Executive Summary:

The IMVITER project is an EU FP7 funded research project which aims to promote the implementation of Virtual Testing in Safety Regulations. The consortium is comprised of 15 partners from Germany, France, Italy, Spain, Hungary and Greece, and represents the main actors involved in the EC motor vehicle type approval process.

In IMVITER Virtual Testing is considered as the use of simulation models (numerical calculations) in the assessment of regulatory acts, replacing or supporting test methods. This represents that the evaluation of type approval technical requirements is assessed with numerical predictions.

All new vehicles in the EC shall meet a number of technical requirements before being allowed to reach the market. The EC Whole Vehicle Type Approval Framework Directive 2007/46/EC is a system allowing a vehicle design to be "type approved" for sale, and comprises all those requirements. For the first time, Virtual Testing is recognised as an assessment method, and can be used in a limited number of regulatory acts. IMVITER ambition is to further introduce and extend the use of VT within the existing regulatory framework, in order to improve the competitiveness of the European automotive industry.

Four regulatory acts are selected as pilot cases for the implementation of VT; two of them related to pedestrian protection in case of impact (head and lower leg), one dedicated to the assessment of seat belt anchorages strength, and a fourth one for the evaluation of the vehicle towing devices. These so named pilot cases are chosen to represent different levels of modelling complexity from the simulation point of view.

A key aspect in the implementation of VT is the assessment of simulation models predictability. VT methods shall provide for the same level of confidence as physical tests, as stated in the framework Directive. For that reason the Verification and Validation (V&V) methodology is adapted to the particular needs of the project. V&V activities are defined to collect evidences to demonstrate that simulation models being used in VT are reliable and provide accurate predictions. Those requirements are described both for simulation codes and models.

Depending on the regulatory act, different approaches are defined in the implementation of VT. Full VT is defined when only simulation predictions are used in the assessment of regulatory act requirements. Hybrid VT combines both test and simulation results, while Extension of Approval based on VT takes advantage of a previously validated simulation model, to assess new versions or variants only with simulation. Furthermore, a Further Type Approval based on VT approach is proposed when the extension is applied for different vehicle types. All VT approaches consist on a

three phase process; phase 1 for Verification, phase 2 for Validation and phase 3 for the assessment of Type Approval requirements.

Validation plans are defined and carried out for each pilot case. A number of validation tests and simulations are preformed in order to create the necessary background to define the validation requirements that simulation models shall meet, as well as the corresponding validation criteria and metrics for each.

Templates are defined for the exchange of sensitive information between carmakers and Technical Services, aiming to avoid confidentiality issues. The whole process is refined thanks to its actual implementation. A comprehensive Cost-Benefit Analysis of the proposed VT approaches gives clear indications on the savings that can be expected in short and long term with the implementation of VT, and also warns about situations in which no advantage is obtained.

Moreover, new technologies used in pedestrian protection are considered, and based on the knowledge created in the pilot cases, approaches for their assessment based on VT methods are defined, including indications on what would be needed in case human body models were improved up to a point in which they could be used to design safer vehicles, and later in a potential VT application for type approval. The consortium gives indications on what are the next steps that should be taken in the implementation of VT in the next decades.

Project Context and Objectives:

Computer aided engineering (CAD) is a routinely used technology for the design and testing of road vehicles, including the simulation of their response to an impact and the prediction of the risk of injuries sustained by the potential victims. But, so far, the release of a vehicle on the market still depends on the verification of the product compliance with safety standards through a series of type approval physical tests. Vehicles in the EC market shall fulfil some minimum technical requirements, according to its type (including safety related ones). The assessment of those requirements imposes a number of tests, which despite being essential, entail a burden in terms of cost and time to the European automotive industry.

Virtual Testing (VT) can be defined as the assessment of any kind of requirement imposed on a physical part or system, which is conventionally accomplished through some kind of test, but performed using a numerical model instead. Thus VT inherently replaces tests (also named Real Testing RT) by simulation models and test results by simulation predictions.

Currently, the use of CAD is allowed to demonstrate compliance with dimensional requirements (dimensional checks) and also several static tests are being replaced in the last years by virtual tests. However the use of VT can be extended to incorporate the assessment of further technical requirements. One example are those involving mechanical loading of vehicles, components or separate technical units. Depending on the loading conditions that shall be applied to a vehicle or part, and the main physics phenomena involved, VT could assess:

- linear deformations produced by static loads (which could be considered as a simple case, e.g. Regulation 77/389/EEC)
- up to non linear deformations produced by dynamic loads (which would be one of the most challenging, e.g. Regulation (EC) No 78/2009)

It is beneficial for all the parties involved (automotive industry, regulatory bodies and users) to study the possibility of a higher content of VT within the existing and future vehicle type approval procedures. For this purpose, recommendations for the implementation of VT techniques in currently existing RT based type approval procedures are being worked out. Besides key issue is to analyse how VT could result in cost reductions and increase European car manufacturers' competitiveness by substituting a set of RT by VT.

Since CARS 21 High Level Group[1] recommended [2] the implementation of VT as a way to improve the European automotive sector competitiveness, the European Commission in the following years has taken the necessary steps to accomplish that challenging objective. The recently published Commission Regulation No. 371/2010 has opened the door to its practical implementation. In fact this project itself is another effort to further introduce and promote the use of VT in safety regulations, more precisely in this case addressing the EC Whole Vehicle Type Approval Directive (ECWVTA) 2007/46/EC, and its corresponding annexes.

The key objective of the IMVITER project is the implementation of Virtual Testing (VT) in existing type approval procedures, and particularly in safety related regulatory acts, by consolidation of advanced VT technologies. The project objective can be broken down in the following particular objectives:

- Identify current physical tests under specific type approval regulatory acts that could be candidates for replacement by VT, based on technical, economical and institutional aspects.
- Development of VT implementation procedures, fully substituting RT in particular regulatory acts, and/or combined with RT (e.g. pedestrian protection legislation).
- Development of simulation models validation criteria independent of software platform or performing organization.
- Investigate the introduction of stochastic methods, reliability analysis and robustness optimisation in the VT framework.
- Enhancement of the accuracy and reliability of type approval requirements assessment, due to the ability to better check points of interest via VT.
- Reduction in costs and number of real tests. The car market demands more and more niche products leading to high increase in number of models and car components which have to be type approved.
- Define procedures for VT including validation of virtual test devices (pedestrian protection impactors). Analyse the feasibility and potential of these procedures.
- Investigate the possibility to transfer the process of VT to assess new advanced safety systems (active and pre-crash safety systems).

IMVITER is part of a long term process which is expected to lead step by step to a complete electronic certification. It is important to address today the technical feasibility, institutional acceptability and economic benefits and cost of introducing VT by working on simple cases. Technology development in this field will progressively provide the automotive industry with more and more realistic and reliable models. The achievement of this objective implies among others, that the accuracy and reliability of the simulation models and related procedures can be assured and rated independently of the modelling process, software tools, computing platform and the performing organizations. Thus, one of the obstacles of the use of VT in type approval is addressed: the lack of confidence in simulation tools for the assessment of type approval requirements. The project is developing evidences to prove the reliability of simulation techniques under certain safety directives. The work is based on the background of previous EC projects such as VITES, ADVANCE and APROSYS. Now the need is to apply that knowledge.

The main focused safety area is pedestrian protection, which has been identified as one of the fields with greatest advantages and potentials for VT implementation. Based on the experience of all the stakeholders taking part to IMVITER, it can be asserted that numerical simulation is highly predictive for the assessment of pedestrian protection safety requirements. Moreover, studies carried out in previous EC projects such as APROSYS concluded also that the implementation of VT in type approval with regards to pedestrian protection directives, could not only lead to tangible benefits in terms of injury reduction, but also in terms of cost reduction in vehicle design.

Participation of all the stakeholders involved in the vehicle type approval process is essential, maintaining a dialogue between industry (car manufactures and equipment suppliers) and regulatory bodies, working together in order to build up a common vision and common understanding regarding the use of VT in vehicles type approval. Also experts of EEVC WG22 (Virtual Testing) and software developers are participating in IMVITER.

Introduction of VT in the vehicle type approval process poses a challenge to all involved stakeholders, and especially to technical services, which will be the institutions responsible to put VT in practice. Besides the use of simulation techniques is a totally new skill to be learnt by technical services, whereas carmakers already do have the necessary knowledge and technical means. Thus a close relationship will have to be established between stakeholders, specially considering that management and exchange of sensible data will be a key issue.

Project Results:

INTRODUCTION

All new vehicles in the EC shall meet a number of technical requirements before being allowed to reach the market. The EC Whole Vehicle Type Approval Framework Directive 2007/46/EC is a system allowing a vehicle design to be "type approved" for sale, and comprises all those requirements. For the first time, Virtual Testing is recognised as an assessment method, and can be used in a limited number of regulatory acts.

The IMVITER project is an EU FP7 funded research project which aims to promote the implementation of Virtual Testing in Safety Regulations. The consortium is comprised of 15 partners from Germany, France, Italy, Spain, Hungary and Greece, and represents the main actors involved in the EC motor vehicle type approval process.

Within this project Virtual Testing is considered as the use of simulation models (numerical calculations) in the assessment of regulatory acts, replacing or supporting test methods. This represents that the evaluation of type approval technical requirements is assessed with numerical predictions.

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SELECTION OF PILOT CASES TO DEMONSTRATE VT IMPLEMENTATION

The first step was to draft a list of pilot cases in which implementation of VT was to be accomplished. From all the possible regulatory acts that could be addressed, defined by the Framework Directive 2007/46/EC, no specific preferences existed apart from the initially agreed priority of addressing the pedestrian protection field. Thus any currently enforced type approval regulatory act was a candidate to be included in the first pilot cases list. A consensus was made to address three levels of technical and simulation complexity, which could be defined through the physical phenomena involved in each test. In doing so, three categories were considered:

- Low technical difficulty level, accounting for linear static cases
- Medium technical difficulty level, non linear static cases
- High technical difficulty level, dynamic non linear cases

Following this criterion the consortium eventually drafted the first list of 10 potential pilot cases.

The next step was to extract three pilot cases out of the complete list initially drafted. A set of criteria were gathered, including technical, economical and legal aspects, which were aimed to evaluate the initial list of proposed regulatory acts, from the point of view of their feasibility to be implemented in VT. While some criteria were related to the quality and accuracy, namely predictability, of simulation models developed to reproduce what happens in the physical regulatory test (the so-called technical criteria), the rest addressed other relevant facets to be accounted for, such as economic or availability aspects (these are called the non-technical criteria). In the selection of the pilot cases not only technical and non technical criteria were observed, but also the changing legal scenario regarding the use of VT under the EC Whole Vehicle Type Approval framework.

Starting from these premises the 10 pilot cases initially selected as candidates for implementation of VT were studied, emphasizing in the analysis of the physical phenomena involved, as well as in the definition of test boundary conditions and requirements assessment that shall be fulfilled. Each criterion was defined to be ranked by the consortium, scoring each pilot case according to the performance observed, from 0 point for lowest/worst up to 3 points for highest/best. Thus a numerical classification was obtained and the potential pilot cases were ranked. Eventually with all that information the pilot cases were selected as follows:

- Pilot case 1: Pedestrian head impact protection case
- Pilot case 2: Seat belt anchorages strength case
- Pilot case 3: Towing devices strength case
- Besides, after discussion within the consortium, it was agreed to also address a fourth pilot case
- Pilot case 4: Pedestrian lower leg impact case

Main reasons for the inclusion of a fourth pilot case were first for completeness of the pedestrian case, second to continue the work already started in the previous EC project APROSYS, and also to take advantage of the experience gained during that project.

Once the scope of activities was identified, vehicle simulation models used in the vehicle development process were provided by carmakers taking part to the project. They have been proactive in providing this input to IMVITER, and this is one of the project key points. Previous EC funded research activities related to VT could not use simulation models corresponding to commercial vehicles, (with the exception of Fiat Brava model within VITES project); only detailed Finite Element generic models have been made available for this kind of research before (APROSYS project), but this time after agreeing on some confidentiality rules among the project partners, carmakers contributed with this essential input data. Because confidentiality has to be granted at any time during the project development, a special organization of work and dedicated data exchange rules and tools (website and ftp site) were developed.

But still further definition of how to implement VT was needed in order to organize the technical tasks. Before defining which tests and simulations were to be accomplished during the project, an approximation was necessary regarding how VT could be effectively brought into play. A generic VT type approval implementation process, divided in three sequential phases, was agreed by carmakers, regulatory bodies and the rest of partners. It follows fundamentally the flowchart annexed in Commission Regulation (EU) No 371/2010, but thanks to its separated phases, includes a more detailed description of the steps to follow in its execution. It is the starting point and reference for the detailed type approval VT procedures that were defined later for all pilot cases. The IMVITER flowchart, introducing the concept of Verification, Validation and Type Approval assessment in three consecutive phases is presented in Figure 4.

VERIFICATION AND VALIDATION OF SIMULATION MODELS

A key aspect in the implementation of VT is the assessment of simulation models predictability. VT methods shall provide for the same level of confidence as physical tests, as stated in the Framework Directive. For that reason the Verification and Validation (V&V) methodology (as described in ASME V&V 10-2006 Guide for Verification and Validation in Computational Solid Mechanics) was adapted to the particular needs of the project. V&V activities were defined to collect evidences to demonstrate that simulation models being used in VT are reliable and provide accurate predictions. From the existing computational techniques, the scope of research was focused on the use of finite element models, which is the predominant (but not unique) numerical calculation method used in the automotive industry.

At the beginning of the project, when pilot cases were selected, it was found that existing and available test and simulation data from partners in the Consortium were not adequate to develop the kind of research activities that V&V required because:

- Simulation and test results were not comparable due to set up differences between them
- Simulation and test data were not comparable since they corresponded to different vehicle development stages

For this reason it was proposed to replace the test results database initially proposed for addressed pilot cases with a dedicated set of sensitivity analyses. The main objective of the sensitivity analyses was the identification of the most relevant system features, in order to focus validation efforts on those components or more influencing phenomena. These sensitivity studies were based on models considered predictable at vehicle design level. In consequence, conclusions derived from the analyses were valid for drafting validation plans.

Applications of findings or this study are twofold:

- In the detailed description of the V&V plan,

  - o setting stringent requirements for influencing components/phenomena
  - o while leaving light requirements for non-relevant components/phenomena.
- In the selection of areas to improve modelling techniques, as model improvement makes more sense on those features that can significantly improve simulation predictability.

For the pedestrian protection pilot case, the sensitivity of the system under analysis was assessed varying model parameters or features independently, i.e. only one parameter or feature was changed each time with respect to the nominal run. The parameters and features with highest potential effect on the system response of interest, which is was the Head Injury Criterion (HIC) value, were increased and decreased within meaningful and reasonable limits. From an initial comprehensive list of parameters and system features, only those potentially relevant were considered in the study. Experts in pedestrian protection being part of the consortium contributed with their knowledge to sort them out. After running the models, the resulting data was processed, finally obtaining a matrix of HIC values for nominal and model variations. From the observed variability within these injury values a Phenomena Identification and Ranking Table (PIRT) was then derived, ranking the influence that the different system features had on the final HIC result. The analysed system features were classified in three different levels, from high effect on the response of interest (HIC), through medium effect, to low or negligible effect.

In the towing hook pilot case, the sensitivity analysis was focused on the different mechanical parameters of the subsystem and applied load parameters. The system performance was assessed through: displacement of the tow eye, Von-Misses stresses computed at six locations of the model and finally reaction forces in the crash boxes. In what concerns to loading conditions, level and angle of the applied load were considered. It was found that the more influencing parameters were those related to material and joints characterisation, as well as the model boundary conditions.

For each pilot case a validation process based on a hierarchical or bottom up approach was adopted, in which tests and simulations were conducted at three levels: whole system, subsystem and unit level. Validation activities were classified in three categories; testing, simulation and data & analysis. The objective was to collect as much detailed and accurate data as possible, both from testing and simulation, so that a fair comparison of test and simulation results could be done considering its scatter and uncertainty. An example of these activities is shown in ¡Error! No se encuentra el origen de la referencia..

The process started with an extensive review of validation metrics that are suitable for the comparison of tests and simulation results, and existing codes implementing such metrics were identified. Validation of simulation models rely on a fair and objective comparison of test and simulation results. Such objectivity can only be achieved with the use of model validation metrics, which are developed to provide a quantitative measure that characterizes the agreement between predictions (simulation results) and observations (test results). Validation metrics are mathematical functions which need at least a pair of results (coming from test and simulation in the case of simulation models' validation), and provide a value that gives a measure of how close are results one to another, not only in terms of topological distance, but also taking into consideration data tendencies, peak values, phases. Then a criterion agreed and based on background knowledge and experience from experts in the field, draws the line of what is acceptable and what is not. When the value of a metric is not within the range of accepted values defined by a criterion, test and simulation results cannot be considered similar enough, and as a result we can conclude that the simulation model that provided the simulation result, can't be deemed as representative enough of the addressed physical test (provided that all tests were adequately conducted according to a previously accepted setup, and the simulation model was built up aiming to reproduce such test setup) The comprehensive review of the state of the art of metrics for an objective comparison of test and simulation curves includes references from the ISO/TC22/SC10/SC12 WG4 Virtual Testing and other research groups like European Enhanced Vehicle-safety Committee (EEVC) WG22, The American Society of Mechanical Engineers (ASME) Standards Committee on Verification and Validation in Computational Solid Mechanics (PTC 60/V&V 10); European funded FP6 research project APROSYS or TRB's National Cooperative Highway Research Program (NCHRP). At the time being, there is no unified model validation metric widely accepted for vehicle safety applications (although the ISO group on Virtual Testing is working on this particular issue). For this reason most used comparison methods were described first, corresponding to global, local and statistical methods. Then model validation metrics, made up from several comparison methods, which are used for an objective and quantitative comparison of curves, were reviewed. Numerous assessment tools (codes which implement one or more of the described model validation metrics) exist in the available commercial codes commonly used in the automotive sector. Such codes often use several metrics. Eventually well known codes and software packages including some of the reviewed model validation metrics were listed. According to the needs of each particular pilot case, the most adequate validation metrics were selected to be applied later in the project

All those results allowed us to derive validation requirements that could be applied for each particular addressed regulatory act, together with verification requirements to be requested for codes and simulation models. Eventually the ideal (without cost and time restrictions) validation requirements were simplified in terms of test repetitions and measured parameters, in order to obtain a feasible and practical VT implementation, keeping in mind that not only technical but also cost requirements are relevant to implement VT successfully. Information and data to be provided by the manufacturer to the Technical Service after passing Verification and Validation phases is then summarised to be used in the next project activities.

Many questions arisen when we faced the implementation of VT in the motor vehicles' type approval framework; how to identify if a simulation model reproducing a regulatory act test is predictable enough? What has to be predicted? How can we measure the predictability of a simulation model? How can we quantify the level of accuracy of the prediction? Can the loading conditions defined by the technical requirements be completely reproduced with a simulation model? Does it make sense to simply compare one to one test results and simulation predictions? How can we define what is an acceptable distance between test and simulation results? In order to answer those questions, the implementation of the V&V methodology was needed in the pilot cases, and for each pilot case, test and simulation data was collected in order to get to appropriate model validation metrics and criteria.

Conventional regulatory act test setups could not provide all the information necessary for the appropriate validation of simulation models, thus whole system test setups were complemented with additional subsystem level ones. Tests were highly instrumented, using additional measurement methods to those described in the corresponding regulatory acts. With the aim of gaining a broader knowledge about used simulation models, and to generate relevant data for validation, additional activities like sensitivity analysis and stochastic runs with a metamodel were carried out from the simulation side (in pilot case 1). Simulation and test results obtained from repetitive tests were analysed in order to compare not only one to one results, but also their fitted statistical distributions and observed scatter. On the basis of the insight gained with tests and simulations, appropriate simulation model validation criterion was defined

In the pedestrian head impact protection pilot case, tests were conducted at two levels, first at subsystem level with headform impactors and secondly with a vehicle at full system level. Tests conducted according to the current regulatory act were performed, but introducing additional instrumentation in the conventional setup, in order to provide insights of the physics involved in tests, with the aim of collecting the best possible information to apply the ideal V&V approach. Repetitive tests were carried out by two laboratories in order to collect data to allow analysing the unavoidable test scatter that may be expected from a testing laboratory, but also among different laboratories. Simulations were also performed with two objectives; in the case of headform impactors, aiming to identify and quantify the existing scatter in simulation results when headform certification tests are reproduced with equivalent simulation models, developed by different analysts and codes.

Pedestrian headforms test certification results of child and adult versions (corresponding to ACEA and JARI) were collected from the two participant laboratories. Results from three certification setups were shown, accounting for the traditional normal (Regulation 78) and a new oblique drop tests, as well as the existing dynamic test (previous European Directive 2003/102/EC). Scatter found at each laboratory and when comparing among laboratories was analysed.

At full system level a metamodel was set up in order to assess how much uncertainty might be obtained from the scatter allowed in the initial impact conditions. Besides data created with the metamodel was used in the assessment of model validation metrics.

With regard to the full vehicle set up data obtained from tests and simulations, a propagation of uncertainty of the headform impact conditions (impact velocity, angle, and position) through the simulation model and its effect on the Head Injury Criterion was performed in case of Virtual and Real Testing. The statistical distributions of RT and VT data were derived using the Polynomial Chaos method and then compared.

In the seat belt anchorages strength pilot case, regulatory act tests were conducted according to the type approval tests, but including additional instrumentation. Rear seat anchorages from two vehicles were tested, representing a new type of vehicle (sedan) and a derivative version from the existing type (familiar). In the same way, equivalent simulation models for each vehicle version were used for the assessment of modifications introduced in the original vehicle version in order to get the derivate vehicle.

In the seat belt anchorages pilot case, the influence of small modifications on the original model, implemented to get the derivative model, were assessed. Based on the simulation study a list of acceptable and not acceptable modifications in simulation models was proposed for Extension of Approval based on VT.

A simulation model was developed in Radioss to reproduce the ECE Regulation 14 test for the assessment of seat belt anchorages strength. The aim of this model was to evaluate the influence of loading misalignments in simulations predictions, to check if test boundary conditions have to be accurately controlled as part of the simulation models verification. A study with two different types of belt was performed: M1 type belt (black) strap and Truck fixative (orange) strap. During the study, anchorage applied force magnitude and loading point positions were changed on the modelled test bench

The towing hook pilot case tests were conducted in two laboratories, as it was done in the pedestrian case, to account for testing uncertainty. Repetitive regulatory act tests were conducted as well, capturing all possible information through highly instrumented tests to collect accurate and redundant measurements to support further model validation.

Regarding the analysis of test and simulation data collected in the towing hook case, the three proposed parameters to be observed (force, displacements and stresses) were analysed, and a throughout review of test and simulation results was accomplished in order to identify reasons for testing and simulation results scatter.

Starting from an initial version of the towing hook simulation model, several versions of the model were developed in three different finite element codes, and various model versions were also developed in the same code by various analysts. Extensive data was collected from testing and simulation activities to study simulation results dependency on code and modeller.

Test and simulation activities were also conducted in the pedestrian lower leg impact protection pilot case, as to develop a validation procedure that takes into account advanced requirements for a more robust and reliable lower leg impactor validation. It was proposed to use an advanced lower legform impactor certification test rig, which was configured to reproduce different front vehicle geometries. Using the advanced certification impactor procedure a better predictability was assured for legform simulation models, validated against more representative and realistic test conditions.

In the lower leg impact case, a study is conducted for the assessment of the lower leg impactor calibration using the advanced certification tests, identifying the input parameters in terms of loading conditions, which lead to higher scatter in simulation and test results when certifying legform impactors.

From the insights gained in all the previous studies, verification and validation metrics and criteria were defined for the pedestrian head impact and towing hook strength regulatory acts. Starting with the verification requirements for codes, a list of benchmark cases used to check the accuracy and robustness of finite element models was described. These benchmark cases were selected from the set of requirements that codes must meet in order to be allowed to be used in the nuclear industry, and were presented as a proposal of benchmark cases that can be used for the assessment of codes quality for VT in the automotive industry. Then solution verification was addressed, dealing with three main topics; verification of spatial discretisation, temporal discretisation and contacts modelling, in order to demonstrate that simulation models implemented have no bugs or discretisation errors. After verification, validation requirements were addressed for two of the pilot cases. A model validation metric is selected for the pedestrian head impact pilot case. Having reviewed metrics available in the literature, 21 metrics were preselected, corresponding to those which seemed to be more promising for the addressed case, and based on a subject matter expert study, results were shown for 6 out the preselected set. Those 3 metrics which better reproduced the criteria of the experts were pointed out, and one out of them was chosen. The assessment of test and simulation results by experts was also used in the definition of a validation acceptance threshold. The concept behind this approach is not rejecting any model that might be accepted as validated by the experts Once the validation metric and threshold were defined, verification and validation processes were applied in the pilot case at three levels; headform impactor model, vehicle model and full system model (vehicle and impactor). A similar approach was deployed in the towing hook strength pilot case, but this time based on confidence corridors for test and joint characterisation tests, which were used for the validation of the equivalent entities in the model.

Eventually a proposal on information and data to be reported by the manufacturer to the technical service was drafted, corresponding to results obtained in verification and validation phases of the VT process. Simulation tools that can support the implementation of VT were briefly discussed. An example was shown of how codes can support in the implementation of VT, integrating all necessary tools such as validation metrics and criteria. As an example Altair HyperSutdy and HyperGraph were used in the certification of the headform impactor used in Pilot case 1. After that, automatic result templates for VT were considered.

A discussion was opened about the possibility to validate simulation codes instead of simulation models. Also the relationship between codes and simulation models developed with those codes was addressed. Dependencies of simulation codes with respect to their versions or releases and hardware in which codes run were described. Potential simulation predictions scatter due to the use of different codes, namely code dependency of simulation results, was addressed. Taking advantage of the simplicity of simulation model used in pilot case 3, calculations in three commercial codes were done, based on the translation of one simulation model from one code into the other two. Issues related to simulation models translation between different codes were also discussed. In particular a translation from Ls-dyna to Radioss of the towing hook model used in Pilot case 3 was shown as an example. Examples are given in terms of translation needs for meshes, material laws, joint laws, and interfaces. A dissertation was given about scatter of test results due to accepted testing inaccuracies. After indicating some of the test scatter sources, the scatter obtained in the evaluation of various headform simulation models developed in different simulation codes is shown. Sources for such scatter are also identified. Then it was studied if simulation codes calibration could be feasible, as a mean to accept all simulation results generated with a calibrated simulation code. In the discussion, a parallelism was established between a generic calibration process of test equipment and a possible adaptation of such process to simulation codes and simulation models. Based on the study it was concluded that simulation models should be validated in conjunction with the code in which they were developed, as both entities are indistinguishable from the validation point of view.

As a conclusion to the activities described in the previous paragraph, we can conclude that the evaluation of simulation models predictability requires far more than computing the "distance" between the response of a model and that of its physical counterpart.

Models must obviously be checked, but:

- Simulation codes must be also tracked in order to establish their validation. Reliability, compatibility and repeatability should be verified (by the user or certified by the code manufacturer).
- Models translation should be avoided, and should be carefully done only if it is unavoidable. It was described that modelling techniques are different from one code to another, and so a model translation can be considered as rebuilding the model from scratch.
- Code specifications are then a very important parameter to verify in VT. Statistical and automatic or scripted tools are efficient in VT. They allow analysts to post-treat results efficiently.

SIMULATION MODELS PREDICTABILITY FOR VT

Modelling of some physical phenomena like material fracture or the behaviour of new advanced materials is crucial to improve the predictability of simulation models. Development of new mathematical or computational models was out of the scope of our research, as the magnitude of such an investigation activity would have needed all the project effort, but the application of novel numerical techniques or modelling methodologies that are not commonly used but are already available in commercial codes was feasible. When assessing the predictive capabilities of current state-of-the-art models, some simulation lacks or rooms for improvement were detected, what guided the matters for a part of the project research work.

Three relevant modelling areas where space for improvement still exists are materials, joints and contacts. In IMVITER, our main efforts addressed the first two, materials and joints. The first part of the work was related to pedestrian head and lower leg protection pilot cases, where innovative material and joint models were trialled. Unlike metals, modelling of plastic materials is a continuously evolving subject, due to its variable and complex nature. A material law developed in 2005 called Semi-Analytical Model for Polymers (SAMP), accounting for specific behaviour of thermoplasts, including rupture, is tested against the traditional piecewise linear plasticity material model. This trial implies a new characterization procedure that considers more load cases than just simple traction and afterwards the obtained material card was implemented in an under bonnet component of the Opel Insignia LS-DYNA model for pedestrian protection assessment. The predictability improvement with respect to the simpler material model was then valued in comparison to test results. In a similar fashion, modelling improvements in elastomers and adhesive materials were presented.

Within the project several examples were shown on how to improve the predictability of models for vehicle type-approval in the selected pilot cases. The main simulation lacks or rooms for improvement detected in the fields of material, joint and contact modelling guided this research work. In all the exemplary cases: thermoplasts, elastomers, adhesives and spot welds; an improvement in the accuracy of the model with respect to real test results was achieved. These improved results were explicitly demonstrated in the pedestrian protection related simulations, where both RT and VT data were available at full system level (type-approval setup). Spot weld modelling improvement could not be however demonstrated at full system level because of practical reasons: spot weld model research work was performed in RADIOSS code while the R14 model was available in LS-DYNA.

Research efforts in terms of join models predictability was focused on developing a characterization methodology for spot welds. This is the type of joint most frequently used in structural metallic assemblies in the car body, thereby a relevant feature when simulating seatbelt anchorages strength tests, which represent the pilot case 2. This kind of joining technique was also used in the crash-box components that support the bumper beam of the car, and where the towing eye can be screwed (pilot case 3). However, as the load requirements for the spot welded joints are much more demanding in pilot case 2, the materials and joints involved in that pilot case were selected for our research work. Several setups for different load modes were designed and subsequently tested in reality and virtually. A calibration and optimization activity was then performed in order to obtain the most predictable, robust and CPU efficient spot weld model for its implementation in the body-in-white model of the car.

The advanced modelling techniques show the path to follow for improved predictability. However, when the improvement is very limited, the question about the suitability of complex and expensive modelling and characterizing techniques naturally arises. Model improvement usually follows the Pareto principle, i.e. 80% of the predictability is related to 20% of the involved phenomena, requiring a restraint 20% effort; however, the remaining 20% of predictability is related to 80% of low influencing phenomena, requiring a big effort, 80% or even more. For this reason, it is important to make sure that the most relevant phenomena and related parameters have been properly addressed prior to make such relevant investments on less influencing aspects. On the other hand, scatter and variability of parts, due to manufacturing processes, as well as RT methods uncertainty, should not fall into oblivion. The idea behind this statement is that the model predictability should be always in balance with those aspects, related to quality of parts and real testing, otherwise high investments in material and joint model improvement would not make sense. Finally, we conclude that more simulation interpretation know-how from the vehicle development process needs to be transferred to the new virtual type approval scenario in the sense of being able of taking advantage of simulation results, even with limited accuracy or predictability. This is occasionally the situation nowadays for some development models, which remain practical in spite of limited computation resources or methods, as they are considered valuable to make correct decisions.

VIRTUAL TESTING IMPLEMENTATION APPROACHES

An introduction to the European legislative framework for motor vehicles type approval was given, in order to identify how VT can fit within the existing structure

The convenience of applying VT (meaning that any advantage can be obtained in comparison with RT or the conventional approach) strongly depends on how simulation and test results are used:

- What kind of tests and simulations are necessary for validation
- How many comparisons would be deemed necessary for a satisfactory validation of simulation models
- At what moment in time during the product development process physical parts (prototypes or pilot parts) shall be made available for validation tests

In principle the smoothest introduction of VT would be that one which wouldn' t imply any modification in the existing product development process, thus physical parts normally available according to the vehicle development plan would be used, without the need to accelerate design process, and also simulation models would be made available for prediction with the desired quality and predictability characteristics, without the need to develop improved simulation models specifically for validation purposes. Besides there has to be clear indication about when information generated during the VT process shall be exchanged between manufacturers and technical services, as well as what information is necessary.

Depending on the regulatory acts under assessment and the vehicle or systems involved, different alternatives emerge naturally for the comparison of test and simulation results. Starting from the project pilot cases, three different implementation approaches were identified, trying to incorporate simulation models and predictions in a similar way as they are used during product development phases. Eventually after studying the exiting possibilities, three alternative or complementary type approval approaches based on VT were identified:

- Full VT: in phase 2 the simulation model is validated against test results. In phase 3 only simulation results are used for the assessment of type approval technical requirements. Deployed in the third pilot case, towing hook strength assessment. This approach would be suitable when simulation model validation can be done at component or subsystem level. Then the assessment of technical requirements would be purely based on simulation predictions
- Hybrid VT: in phase 3 mainly simulation results are used for the assessment of type approval technical requirements, although complementary test results are used. In phase 3 simulation and test results are not compared, because the simulation model was previously validated against test results in the phase 2. Deployed in the first and fourth pilot cases (related to pedestrian protection). In this approach, simulation models are validated at component, subsystem and/or full system level, and in the assessment of technical requirements both RT and VT can be used in a complementary way, meaning that RT data is completed with VT, but no further compassion is established after validation is met. This approach is suitable for regulatory acts in which repetitive testing is involved
- Extension of Approval (EoA) based on VT: a previously validated simulation model (Version 1) is the base for the introduction of small modifications (materials, geometry ⍰), as a consequence the new simulation model (Version 2) is validated starting from the assessment of the influence of introduced modifications. A reduced number of validation tests (if any) would be used in phase 2 taking advantage of the validation work already done in Version 1. In this case the second pilot case is used as showcase, in which the assessment of seat belt anchorages strength is performed. Basically first an already certified model (a model that has met a validation process previously) is necessary as an input as reference model. A derivative model is compared to the original one, in order to assess whether its predictability still can be considered acceptable, after introducing small modifications from the reference model. If this phase is met, the simulation model would be used later in the assessment of the

technical requirements, in a similar fashion as it is done in the Full VT approach. This approach is suitable is several regulatory acts, especially in those cases in which a product is developed as a derivative of an existing product, like versions or variants of a base vehicle model.

Furthermore, a Further Type Approval based on VT approach was proposed when the extension is applied to different vehicle types.

The general approach divided in three phases was the origin to develop the 3 VT approaches, depending on regulatory acts particularities All VT approaches consist on a three phase process; phase 1 for Verification, phase 2 for Validation and phase 3 for the assessment of Type Approval requirements.

The different approaches for implementation of VT were explained in general terms (at a level that could be applicable for several regulatory acts) and then applied and deployed in detail for the addressed pilot cases. These three approaches were described in detail with the support of flowcharts.

These simple flowcharts were a guideline to further and specifically define VT implementation in each pilot case:

- Pilot case 1: pedestrian head impact. Is a good example of a repetitive test, meaning that according to the ECWVTA requirements, 18 impacts have to be conducted on the vehicle bonnet. A reduction of test impacts was addressed, and the verification and validation methodology that was developed in this pilot case, is applicable to any other regulatory act based on repetitive tests.
- Pilot case 2: seat belt anchorage points strength: in this case the methodology was focused on cases where type approval extension is suitable, thus criteria to assess when small modifications do not invalidate an already validated simulation model were studied.
- Pilot case 3: towing hook: this case provided data to evaluate how different simulation results may be depending on codes.
- Pilot case 4: pedestrian lower leg impact: apart from the verification and validation methodology, this case addressed lower leg impactor advance certification requirements within VT approaches.

Detailed VT flowcharts created for IMVITER pilot cases can be downloaded from the project website.

The use of calculation methods and numerical models as an accepted mean for the assessment of type approval technical requirements does not only entail new verification and validation methods or VT procedures. There is a legal and formal structure that needs to be reviewed and updated in order to define the new roles, responsibilities and required skills of involved actors and how these actors interact and exchange information.

A description of the aforementioned formal and legal structure of the ECWVTA system was done. Each institution taking part to a generic conventional type approval process was identified and its functions described. The basic reference or legal texts describing the system were listed and its content relevant to our topic identified, including the motor vehicle framework directive and international standards that shall be observed by testing laboratories.

The accreditation structure that institutions involved in the ECWVTA system shall fulfil was described, in particular paying special attention to aspects related to the accreditation requirements for Technical Services. Their competence and ability is evaluated before being recognised as accepted bodies to carry out type approval activities. Accreditation requirements for people, hardware and software were revised. After looking at the overall picture, a proposal was given on modifications to the accreditation system, that the consortium consider necessary, as a consequence of introducing VT.

New documents that are to be exchanged between type approval actors were described in terms of its content, responsible and identification of when they are requested during the VT type approval process proposed by IMVITER. Such documents were elaborated and filled during the actual implementation of VT in the last part of the project.

Directive 2007/46 EC clearly describes all necessary information to carry out motor vehicles type approvals, no only in terms of technical specifications for each regulatory act, but also about the interaction of involved stakeholders, documentation to be exchanged and requested accreditations. Article 41 (chapter XVI) describes required competences for TS whether type approval tests are directly performed by the TS or witnessed, as well as the inspections specified in regulatory acts listed in annex IV. Previous references rely also on the prescriptions given in Standards EN ISO/IEC 17025:2005 and EN ISO/IEC 17020:2004, regarding general requirements for the competence to carry out tests and/or calibrations and general criteria for the competence of impartial bodies performing inspection irrespective of the sector involved, respectively. But in these two standards there are not distinction between RT and VT, and therefore, any TS can take advantage of this legal gap to carry out or supervise VT for a certain Regulatory act, when in fact technical services have only accredited their competences for RT methods. However, it is clear that the essential knowledge, skills, and experience are completely different in many areas between RT and VT.

The main conclusion drawn after reviewing currently accreditation requirements for testing laboratories is that there are some omissions in the legislation regarding features specific to VT.

Besides, it would be strongly beneficial if ISO 17020 could be amended in order to incorporate specific content for general criteria for the operation of bodies or entities performing inspection based on VT processes and activities, and ISO 17025 in terms of general requirements for the competence of entities performing VT as well. Apart from existing standards of specific industrial sectors (nuclear energy), there are almost no harmonised or recognised methods for the assessment of simulation codes predictability. The ASME “Guide for Verification and Validation” is the only recognised reference that helps in the assessment of simulation models predictability. Its recommendations are being transposed into the pilot cases in IMVITER, but still harmonised methods for V&V need to be defined in each particular application. The documentation for the type approval process based on VT defined in this project, aims to support this task.

IMPLEMENTATION OF VT AND DEFINITION OF V&V REPORT TEMPLATES

Based on the project experience, there are promising potentials with VT, which will appear much clearer as its implementation by the industry becomes a reality. Virtual techniques have become basic methods in vehicle development during the last two decades. Now simulation technology is permanently improved and more advantageous than real testing in many aspects for manufacturers. However, it is not so in vehicle regulations. The basic structure of vehicle regulations was set up for real tests and it was slightly changed for 30 years. E.g. the passive safety requirements were founded on the so called standard accident situations and these are also not modulated due to the challenges of modern age. It is time for technical experts in the European technical committees dealing with vehicle regulations to find the appropriate place for VT in the approval procedures. This project has tried to pave this road too.

Three main outcomes are provided by IMVITER, that are produced to foster the implementation of VT:

- VT implementation approaches, described as detailed flowcharts
- VT methods, describing V&V requirements as well as validation metrics and criteria, as an example for each pilot case
- V&V templates, which serve as reference documents that help to exchange essential information between involved actors

As it happens in any new process, a refinement effort is indispensable, because there are always aspects that are not known from the beginning.

In the last period of the project, the methodology developed for the implementation of VT was put into practice, with the aim of learning from its practical development and refine when needed. This was possible because partners in the consortium represented the main actors involved in the type approval system (except for the Approval Authority). A dialogue was established between carmakers and technical services, reproducing the conversations foreseen for drafting a validation plan. VT implementation was easy thanks to the existing confidence in the consortium, promoted by the previous months of cooperation.

Every step defined in the VT flowcharts was followed, and the V&V documentation was created. During this process a continuous improvement and refinement took place. Apart from technical or practical reasons, input from the cost benefit analysis being developed in parallel in WP5 was very useful, leading at the end of WP4 to achieve a really practical methodology.

As part of the VT process implementation, a set of V&V report templates for tools and vehicles, were presented. These templates specify which information is to be provided by the carmaker to the TS during a type approval based on VT. It can be considered as an equivalent test report for simulation results, although with specific contents that are totally new in the type approval framework. The whole VT process is refined thanks to its actual implementation. The final versions after the aforementioned refinement are shown in the project deliverables, and were updated according to the experience gained during the actual VT implementation.

A description was given about the pilot cases in which the VT process was implemented. For each pilot case addressed, the process was described in detail, and the roles were distributed among partners. One of the main outcomes of the VT implementation were the section reported as frequently asked questions, for which the consortium, who faced all of them during the project, tried to give an answer based on its own practice.

Besides VT implementation approaches and flowcharts, a formal adaptation and transformation of existing RT based regulations into VT based or combined VT/RT regulations was addressed. A broad dialogue among all partners was initiated to guarantee a fair and consensus oriented approach. The various possible VT implementation alternatives are proposed to feed this dialogue, specified and investigated with the support of testing and simulation activities.

During VT implementation a discussion was established based on the documentation proposal, aiming to collect feedback from the consortium about its adequacy, completeness and practical aspects. For the ease of discussion those documents were classified and differentiated between Verification and Validation, and also a distinction was made with respect to those dedicated to simulation tools (impactors in IMVITER pilot cases) and vehicle simulation models. V&V report templates are linked with VT implementation flowcharts, its content conforms to the indicated V&V results to be reported during phase 1 and phase 2.

Moreover, such templates were filled with the data obtained from the pilot cases, in order to serve as an example of VT implementation with real data.

COST BENEFIT ANALYSIS

It is a general belief that VT implementation will lead to significant benefits for the industry in terms of cost and time savings. This is based in the feeling that extracting information from simulation models is fast and easy, and much more flexible than performing any test. That feeling is right, good simulation models can provide accurate and comprehensive predictions on how a system performs under certain loading conditions, and moreover, in less time that any test would do. But this belief fails in forgiving about the effort needed to build a good and predictable simulation model. A fair comparison between testing and simulation cost shall encompass all activities needed in both cases.

But experts in simulation from the industry know that although the effort (cost and time) that has to be invested in the development of a predictable vehicle simulation model is huge, once it is done, they have to make the most of it. The use of predictable simulation models available from vehicle design processes for the assessment of type approval requirements is the next step, and benefits are expected because all the effort related to setting up those models was already spent during design, so we can say that simulation models can be provided for free to type approval activities. Under this premise, a cost benefit analysis of the implementation of VT was done.

All information needed for the analysis came from the previous project activities. Pilot cases were selected, different VT approaches were identified for each, and the VT process was defined in detail, including V&V requirements for the assessment of simulation models predictability. Even templates for the information to be exchanged between TS and OEMs were described. Thanks to all those inputs, and for each pilot case, this study gave a comparison of costs and benefits that can be expected from the conventional (test based) type approval system, and the new proposed type approval system based on VT (supported by simulation predictions in the assessment of regulatory acts). In this analysis a CBA tool was adopted to the particular needs of this study.

A straightforward methodology was used, according to the following steps (implemented for each pilot case):

- Identification of the number of conventional type approvals developed for the addressed regulatory act during two periods of time, one named short time accounting for one year, and a second one named long time, extended to 10 years time. This is the reference scenario for the comparison between RT and VT

- Analysis of the vehicle product development process in order to place where type approval takes place, and when physical parts or prototypes of parts or components addressed in the type approval are available.
- Integration of V&V activities within the product development process. This completes the time scenario for the study.
- Based on the VT flowcharts (for different VT implementation approaches like Full VT, VT or EoA based on VT), identification of all activities (not only activities related to OEMs, but also interaction between OEMs and TSs)
- Collection of cost and time inputs from partners involved in each pilot case. After carrying out all tasks identified in VT flowcharts, it was easier to specify the effort it took to put VT in practice
- Based on the different paths that can be followed in the VT flowcharts, and using the CBA tool, calculation of estimations of cost and time that VT would imply in each situation.
- Analysis of CBA results, identifying cost drivers, most time consuming activities, achievable time savings due to shifting of type approval activities within the product evolution process
- Flexibility in cost and time were calculated based on the Penalty of Change theory for cost and time respectively.
- Give recommendations on how to get benefit from the implementation of VT

The comprehensive Cost-Benefit Analysis of the proposed VT approaches gave clear indications on the savings that can be expected in short and long term with the implementation of VT, and also warned about situations in which no advantage was obtained. We can sum up the key aspects that need to be taken into account in order to achieve savings in the implementation of VT. Main outcomes are summarised below.

In the Pilot case 1 (EC Reg. 78/2009) for pedestrian head protection, savings in cost and time were identified both in the short term and long term scenarios. For long term the cost saving potentials were higher. The use of a validated simulation model instead of tests in the Extension of Approval based on VT, provides significant benefits in terms of cost reduction, reduction of risks in case of unexpected tests failures, and increases the flexibility in time. In general we can conclude that due to the repetitive nature of this regulatory act, in which up to 18 impact tests shall be conducted, replacement of tests with simulation predictions can provide clear savings, and increase in flexibility during vehicle design as well.

In the Pilot Case 2 (ECE R14), it was found that VT can provide any benefit for OEMs (whether it might be cost reduction or increase in flexibility in design) only if a highly predictable simulation model is available from design and development activities. If simulation models to be used in VT have to be developed only for VT purpose, it is likely that no advantages exist in comparison with the conventional tests based type approval approach. In this pilot case we can see a very worst case, in which seat models were developed only to be used in the project, and as the cost-benefit analysis demonstrated, this situation is not suitable at all for VT. Moreover, the regulatory act test carried out in the conventional approach is a relatively simple test, that can be performed in a short period of time, and that is not excessively expensive (only taking into account test laboratory fees). It is also worth to note that although the seat anchorages strength test is a destructive experiment, the advantage of not destroying a prototype vehicle was not considered in the analysis, but it is quite evident that if a vehicle prototype can be saved avoiding this destructive test, it would be an advantage for the OEM, who could use it for other type approval assessments if necessary (flexibility in design) or directly avoid building a prototype.

In the Pilot Case 3 (Directive 77/389/EEC) for towing hook, was found that in this kind of simple regulatory acts, VT would only provide any advantage if a Full VT approach is implemented, but moreover, it would be necessary that a validated simulation model from a vehicle type could serve as a validation prove for a new vehicle type. This approach is closer to the validation of modelling techniques rather than validation of simulation models. Following this approach, any simulation model developed with validated simulation methodologies (basically modelling techniques for material and joint models) would be validated de facto. OEMs would have a kind of database of validated material cards and joining techniques, and based on that, in simple cases were only elastic deformations or limited plastic deformations were observed in quasi-static loading conditions, no more validation efforts would be requested. This approach is inherently adopted nowadays in design, because in the case of the towing hook, parts with different geometry but same materials and joining techniques are developed for different types of vehicles, and once a part meets the regulatory act requirements, it is used in other vehicle types. This could be seen as an aggressive approach for the implementation of VT, but is the only alternative that would allow replacing tests by simulation. We have to note that the regulatory act test is almost costless, because is a non destructive test, that can be carried out in a few hours, and parts involved are designed to withstand much more stringent requirements (mainly impact requirements). As demonstrated in the cost analysis, the automatization of V&V templates filling is almost mandatory, in order to optimise as much as possible the whole VT process in terms of time and cost.

In the Pilot Case 4 (EC Reg. 78/2009) for pedestrian lower leg protection, savings in cost were obtained both in the short and long term, but time required for VT was longer than what is needed in the conventional approach. This situation can be compensated with an earlier start of the type approval process.

From this study, the following main conclusions related to the implementation of VT regardless the regulatory act, can be drawn:

- This study outcomes are based on the first time ever implementation of VT with commercial simulation models and type approval regulatory acts. It is clear that although the process was refined in WP4, it still has great potentials for optimisation in terms of cost and time.

Nevertheless the CBA of VT is compared to the conventional approach, which is highly refined after years of experience.

- This study considers VT as a simply replacement of regulatory act tests with equivalent simulation models, thus potentials of simulation are limited. In case VT would be considered since the beginning of a regulatory act definition, the whole VT process could be optimised because V&V activities could be better integrated. In this study V&V activities are merely added into an already existing test method.
- In those regulatory acts in which repetitive testing is needed, VT implementation according to the IMVITER proposal shows a clear benefit.
- For those regulatory acts based on costless tests (meaning that regulatory tests can be carried out in a few hours and are not destructive), no savings are expected with VT if simulation is simply used to substitute the test.
- Not all VT approaches identified in IMVITER are adequate for all regulatory acts. Ideally in the near future, when enough confidence exists in VT and the V&V method, all regulatory acts could be addressed with Full VT, and that would lead to savings. Until then intermediate solutions like the VT approach have to be explored, knowing that it leads to lower savings
- Great potentials in terms of savings are expected for the EoA based on VT approach, especially if it could be applied among different vehicle types (what was named Further type approval in the project)
- In general, documentation efforts are cost drivers for the VT approach. An improved integration of these activities within the vehicle development process, and the automatisation thanks to post-processing software, of information collection and reporting of data into agreed V&V templates would reduce those efforts, increasing the efficiency of VT.
- No differences were found with regard to TS fees regardless the type approval approach implemented. Even if more frequent interaction is expected to happen between TS and OEM in the initial period of VT implementation and new documentation is exchanged.

NEW TECHNOLOGIES FOR PEDESTRIAN PROTECTION AND POTENTIAL USE IN VT

As a first step in the implementation of VT, IMVITER took the current regulatory acts as they are and adapted them to include the use of simulation models. In doing so, for the pedestrian protection cases, the rigid legform impactor according to EEVC WG 17 and prescribed by EC Regulation 78/2009 was used. However there is a continuous research effort working to develop more biofidelic simulation tools. Those new tools are not accepted neither included in any directive or regulation yet (although they are being used to some extent in EuroNcap assessment protocols of active bonnets), but it is expected that they will be in the near future. For this reason a brief study of the new impactors was done, in order to analyse if the V&V methods defined for nowadays simulation tools would be suitable for the next generation of impactors. Besides, different human body models are described, from very simplified ones based on multibody ellipsoids to the most complete and realistic finite element models.

The most important aspect of the VT methodology defined in IMVITER in terms of simulation models predictability assessment is the application of V&V. This is to be applied not only to the vehicle or system simulation model, but also (and specially) to the so named simulation tools. In the last part of the project all efforts were focused in the pedestrian protection regulatory act, thus simulation tools under analysis are those reproducing pedestrians, whether as impactors or as full body models.

Validation activities were addressed for the following simulation tools:

- Flexible lower leg impactor
- Flexible lower leg impactor with an added Upper Body Mass
- Thums-D Full Body model family

Towards a realistic injury assessment, a summary of investigations performed with an improved flexible lower leg impactor, in which an Upper Body Mass (UBM), added to represent the inertial effects of the whole body, was described. After that an introduction to initial V&V results of the Flexible lower leg impactor with the UPM is addressed. Then different validation activities were described taking into account an advanced validation set up, representing a configurable vehicle front end. Besides an advanced validation test is also developed for the rigid or TRL-Pli, representing a vehicle front end too, in order to achieve better comparisons between both impactors in the advanced validation configurations.

An inventory of full body pedestrian models available to the consortium and a proposal for their verification (not harmonised among users nowadays) was described. First the evolution of human body models was shown, starting from multibody models and then addressing a family of finite element models derived from THUMS. As part of human body models verification, a direct comparison of all the model dimensions with anthropometric data was performed, including its positioning and stance, which is also under harmonisation discussions. The FEM human body model family, THUMS-D, was improved featuring the Strasbourg University Finite Element Head Model (SUFEHM), which was coupled to the aforementioned THUMS-D model.

A validation of a flexible lower leg impactor was shown based on the comparison of 4 tests against results from the equivalent simulation model. Validation was planned at three levels:

- The 12 channels evaluation: defined by the GEM scoring method
- The 3 segment evaluation (tibia, knee, femur): based its average performance
- The model evaluation (only one): based its average performance of the segments

After that an advanced certification test frame, which was conceived and developed within IMVITER for the rigid legform impactor (TRL-Pli) is also put to test with the flexible lower leg impactor simulation model. The proposed advanced certification test frame was designed in order to have a more complete and adequate set of reference experimental test results available for the validation of this type of lower legform impactor numerical models.

After validation tasks with impactors, human body models were addressed. THUMS (Total Human Model for Safety) is a virtual human model that was improved and validated, henceforth this improved THUMS is called as THUMS-D. Details of the strategy followed were given, simulations conducted and their results to validate this THUMS-D pedestrian human body model. To validate the impact response of the THUMS-D pedestrian model, 2-step validation strategy was followed:

- First, impactor tests were simulated to validate different body segments like head, neck, thorax, abdomen, pelvis, shoulder, knee, femur, tibia.
- Second, to validate the full body kinematics of the THUMS-D model, 1 SAE test was simulated to evaluate the trajectories of head center of gravity, thorax, pelvis and knee.

To evaluate the response of the THUMS-D model in comparison with cadaver tests, 10 car-pedestrian impact tests conducted by Ishikawa et al. were simulated. The simulation car model was modified to achieve the bumper and hood-edge stiffness' of cadaver test car. The anthropometry of THUMS-D model was scaled to match the anthropometry of different sized cadavers used in tests.

Two of the characteristics that have to be checked during V&V of simulation models; model stability (related to simulation model verification in the phase 1 of the IMVITER VT approaches) and model validity (related to validation in phase 2) For the THUMS-D model, these two aspects were addressed extensively. Another important aspect that was addressed is the sensitivity of the model with respect to certain parameter variations. The model sensitivity basically classifies the quality of the results with respect to small perturbations of model parameters or constraints. Ideally, the solution of a simulation should be insensitive to such small changes. Thus the results of a sensitivity analysis using the THUMS-D model were included. The model was stabilized and validated w.r.t. standard and other relevant load cases. To improve the usability, the sensitivity analysis was used to reveal problematic model parameters, containing for instance material parameters or the model geometry. First the general analysis setup was described, then relevant parameters were discussed and finally the actual sensitivity analysis was addressed.

An investigation of the flexible lower leg impactor model with and without upper body mass was shown.

References were made with regards to the adequacy of the validation methods used in the development of the studied simulation tools, which give indications on how those tools could be used in a future implementation of VT for pedestrian safety assessment in the vehicle type approval framework. After reviewing the existing advanced impactor and human body models, it was found feasible to adapt the V&V methodology developed in IMVITER to the new simulation tools. Advanced impactors certification method can be used for the validation of its simulation counterparts' , while additional validation requirements are also proposed in order to assess simulation model performance in more realistic impact situations, against test rigs designed to account for the average and extreme commercial vehicles front end. On the other hand for human body models, harmonised validation metrics and criteria are needed in order to develop a validation methodology that could be the basis for V&V.

Pedestrian protection systems and its related assessment methods are quickly evolving nowadays to consider new passive and active safety systems. Computational methods are suitable tools to tackle such system complexity and setup diversity; even current simulation technology for active safety systems is not as mature as in the case of structural design. What is clear is that new specific V&V procedures will have to be agreed for the establishment of VT as an accepted assessment methodology for new active / pre-crash / advanced passive safety systems for pedestrians in the type-approval scenario. The possibility to transfer the VT process also to integrated safety systems (active and pre-crash safety systems) was addressed. The use of VT was discussed within a global approach respectively as a complete tool chain within the evaluation of integrated safety systems.

For some chosen safety systems related to pedestrian safety such as the Brake Assist (BAS) and pedestrian detection systems, former presented simulation technology (HBM) was applied to investigate the potential of VT to evaluate advanced safety systems (Parameter study including discussion of criteria (SUFHEM). As well, a related tool set to position and to scale the simulation models within this real life scenarios was used and presented.

Eventually the consortium gave indications on what are the next steps that should be taken in the implementation of VT in the next decades. An outlook to the next milestones in VT implementation was given as a roadmap. Using the SWOT (Strength, Weaknesses, Opportunities and Threats) methodology, the consortium carried out a prediction on the main milestones that should be achieved in the next years, and described the progressive introduction of VT complementing or replacing RT.

Potential Impact:

The most effective and efficient resources investment

Implementation of VT in safety regulations within the automotive industry can only be accomplished through its inclusion in the European Community Whole Vehicle Type Approval system, and in particular in the Directive 2007/46/EC, since it is the legal framework applying to motor vehicles.

EU directives are prepared by the European Commission, it is responsible for drawing up proposals for new European legislation, which it presents to Parliament and the Council. According to the EU's legislative procedure, proposals for new legislation are worked out with the technical advice of experts from all the Member States. Such proposals are based on technical considerations and/or scientific grounds. IMVITER developed the necessary technical and scientific background for the implementation of VT.

In order to achieve the project aim, results were disseminated to relevant groups of experts:

- Participation to the European Enhanced Vehicle-Safety Committee (EEVC): regular contact existed since the beginning of the project, because the chairman of the committee took part as INRETS representative. The project coordinator was invited to take part to a EEVC meeting in 2009/10/30 in Lyon, were the project was introduced to the EEVC members. Besides some partners are also members of the EEVC and take part to the Committee activities. Project results will be formally communicated to the Committee after the project.
- Contact was also established with the ISO TC22 SC10 and SC12 WG4 Virtual Testing, providing to IMVITER a relevant background on Validation Metrics and Process for Objective Comparisons and Ratings of Two Different Signals to Support Virtual Testing in Various Road Vehicle Crash Modes. After this first contact, the project coordinator was invited to join the group as national representative, and took part to the group meetings. Project results will be formally communicated to the Committee after the project.
- Contact was established in the last part of the project with the Type Approval Authorities Expert Group (TAAEM), all their members were invited to the project final event and the group chairman kindly invited the project coordinator to present results after the project end.
- Meetings were held on a yearly base with the EUCAR Integrated Safety Program Board, in order to report about the progress of research activities. Industrial experts were informed and their feedback was taken into account.

Innovation, not only technological, but also in business models that add value for users

IMVITER aims to support the work of pre-normative working groups in the introduction of VT technologies in the ECWVTA framework. Project results will have a direct impact on the development of more comprehensive type approval assessment methodologies. Boosting an extending the application of CAE current and future technologies, will also contribute to raise the quality of such computer simulation tools.

Besides, VT can enhance safety regulations standardisation worldwide, avoiding currently extra engineering to make different versions of vehicles for different markets. There are dozens of minor differences in safety regulations, depending on the country, and those differences do not necessary make vehicles any safer for consumers. VT would help a more reasonable standardisation, which eventually would benefit consumers when fewer resources are necessary to meet unjustified non standardised safety requirements.

Contribution to European priorities such as promoting economic growth and jobs

VT will have a significant impact in enhancing the European automotive industry competeviness, reducing the burden associated to type approval procedures, and allowing a closer relationship between OEMs and Technical Services for a better informed assessment of vehicles safety features, but more importantly, facilitating the natural development of the automotive market towards an increasingly diversified vehicles' offer, without the limitation of numerous, costly and time consuming type approval evaluations of small vehicle modifications.

IMVITER results aim to support and boost the European automotive industry competitiveness through a broad implementation of VT, which at the end, together with other innovations will have a socio-economical impact allowing the European automotive industry to continue being a pillar of the European economy, representing 3% of Europe's gross domestic product, 7% of employment in the manufacturing sector and 8% of EU governments' total revenue.

Directly linked to how VT could enhance the European Automotive industry technological development and competitiveness, the opportunities and advantages that VT can bring to the Industry will be reflected in a reinforced economy and employment. This aspect is even more critical in the current economical crisis, when employment can be reinforced thanks to a more robust and competitive automotive industry.

Eventually any initiative promoting or fostering the European automotive industry competitiveness will directly lead to benefits for the society in terms of employment and improved economic situation

List of Websites:

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