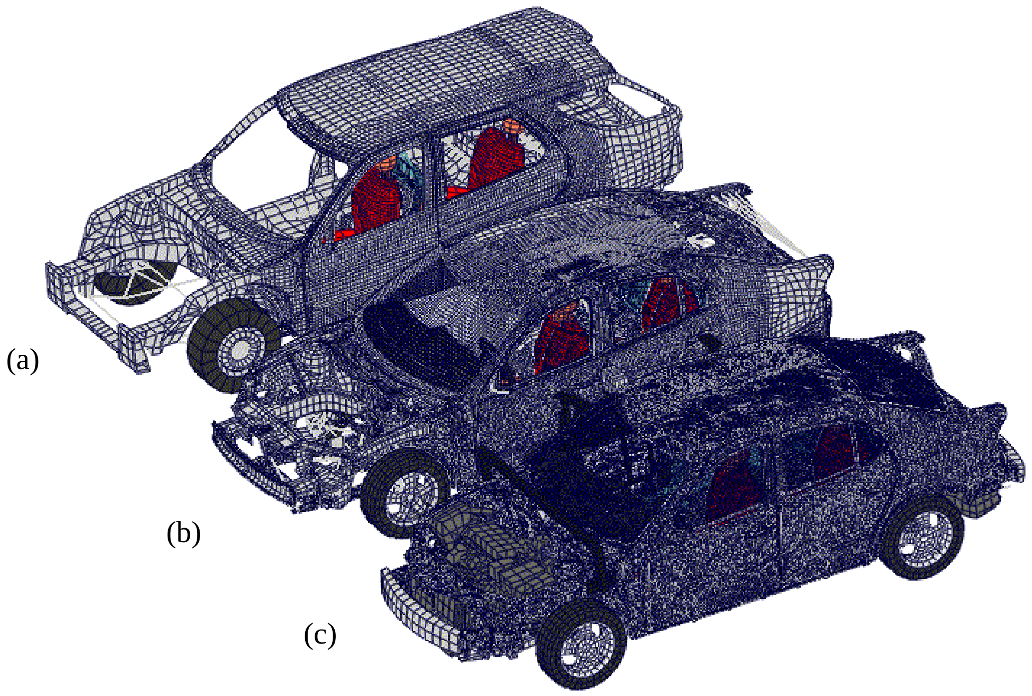


Fig.2. Finite Element model development. (a) Year 1995 Saab 9-5 Combi (<100,000 elements), (b) Year 1999 Saab 9-3 Sedan (<400,000 elements), and (c) Year 2004 Saab 9-3 Sedan (>1,000,000 elements). Courtesy Saab Automobile AB

As a consequence of the balance between accuracy and efficiency, OEMs using a design process driven by simulation are utilizing FE models which contain more than two million elements, excluding safety systems and crash dummies (Mercedes, BMW, Porsche, Saab Automobile, Opel), cf. Figure 2. The corresponding FE model size at OEMs still using a design process driven by testing is about 400,000 to 600,000 elements (Ford NA, GM NA, Volvo Car Corp.).

3.3 State-of-the-art in related fields

In the railway and naval industries, computer aided engineering is also widely used for the development of products as it is in the automobile world. The role of virtual testing in these domains is also increasing, because testing is very expensive. Very little information could be gathered on the situation in railway industry and nothing on the naval side. However, a group member having some activity in the aircraft industry could provide some input on this field.

3.3.1 In railway domain

The tools used by train manufacturers are the same as those used in the automotive world. Concerning the rolling stock structure, due to the cost of full scale crash tests, physical crashworthiness tests are now partially replaced by numerical simulation, including for certification. A new standard is in preparation (prEN15227) and to support the work, a project proposal concerning the use of computation for regulatory tests is being prepared by UNIFE in response to the first call of FP7.

Concerning the occupants, numerical simulation involving digital crash dummies is also used to study design alternatives. In order to prepare future TSI (technical specifications for interoperability) on train interior passive safety performance, a project devoted to the design of tools and procedures including virtual tests is in progress (FP6 STREP SafeInteriors). No specific information concerning the procedures or the evaluation criteria could be collected during this first period. But first contacts have been taken with the CEN TC256 Railway applications WG2 in charge of the question of virtual testing for “Crashworthiness requirements for railway vehicle bodies”.

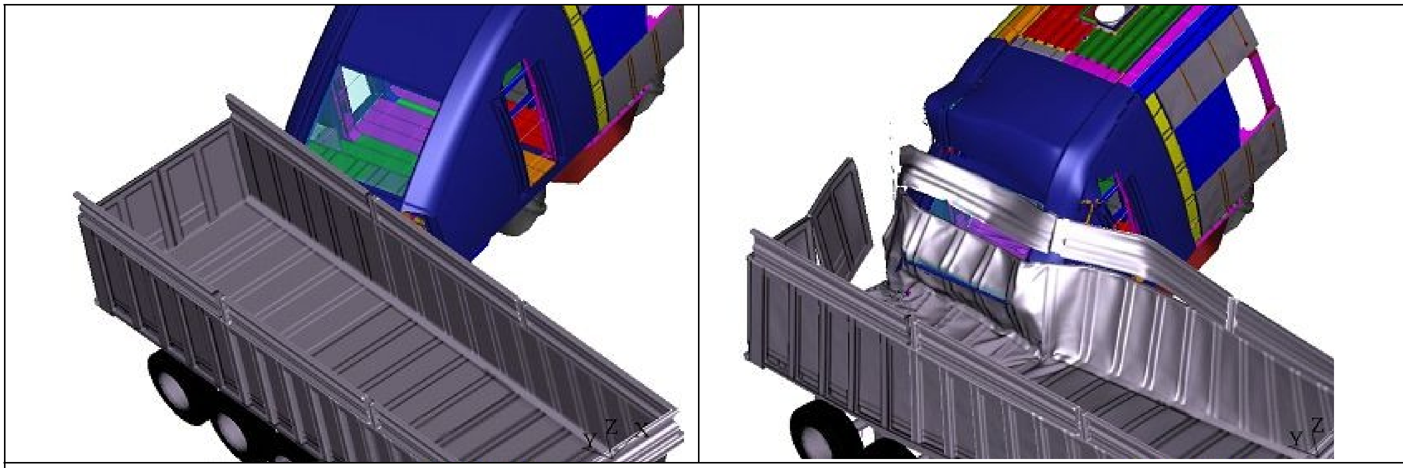


Fig 3 : Simulation by means of FE model of a collision between a train and a truck
(Courtesy SNCF - French National Railways)

3.3.2 Virtual technology use in aircraft industry

In aircraft industry, virtual testing is widely used for development and in some cases for approval. But most of these tests mainly concern vibrations, fatigue and static loads. There are few crash simulations for example but at low speed which can be considered as static tests (SAE AS8049a). Another specificity of aircraft industry and approval is that all materials are known and material models have been validated by the federal aviation administration (FAA) in the US. This conducts to a monopole for the software (NASTRAN) and a restriction for the development.

Important Difference in Approach to Safety Problems in Aircraft and Car Industry

Designers (and users) of cars accept the fact that at the current stage of technology, road accidents happen (and will happen in predictable period of time) despite active safety measures undertaken and that passive safety systems/car design solutions play very important role in reducing risk of car users injuries and number of fatalities. Efforts in both active safety and passive safety are balanced. Passing of full-scale crash test with good results is an obligatory step in a process of allowing a new car dissemination on the market.

It seems that “a philosophy” of designing airplanes and organizing exploitation of them is very different — it seems to be assumed that planes, air traffic organization, pilots and all the personnel (both in the air and on the ground) should be so perfect to avoid crashes. And the most of the efforts is directed towards accident/crash avoidance not mitigation of crash consequences. Regulations concerning aircraft certification process require a lot of in-flight tests; however no full-scale crash tests are required (and normally are not performed).

This can be easily explained by a very different course of road and airplane accidents (the problems in typical cases start in the air), different level of loads (loads in a typical plane crash are much higher compared to even very severe car crashes), the fact that most of cars are driven by “amateurs” with only basic (compared to airplane pilots) training and road traffic is almost (compared to air traffic) not coordinated.

VT use in aircraft industry

Virtual Technology is extensively used in aircraft industry during design and production phases, probably even more (e.g. because of much higher costs of making prototypes) than in car industry.

On official web-page [http://www.boeing.com/commercial/777family/compute/index.html] of the Boeing Company, one can find information confirming the previous sentence: *„The Boeing 777 is the first jetliner to be 100 percent digitally designed using three-dimensional computer graphics. Throughout the design process, the airplane was "pre-assembled" on the computer, eliminating the need for a costly, full-scale mock-up.”*

„Through innovative applications of computing technology, the 777 program exceeded its goal of reducing change, error and rework by 50 percent.”

At the same time application of VT methods for regulatory purposes seems to be marginal.

In Europe, the EASA **—** European Aviation Safety Agency, established through Regulation (EC) No 1592/2002 of the European Parliament and the Council of 15 July 2002 (formally started its work on 28 September 2003) takes over the responsibility for regulating airworthiness and maintenance issues within the EU Member States.

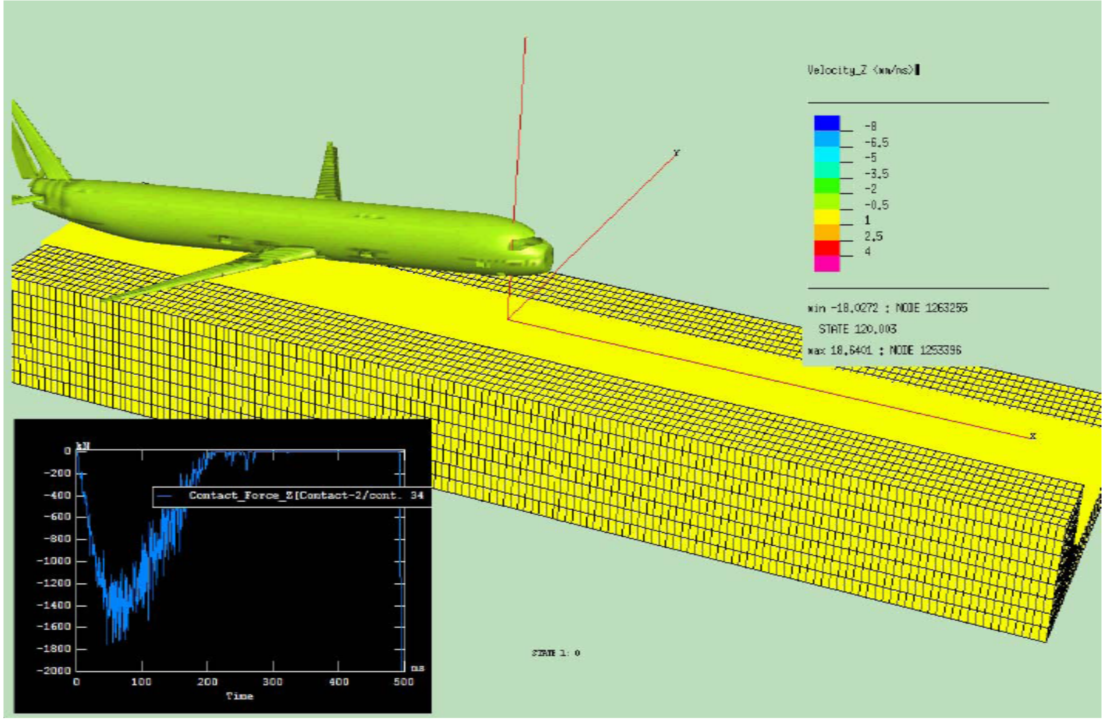


Fig 4 : Simulation of ditching of an aeroplane by mean of finite element model of the aircraft and the ground (From, presentation made at APSN workshop in Lisbon, Feb 2005, by C. Kindervater, DLR, Germany

The EASA acts as a successor of the former JAA — Joint Aviation Authorities, authors of JARs — Joint Aviation Requirements. The JARs create the basis for current regulations in the EC enforced by the EASA:

In most important JARs that covers all requirements for design, production and certification of different types of aircrafts, only few examples clearly indicate the possibility of acceptance of computational methods. Two of them are presented below (they concerns <u>flutter resistance</u> and <u>proof of structure</u>). These two cases are described in appendix 2.

Conclusions

Virtual Technology is extensively used in aircraft industry during design and production phases.

At the same time application of VT methods for regulatory purposes seems to be marginal. Normally, good performance of a plane during in-flight tests is necessary for obtaining a certificate (the only clear exception found is acceptance of use of calculations to proof the flutter resistance of a plane beyond the velocity allowed for in-flight tests; in some, very restricted cases, calculations can also be accepted for the proof of structure).

In a certification process of a new airplane a commission established by a proper certification body decides if all evidences gathered during ground and in-flight tests, calculation results provided by manufacturer (as supplementary data) and also reports of inspections done at the design and production sites are enough to give the certificate = permission for exploitation of the aircraft (like judge who decide, based on collected evidences, cases brought before a court).

4 EXPECTED BENEFITS

The potential benefits offered by the introduction of virtual testing in regulation can be seen from two standpoints. On the one hand, the objective could be to use virtual testing to extend the scope of regulation, i.e. address accidental situations or populations not taken into account by present regulatory tests. On the other hand, industry is more in favour of using virtual testing to lighten the burden of regulatory tests, i.e. replacing some real tests by virtual ones. For instance, when a small modification is introduced in a design, the validation could be done through virtual testing instead of real testing. The general feeling of the industry is that regulations are too numerous and complex and that virtual testing should be contribute to lighten the burden of regulatory tests and should not be a reason to introduce new regulations. If new regulations were to be included through virtual testing to extend the scope of protection, this should be balanced by tangible benefits for the industry.

4.1 Expected benefits for the industry in terms of competitiveness

Computer-based crash simulation was originally developed for the nuclear power industry, then it spreaded over various industrial sectors, including automobile. With numerical simulation, the industry can get accurate predictions of the behaviour of the product subjected to certain loading situations. Different design alternatives can efficiently be evaluated and compared to each other and the best decision can be made for each situation. According to car manufacturers it takes about 100 crashes to bring a new model to market. Since the cost of a prototype crash test can exceed $1 million, financial benefits for virtual prototype testing can be substantial. Crash simulation is now becoming a general purpose tool, used by all manufacturers who must study the ability of their products to withstand collisions, from aircraft to train, off-shore platform or appliances.

Virtual testing could lower the cost of regulatory testing, e.g. avoid testing for small changes (judgement based on engineering examination and virtual testing). This is already done by some approval authorities today. Another advantage to use simulation for technical approval is to reduce delays. Virtual testing is presented in the development phase and the final approval could be done on the confrontation with real physical test results as a confirmation.

The benefits cited above were mentioned by members not from industry. In fact, no clear indications on this item could be obtained from industry so far.

4.2 Expected benefits for society (extension of safety regulation scope)

Benefits for the society (welfare benefits) by means of higher safety standards can be expected. The following paragraphs will give examples for those benefits, based on the assumption that numerical and model based problems are completely solved and virtual crash analysis would produce technically acceptable results.

4.2.1 Welfare benefits by improvement of crash test reliability

At first hand the reliability of crash test can be improved significantly. Forces, strains and accelerations can be taken from the model with high accuracy and at any desired location on the vehicle. The measuring of special parameters– e.g. the intrusions in the firewall region – can be conducted more easily. In addition stresses can be made visible for the whole compartment zone, indicating weaknesses of the construction even before any intrusions are visible. This means, that weak points of the vehicle can be evaluated which are not accessible by conventional crash testing. The availability of such parameters might even make regulatory bodies thinking of new performance criteria, e.g. level of stress, to enhance the safety level for car occupants.This can also contribute to the prevention of single point optimizations. For instance, the use of virtual testing could prevent design optimisation for a single crash test, by virtually testing other conditions around the nominal conditions of the real testing (WD023).

Furthermore virtual testing supplies the opportunity for stochastic simulations. Today, a crash test rating is based on one crash test only. However, the inherent variability of the mechanical systems involved in a crash test leads to a substantial scatter of results. This means that when a vehicle meets requirements in one or more tests, a repeated test by a consumer organization may lead to different results. For vehicle design there is a need to estimate not only average response but also the expected dependencies of results on variable test conditions, production tolerances and a variety of further parameters. Models are now used to predict the average response, where they could efficiently predict the stochastic response.

With regard to regulatory crash test rating the standardized variability is again a candidate to be taken as a new performance criterion, and will again contribute to the avoidance of single point optimization.

4.2.2 Welfare benefits by increasing the number of current crash test configurations

Apart from looking at the sensitivity of crash tests results by varying test condition parameters, production tolerances or other quantities, more extensive variations of the test set up including variables like impact direction, impact speed or barrier overlap will lead to further improvements in car safety standard. From an economic point of view, the marginal costs of additional crash tests are small as compared to the costs of full scale car crash testing, provided a suitable model is once on hand. The cost benefit ratio can thus be expected to legitimate the enlargement of the number of current crash test configurations.

One example could be a small overlap frontal crash scenario which – based on recent accident data - happens to be of high relevance to MAIS 2+ injuries to the lower extremities (priority on femur fractures). Other possible scenarios have been found in the European Project VITES which considered the increased risk of female passengers in frontal impacts or the hazard to non struck side occupants in side crashes.

Any extension of recent crash test configurations into the virtual dimension must however always be accompanied by prior careful accident analysis and an appropriate cost benefit computation. The availability of VT tools must not lead into temptation to cover any “possibly dangerous” accident configuration, which will in fact not be cost efficient. Further investigation on this issue is necessary to initiate the political implementation of virtual testing. Direct comparisons of the costs of a virtual and a real world test have to be made and shall be done in the second phase [2007+] of the Working Groups mandate.

4.2.3 Welfare benefits by the use of Human Models instead of Anthropomorphic Test Devices (Dummies)

More benefit can be expected from the use of Virtual Human Bodies (Human Models) in virtual test scenarios. At present, much work is spent on the development of more biofidelic

Dummies for a variety of impact configurations. BioRID, RID 3d, THOR or the WorldSID - Dummy might serve as examples. The achievement as well as the maintenance of such research tools is quite expensive (costs for a fully equipped and instrumented WorldSID – Dummy is about 400,000 US$), leading to the result that the use of virtual Crash Test Dummies might be more cost effective.

The high level of passive safety reached by most of the current vehicles calls however for even more sophisticated test devices. A new challenge for car makers and equipment suppliers is the optimization of safety devices for a more humanlike substitute. The European Projects HUMOS started in 1998 with the development of a biofidelic FE model, structurally very close to the human body. Emphasis was put on the correct representation of the main human structures, covering most of the bony parts, but of course also the main organs and muscles.

By using such kinds of occupants in a virtual test the safety level can be extended to respect a variety of human statures, meaning different body heights, masses or even the consideration of people with disabilities. Results could be presented for each single case [e.g. for special disabilities] or for a group of cases [e.g. for different body heights] by means of stochastic simulations. Furthermore, human models offer the ability to predict real injuries to a human body, instead of predicting injury severity in terms of AIS to certain body parts.

5 VT FOR REGULATION

There are short, medium and long-term opportunities for simulation as a legislative tool. Short-term options include the use of CAD models in replacing physical dimensional checks; medium and long-term opportunities depend upon the intended use of simulation for example, in replacing physical tests, complimenting tests (extending the scope) or allowing design changes without re-test.

CARS 21 (Competitive Automotive Regulatory System for the 21st century) considered that the introduction of virtual testing could provide more flexibility and reduce costs for the European automotive industry. However, because of the lack of experience in this area, which is still under development, the recommendation was to follow a step-by-step approach to the introduction of virtual testing. From the list of subjects that CARS 21 identified as offering short-term opportunities for virtual testing it is clear that their intention was to initially allow the use of CAD to demonstrate compliance with dimensional requirements rather than the use of complex structural or fluid flow analysis software.

5.1 Purpose of regulations

The objective of homologation is to verify, by means of appropriate tests, that a product (whole vehicle or component) is complying with a safety requirement and hence, it behaves in a safe manner with respect to its users or other road users. This verification is a pass/fail trial. In consumer tests, the objective is to attribute a score (in terms of number of stars) indicating the level of safety performance.

In regulatory tests, the specifications can be of various kinds. They can be pure geometric requirements for which the compliance can be easily checked from drawings or CAD files. But, most often, specifications are functional and need to be checked on a working model, either physical or numerical.

If the numerical simulation constitutes today an unavoidable tool in the industry for product development and enables time and cost cuts, its use in a regulatory context raises two fundamental questions.

The first is to know whether numerical simulation is able to bring improvements in the certification procedure, leading to gains in performance and efficiency of safety devices, time to market delivery and cost reduction.

The second is to know how to design the tests procedures to use this technology in the best possible way.

5.2 Existing regulation allowing virtual testing

There are few directives/regulations offering the possibility to use virtual testing. The list (*EEVC_WG22_WD006, Virtual_testing_and_regulation_UTAC.pdf*) is the following:

- 78/549: CAD for wheel arches
- 2003/97(Reg 46): CAD for mirrors retro vision
- 2001/192: CAD for pedestrian test zone definition
- Reg11: door locks (dynamic inertia)
- Reg21: impacts in dashboard (dynamic impact)
- Reg29: lorry cabin deformation (static load)
- Reg66: Bus rollover (dynamic fall)
- Reg67: GPL tanks anchorages (dynamic load)
- Reg110: GNV tanks anchorages (dynamic load)

In all cases, the use of virtual testing (CAD, static load or dynamic simulations) is an alternative of the real tests. For ECE R21 concerning stiffness of the dashboard, the possibility offered by virtual testing is to present as many as possible results of virtual impacts distributed over the whole surface. The approval authority then chooses 3 points (the worst cases) to be physically tested. Virtual testing results and real testing ones are compared and if they are consistent, the whole dashboard is then certified as complying with the regulation. It is a good example of an alternative offered by virtual testing to limit tests and time.

In all existing regulations/directives, the decision to accept the use of virtual testing results is up to the technical approval authority. There is no guideline for that. This should be an issue to address in the future work of the group.

The question of who should perform the tests is also not covered. Should it be the manufacturer’s technical department under the control of a certification body or should it be a certification office? In any case, the procedures must be clearly defined in order to get results accepted by all parties.

5.3 Potential extension of regulations accepting VT

There are further regulations in passive safety fields that could be using virtual testing. The German Ministry of Transport, Building and Housing (BMVBW) started activities, within a special advisory group, to think about a possibility to improve the European technical approval system using virtual testing (*WD020*). As there are 56 directives and 76 regulations, the German sub-group stated that it was not possible to modify everyone independently. So in June 2003 they recommended to the European commission to consider virtual testing in technical approval as a general approach in Directive 70/156/EEC. A first list of such regulations was provided by this group which concluded that full scale dynamic tests were out of the scope of virtual testing and the use of complex computer analysis in legislation remains a long term opportunity.

5.4 Obstacles to the introduction of virtual testing

There are a number of barriers that restrict the use of simulation within the current type approval system. Its implementation within the current regulatory system depends upon the reliability and confidence levels offered by the current physical test regime and those that might be gained from using computer simulation. Among the questions that should be addressed in order to introduce VT are the capability and validation of the models, quality control procedures, the need for improved COP testing (to ensure the capability of processes to reproduce the intended design) and the need to determine who should be responsible (ultimately liable) for the accuracy of the simulation.

5.4.1 Technical issues

One of the main problems using virtual testing is the validation of the model used and the definition of clear objective criteria to validate (or not) a model to be used for regulation purpose. That seems to be a major obstacle to the use of virtual testing in place of the real testing.

From a technical point of view, there are four main issues to consider in view of using simulations for regulation:

- Robustness of models
- Predictability of the models
- Objective rating of results (virtual testing metric)
- Standards for model/simulation quality

To be used in technical approval, virtual testing has to prove its validity. Numerical models are generally approximations of the real world and there is no way to bring the formal proof of their validity. So, the only way to validate models is to compare simulation results to real test results as it is demanded in reg66 on bus rollover: “The validity of the calculation method shall have been established by comparison with the results of physical tests” (Reg66 annex 6).

From this definition, real tests could not be replaced by virtual tests. The only possibility would be to extend the scope of regulatory tests, using models validated against results of existing physical tests belonging to the same kind of situation.

This raises several questions :

- how is measured the “distance” between the results of a simulation and those of a real physical test? According to which criteria? and how many?
- are there universal criteria or are specific criteria needed for different tests?
- what is the maximum distance accepted between simulation and real tests to consider a model is valid?
- what is a validity domain and what is its extent? To what extent test conditions can be changed without exiting the validity domain of a model?
- what is the appropriate level of detail to perform the validation.

Several international working groups such as ISO TC22/SC10-12/WG4 and CEN TC226/WG1/TG1 (CME), many product manufacturers (Ford, VW, FIAT, RENAULT, …) and also code/model vendors have developed procedures and tools in order to validate the numerical models. Some of these works could be collected. Many of these methods do not consider the technology used to produce the model. They concentrate on some variables that characterize the response of the system considered and compute quantities which deal with the amplitude, the timing and the shape of the signals (see WD011, WD016). Such a tool was developed within the European project VITES (VIrtual TESting). The advantage is that it does not assume any kind of modelling technology (FE or multibody for instance).

The validation of a model can be a very difficult exercise, even impossible, if the model is fairly complex. Even at low level of complexity, the simulation of a simple traction test on a sample can provide different results depending on the code used and the person who built the model. The origin of such differences in the results and their effects at a higher level of complexity should be identified in order to raise the quality of modelling and give a chance to validate more complex models.

For test tools such as dummies, barriers, impactors, certified models should be made available. The question is also for these tools how large the validation test base should be. An example of validation database and validation procedure for crash dummy models was presented to the group by TNO, showing the way how this task could be handled (see WD 035).

But all parties involved in the development of these methods agree on the fact that physical testing has an established role in approving products, little experience is available for computational mechanics. All methods developed at the moment are based and that axiom: virtual testing to be predictable need physical results and rating methods do not replace engineering judgment.

5.4.2 Organisational issues

If type approval is to be performed by means of virtual testing, one important question is who will do the tests? Is it the manufacturer or a third party mandated by the regulatory authority?

Of course the manufacturer has the competency and the resources (personnel, hardware and software) for building and running the model and interpret the results. But to guarantee the fair and objective evaluation required by regulation, leaving the tests being performed by an independent test house is preferable. But this raises the question of the resources available and the accreditation of this test house for simulation as it is in the physical testing domain and also the question of the transfer of the models by the manufacturers to a third party (see legal aspect below).

Little experience is available from existing regulation allowing VT. Method has to be approved by the technical service and anyway, the conformity of production requested in 70/156/EC will only be done on a “real” system. This is a kind of guaranty of the quality of the models/results provided by the manufacturer for technical approval.

In a virtual testing procedure, besides an accurate model of the vehicle or the equipment to be tested, certified test tools must be used. These are compulsory tools defined by the various regulations (dummies, barriers, impactors, ….). These tools should be made available to any OEM who wants to perform virtual testing of its product. The specifications for their certification should be defined so that all code editors can provide these tools to their customers.

The same questions as for product certification raise: what criteria should be used, who should perform the tests, etc...

5.4.3 Legal issues

The question of liability is of course very important. There was no expert in this field in the group and no resource available to launch a consultancy on the topic. This should be done in further work.

Another issue concerns the confidentiality of the models. A numerical model contains a lot of information related to the know-how of its developer. Even if clear rules for confidentiality are imposed and encryption techniques exist, OEMs are reluctant to take the risk of dissemination of their know-how. This is true not only for car makers but also for equipment suppliers and it could be difficult to handle a model including subsystems and parts with various levels of confidentiality.

This is why alternative ways to type approval should be investigated, such as self-certification, which should help to prevent dissemination of critical knowledge and help to make easier the liability definition.

6 EU FUNDED PROJECTS

In the field of passive safety, numerous projects include at least one task centred on numerical simulation for different purposes. A list of 12 projects or sub-projects is given in appendix 2 along with a short description of the objectives and the use of VT made in each.
Three important projects (ADVANCE, VITES and HUMOS) provided an important contribution to the development of the virtual testing concepts and tools. Other projects made use of these tools in a particular application field (occupant restraint systems, road equipment, safety of gas tanks, …). Finally, the APROSYS Integrated project, currently running, is mixing both development aspects (tools and procedures) and application to various crash scenarios.

7 RELATIONSHIPS WITH OTHER GROUPS

Contacts were taken with two groups whose work items are close to those of the present group: the ISO TC22/SC10-12/WG4 deal with "Validation methodologies of mathematical simulations for safety tests" and a CEN task group on Computational mechanics in road furniture.

7.1 ISO TC22/SC10-12/WG4 Validation methodologies of mathematical simulations for safety tests

The ISO group, chaired by Saeed Barbat from Ford Motor Company, focuses on the question of appropriate metrics to evaluate the quality of models and simulations. Documents have been exchanged with this group and it appears that the activities are really complementary. However, the work of ISO is directed towards industry standards, not regulations. A survey of scientific activities in the field is being established.
The ISO chair was invited to the last plenary meeting of WG22 in Delft where he presented the status of ISO progress. Symmetrically, WG22 chair was invited to present EEVC work progress to the ISO group. In the future, exchanges of documents and possibly joint work action could be coordinated.

7.2 CEN TC226/WG1/TG1/CME task group on Computational mechanics in road furniture

The CEN TC226 WG1 is in charge of road equipment and works in view of a future revision of the EN1317 standard. The task group chaired by Chalmers University is addressing the topics of using computational mechanics in type approval of road furniture. But they have not focussed on benefit studies.
This group is now focusing on a program to develop guidelines for applying simulation techniques to the certification process. The work includes a review of existing models and their performance, a round robin simulation, the development of a curve analyzer software and the simulation of accelerometer data processing. The curve analyzer topic is close to what is discussed in the ISO group. Concerning the quality of simulations the group is trying to define reporting procedures and objective validation procedures for simulations, define requirements for models to be tested and test tools (bullet vehicles) and define requirements for analyst competences and quality control.
The work topics of this group are really close to those of the WG22 and cooperation in the future work is certainly welcome.

7.3 APROSYS SP7

APROSYS is an EU funded FP6 Integrated Project comprising several sub-projects. One of these (SP7) deals with virtual testing and its activity include the topic of VT for regulation. In this perspective, APROSYS organised in March 2006 a workshop partly devoted to this question. State of the art related to different topics of VT were presented and a brainstorming discussion took place. The emphasis was rather on the tools available for full crash testing scale (frontal impact, side impact and pedestrian impact. This position was not in complete accordance with the one discussed in the group. In particular, the group expressed its concerns about differences observed when simple tests (sample traction test and crash box dynamic crush) were simulated using different codes and what could be the effect on a test of a more complex object. So, more discussions with this group is necessary. The link should be kept tight since it develops the appropriate technology for VT and is supported by EU funding for this.

8 FUTURE WORK AND TERMS OF REFERENCE FOR A NEXT MANDATE

This short review leads to propose for the future, in view to examine the conditions in which the virtual test could be introduced in the regulatory process, the following workplan.

8.1 Rationale

The simulation technologies have been improved a lot these last years thanks to several R&D projects (e.g. VITES, ADVANCE, APROSYS). Some aspects still face theoretical problems (e.g. rupture modelling) and need more effort to be solved and others require more data collection (e.g. exotic material characterization). Besides, one of the obstacles preventing the use of numerical simulation for virtual testing is the lack of confidence in the simulation technologies from regulatory bodies. To overcome this problem, an objective validation of the predictability of the models based on a widely accepted set of evaluation criteria, must be applied. The results of this validation should be independent of the code, the platform and the performing organisation.

8.2 Objective

The general objective is twofold :
- to develop procedures and tools to enable the use of numerical simulation in regulatory certification of safety systems.
- an important issue is to establish how VT could result in cost reduction and competitiveness increase for car industry (diminish the number of physical tests, reducing the time needed for approval, …) and in benefits for the whole society (more reliable testing, better protection afforded, …) without increasing the burden of regulatory tests.

8.3 Approach

The general approach (illustrated by the schema) could be organised around the following tasks :

- definition of reference scenarios : they could address several levels of complexity, including regulatory tests and engineering tests. For example :
  - sub-assembly test (door, roof, seat …)
  - part (crash box, beam, …)
  - sample (traction, compression, …)

  Objects could involve derived designs in order to test the extrapolation validation by simulation

- definition of sets of evaluation criteria : depending on the kind of test, they can be based on geometric, kinematic, dynamic, deformation or stress data. The resolution or accuracy level can be set to various values.

- Development of numerical models of the selected test objects (and/or collection of existing ones) on different platforms/codes by different teams, from common CAD geometry and material characteristics

- Perform the physical testing of the test objects with appropriate measurement of experimental data and boundary conditions, by different test houses

- Compare simulation and experimental results in order to :

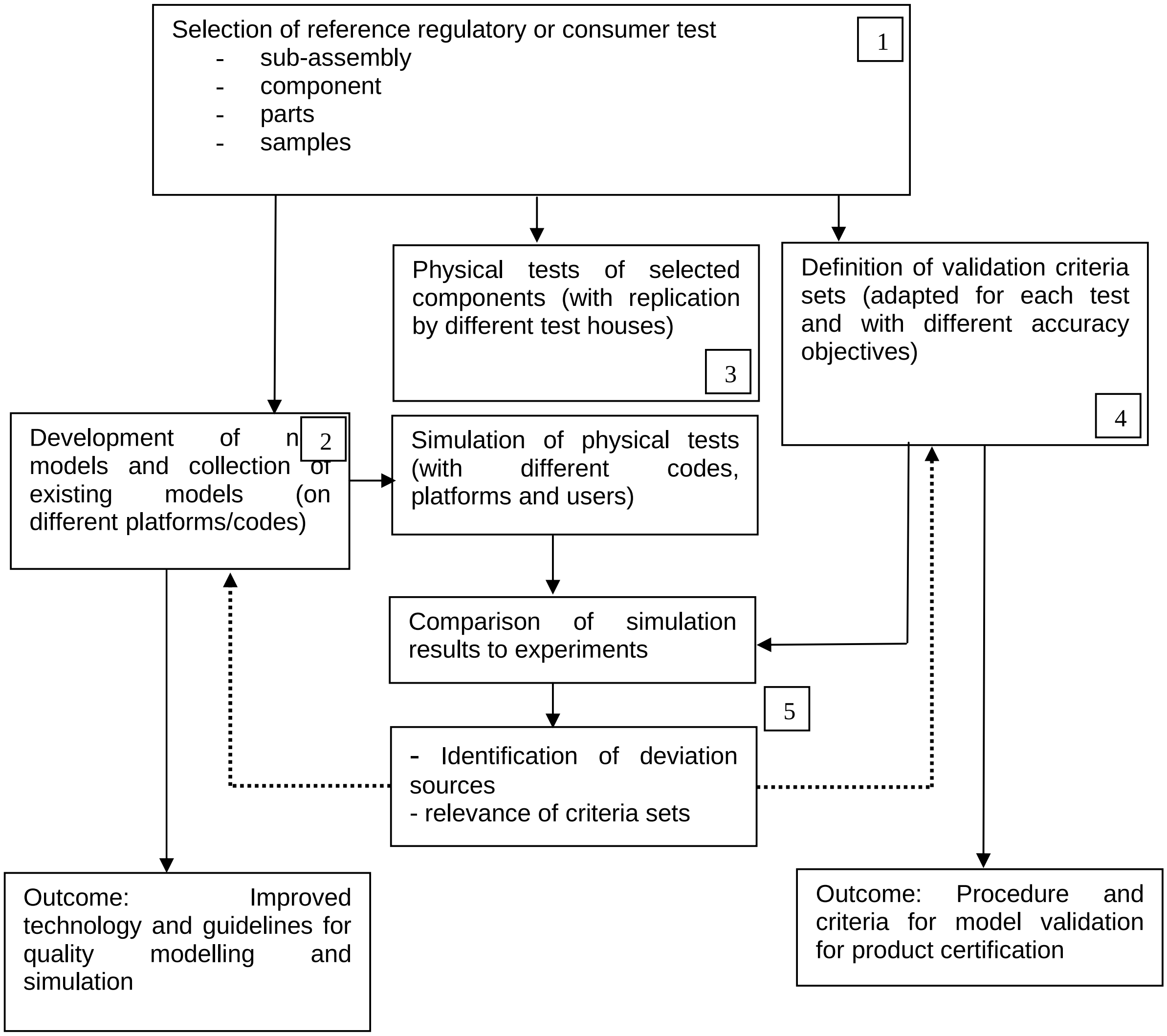
    - Identify sources of discrepancies between physical and simulated tests
    - Evaluate capabilities of criteria set to qualify model realism
    - Feed back to model development technology
    - Feed back to criteria development

- Update model guidelines, procedures and criteria accordingly and perform a second iteration
- Option : validate use of simulation for changes in design or test conditions

The outcome consists of :
- improved modelling technology guidelines for quality of simulation
- validation criteria and procedures for using numerical simulation in regulatory and consumer testing

In parallel, actions should be undertaken to elaborate procedure for validation
- definition of who performs the simulation (OEM, test house, model provider, …)
- definition of who interprets the results
- definition of who verifies the results
- conditions of model provision
- qualification of personnel (who interprets and who verifies)

And finally, a cost-benefit analysis should be also undertaken both on the procedure and on the possibility to introduce new tests (link with WG21)



9 CONCLUSION

The objective of WG22 was to establish a state of the art in terms of available technology, to explore what was done in other related domains (railway, aircraft, …) where full scale physical tests are not possible due to the size of the vehicles and the cost of the facilities it would need, and propose a work plan for a further 3 year mandate.
The term “virtual testing” covers various degrees of complexity spanning from the simple examination of geometrical specifications on a technical drawing to the numerical simulation of a full crash test with a FE code and a model comprising millions of nodes.
The use of numerical simulations in regulatory tests consists in replacing homologations tests on a physical device by an examination on a virtual representation of this device.
Whatever the complexity of the model is, the questions raised are of the same nature : what is the validity of the model used, which method and which criteria should be used to establish this validity, who performs the simulation, how to verify the conformity of the real product and who does it, etc…?

Depending on the model complexity, it is more or less difficult to answer these questions of course. The verifications from technical drawings or CAD files don't raise particular technical problems, the reflexion matter is more of legal and organisational nature. On the contrary, the numerical simulation of complex phenomena does not offer all the required level of reliability and predictability for regulations and still requires technological developments.

Besides, although numerical simulation enables to realize time and cost gains in the product development process, it has not been demonstrated that the introduction of virtual tests in regulation will lead to substantial gains. This point remains open.

Hence, it is proposed to work on simple cases, although realistic, in order to address in a technical context not too complex, the issues of validation and procedures, of cost-benefit analysis, organisation, and liability. In this perspective, procedures used for physical homologation tests will be translated into a virtual homologation scheme.

The on-going FP7 call for proposal of the EC is a good opportunity to submit a project of co-operative research on these questions, which should allow to progress on these items and propose action directions for the possible introduction of virtual testing in the regulatory process.

10 REFERENCES :

EVPSN2 – Task 4.3 Virtual testing & modelling. State-of-the-art review (January 2004)

APROSYS, Workshop Virtual Testing in Regulations, 22-23 March 2006, Deliverable D7.2.3B, AP-SP81-003

Haug E., Beaugonin M., Montmayeur N, Marca C., Choi H.Y. – Towards legal virtual crash tests for vehicle occupant safety design using human models. Proc. of ICD 2003

SAE AS 8049a, Performance Standard for Seats in Civil Rotorcraft, Transport Aircraft, and General Aviation Aircraft

List of working documents provided to the group

EEVC_WG22_WD001 Presentation of BASt
EEVC_WG22_WD002 C. Rzymkowski, Presentation of VISEB
EEVC_WG22_WD003 Presentation of UTAC
EEVC_WG22_WD004 Towards legal virtual crash tests for vehicle occupant safety design human models
EEVC_WG22_WD005 C.Rzymkowski, An attempt to estimate virtual testing tools uncertainty
EEVC_WG22_WD006 F. Minne, Virtual testing and Regulation, UTAC
EEVC_WG22_WD007 FIAT, VITES validation and rating of numerical models
EEVC_WG22_WD008 L. Nilsson, Status of crash simulation in Sweden
EEVC_WG22_WD009 CIDAUT Presentation
EEVC_WG22_WD010 ISO/TC22/SC10 N474
EEVC_WG22_WD011 FORD, CAE Model Validation
EEVC_WG22_WD012 Vanderbilt University, Model Validation under uncertainty
EEVC_WG22_WD013 ISO/TC22/SC10/WG6 N2
EEVC_WG22_WD014 Institute of Transportation Systems brochure
EEVC_WG22_WD015 FIAT, Virtual crashworthiness and biomechanics
EEVC_WG22_WD016 Dr H. Gades, Validation guide line
EEVC_WG22_WD017 APROSYS, Workshop on Virtual Testing and Regulation March06
EEVC_WG22_WD018 ASPN Session 2
EEVC_WG22_WD019 Test centres recognized by Italian Ministry of Transport
EEVC_WG22_WD020 Virtual test procedures and type approval(Anlage zur NS II_03 Virtual_Testing)
EEVC_WG22_WD021 VDA, Applications of virtual testing in automotive industry
EEVC_WG22_WD022 PSA, French automotive virtual testing
EEVC_WG22_WD023 UTAC, Virtual testing flow chart
EEVC_WG22_WD024 Overview PRISM for EEVC WG22
EEVC_WG22_WD025 Short overview of APROSYS SP7 for EEVC WG22
EEVC_WG22_WD026 Overview VITES for EEVC WG22
EEVC_WG22_WD027 VT use in aircraft industry
EEVC_WG22_WD028 CIDAUT, Benchmark on explicit codes for safety simulation
EEVC_WG22_WD029_CME presentation.pdf
EEVC_WG22_WD030_activity report to SC.pdf
EEVC_WG22_WD031 cars21finalreport.pdf
EEVC_WG22_WD032_BAST, Public Welfare.ppt

EEVC_WG22_WD033_C. Pastor, Welfare Benefits.doc
EEVC_WG22_WD034_Draft_Report_CIDAUT.doc
EEVC_WG22_WD035_TASS, GeneralObjectiveRating.pdf

11 APPENDICES

11.1 Certification specification in aircraft industry allowing simulation

Citations below are based on the JAR 23 adopted by the EASA as **C**ertification **S**pecification CS 23. For other types of planes similar paragraphs can be found in proper JAR (CS) documents.

<u>CS 23.629 Flutter</u>

(a) It must be shown by the methods of (b) and either (c) or (d), that the aeroplane is free from flutter, control reversal and divergence for any condition of operation within the limit V-n envelope and at all speeds up to the speed specified for the selected method.

In addition –

(1) Adequate tolerances must be established for quantities which affect flutter; including speed, damping, mass balance and control system stiffness; and

(2) The natural frequencies of main structural components must be determined by vibration tests or other approved methods.

(b) Flight flutter tests must be made to show that the aeroplane is free from flutter, control reversal and divergence and to show by these tests that –

(1) Proper and adequate attempts to induce flutter have been made within the speed range up to VD;

(2) The vibratory response of the structure during the test indicates freedom from flutter;

(3) A proper margin of damping exists at VD; and

(4) There is no large and rapid reduction in damping as VD is approached.

(c) **Any rational analysis** used to predict freedom from flutter, control reversal and divergence must cover all speeds up to 1.2 VD.

The point (a) and (b) require experimental in-flight tests.

The last point (c) is allowed to be proven by calculations (it can not be experimentally tested during in-flight test, because the plane is not allowed to cross the speed VD; the 1.2 factor is used to take into account an emergency situations)!

<u>CS 22.307 Proof of structure</u>

(a) Compliance with the strength and deformation requirements of CS 22.305 must be shown for each critical load condition. **Structural analysis may be used only if the structure conforms to those for which experience has shown this method to be reliable. In other cases, substantiating load tests must be made.** (See AMC 22.307(a))

(b) Certain parts of the structure must be tested as specified in Subpart D.

Usually computational methods are sufficient in this case only if experimental test were performed earlier for very similar design.

11.2 Appendix 2 EC funded project related to Virtual testing

11.2.1 PROJECT VITES : VIrtual TESting for extended vehicle passive safety

Objectives

This project deals with virtual testing in vehicle passive safety design. Procedures and guidelines for virtual testing will be developed with the following prime objectives:

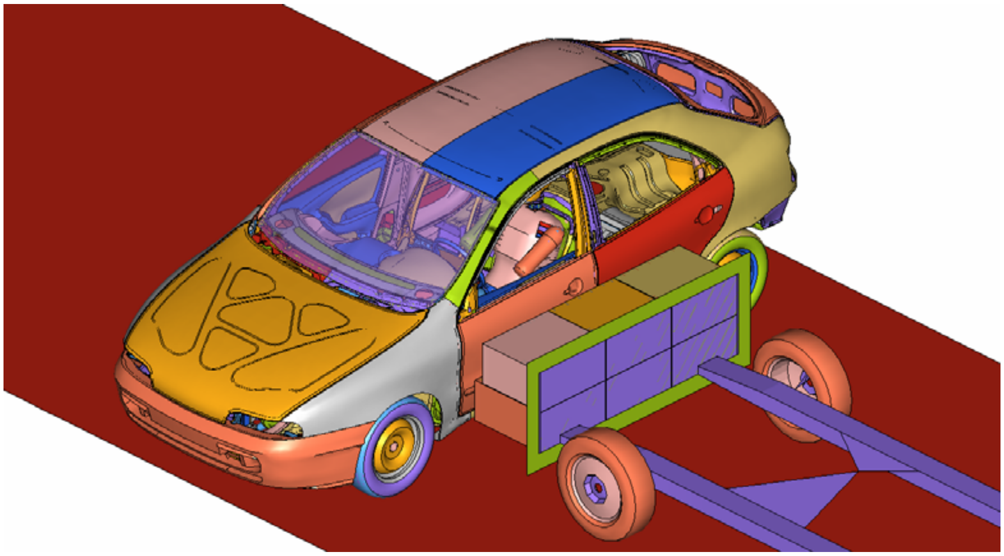
- **To enhance passive safety for a wide range of conditions thus leading to a reduction of injury numbers**. A validated virtual test procedure is developed including frontal and lateral impacts as well as intermediate impact directions for a range of impact velocities as well as occupant body sizes and body positions.
- **To gain efficiency in vehicle design thus leading to a reduction in the duration and costs of the design process**. New procedures and guidelines for model development, validation and application are developed including a method predict scatter in crash test results. These procedures enhance reliability of VT and improve the quality of methods and products.

The focus of the project is on passenger car occupant protection in frontal and side impact collisions as well as intermediate impact directions. The methods developed will, in a more general sense, enhance our capability to address safety for other accident scenarios such as roll over and rearward loading and the protection of vulnerable road users such as pedestrians.

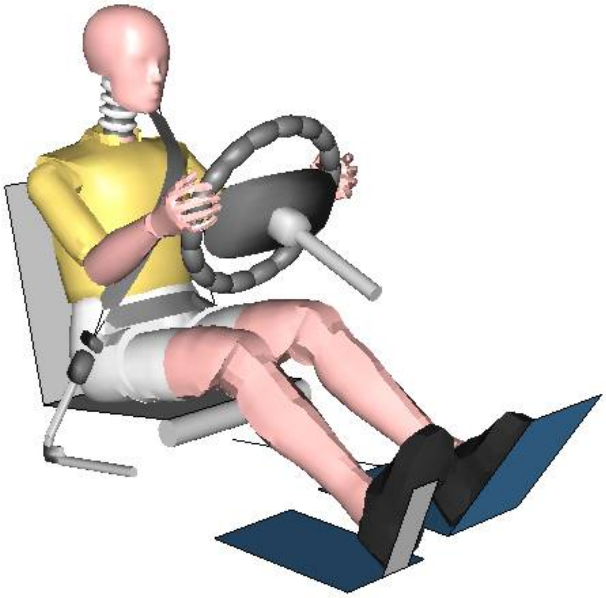
Use of VT

The main innovations resulting from this project are the following:

- Procedures and guidelines developed for virtual testing provide **objective criteria of the quality of models and of the accuracy and reliability of the virtual test results** obtained.
- **One full vehicle model and two vehicle compartment models** enhanced and validated for a wide range of scenarios.
- **A method developed to predict the stochastic response of crash tests** in relation to the scatter of component responses in the system. In particular, the variability of regulated crash dummies is evaluated and implemented in stochastic analysis tool.
- The procedures developed lead to **more effective use of virtual testing as well as to an improved acceptance of virtual testing**. This allows a much more effective use of VT in vehicle design and reduces the need for hardware testing, thus reducing duration and cost of design.
- A **validated virtual test procedure** developed to extend the range of protection beyond current regulations to real life crash conditions.



Full crash side impact simulation



MADYMO stochastic Hybrid-III dummy model

11.2.2 PROJECT ADVANCE : ADvanced Virtual ANalysis of Crash Environments

Objectives

The "Virtual testing technology" Project *ADVANCE* allows in-depth evaluation of vehicle passive safety criteria in advanced design stage. It allows for **meaningful correlation between a numerical model and a real world, thus allowing advanced parametric studies based on "corrected" interpolations and extrapolations of the model**. Simplified "phase one" models may also benefit from this, since **dispersion and uncertainties may be quantified and**

introduced into models, either as fictive structural elements or statistical correction factors. Current "tuned" safety responses may be harmonised and rendered more robust. Structural modelling techniques as well as restraint systems integrated models were reviewed and improved. Car manufacturers as well as design offices may benefit from the guidelines of such insight into the sources of errors and perspectives of the new "robust" modelling techniques.

Structural uncertainties are the primary source of discrepancies in the passenger safety evaluations. **The *ADVANCE* project aims at understanding and relieving such sources or error which lead to erroneous over or under estimations of the passenger safety criteria**. The structural modelling consequences to be studied range from modelling techniques to stability, dispersion and sensitivity considerations. Material behaviour, structural bifurcation due to modelling methods, restraint systems deployment (airbags in particular), welding and dummy modelling interactions will be studied. The sensitivity of the current injury criteria to such modelling consequences will be a primary outcome of this project leading to complementary guidelines and enhancements to the "status of virtual testing" project *VITES*.

Use of VT

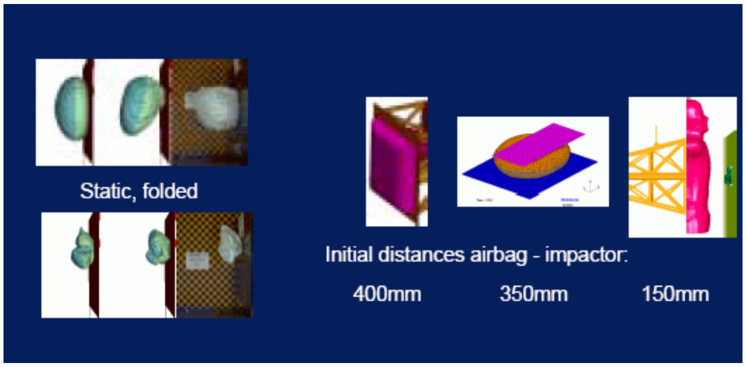
The exploitable project results are:

- Theoretical and implementation enhancements to simulation methodologies, and software (RADIOSS, LS-DYNA, MADYMO; PAMCRASH)
- General purpose evaluation tool for the components, vehicle and dummy response evaluation and rating methodology. (***ADVISER***).
- Improved airbag modelling (Constant pressure, ALE, SPH, CFD, FPM).
- Parametric studies of modelling consequences on dummy injury criteria. (HIII 5%, 50%).
- "Standard" assessments models (bench marks, SLED test models, Full car model of RENAULT MEGANE).
- Experimental data (material, crash boxes, sled tests, spotwelds).

Improvements in VT technology may be summarised as follows:

- **Improvement of structural simulation modelling** (complex deformation modes, meshing, contacts, failure modes, assemblies). In particular it was intended to reduce dispersion (essentially due to uncertainty of data, modelling details such as assemblies and mesh definitions and hourglass energy loss resulting from elements formulations).
- **Improvement of major restraint systems modelling** (airbags inflation and unfolding). The airbag deployment, particularly important for OOP simulations, needs to be much more precise that currently achieved.
- The project aims at the **improvement of complex material behaviour modelling** (foams, rubbers, plastics, composites). Current material modelling and identification parameters, specially for strain rate dependencies.
- **Generalised simulation evaluation methods and tool** are to be devised for an industrial end use.
- **Reliable experimental data for models input** (parametric studies on dummy response).

ADVISER Objective evaluation tool. Developed within ADVANCE project.



Benchmarking on airbag modelling techniques based on static and dynamic testing.

REFERENCE: *ADVANCE Technological implementation plan Part 1.*

11.2.3 PROJECT PRISM

Proposed Reduction of car crash Injuries through improved SMart restraint development technologies

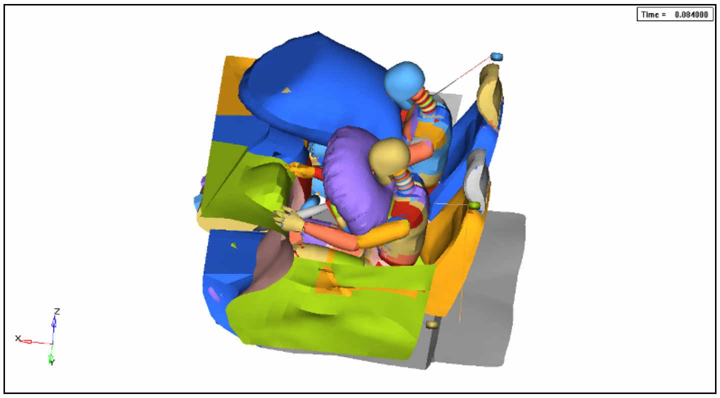
Objectives

This project has dealt with a number of issues regarding the **implementation of smart restraints, including the assessment of the likely effects of the implementation of different types of smart restraints in terms of injury benefit**. The project has also contributed to the core information set and mathematical tools for the development and implementation of such systems in an efficient manner. Finally, it has produced guidelines for the functionality and the validation of such restraint systems.

Use of VT

Within this project, no physical testing has been performed. **All the research work has been made through virtual testing**. Besides, the main deliverables of the project (injury benefit, guidelines…) are based in comparisons between different MADYMO models. The project has been focused to frontal impacts.

Baseline MADYMO models have been built up from interior geometry measurements of representative production vehicles from different vehicle types (super-mini, MPV and large family cars), including belt and airbag for frontal passengers. Advanced and smart restraints have been implemented to the models in order to evaluate different behaviours between baseline and updated models.



PRISM MPV MADYMO Model

11.2.4 PROJECT RISER

Roadside Infrastructure for Safer European Roads

Objectives

This project was focused on roadside safety, that is to say, the risks and consequences of vehicles leaving their travel lane and experiencing impact events in the areas bordering the roadway. The main goal of the RISER project was **to provide a technical foundation upon which the implementation and operation requirements for European roadside areas and infrastructure could be based**. Specific objectives were:

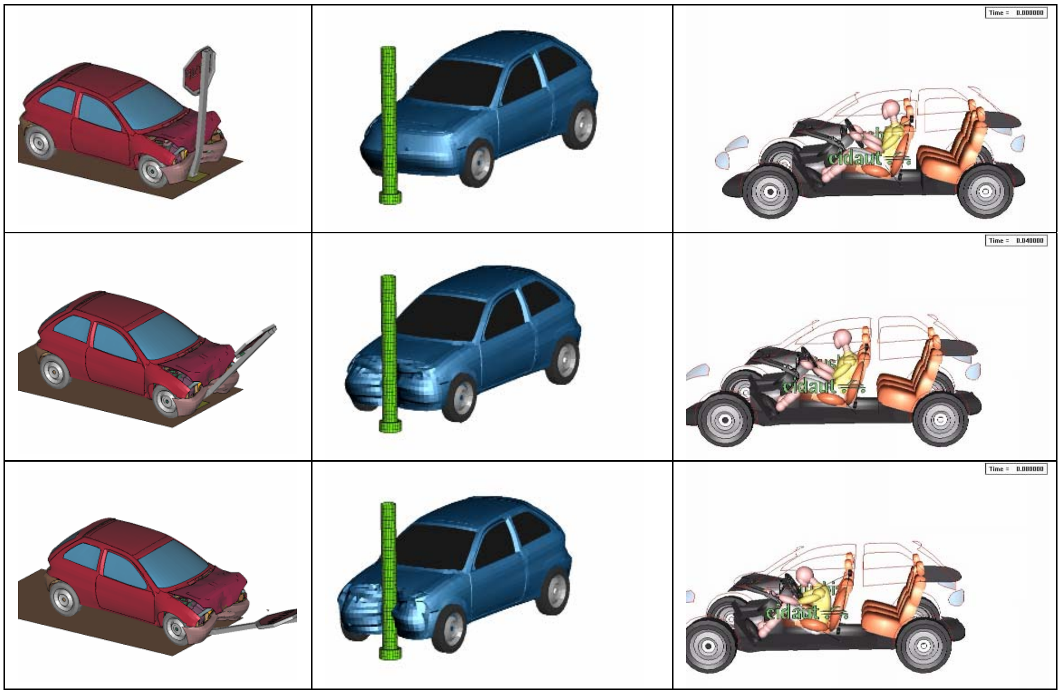
- To develop a database(s) with information describing run-off-road crashes.
- To analyse the interaction of roadside infrastructure with vehicles and drivers, from various points of view: from the mechanical analysis of the impact response, to human factors.
- To develop a set of best practice guidelines that will improve the state of roadside safety in Europe.

Use of VT

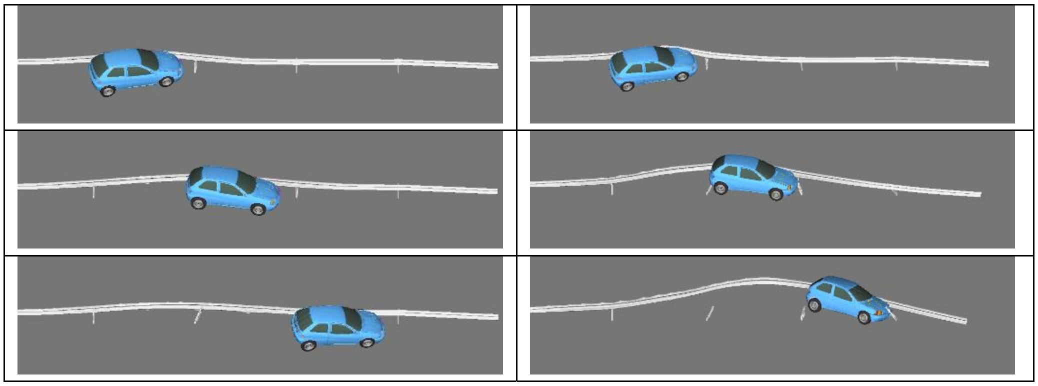
Simulation was used in the project to **analyse the impact phenomena that take place on roads**. The involved "hit objects" addressed were mainly of two types:

- Fixed, narrow-shaped point obstacles, such as trees, poles and posts, and
- Continuous and generally deformable objects, such as safety barriers.

Test standards (*EN 1317*, *EN 12767*) assess the passive safety behaviour of roadside poles and barriers by full-scale crash testing in certain impact conditions. In RISER, **computer models of generic systems allowed studying their behaviour in different conditions that can occur on roads**. The activity provided detailed description of crashes, in terms of vehicle kinematics, loads and deformations taking place on road restraint systems, and the effects on vehicle occupants. These **results supported the composition of the roadside safety guidelines** that were part of the RISER project output.



Simulations of impacts between vehicles and fixed narrow objects. Occupant response inside the vehicle.



Comparison between different vehicle-barrier interactions in real life accidents. Proper containment (left) vs insufficient containment due to overloaded anchorage (right)

11.2.5 PROJECT ROBUST

ROad Barrier Upgrade for STandards

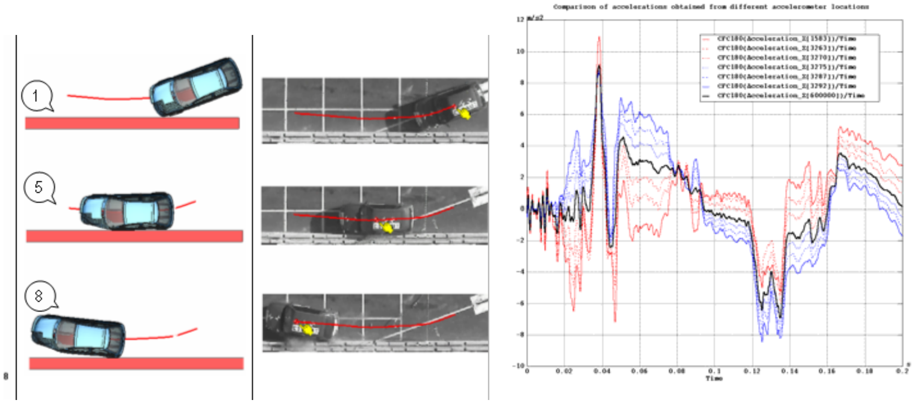
Objectives

ROBUST was a project intended **to develop the technical basis for the next update of *EN1317* by the standardisation working group *CEN/TC226/WG1***. EN1317 is the current European Standard for the safety evaluation of road restraint systems. The standard defines procedures for full-scale crash testing, and identifies impact test tolerances and performance criteria that need to be met by the systems to gain approval. In this context, ROBUST aims to constitute a rationale with scientific and technical knowledge acquisition on the main issues still open in CEN standards on road restraint systems.

Use of VT

ROBUST work plan included a **work package devoted specifically to simulation (*Computational mechanics*)**. Its main objective was **to analyse the possibility and the ease of use of computational mechanics as a complement to full-scale test**, e.g., for performance evaluation in off-standard conditions, to help the choice of critical impact points, to accept small modifications, etc. In order to do this, **validation criteria together with qualification procedures need to be defined**.

Performed work included the simulation of crash tests, i.e., modelling impacts of vehicles against various types of barriers in normalised test conditions. From these results, analysis were performed on research topics such as the correlation level of the simulations, influence of variations in test parameters, and procedures for the measurement and acquisition of relevant variables -such as accelerations- in simulations.



Simulated and real impact test between passenger vehicle and rigid barrier.

11.2.6 PROJECT APROSYS

Advanced PROtection SYStems

SP4 – Motorcycle Accidents

Objectives

The purpose of this sub-project is to **reduce the number and severity of powered two wheelers** (PTWs) (including mopeds) **user injuries** for the most relevant vehicle accident types by means of an in-depth analysis of the different accident scenarios in which motorcyclists are involved, focusing on:

- Providing **guidelines to test the performance of the infrastructure with regards to motorcyclists** and developing new systems that could protect the riders.
- **Motorcyclists advanced protection systems**, improving the performance of helmets and protective clothing.

Use of VT

In APROSYS SP4, virtual tools are used in the following issues:

- **Providing guidelines** for a future European Standard: trajectories of motorcyclists impacting into roadside barriers and obstacles (trees, poles, signs) will be identified by means of numerical simulation using MADYMO and ADVISER.
- Investigation into the **main injury mechanisms** relevant to impacts of motorcyclists into infrastructure using the **HUMOS model**.
- Comparison between different dummy models and the **HUMOS to select a valid dummy representing motorcyclists** sliding on the road surface and hitting infrastructure.
- Adjustment of the parameters of the standard. **Analysis of the sensitivity** of the outputs (dummy values) to slight variations of the inputs.
- Development of **new impact protectors**.
- Analysis of the helmet **standard *ECE R22/05***.
- **Analysis of the kinematics** of rider and PTW in impacts of motorcyclists vs. passenger cars, to identify the working parameters of a safety system that could be implemented in the rider garment and activated just before the impact.

11.2.7 PROJECT APROSYS

Advanced PROtection SYStems

SP5 – Biomechanics

Objectives

The general objective of SP5 is to provide the other APROSYS Sub-Projects with predictive tools enabling them to address the most life threatening and high societal cost injury types encountered in the accident scenario addressed by these Sub-Projects. Among these tools are the human body numerical models.

Development of VT

The work undertaken in HUMOS projects (see below) to build whole human body FE models is continued in order to improve the simulation capabilities and the predictability of injuries.

11.2.8 PROJECT APROSYS

Advanced PROtection SYStems

SP6 – Intelligent Safety Systems

Objectives

The objective of this Sub-Project is the **development, realisation and verification of novel side pre-crash systems for road user protection**. This includes system definition, realisation of suitable sensing systems, the development of new actuators for side pre-crash applications as well as the system integration and testing. Main SP6 objective is a **technology showcase showing the potential of a combination of different advanced technologies to be developed for further crashworthiness improvement**. It is not the objective to improve crashworthiness of a specific car. Therefore, technology will be shown in a generic car structure rather than in a specific model.

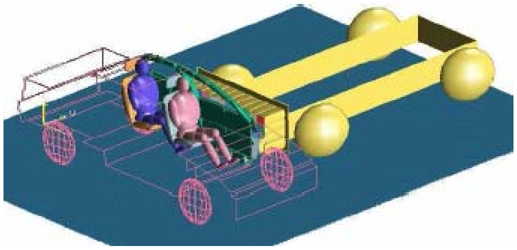
In this sub-project further progress in car safety technology is envisioned from the use of **pre-crash systems**. Such systems make use of sensing which looks around the vehicles. So triggering information can be available prior to the impact. This enables the use of actuators which are somewhat slower than pyrotechnical ones. Typical pre-trigger times are a few hundred milliseconds corresponding to a pre-trigger distance of 0.5 to 5 m. The adaptable actuators to be used in the subproject change the car structure based on intelligent or smart material systems that will reduce the peak acceleration of the passengers and to reduce the intrusion.

Work in this sub-project has been divided into 5 work packages reflecting the general work flow: system definition (WP 6.1), sensor systems (WP 6.2), actuators (WP 6.3), system integration (WP 6.4) and testing (WP 6.5).

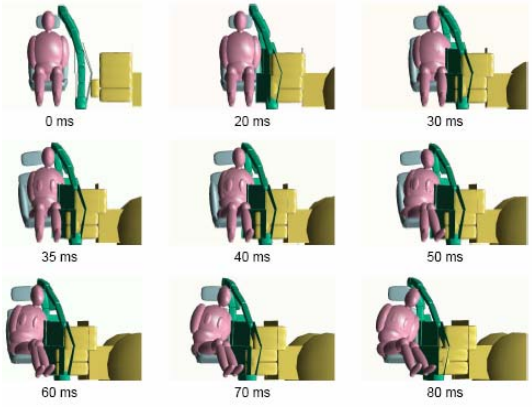
Use of VT

The improvement on the side impact protection may require an intelligent actuator at the level of the structural components of the vehicle side structure, i.e., front and rear doors, B-pillar, roof and floor or even at the level of the seat module. That actuator is required to absorb a given amount of energy, to control the maximum intrusions on the survivability space of the occupants and to improve the aggressiveness of the contact of the side structure to the occupants.

The development of the active actuator for improved side impact protection requires that the initial concept is identified. **The actuator concept was defined using multi-body (MB) analysis tools** by providing results and trends for the deformation, intrusion velocities and accelerations for various actuator concepts and setups.

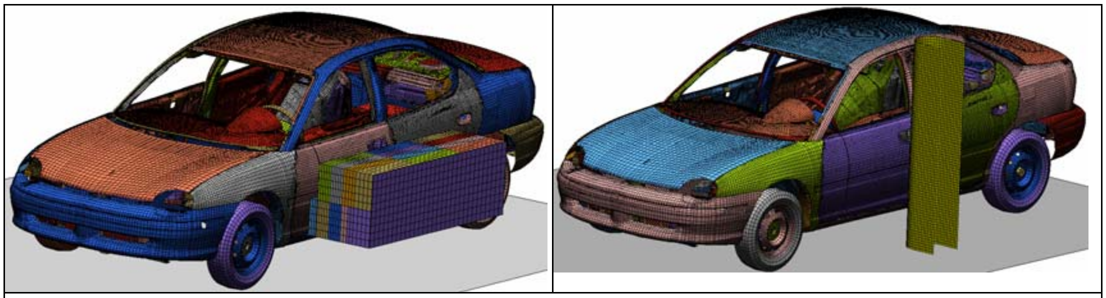


Multi-bodies side impact model



Kinematics of the side crash

After the initial concept was defined, the development process started. This development process of the actuator system is an iterative procedure in designing, testing and redesigning the part. The **procedure in designing and redesigning was carried out by using finite elements simulations**. Two type of impact have been considered: EuroNCAP side barrier test and pole test.



Full car crash model (side barrier and pole tests)

11.2.9 PROJECT APROSYS

Advanced PROtection SYStems

SP7 – Virtual Testing

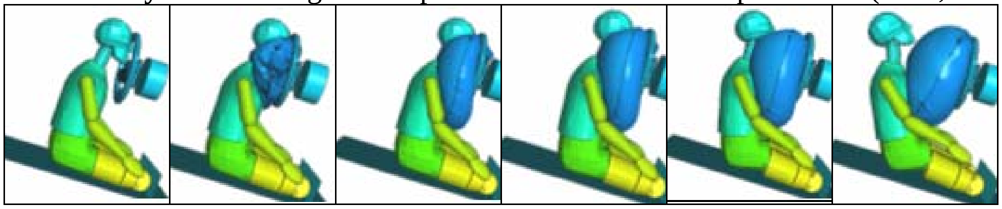
Objectives

The objective of this Sub-Project is **to develop a particular innovative methodology, with computer based crash simulations as its core instrument, which combines most enhanced modelling techniques along with quality control assessment tools and procedures, allowing for regulated thus most predictive and reliable evaluations**. It is a common belief that experimental assessment crash evaluation programmes such as EuroNCAP have contributed effectively to the improvement of current passenger vehicles. The Virtual Testing sub-project has the ambitious objective of paving the way for similar breakthroughs with much more flexibility and diversity, due to the cost-effective and non-destructive nature of computer simulations of real world accident scenarios.

Work in this sub-project has been divided into 4 work packages reflecting the general work flow: virtual testing models (WP1), virtual testing methods (WP2), virtual testing tools (WP3) and virtual testing applications.

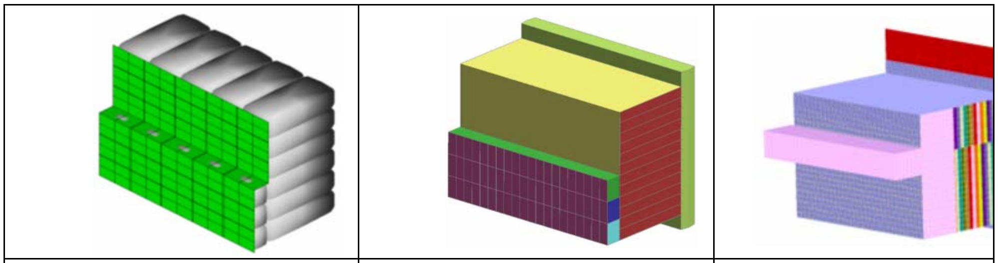
Use of VT

- **Dummy models developments**: manufacturing updates and modifications to the existing dummies are being done in order to provide to the other APROSYS sub-projects the specific dummies that fulfil their requirements.
- **Restraint systems**: airbags out of position simulations were performed (CFD, ALE, FPM)



OOP simulations FPM

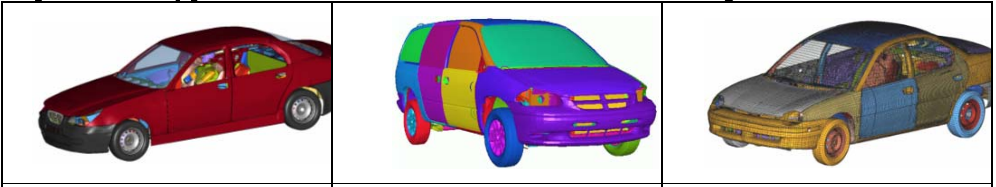
- **Barrier models**: numerical models of new deformable barriers types are being developed, validated and improved



Multi-body ODB Barrier | *FE ODB Barrier* | *FE PDB Barrier*

Barrier models

- **Generic vehicle models**: generic means that the models represent a certain car class, but not a specific cat type. FE and multi-bodies car models are being built.



GCM3 *GCM4* *GCM5*

Generic FE car models

- **Material and assemblies**: modelling and simulation techniques suffer from certain deficiencies in the description of mechanical behaviour under complex loading conditions. Independent of the material, open questions remain in areas such as fracture, strain rate sensitivity or statistical scatter of properties, and specifically with respect to the representation of these characteristics in simulation. Specific aspects from this research domain have been covered by the investigations performed in this sub-project.
- **Robustness and reliability assessment in crash design (stochastic analysis)**: test conditions → EuroNCAP frontal and side impact. The studies are being developed taking into account different dummies, Hybrid III (frontal), EuroSID2 (side) and Humos model (frontal and side).

11.2.10 PROJECT STORHY

HYdrogen STORage systems for automotive application

SP SAR – Safety Aspects and Requirements

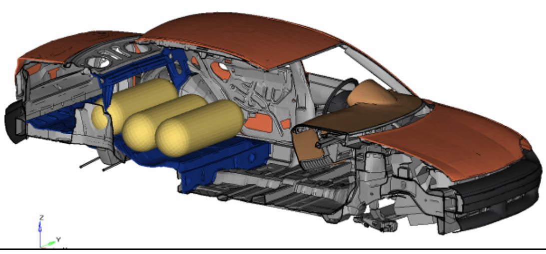
Objectives

The sub-project SAR comprises **all safety relevant issues regarding the different storage technologies for hydrogen**. These assessments are focused on statistical material properties, typical load distributions, pressure-relief devices, sensors, accident typologies, interaction crash behaviour of storage receptacles and chassis, and existing European, Japanese and US regulations.

Use of VT

Finite element tools are being used to analyze the crash behaviour of the tanks in a full-vehicle crash. The optimal survival configuration will be identified as a function of the most probable crash scenarios.

FE models; different test configurations



FE car model + tanks

11.2.11 PROJECT STREP HELISAFE TA

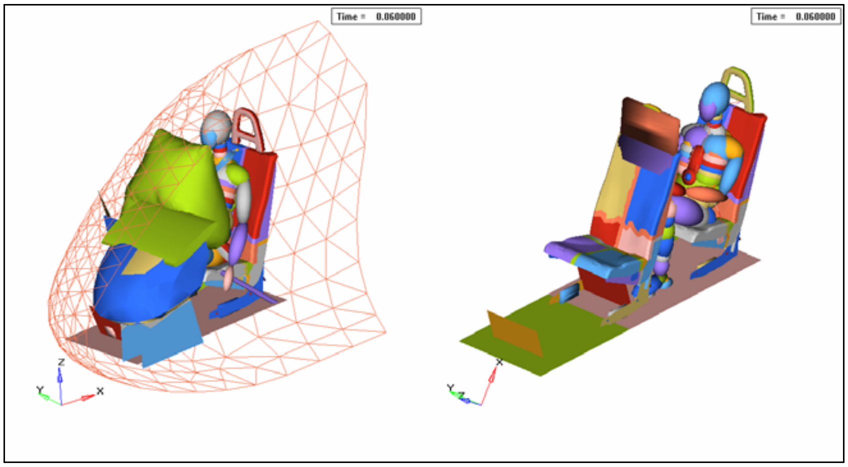
HELIcopter occupant SAFEty Technology Application

Objectives

The aim of HELISAFE TA is to apply knowledge gained in the EU-project HeliSafe **to save lives and to mitigate the consequences of survivable aircraft accidents under real world crash conditions**. The scientific challenges are a better understanding through full-scale tests and computer modelling of helicopters crash dynamics, and improved knowledge of human body limits and injury criteria.

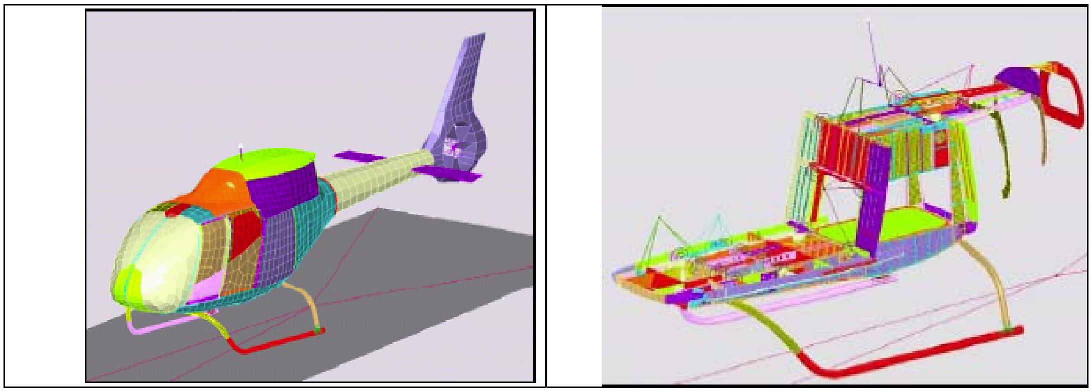
Use of VT

Within this project, **different computational models are developed under different codes**. A Bell UH-1D model has been developed with DRI-KRASH to asses crash pulses related to different crash configurations; this model has been validated with respect to a complete helicopter drop test. MADYMO models for the cockpit mock-up and for the cabin mock-up have also been developed. These models will be validated through sled testing and will be used to carry out parameter studies and also to asses improved restraints with respect to occupant injuries. A Bell UH-1D MADYMO model has also been developed to perform parameter studies as well as an EC120 RADIOSS model. It is also planned to develop an Abaqus cabin mock-up model.

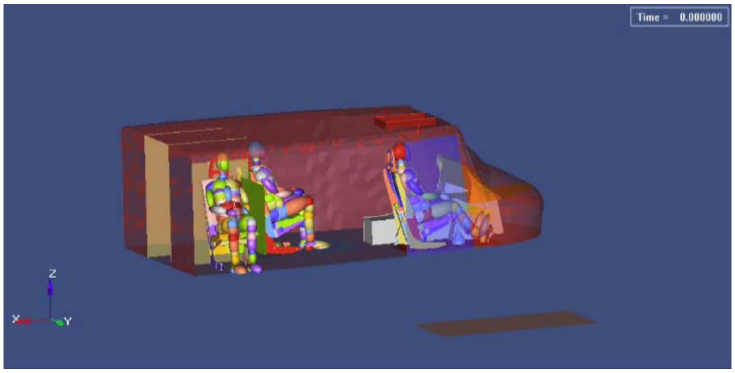


MADYMO Cockpit Mock-up Model ***MADYMO Cabin Mock-up Model***

DRI-KRASH Bell UH-1D Model



EC120 RADIOSS Model



MADYMO Bell UH-1D Model

11.2.12 HUMOS (1 & 2) Human model for safety

Objectives
The objective of the EC funded HUMOS2 project was to develop a set of Finite Element models of the human body capable to represent a large range of the population of road users involved in any type of road accident and allowing an accurate prediction of the injury risk.

Development of VT
Various experimental activities were devoted to the collection of basic data needed to develop and refine human body models, starting from a first generic version of a sitting average male.

Three finite element whole human body models were implemented on 3 different FE crash codes and have been used to simulated a set of chosen cases in order to evaluate their performance in terms of behaviour biofidelity and injury prediction capability. Results show that good overall kinematics of the human body can be reproduced in various accidental situations. Body part loading can be calculated and resulting injury risk evaluated. Some improvements are still necessary to improve the robustness of the model in certain cases and extensive testing against real accident cases should be performed in order to fully validate the models. Part of this work is being conducted in the APROSYS/SP5 EU funded integrated project.

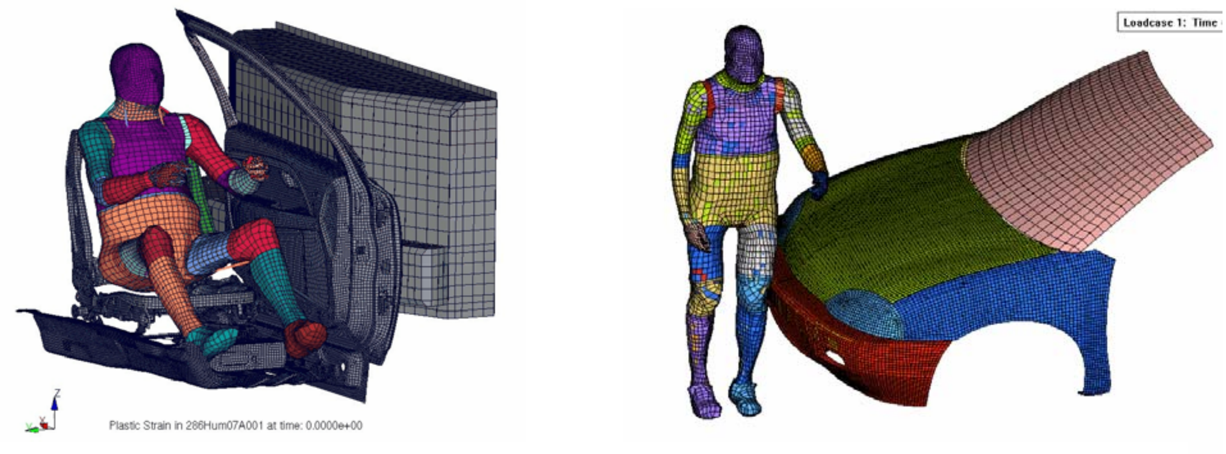


Fig. 5 – Simulation of a car occupant in side impact (left) and of a pedestrian (right) with the HUMOS2 50th male model.

11.3 Appendix 2 : regulations for which VT could be used

- Reg110 : GNV tanks anchorages
- Reg66 : Bus rollover
- R67 GPL tanks anchorages
- Reg 21 : impacts in dashboard
- R11 : door locks
- Reg29 : lorry cabin deformation
- 78/549 : CAD for wheel arches
- 2003/97(reg46) : CAD for mirrors retrovision
- 2001/192 : pedestrian CAD test zone

11.3.1 R110 CNG tanks APPROVAL OF SPECIFIC COMPONENTS OF MOTOR VEHICLES USING COMPRESSED NATURAL GAS (CNG) IN THEIR PROPULSION SYSTEM

§17.4.4. The fuel container(s) or cylinder(s) must be mounted and fixed so that the following accelerations can be absorbed (without damage occurring) when the containers are full:

- Vehicles of categories M1 and N1:
    - 20 g in the direction of travel
    - 8 g horizontally perpendicular to the direction of travel
- Vehicles of categories M2 and N2:
    - 10 g in the direction of travel
    - 5 g horizontally perpendicular to the direction of travel
- Vehicles of categories M3 and N3:
    - 6. 6 g in the direction of travel
    - 5 g horizontally perpendicular to the direction of travel

A calculation method can be used instead of practical testing if its equivalence can be demonstrated by the applicant for approval to the satisfaction of the technical service.

11.3.2 R66: Bus rollover (1/2) Annex 6

1.1.1.1 Verification of strength of superstructure by calculation

- A superstructure or sections of a superstructure may be shown to meet the requirement specified in paragraph 5. 1. of this Regulation by a calculation method approved by the technical service responsible for conducting the tests.
- If the structure is likely to be subject to deformations beyond the elastic limit of the materials used then the calculations shall simulate the behaviour of the structure when undergoing large plastic deformations.
- The technical service responsible for conducting the tests may require tests to be carried out on joints or parts of the structure to verify the assumptions made in the calculation.

1.1.1.2 Preparations For Calculation

- 4. 1. Calculations **cannot be started until the structure has been analysed** and a mathematical model of it produced. This will define the separate members to be considered and identify the points at which plastic hinges may develop. The dimensions of the members and the properties of material used must be stated. Physical tests must be made on the hinge points to determine the force (moment of rotation) - deformation characteristics in the plastic mode as this is essential data for the calculations. The strain rate and the dynamic yield stress appropriate for this strain rate must be determined. If the calculation method will not indicate when a significant fracture will occur it will be essential to determine, by experiment, separate analyses or appropriate dynamic tests that significant fractures will not occur. The assumed distribution of loading along the length of a vehicle shall be stated.

- 4. 2. The calculation method shall include the deformations up to the elastic limits of the materials followed by the identification of where plastic hinges will form and the subsequent formation of other plastic hinges unless the position and sequence of formation of plastic hinges is known from previous experience. The method shall accommodate the changes of geometry of the structure that take place, at least up to the stage where the deformations have passed the acceptable limits. The calculations shall simulate the energy and the direction of impact which would occur if that particular superstructure were to be submitted to the roll-over tests prescribed in annex 3 .
- The validity of the calculation method shall have been established by comparison with the results of physical tests, which need not necessarily have been made in connection with the vehicle now being approved.
- R67 LPG tanks anchorages §1. 6. 2. Calculation of the parts under pressure for all-composite containers The stresses in the container shall be calculated for each container type. The pressures used for these calculations shall be the design pressure and burst test pressure. The calculations shall use suitable analysis techniques to establish stress distribution throughout the container."
- §17.4.6. The fuel container(s) must be mounted and fixed so that the following accelerations can be absorbed (without damage occurring) when the containers are full:
  - Vehicles of categories M1 and N1:
    - 20 g in the direction of travel
    - 8 g horizontally perpendicular to the direction of travel
  - Vehicles of categories M2 and N2:
    - 10 g in the direction of travel
    - 5 g horizontally perpendicular to the direction of travel
  - Vehicles of categories M3 and N3:
    - 6. 6 g in the direction of travel
    - 5 g horizontally perpendicular to the direction of travel

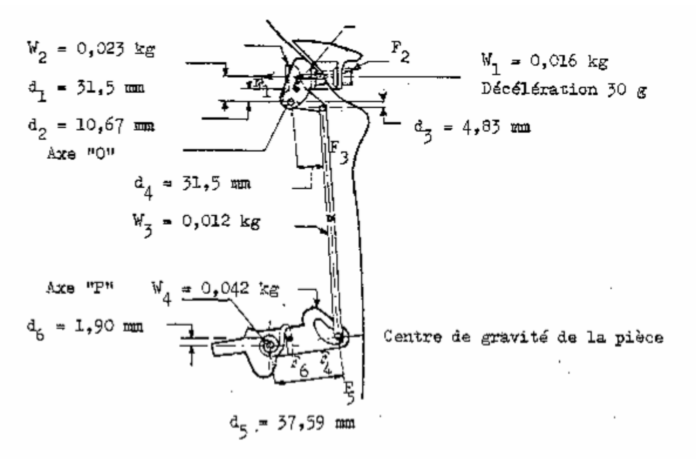
A calculation method can be used instead of practical testing if its equivalence can be demonstrated by the applicant for approval to the satisfaction of the technical service.

11.3.3 R21: impacts in dashboard Annex 8 : DETERMINATION OF A DYNAMICALLY DETERMINED HEAD IMPACT ZONE

4. The manufacturer or his representative is entitled to present calculations, simulations, test data or test results which sufficiently prove the dynamically determined head impact zone.

11.3.4 R11 : door latches Annex 3 TEST PROCEDURE FOR THE DOOR LATCHES AND DOOR RETENTION COMPONENTS

4. 1. Equivalent non-destructive test methods are permitted, provided that the results referred to in paragraph 5. of the Regulation can be obtained either entirely by means of the substitute test or by calculation from the results of the substitute tests.



11.3.5 R29: lorry cab deformation

§5.5.Tests B and C need not be carried out if the manufacturer can show by calculations of the strength of the component parts of the cab or by other means that the roof or rear wall will not undergo deformation dangerous to the occupants (penetration into the survival space) if subjected to the conditions of tests B and C.

Roof strength (test B)

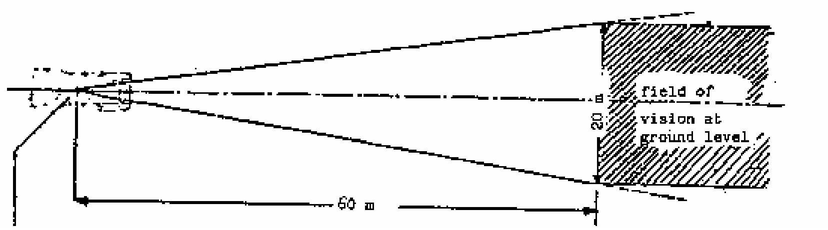
The roof of the cab shall withstand a static load corresponding to the maximum mass authorised for the front axle or axles of the vehicle, subject to a maximum of 10 tonnes. This load shall be distributed uniformly over all the bearing members of the roof structure of the driver's cab or compartment by means of a suitably-shaped rigid former.

Rear-wall strength (test C)

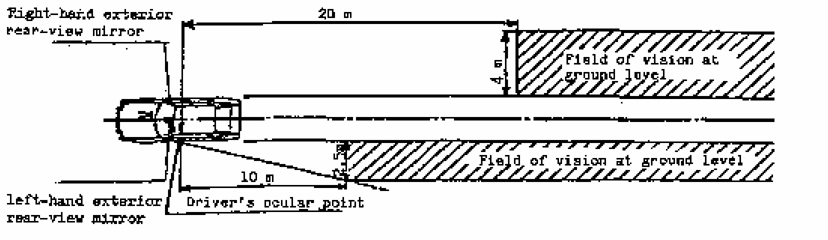
The rear wall of the cab shall be capable of withstanding a static load of 200 kgf per tonne of permissible useful load. This load shall be applied by means of a rigid barrier perpendicular to the longitudinal median axis of the vehicle, covering at least the whole of the cab rear wall situated above the chassis frame, and moving parallel to that axis.

11.3.6 2003/97(R46) : CAD for retrovision : Annex 6 REAR-VIEW MIRROR FIELDS OF VISION AT GROUND LEVEL

- **I. INTERIOR REAR-VIEW MIRROR (Class I) (see paragraph 16. 5. 2. of this Regulation)**

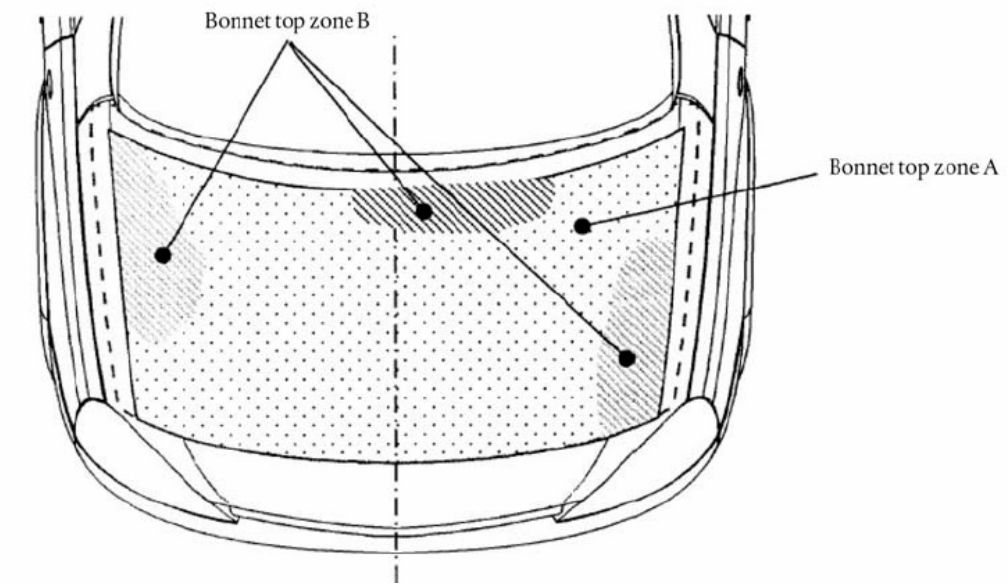


- **II. EXTERIOR REAR-VIEW MIRRORS (EXAMPLES OF VEHICLES DRIVEN ON THE RIGHT)**



11.3.7 2001/192 : pedestrian test zone

CAD : 3.3.2. Marking of the ‘bonnet top' impact area as well as ‘bonnet top zone A' and ‘bonnet top zone B' will be based on a drawing supplied by the manufacturer (…).



11.3.8 78/549 : CAD for wheel arches : Allowed in France to present CAD instead of a car for type approval