Final Report Summary - IMVITER (Implementation of virtual testing in safety regulations)

The IMVITER project is European Union (EU) Seventh Framework Programme (FP7) funded and aims to promote the implementation of virtual testing (VT) 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 European Commission (EC) motor vehicle type approval process. VT is considered as the use of simulation models 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 requirements.

For the first time, VT is recognised as an assessment method and can be used in a limited number of regulatory acts. IMVITER’s 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, one to the assessment of seat belt anchorages strength and a fourth one for the evaluation of 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. The verification and validation (V&V) methodology is adapted to the 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. A further type approval based on the 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. Validation tests and simulations are performed 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. 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 warns about situations in which no advantage is obtained. 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.
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. 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. The assessment of those requirements imposes a number of tests entail a burden in terms of cost and time to the European automotive industry. 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 by simulation models and test results by simulation predictions. Currently, the use of CAD is allowed to demonstrate compliance with dimensional requirements and several static tests are being replaced by virtual tests. However, the use of VT can be extended to incorporate the assessment of further technical requirements.

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 up to nonlinear deformations produced by dynamic loads. It is beneficial for all the parties involved 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 existing RT based type approval procedures are being worked out. The 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 the implementation of VT as a way to improve the European automotive sector's competitiveness, the EC in the following years has taken the necessary steps to accomplish this. The recently published Commission Regulation No. 371/2010 has opened the door to its practical implementation. This project itself is another effort to introduce and promote the use of VT in safety regulations, in this case addressing the EC Whole Vehicle Type Approval Directive (ECWVTA) 2007/46/EC, and its corresponding annexes.

The key objective of the project is the implementation of VT in existing type approval procedures and particularly in safety related regulatory acts, by consolidation of advanced VT technologies.

The project has the following objectives:

- identify current physical tests under 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;
- development of simulation models validation criteria independent of software platform or performing organisation;
- 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 and analyse the feasibility and potential of these procedures;
- investigate the possibility to transfer the process of VT to assess new advanced safety systems.

IMVITER is part of a long-term process which is expected to lead to a complete electronic certification. Technology development in this field will progressively provide the automotive industry with more realistic and reliable models. The achievement of this objective implies 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 platforms and the performing
organisations. One of the obstacles of the use of VT in type approval is 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 safety directives. The work is based on previous EC projects such as VITES, ADVANCE and APROSYS.
Pedestrian protection has been identified as one of the fields with the greatest advantages and potentials for VT
implementation. Based on the experience of all stakeholders taking part to IMVITER, it can be asserted that numerical
simulation is highly predictive for the assessment of pedestrian protection safety requirements. Studies carried out in previous
EC projects concluded 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 stakeholders involved in the vehicle type approval process is essential. Experts of EEVC WG22 and software
developers are participating in IMVITER. Introduction of VT in the vehicle type approval process poses a challenge to all
stakeholders and especially to technical services, which will be the ones responsible to put VT in practice. The use of
simulation techniques is a 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, especially
considering management and exchange of sensible data.

Project results

All new vehicles in the EC have to meet a number of technical requirements before being allowed to reach the market. The
ECWVTA Framework Directive 2007/46/EC is a system allowing a vehicle design to be ‘type approved’ for sale and comprises
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regulatory acts. The project is EU FP7-funded and aims to promote the implementation of VT 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, VT is considered as the use of simulation
models in the assessment of regulatory acts, replacing or supporting test methods. This represents the evaluation of type
approval technical requirements that is assessed with numerical predictions. IMVITER’s 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.

Selection of pilot cases

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, no specific preferences existed apart from the initial priority of addressing the
pedestrian protection field. Thus, any currently enforced type approval regulatory act was a candidate to be included. 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. Three categories considered were the low technical difficulty level, accounting for
linear static cases; the medium technical difficulty level, nonlinear static cases and the high technical difficulty level, dynamic
nonlinear cases. Following this criteria, the consortium drafted the first list of 10 potential pilot cases. The next step was to
extract three pilot cases of the list. A set of criteria was gathered, which aimed to evaluate the initial list of proposed
regulatory acts on their feasibility to be implemented in VT. In the selection of pilot cases, not only technical and non-technical
criteria were observed, but also the changing legal scenario regarding the use of VT under the ECWVTA framework.

For the 10 pilot cases initially selected, the definition of test boundary conditions and requirements assessment shall be
fulfilled. Each criterion was ranked with a score from 0 point for lowest to 3 points for highest.

Eventually, the pilot cases that were selected were the following:
- Pilot case 1: Pedestrian head impact protection case;
After discussion within the consortium, it was agreed to also address a fourth pilot case; Pedestrian lower leg impact case. Main reasons for the inclusion of a fourth case were completeness of the pedestrian case and to continue the work already started in the previous EC project APROSYS and to take advantage of the experience gained during that project.

Once the scope of activities was identified, vehicle simulation models were provided by carmakers taking part to the project. They have been proactive in providing this input. Previous research related to VT could not use simulation models corresponding to commercial vehicles, but this time after agreeing on confidentiality rules, carmakers contributed with this input data. Because confidentiality has to be granted, a special organisation of work and data exchange rules and tools were developed. Still further definition of how to implement VT was needed in order to organise 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 was agreed by carmakers, regulatory bodies and the other partners. It follows the flowchart annexed in Commission Regulation (EU) No 371/2010, but includes a detailed description of the steps to follow in its execution. It is the starting point and reference for detailed type approval VT procedures that were defined for all pilot cases.

Verification and validation of models

A key aspect in the implementation of VT is the assessment of simulation models' predictability. VT methods have to provide for the same level of confidence as physical tests. For that reason, the V&V methodology was adapted to the particular needs of the project. V&V activities were defined to collect evidence to demonstrate that simulation models being 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 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. Also, 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 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 studies were based on models considered predictable at vehicle design level. 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, setting stringent requirements for influencing components while leaving light requirements for non-relevant components and 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 case, the sensitivity of the system under analysis was assessed varying model parameters or features independently. The parameters and features with the highest potential effect on the system response of interest were increased and decreased within meaningful limits. From an initial comprehensive list of parameters and system features, only those potentially relevant were considered. After running the models the resulting data was processed, 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 derived, ranking the influence that the different system features had on the 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 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 reaction forces in the crash boxes. In 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 and 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 so that a fair comparison of test and simulation results could be done considering its scatter and uncertainty. 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 metrics were identified. Validation of simulation models relies on fair and objective comparison of results. Such objectivity can only be achieved with the use of model validation metrics, which are developed to provide a quantitative measure that characterises the agreement between predictions and observations. Validation metrics are mathematical functions which need at least a pair of results and provide a value that gives a measure of how close results are to each other, not only in terms of topological distance, but also taking into consideration data tendencies, peak values and phases. Then a criterion 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, test and simulation results cannot be considered similar enough and as a result we can conclude that the simulation model cannot be deemed as representative enough.

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 VT and other research groups like the 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 Sixth Framework Programme (FP6) research project APROSYS, or TRB's National Cooperative Highway Research Programme (NCHRP). Currently, there is no unified model validation metric widely accepted for vehicle safety applications. For this reason, the most used comparison methods were described first. Then model validation metrics, made up from several comparison methods were reviewed. Numerous assessment tools exist in the commercial codes commonly used in the automotive sector. These often use several metrics. Eventually well-known codes and software packages 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 results allowed 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 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 provided by the manufacturer was then summarised to be used in the next project activities.

Many questions arise when we faced the implementation of VT in the motor vehicles' type approval framework. In order to answer those questions, the implementation of the V&V methodology was needed in the pilot cases and 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 information necessary for 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. Additional activities like sensitivity analysis and stochastic runs with a meta-model were carried out from the simulation side. Simulation and test results obtained were analysed in order to compare one to one results and 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; at subsystem level with headform impactors and with a vehicle at full system level. Tests conducted according to the current regulatory act were performed, introducing additional instrumentation, 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 performed with two objectives; 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 were collected. Results from three certification setups were shown, accounting for the traditional and a new oblique drop tests, as well as the existing dynamic test. Scatter found at each laboratory and when comparing among laboratories was analysed. At full system level, a meta-model 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 meta-model 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 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, including additional instrumentation. Rear seat anchorages from two vehicles were tested, representing a new type of vehicle and a derivative version from the existing type. 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 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 types of belt was performed: M1 type belt strap and truck fixative strap. 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 to account for testing uncertainty. Repetitive regulatory act tests were conducted, capturing 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, the three proposed parameters to be observed were analysed and a 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 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 conducted in the pedestrian lower leg impact protection pilot case, 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 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 previous studies, V&V metrics and criteria were defined for 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
solution verification was addressed, dealing with 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 pilot cases.

A model validation metric is selected for the pedestrian head impact pilot case. Twenty one metrics were preselected, corresponding to those which seemed more promising for the case and based on a subject expert study, results were shown for 6 out of the preselected set. Three 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 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, V&V processes were applied in the pilot case at three levels; headform impactor model, vehicle model and full system model. 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.

A proposal on information and data to be reported by the manufacturer to the technical service was drafted, corresponding to results obtained in V&V phases of the VT process. Simulation tools were briefly discussed. A discussion was opened about the possibility to validate simulation codes instead of simulation models. 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 was addressed. Taking advantage of the simplicity of the 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. A dissertation was given about scatter of test results due to accepted testing inaccuracies. After indicating some test scatter sources, the scatter obtained in the evaluation of various headform simulation models developed in different simulation codes is shown. Sources for scatter are identified.

It was studied if simulation codes calibration could be feasible as a mean to accept all simulation results generated with a calibrated simulation code. 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. We can conclude that the evaluation of simulation models predictability requires 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 tracked in order to establish their validation. Reliability, compatibility and repeatability should be verified. Also, models translation should be avoided and should be carefully done if unavoidable. It was described that modelling techniques are different from one code to another and a model translation can be considered as rebuilding the model from scratch. Next to that, code specifications are an important parameter to verify in VT. Statistical and automatic or scripted tools are efficient in VT. They allow analysts to post-treat results efficiently.

Predictability of simulation models

Modelling of physical phenomena is crucial to improve the predictability of simulation models. Development of new mathematical or computational models was out of the scope of our research, but the application of novel numerical techniques or modelling methodologies that are not commonly used but are already available was feasible. When assessing the predictive capabilities of current state-of-the-art models, some simulation’s lacks or rooms for improvement were detected, which guided matters for part of the project. Three modelling areas where space for improvement exists are materials, joints and contacts. Main efforts addressed 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) is tested against the traditional piecewise linear plasticity material model. This trial implies a new characterisation procedure that considers more load cases than simple traction and afterwards the 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 valued in comparison to test results. Modelling improvements in elastomers and adhesive materials were presented. Several examples were shown on how to improve the predictability of models for vehicle type-approval. 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 improvements were demonstrated in the pedestrian protection related simulations, where both RT and VT data were available at full system level. Spot weld modelling improvement could not be demonstrated at full system level because of practical reasons.

Research efforts in terms of join models predictability was focused on developing a characterisation methodology for spot welds. This is the type of joint most frequently used in structural metallic assemblies in the car body. This kind of joining technique was used in the crash-box components that support the bumper beam of the car and where the towing eye can be screwed. However, as the load requirements for the spot welded joints are 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 tested. A calibration and optimisation activity was 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.

Advanced modelling techniques show the path to follow for improved predictability. However, when the improvement is limited, the question about the suitability of complex and expensive modelling and characterising techniques 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 more. Therefore, it is important to make sure that the most relevant phenomena and related parameters have been properly addressed prior to making relevant investments on less influencing aspects. On the other hand, scatter and variability of parts as well as RT methods uncertainty should not fall into oblivion. The idea behind this statement is that the model predictability should always be in balance with those aspects, related to quality of parts and real testing. We conclude that more simulation interpretation know-how from the vehicle development process needs to be transferred to the new virtual type approval scenario.

VT implementation

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 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 and at what moment in time during the product development process physical parts will be made available for validation tests. The smoothest introduction of VT would be that one which would not 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 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 and what information is necessary.

Depending on the regulatory acts under assessment and the vehicles or systems involved, different alternatives emerge 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. After studying the exiting possibilities, three alternative type approval approaches 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 is suitable when simulation model validation can be done at component or subsystem level. 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 phase 2. In the first and fourth pilot cases simulation models are validated at component, subsystem and 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 are 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 is the base for the introduction of small modifications. As a consequence the new simulation model is validated, starting from the assessment of the influence of introduced modifications. A reduced number of validation tests would be used in phase 2, taking advantage of the validation work already done. The second pilot case is used as showcase in which the assessment of seat belt anchorages strength is performed. An already certified model is necessary as an input as reference model. A derivative model is compared to the original one in order to assess whether its predictability can be considered acceptable after introducing modifications from the reference model. If this phase is met, the simulation model would be used in the assessment of technical requirements in a similar fashion as in the Full VT approach. This approach is suitable in several regulatory acts, especially in those cases in which a product is developed as a derivative of an existing product.

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 three VT approaches, depending on regulatory acts particularities. All VT approaches consist of a three-phase process; verification, validation and type approval requirements.

The different approaches for implementation of VT were deployed in detail for the pilot cases, as shown below:

- Pilot case 1: Pedestrian head impact. 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 V&V methodology that was developed is applicable to any regulatory act based on repetitive tests.

- Pilot case 2: Seat belt anchorage points strength. 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. This case addressed lower leg impactor advance certification requirements within VT approaches.

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 V&V 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 they interact and exchange information. A description of the formal and legal structure of the ECWVTA system was done. Each institution taking part was identified and its functions described. The basic reference or legal texts describing the system were listed and its content identified. The accreditation structure that institutions involved in the ECWVTA system will fulfil was described. Their competence and ability is evaluated before being recognised as accepted bodies to carry out type approval activities. Accreditation requirements were revised. A proposal was given on modifications to the accreditation system as a consequence of introducing VT.
New documents that are to be exchanged between type approval actors were described in terms of content, responsible and identification. Directive 2007/46 EC clearly describes all necessary information to carry out motor vehicles type approvals in terms of technical specifications for each regulatory act and about the interaction of involved stakeholders, documentation to be exchanged and accreditations. Article 41 describes required competences for TS and the inspections specified in regulatory acts listed. Previous references rely on the prescriptions given regarding general requirements for the competence to carry out tests and calibrations and general criteria for the competence of impartial bodies performing inspection. But in these standards there is no distinction between RT and VT. Therefore, any TS can take advantage of this legal gap to carry out or supervise VT for a 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 between RT and VT. The main conclusion is that there are 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 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. There are almost no harmonised or recognised methods for the assessment of simulation codes predictability. The ASME ‘Guide for V&V’ is the only recognised reference that helps in the assessment of simulation models predictability. The documentation for the type approval process based on VT defined in this project aims to support this task.

V&V reporting

Based on the project experience, there are promising potentials with VT, which will appear clearer as its implementation by the industry becomes reality. Virtual techniques have become basic methods in vehicle development during the last two decades. Simulation technology is permanently improved and more advantageous than real testing in many aspects. However, this is not so in vehicle regulations. The basic structure of vehicle regulations was set up for real tests and was only slightly changed for 30 years. It is time for technical experts to find the appropriate place for VT in the approval procedures. Three main outcomes are produced to foster the implementation of VT: VT implementation approaches, VT methods and V&V templates.

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. A dialog 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 V&V documentation was created. During this process, 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 useful, leading to achieve a 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 new in the type approval framework. The whole VT process is refined thanks to its implementation. The final versions after refinement were updated according to the experience gained during the VT implementation. A description was given about the pilot cases in which the VT process was implemented. One of the main outcomes was the section reported as frequently asked questions, for which the consortium 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 dialog among all partners was initiated to guarantee a fair and consensus-oriented approach. The various possible VT implementation alternatives are proposed to feed this dialog, specified and investigated with the support of testing and simulation activities.
During VT implementation, a discussion was established based on the documentation proposal. The documents were classified and differentiated between V&V, and a distinction was made with respect to those dedicated to simulation tools 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. The templates were filled with the data obtained from 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 leads to significant benefits for the industry in terms of cost and time savings. Extracting information from simulation models is fast and easy and more flexible than any test. Good simulation models can provide accurate predictions on how a system performs under loading conditions and takes less time than a test. But a lot of effort is needed to build a good simulation model. A fair comparison between testing and simulation cost shall encompass all activities needed in both cases. The use of predictable simulation models available from vehicle design processes for the assessment of type approval requirements is the next step. Benefits are expected because all effort related to setting up those models was already spent during design, so 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 analysis came from previous project activities. Pilot cases were selected, different VT approaches were identified and the VT process was defined in detail. Thanks to all inputs this study gave a comparison of costs and benefits that can be expected from the conventional type approval system and the new proposed type approval system based on VT. In this analysis, a CBA tool was adopted to the needs of the study.

A straightforward methodology was used:

- identification of the number of conventional type approvals developed for the addressed regulatory act during two periods of time, one accounting for one year and a second one extended to 10 years. 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 addressed are available;
- integration of V&V activities within the product development process;
- identification of all activities;
- collection of cost and time inputs from partners involved in each pilot case;
- 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, calculated based on the penalty of change theory;
- recommendations on how to benefit from the implementation of VT.

The comprehensive cost-benefit analysis of proposed VT approaches gave clear indications of the savings that can be expected with the implementation of VT and warned about situations in which no advantage was obtained. In pilot case 1 for pedestrian head protection, savings in cost and time were identified both in short-term and long-term scenarios. The use of a validated simulation models instead of tests in the EoA based on VT provides significant benefits in terms of cost reduction, reduction of risks of unexpected tests failures and increases the flexibility in time. We can conclude that due to the repetitive nature of this regulatory act replacement of tests with simulation predictions can provide clear savings and increase flexibility during vehicle design. In pilot case 2 was found that VT can provide benefit for OEMs only if a highly predictable simulation model is available from design and development activities. If simulation VT have to be developed only for VT purpose, it is likely that no advantages exist in comparison with the conventional tests. The regulatory act test carried out in the conventional approach is a relatively simple test that can be performed in a short time and that is not excessively expensive.
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 evident that if a vehicle prototype can be saved avoiding this destructive test, it would be an advantage for the OEM. In pilot case 3 for towing hook was found that in this kind of regulatory acts, VT would only provide advantage if a full VT approach is implemented. This approach is closer to the validation of modelling techniques rather than validation of simulation models. Any simulation model developed with validated simulation methodologies would be validated de facto. OEMs would have a kind of database of validated material cards and joining techniques and based on that no more validation efforts would be requested. This approach is inherently adopted nowadays in design, because parts with different geometry but same materials are developed for different types of vehicles. This is the only alternative that would allow replacing tests by simulation. The regulatory act test is almost costless. The automatisation of V&V templates filling is almost mandatory in order to optimise the whole VT process in terms of time and cost.

In pilot case 4 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.

The following main conclusions can be drawn:

- the process has potential for optimisation in terms of cost and time;
- potentials of simulation are limited. 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 shows clear benefits;
- for regulatory acts based on costless tests, no savings are expected with VT if simulation is simply used to substitute the test;
- not all VT approaches identified are adequate for all regulatory acts - ideally in the near future, 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:

- 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;
- documentation efforts are cost drivers for the VT approach - an improved integration of these activities within the vehicle development process, and the automatisation of information collection and reporting of data into agreed templates would reduce those efforts, increasing the efficiency;
- no differences were found with regard to TS fees, regardless the type approval approach implemented.

Pedestrian protection

IMVITER adapted current regulatory to include the use of simulation models. For the pedestrian protection cases, the rigid legform impactor was used. New biofidelic tools are not accepted neither included yet, but it is expected that they will be in the near future. A brief study of new impactors was done in order to analyse if the V&V methods defined for simulation tools would be suitable for these impactors. The most important aspect of the VT methodology defined is the application of V&V. This is to be applied to the vehicle or system simulation model and to the simulation tools. 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 flexible lower leg impactor, flexible lower leg impactor with an added upper body mass (UBM) and the thums-D full body model family. An inventory of full body pedestrian models and a proposal for their verification was described. First, the evolution of human body models was shown. A direct comparison of all model dimensions with anthropometric data was performed. The FEM human body model family, THUMS-D, was improved featuring the Strasbourg University finite element head model (SUFEHM). A validation of a flexible lower leg
impactor was shown based on the comparison of tests against results from the equivalent simulation model. Validation was planned at the 12 channels evaluation defined by the GEM scoring method, the three segment evaluation (based its average performance) and the model evaluation, which based its average performance of the segments.

Also an advanced certification test frame is 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 for the validation of this type of lower legform impactor numerical models. After validation tasks with impactors, human body models were addressed. THUMS is a virtual human model that was improved and validated and after that was called THUMS-D. Details of the strategy followed were given, simulations conducted and their results to validate this model. To validate the impact response of the THUMS-D pedestrian model, impactor tests were simulated to validate different body segments. To validate the full body kinematics of the THUMS-D model, the 1 SAE test was simulated to evaluate the trajectories of head centre 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 were conducted. The simulation car model was modified to achieve the bumper and hood-edge stiffness of cadaver test car. The anthropometry of the THUMS-D model was scaled to match the anthropometry of different sized cadavers used in tests. Characteristics that have to be checked during V&V are model stability, model sensitivity and model validity. The model sensitivity classifies the quality of results with respect to small perturbations of model parameters or constraints. Ideally, the solution of a simulation is insensitive to small changes. The model was stabilised and validated w.r.t. standard and other relevant load cases. The sensitivity analysis was used to reveal problematic model parameters. References were made with regards to the adequacy of the validation methods used in the development of the simulation tools, which give indications on how those tools could be used in future implementation of VT. After reviewing the existing models, it was found feasible to adapt the V&V methodology developed to new simulation tools. Advanced impactors certification method can be used for the validation of its simulation counterparts, while additional validation requirements are proposed in order to assess simulation model performance in more realistic impact situations. 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 related assessment methods are quickly evolving. Computational methods are suitable tools to tackle system complexity and set-up diversity. New specific V&V procedures will have to be agreed for the establishment of VT as an accepted assessment methodology for new safety systems for pedestrians in the type-approval scenario. For some safety systems related to pedestrian safety, simulation technology (HBM) was applied to investigate the potential of VT to evaluate advanced safety systems. A related tool set to position and to scale the simulation models within these scenarios was used and presented. The consortium gave indications on what are the next steps that should be taken in the implementation of VT in the next decades. Using the SWOT methodology, the consortium carried out a prediction on the main milestones that should be achieved in the next years.

Potential impact

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. According to the EU’s legislative procedure, proposals for new legislation are worked out with technical advice of experts from all Member States. These are based on technical considerations and 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 through participation in committees, meetings and events.

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 and extending the application of CAE current and future technologies will also contribute to raise the
quality of computer simulation tools. Besides, VT can enhance safety regulations standardisation worldwide, avoiding 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 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

VT will have a significant impact in enhancing the European automotive industry competiveness, 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 together with other innovations will have a socioeconomic impact allowing the European automotive industry to continue being a pillar of the European economy, representing 3 % of Europe's gross domestic product (GDP), 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 economic 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.

Project website: [http://www.imviter.com](http://www.imviter.com)

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