OSCCAR:

FUTURE OCCUPANT SAFETY FOR CRASHES IN CARS

Standardised procedure for validating a vehicle environment for VT

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GLOSSARY

Term	Definition
Verification	Assessment of accuracy of computational model solving the mathematical problem. • As a first assessment of a model, it is appropriate to check whether the equations are solved correctly. This can for instance be done by simulation of a problem with known analytical solution (benchmark) and is referred to as verification.
Validation	Assessment of the degree to which a computational model is an accurate representation of physics being modelled. • As a next step, checking whether the *right* equations are solved is to be done. The question to be answered is how the model predicts physical reality. Experiments under well controlled conditions provide measurements that are used for this. For such a validation, there is hardly a natural termination. Instead, with new experiments becoming available, the question needs to be answered again if a model predicts the physical reality accurately. Also, validation is specific for an application, i.e. for the addressed problem.
Calibration	The process of modifying (parameters of) a model or tool to reach a performance target defined beforehand. • Unfortunately, many modellers use the term “validation” for what should be referred to as Calibration • Hence, calibration often follows the objective of improving the result (assessed accuracy) gained in the validation.
Certification	The process of official approval that a model and its associated data are acceptable for a specific purpose. Purpose describes the use in an existing procedure, e.g. consumer rating or legislation with Virtual Testing. • From the idea of validation described above, it can be easily understood that rather few end users will be able to decide whether a model is predicting the physical reality accurately enough for their problem. It is therefore useful to install a processes for creating trust of users in models. A certification of a model is one option. This may include some kind of prevention of undesired modifications to the model. Certification of a model by an authority reduces the responsibility of the user for model validity. A model certification needs to be done for single problems/applications.
Correlation	Strength of a relationship between two sequences of values • Correlation is a widely used, basic and objective metric to evaluate the relationship between two variables. These variables can be, for example, the values of experimental and calculated result data. In comparison to other metrics, correlation simply answers the question of whether there is a relationship between those two sequences of values, and if so, how strong it is. This metric per se does not consider differences such as phase shift or similarities between those data sets.
Goodness of fit analysis	Assessment of how close two results (curves) are. • Correlation of Y-values from both curves at same X-values may be one part of goodness of fit analysis.

ABBREVATIONS

Abbreviation	Definition
ATD	Anthropomorphic Test Device
CAE	Computer Aided Engineering
CORA	CORrelation and Analysis
HAV	Highly automated vehicle
HBM	Human Body Model
IMVITER	IMplementation of Virtual TEsting in Safety regulations: EC funded project within the Seventh Framework Programme (FP7)
IR-TRACC	Infra-Red Telescoping Rod for the Assessment of Chest Compression
ISO	International Organization for Standardization
NCAP	New car assessment programme
NHTSA	National Highway Traffic Safety Administration
OEM	Original equipment manufacturer; within this context vehicle manufacturer
PMHS	Post mortem human subjects
RT	Real Testing
THOR	Test Device for Human Occupant Restraint
THUMS	Total Human Model for Safety
VD	Validation Device
VPS	Virtual Performance Solution: Software for Finite Element Simulation developed and distributed by ESI Group
VT	Virtual Testing

1 EXECUTIVE SUMMARY

The main achievement of this report are proposals and guidelines to define a process to admit vehicle environment simulation models to be used in a VT (Virtual Testing) procedure involving Human Body Models (HBMs). A validated vehicle environment model is a prerequisite for any VT approach involving ATDs (Anthropomorphic Test Devices) or HBMs to assess the safety performance of occupant protection systems, which is a key objective of OSCCAR.

The motivation for the use of HBMs in VT – in addition to other physical testing - is to overcome the limitations of ATDs in physical test procedures, which have reached their limits of applicability and complexity to assess occupant protection systems in new accident scenarios and especially occupant seating positions expected for highly automated vehicles. Furthermore, HBMs are more suitable to consider user diversity related to age, gender and anthropometry. The high importance of a reliable process to validate a vehicle environment simulation model in an HBM-based VT procedure is related to the fact that no corresponding real test is available to assess the credibility of the simulation results. There is no option for direct comparison to physical test results, because no corresponding real test tool is available.

Testing and validation procedures from previous VT-related projects like the EU-project IMVITER were reviewed. Based on that, a new HBM-based Virtual Testing procedure was developed. This procedure is outlined in a flowchart consisting of three phases. In Phase 1 the simulation model is developed, which is done by the vehicle manufacturer. After that on official validation (Phase 2) is required, to demonstrate that the model correctly represents the real vehicle Phase 3 is the key part of the procedure the new VT based homologation (or assessment) load case including an HBM suitable and certified for this new load case, which requires a detailed VT procedure as well as HBM-based assessment criteria e.g. in terms of kinematics and injury.

This report describes in detail the necessary elements of Phase 2, the environment model validation process, which needs to be fulfilled before the model can be admitted to VT. The selection of appropriate validation tests, a validation device and validation channels should consider the relevant aspects of the new homologation/assessment load case.

Proposal are made how to select reasonable validation tests, which could be sled tests or sub-system tests. Furthermore, possibilities to select an appropriate validation device are discussed. The requirements for a validation device (VD) were identified to be on the one hand a similarity in terms of interaction with the vehicle environment to the assessment tool (HBM). On the other hand, the VD should fulfil practically oriented requirements like robustness or repeatability. These considerations make the selection of a VD among available options (standard ATD, simplified dummy or new specifically developed VD) challenging. Furthermore, guidelines were discussed to select appropriate validation channels to compare between test and simulation.

The environment model validation procedure was applied to the OSCCAR homologation test case, which is a frontal impact load case with an average occupant in a reclined seating positioning. The investigated validation load case is a sled test in the same loading condition with a THOR-50M ATD. Comparisons of HBM simulations with ATD simulation in these loading conditions showed some difference suggesting that the THOR ATD might not be an appropriate validation device for this load case.

To assure the same level of trust in a Virtual Testing procedure as in today's physical testing procedures, the definition of responsibilities of the involved parties to carry out tests or simulations is a critical aspect. Different options were outlined and discussed. In any possible option the simulations will be carried out by the vehicle manufacturer, as the transfer of the vehicle model to a consumer testing lab or a technical service is not a favourable option due to confidentiality issues as well as technical reasons. There are different options for the validation hardware tests, which could be done by the vehicle manufacturer or a consumer testing or technical service lab. However, this could increase the effort and might be done only on a case-by-case basis. Witnessed tests are seen as an option, which could increase the trust in the whole procedure.

To admit a vehicle environment model to Virtual Testing, an objective method is needed to compare experimental test data and model response in the defined validation load cases. Pass or fail criteria to objectively distinguish between the responses of a valid and a non-valid model should be on the one hand stringent enough to achieve a similar level of trust as in a real testing procedure. On the other hand, meeting the criteria must be achievable with reasonable effort.

The two most widely used available metrics CORA (CORrelation and Analysis) and the ISO/TS18571:2014(E) metric were reviewed. The applicability for the OSCCAR vehicle environment certification procedure was confirmed for both metrics. CORA still requires the definition of various parameters and employed limits as well as rating scheme. For the ISO metric a rating is already validated, but it would be necessary to decide which rating is acceptable for each individual validation channel considering real test scatter.

Furthermore, general ideas and concepts how to address scatter to define reasonable admittance criteria were discussed. Proposals were made how to address – within a validation procedure – scatter resulting from the test procedure, scatter from the validation device and scatter in vehicle environment components. It will require further work to decide how to consider scatter to set achievable criteria to admit a vehicle environment for Virtual Testing in a practically feasible approach.

Pre- and post-processing criteria were reviewed to propose the most relevant criteria which should be checked as a minimum requirement to ensure a reasonable level of model quality additionally to the validation-based procedure. The main recommendations are to avoid changes in global controls over the full processes, assure adequate mesh quality and proper element formulation, appropriate contact modelling, robust modelling, and to include a thorough analysis of global energies and animation as well as numerical stability.

These recommendations should be considered minimum requirements, which can be supported by model quality check lists or software-based automated check tools. However, the simulation engineer and finally the vehicle manufacturer who submits the model to Virtual Testing should be responsible for the overall quality of the simulation. By taking due care and this responsibility for the model quality it should be assured that the results achieved with the model in a Virtual Testing procedure provide the same level of trust as a test with the corresponding real vehicle environment.

In order to avoid confusions regularly observed with terms used related to simulation and Virtual Testing, a glossary is included at the end this deliverable.

Finally, the concepts and recommendations provided in this deliverable shall serve as foundation of future standardisation activities and implementation in regulatory or consumer testing.

Keywords: Virtual Testing, validation procedure, occupant environment, vehicle model, objective rating, pre- and post-processing requirements, HBM, certification

2 OBJECTIVES

Due to increasing requirements for occupant safety, assessment methods are developed in the context of more complex crash configurations related to automated driving vehicles and the approach to also consider user diversity. Real testing with ATDs will eventually be complemented and in the long-term maybe even replaced by Virtual Testing with HBMs. For this new Virtual Testing procedure with HBMs, there will be a need for vehicle environment simulation models that are sufficiently validated to ensure a similar level of trust in results like in a real testing-based procedure. As an intermediate step VT with simulation models of ATDs would also be possible addressing other limitations of physical testing like limited number of load cases, which can be tested physically due to limited effort. ATD-based VT is not considered within OSCCAR. However, the vehicle environment validation procedures disused within OSCCAR should also be applicable in a similar way to ADT-based VT.

The main objective of Task 5.1 is to provide guidelines for a standardised validation procedure for a vehicle environment model to admit it to a virtual test procedure together with HBMs. Therefore, the selection of appropriate validation tests and a validation device are needed, including the specification of relevant validation result channels. The proposed procedure will be discussed based on experience gained from OSCCAR validation test and simulation work conducted in Task 2.4. Furthermore, it reflects the application to the OSCCAR homologation test case in WP4.

The next step is the definition of an objective procedure to compare test and simulation results to decide whether a vehicle environment simulation model can be admitted for Virtual Testing. For this purpose, available metrics are reviewed. The objective is also to discuss how to select appropriate acceptance criteria considering test scatter.

Another objective of Task 5.1 is to specify pre- and post-processing requirements to verify robustness, stability and quality of the results independent of the solver. Within the project, this should serve as input for work package (WP) 4.

Finally, the considerations on organisational processes and wording of the different elements of Virtual Testing shall serve as a foundation for discussions in the stakeholder community.

3 STANDARDISED PROCEDURE FOR VALIDATING A VEHICLE ENVIRONMENT FOR VT

3.1 Background: need and motivation for a standardised vehicle validation procedure

It is expected that high levels of automation will bring new accident scenarios (primarily in mixed traffic) as well as new vehicle interior concepts. Such interior concepts may include new seating positions, such as, for instance, reclined seat backs, and seats rotated about the vertical axis enabling interactions between occupants in a “living room environment” (see Figure 1).

Figure 1 Example of new interior concept and user behaviour in HAV (highly automated vehicles) and automated driving mode (Source: Daimler)

Ensuring the safety of occupants in such altered conditions requires the design of new protection principles and safety systems. To evaluate and assess the safety level of these new concepts and systems the adaption or new development of new assessment procedures as well as related new evaluation tools will be necessary. It may not be possible to develop test procedures with currently available standard ATDs that have the potential to address the mechanical effects of interest under those conditions. Therefore, a possible alternative is seen in complementing RT under established conditions with VT employing HBMs under new conditions.

3.1.1 Motivation for virtual testing with human body models

Motivation for Virtual Testing in previous discussion or projects was initially focusing on replacing existing RT based procedures by VT. One example is the EU-Project IMVITER (**Im**plementation of **Vi**rtual **Te**sting in Safety **R**egulations). The main motivation was on saving costs and increasing the flexibility of the type approval process, but not introducing new test conditions or requirements.

Another motivation for VT of previous projects combining RT and VT was the extension of the scope of protection by adding additional test conditions for example a standard occupant in a slightly modified setting of the seat position or seatback angle. This can still be done by using existing test tools (ATDs / impactors) by combined real testing and Virtual Testing. This way additional test conditions can be added to encourage a more robust or adaptive design of safety systems without increasing the hardware-based testing effort.

The main motivation for Virtual Testing within OSCCAR is the use of HBMs in a VT process to address the limitation of current ATDs. With HBMs it is possible to represent the occupant by a more detailed and biofidelic model of the human body rather than in terms of a crash test dummy or ATD. ATDs have several limitations in the accuracy of representing the injury mechanics of the human body due to their nature of a rather robust physical test tool. Finally, new accident scenarios and new interior concepts might lead to new test load cases, which existing ATDs are not designed for, respectively are not valid anymore. To fulfil the needs to assess occupant safety physically ATDs will reach their limit and will be eventually replaced by HBMs in new test and assessment procedures. Figure 2 shows the increasing vehicle safety complexity also resulting from autonomous driving vehicles, which will lead to increasing needs for occupant safety assessment tools. There might be a phase where both new virtual and physical test tools will be used for occupant safety assessment. However, eventually due the increasing complexity only HBMs might be able to address the high needs in terms of biofidelity and robustness at the same time.

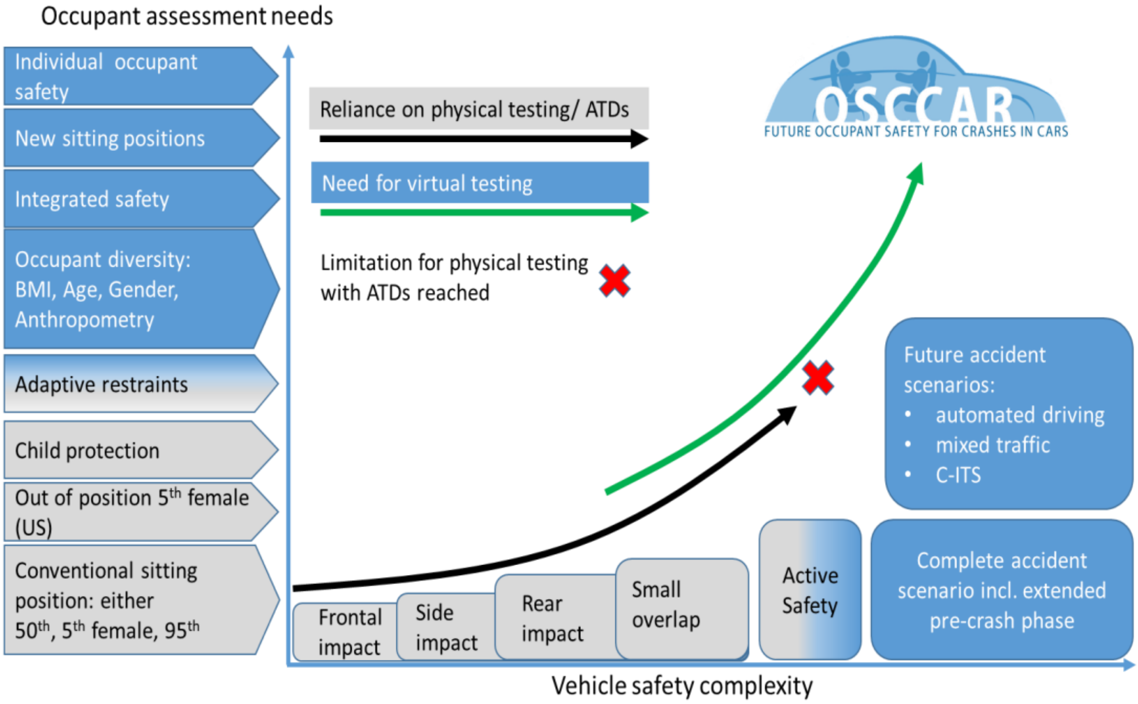


Figure 2 Increasing vehicle safety complexity leading to increasing needs for occupant safety assessment tools

ATDs can by definition only represent a very narrow bandwidth of the population, usually indicated by a target anthropometry like a 50th percentile male Northern American male. Addressing specific population groups of vehicle occupants such as people with smaller stature, obesity, or the core of the female population, already constitutes a remarkable challenge.

In addition, latest research and development offers the opportunity to implement human behaviour in terms of muscle activity to HBMs to represent human characteristics also in pre-crash driving modes and scenarios (Figure 3).

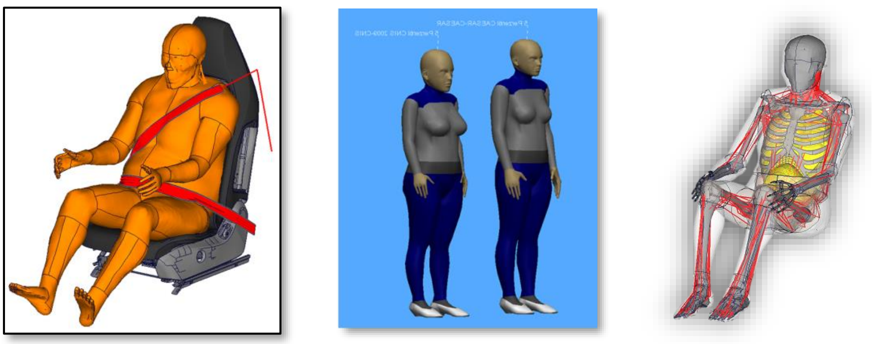


Figure 3 Examples of HBMs: Obese occupant, small female (Asian & Western anthropometry), HBM with active muscles

Furthermore, the injury criteria that have been developed for the use with ATDs cannot always discriminate between more effective and less effective protection of the occupant. The criteria are in some cases not sufficiently sensitive or criteria are just not existing. For instance, the injury mitigating benefits of inflatable seat belts cannot be adequately demonstrated by ATD injury criteria [1]. Established ATD chest instrumentation and related criteria are very limited in showing the positive effect of increasing the contact area between thorax and belt [2]. In other cases, criteria may not be available or the design of the ATD may not allow addressing newly arising injury mechanisms.

A core requirement of an ATD is its biofidelity, i.e. the representation of the behaviour of the human body under impact loading in the intended application scenario. ATDs are usually strongly limited in their biofidelity to a specific application, such as side impact, frontal impact, etc. If loading conditions and spatial measurement orientations outside an established scenario are to be addressed, the biofidelity of an ATD is in a first step to be questioned. In cases where the whole occupant, as in a far-side impact, or a certain body region as by a reclined seat-back are loaded in a new way, major modifications would be needed to achieve a reasonable ATD kinematic biofidelity.

Finally, design peculiarities of existing standard ATDs may limit the usability in newly arising loading conditions. Reclining a seatback for instance implies challenges in positioning and handling of the dummy.

3.1.2 Review of VT procedures for application in consumer testing and type approval

Due to the advantages described above, HBMs have already been used in injury biomechanics research for decades. Meanwhile HBMs are also used in automotive industry for the design and evaluation of safety systems whenever the use of ATDs is limited due to the above-described issues. However, up to now no procedure for Virtual Testing is available that includes the use of HBMs for vehicle safety assessment in type approval or consumer testing in a similar way like for the current ATDs and associated injury criteria. One main objective of OSCCAR is to propose a new VT procedure making use of HBMs.

To develop a new VT procedure, the results of the EC-funded project IMVITER (**Im**plementation of **Virtual Testing** in Safety **R**egulations FP7-2007-SST-218688) were reviewed. The main focus of IMVITER was the development of VT procedures for existing RT-based regulations. In these procedures no HBM as virtual test tool was involved. Nevertheless, the procedures developed within IMVITER [3] will be discussed regarding their applicability towards a possible new OSCCAR VT process based on HBMs.

The starting point for the procedures developed within IMVITER was the EU regulation No. 371/2010 Annex 3 [4] of the regulation defines the validation process of the mathematical model and the following approval process in a general way in form of a flowchart (Figure 4) The key part of this procedure is based on a validation process. However, many details of this validation procedure were not specified in the regulation. Based on that within the IMVITER project a more detailed flow chart was developed (Figure 5).

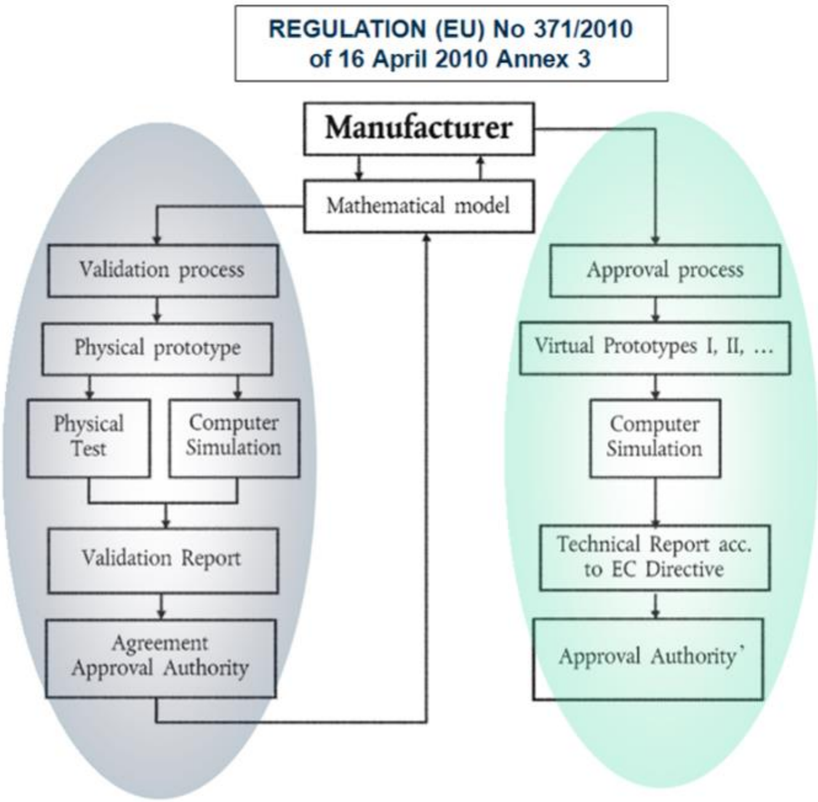


Figure 4 in commission regulation (EU) No. 371/2010

Phase 1 of this procedure is the model development and verification, which is always within the main responsibility of the vehicle manufacturer. The vehicle manufacturer has to assure that the simulation model is developed according to state-of-the-art modelling quality criteria. Phase 1 can also already include comparison of simulations and validation tests.

Within phase 2 validation and certification of the model is done by comparing simulation results to a range of defined real tests. After that step, in a third phase the simulation model can be used for virtual approval tests.

Furthermore, different approaches (ways to proceed through the flowchart), hybrid and full virtual, were developed within IMVITER and applied to different regulations (pilot cases). Details can be found in the IMVITER deliverables and publications [3], [5]. The approaches and the potential applicability towards the OSCCAR pilot cases are discussed in the following.

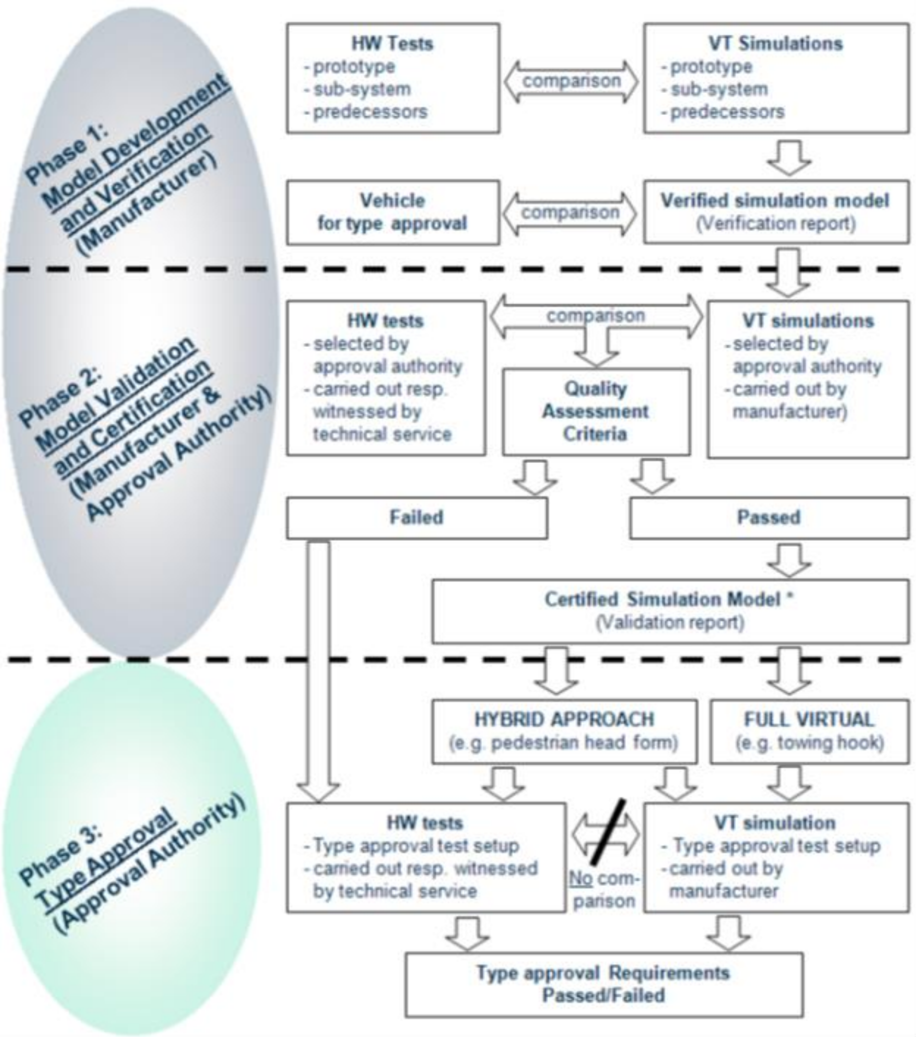


Figure 5 General IMVITER virtual testing implementation flowchart

A hybrid approach was proposed within IMVITER, which can be applied to test procedures involving high number of test cases in phase 3. The concept of the hybrid approach is that all tests assigned to phase 3 are carried out by Virtual Testing. A subset of test cases is performed by real testing. The results are compared within phase 2 of the procedure. If the validation is confirmed by agreed validation criteria, the RT results are transferred to phase 3 and complemented by the VT results. Within IMVITER this approach was successfully demonstrated by the pedestrian head impact and lower leg impact regulation [4].

Application of the hybrid approach to an OSCCAR pilot case would make it necessary to compare virtual tests carried out in phase 3 to real tests in the same loading condition. However, this is not possible, because the assessment or homologation load case in phase 3 will include an HBM as virtual test tool. A corresponding real test is not feasible, because no according real test device is available. Thus, the hybrid approach of IMVITER cannot be directly transferred to the HBM-based OSCCAR pilot cases.

Another approach developed within IMVITER is called full virtual approach. The main idea of this approach is that no real tests are carried out within phase 3. This requires a more extensive detailed validation-based certification of the vehicle simulation model in phase 2. The validation is not done in a loading condition which is exactly representing the assessment or homologation condition of phase 3. Instead, the validation is done on sub-systems, component or material level. This approach seems to be appropriate for OSCCAR. Within IMVITER this approach was demonstrated for the EC Regulation 77/389, Motor-vehicle towing-devices.

However, the most important difference between the IMVITER towing hook pilot case and a potential OSCCAR pilot case is, in addition to the higher complexity of the load case itself and the involved vehicle components, is the virtual test tool (HBM) that will be used in phase 3. The IMVITER full VT approach still offers the possibility to carry out the assessment test in phase 3 by a real test in case any validation fails or there is any doubt in the credibility of the Virtual Testing results.

In an HBM-based fully Virtual Testing approach no corresponding test device exists to perform the matching RT (Figure 6). Thus, in an HBM-based VT process, no hybrid approach and no RT-based approach is applicable at all (Figure 7) in case the validation criteria are not fulfilled. Hence, there is no fall-back option.

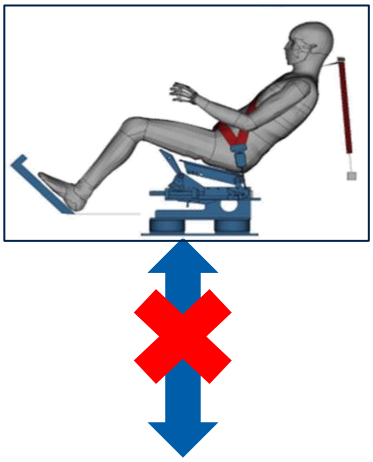


Figure 6 In an HBM-based VT procedure no corresponding real test available

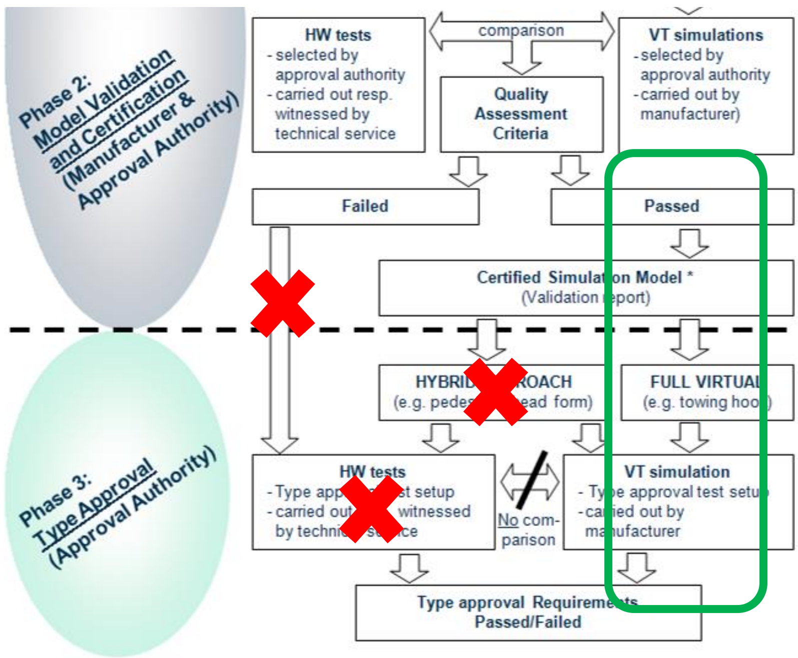


Figure 7 In an HBM-based VT procedure only full VT is possible – no alternative ways to proceed through the IMVITER flowchart

Therefore, in an HBM-based Virtual Testing procedure the phase 2 to ensure the validity of the simulation model to be used in phase 3 is critical. On the one hand the validation procedure should be demanding enough to guarantee the needed trust in the whole full VT-based procedure. On the other hand, it has to be possible to fulfil the requirements as no alterative RT-based option is available.

3.1.3 HBM-based virtual testing procedure

The general process of HBM-based Virtual Testing is shown in Figure 8. A new virtual load case requires a detailed specification of the load case itself including loading conditions (e.g. collision type, impact velocity, direction), the virtual test procedure, evaluation criteria and an HBM, which is specifically suitable for this new load case. This has to be proven by HBM certification requirement for this load case. Furthermore, for any HBM-based occupant VT procedure a simulation model of the vehicle environment is needed. To make sure that this model can be used for this new load case, it should also fulfil specific requirements, before it can be admitted to the VT procedure.

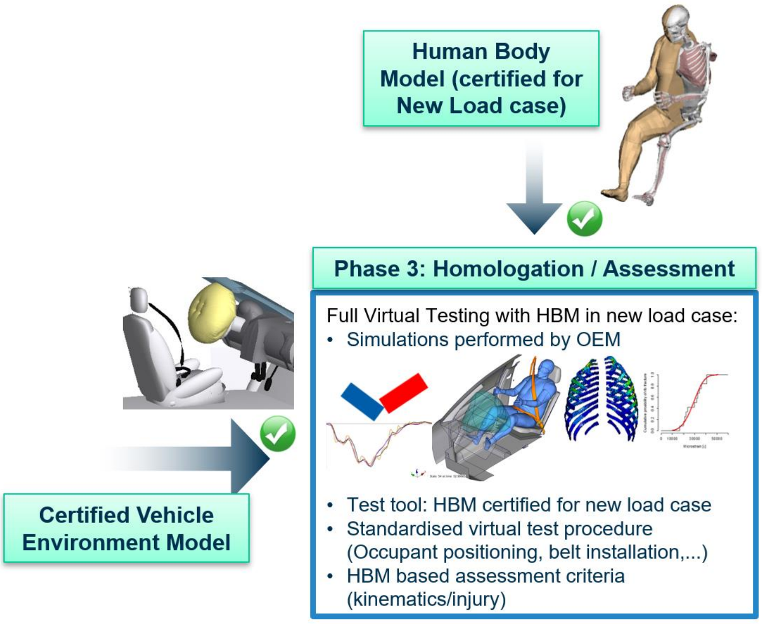


Figure 8 HBM-based virtual testing procedure

Based on these considerations the IMVITER flowchart was adjusted. A new flowchart outlining the OSCCAR HBM-based VT procedure is shown in Figure 9. The main part of the procedure is the new VT based homologation or assessment load case. For this new fully virtual load case an HBM is required, which initially has to be certified for the loading characteristics to be applied in this specific new load case. Further work to define certification and validation requirements for the HBM including a detailed procedure is additionally needed. This will not be further discussed in this report. Some work related to the definition of HBM requirements is done within OSCCAR Task 5.2. In OSCCAR WP3 some fundamental research work to improve HBMs for this new load cases are done, e.g. developments related to at tissue in the pelvis and abdomen area.

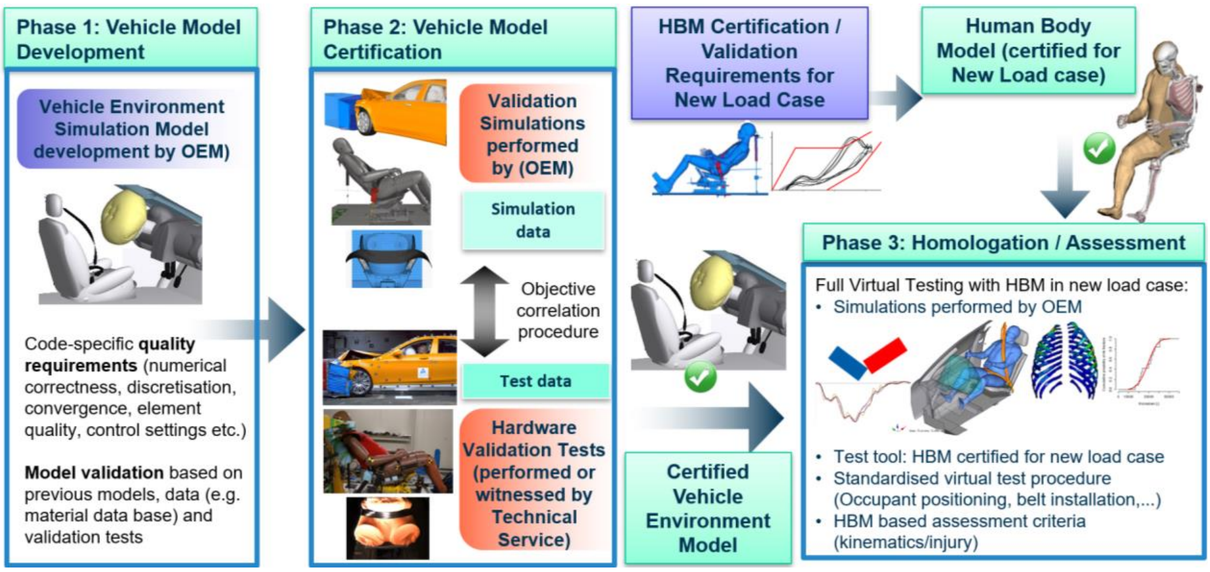


Figure 9 Flowchart of OSCCAR HBM-based virtual vesting procedure

Furthermore, within the new load case procedure a standardised virtual test procedure needs to be defined, including for example an occupant positioning method. To evaluate occupant safety in the new load case HBM-based kinematics or injury assessment criteria are needed. Within WP3 some work related to this is carried out.

As described before a key requirement for this HBM-based VT procedure is a validated vehicle environment model. Therefore, the following sections of this report will mainly focus on the vehicle environment validation procedure. The starting point for this process is the model development (Phase1) which is usually done by the vehicle manufacturer. For this part it is recommended to consider code-specific requirements. Pre-processing requirements are described in more detail in chapter 5. A first prototype of a quality check tool is developed in Task 4.1 (see deliverable D4.1 [6]). Documentation to comply with these quality requirements could be defined as a requirement to certify a vehicle environment model for VT. Phase 1 will also include internal validation tests at the OEM to validate the model. These tests are usually done within the model development process.

For a vehicle simulation model, which is intended to be used in a regulatory or consumer VT procedure after this phase, a more formal process step is needed to show on a more formal official level the validity of the model. Whereas a modification of the model with the purpose of reaching a specific performance (calibration) can be performed in phase 1, this is not admitted in phase 2. The vehicle model validation has to be proven to the institution that is responsible for homologation or assessment of the vehicle. This can be the technical service in case of type approval (homologation) or a consumer testing organization. A set of relevant validation load cases including an appropriate validation device needs to be defined. Furthermore, an objective correlation procedure to assess the validation quality level is needed. After the validation requirements are fulfilled the vehicle environment model can be used in phase 3 for VT with human models.

3.2 Proposal for a standardised procedure for vehicle environment model certification

The definition of the main points needed to define a procedure for phase 2 is the key part of Task 5.1 and will be explained within this chapter.

3.2.1 Definition of validation tests

As explained before the availability of an accepted comprehensive validation procedure to certify the vehicle environment model is crucial for an HBM-based VT procedure. Phase 3 of the VT procedure describes the new Virtual Testing load case including the test tool and evaluation criteria. To choose the appropriate validation load cases for phase 2 including the validation devices a detailed review of the new load case defined in Phase 3 should be the starting point. It should also be considered which safety systems or restraint concepts will be motivated or adapted in the case of the new requirements defined in phase 3. New safety concepts might result in different interaction of the HBM with the vehicle environment which have to be considered for the definition of validation tests.

The objective of the validation tests is to prove (within an official process opened after phase 1) the validation of all components of the vehicle environment interacting with the occupants in the new load case. For clarity, this activity should be largely prepared for in the previous phase concerning the technical level of the work. For these components, key focus should be given on the body regions and phaenomena that are most relevant for the injury assessment.

In general, different options are available for validation tests:

- Full scale crash in standard configuration (NCAP, homologation)
- Sled tests in standard configuration and in new load case configuration (new loading direction, seat rotated/reclined)
- Subsystem/component tests (airbag, seat, …)

<u>Full scale crash tests in standard configuration</u>

Real tests in standard configuration with standard dummies are expected to be performed for regulation or NCAP also in future. Thus, the test data would be available without extra effort and could be used for validation within a certification procedure. However, additional measurements for validation might be needed which are not recorded in standard tests. Furthermore, the vehicle environment model might not be always validated by the OEM for this load case in a way that it automatically would fulfil all quality requirements and correlation requirements which would be defined for a more stringent validation procedure for VT. Moreover, in full scale crash tests the test scatter is usually high which limits the usefulness of this load case for validation of the vehicle environment. However, it might be useful to have a crash test included in a validation procedure as base line validation requirement.

Sled tests in standard configuration e.g. position (upright) with standard ATD

Based on above mentioned crash test a sled test configuration could be defined with a standard ATD in a standard test configuration. The pulse from the crash test could be used. The sled test will have less scatter and uncertainty compared to full-scale test. However, if the test configuration is very different compared to the new test condition defined in phase 3 of the VT procedure this load case can also only serve as baseline validation.

Sled tests in test configuration of a new test condition (or close to new condition) with standard ATD

In case of a crash condition, which is only addressed by Virtual Testing, an according crash pulse is needed which could be used from full-scale tests or full-scale simulation. Another approach would be to use a generic pulse representing this new crash configuration.

The applicability/ biofidelity of a standard ATD as validation device might be questionable. For example, if the new load case is representing a highly reclined seating position, the ATD might not be useable for this condition. However, even if the ATD can be placed in this condition, biofidelic kinematics cannot be automatically expected and are required to ensure a representative interaction with the restraints. This is questionable for standard dummies that are not designed for these new load cases.

If the new test condition is including an HBM representing a non-standard occupant, the validation device should also represent this occupant as close as possible. If a standard ATD that represents the HBM in terms of body size and mass (e.g. obese, tall male or average female) is not available, a sled test with a standard ATD can only serve for base line validation. Further tests on subsystem level might be needed to represent the relevant loading representative of the new occupant. An alternative would be to develop a new validation device representing the new non-standard HBM occupant. Any application of Virtual Testing outside the validation space that can be realised might be desirable, but would be limited in trustworthiness.

Subsystem or component tests

Subsystem or component tests to validate the individual components or restraints of the vehicle interior that are in contact with the occupant are already done by the OEM or supplier to validate the model to be used within vehicle development process. However, the purpose is the validation of the component models to predict the model behaviour in real testing-based homologation or assessment procedures with dummies. To validate the interaction of the vehicle environment to be used in a VT process with HBM new subsystem tests might be needed. This possibly also will require new test devices which are more representative of the human body in terms of shape and stiffness.

With subsystem tests it might be possible to achieve a validation of the relevant vehicle components (seat, belt and airbag) in a higher number of relevant loading conditions in a more detailed and robust way.

3.2.2 Requirements to choose or define a validation device

To validate the vehicle environment to be used in an HBM-based VT process the components of the vehicle environment should be loaded in a similar way as by the HBM in the assessment or homologation load case. To enable this, a validation device is needed that represents the loading as similar as possible to the HBM.

The requirements for a validation device are listed below:

- Representative resulting loading between vehicle environment and HBM in the new assessment load case (including possible new restraint concepts), which is to be achieved most easily by the VD incorporating:

  - In terms of anthropometry as similar as possible to the occupant represented by the HBM in the new load case
  - In the new load case realistic human-like (HBM-like) occupant kinematics considering the principal direction of loading (e.g. front, side, rear, ...)

- Robust, repeatable, reproducible, re-usable in real testing
- Corresponding CAE model applicable in new (validation) load case

The first choice of a validation device would be a standard ATD (e.g. THOR, Hybrid III, WorldSID) that is very similar to the respective HBM in terms of size, mass, shape and can be used in the relevant loading direction (frontal, side, oblique, rear). One main advantage of choosing a standard ATD is its availability including the corresponding CAE counterpart.

However, a standard ATD might usually not fulfil all the above listed requirements. For example, a standard ATD is usually not designed for a new very different loading condition, which could be the main motivation to use an HBM instead of an ATD in this new load case.

Furthermore, the interaction with the restraint might not be sufficiently similar, if the HBM is representing a new kind of occupant (obese or average female) which is not yet covered by a currently available ATD. Furthermore, the HBM might be used in a new loading condition (e.g. reclined seating position) where the ATD shows limitations. In this condition a standard ATD might also not be appropriate or sufficient for validation of the vehicle environment in this loading condition. In this case it has to be carefully investigated what level of biofidelity in terms of restraint interaction is needed by the validation device.

In such a case, a standard ATD could be used for base line validation of the vehicle environment. However, additional validation on subsystem level with a loading that is more representative of the loading to the restraints of HBM might be needed to ensure a robust validation. For validation tests on subsystem level as well as for sled test a new validation device might be necessary. This could also be a very simple ballast dummy or device. Figure 10 shows an example of a ballast dummy. This kind of simple dummy which might be useful for very basic validation of a belt system model based on belt load measurements. A ballast dummy could also consider an increased load caused by the higher mass representing an obese occupant.

However, for more complex load cases involving new assessment criteria a new validation device more representative of the HBM in terms of shape and kinematics in the relevant loading conditions might be needed. An example for this is a validation device developed within the VIVA II project. To validate a seat model to be evaluated with a 50-percentile female HBM (Figure 11) no corresponding rear impact validation device in terms of using a standard ATD is available. All available rear impact dummies for real testing are representing an average male occupant. For a new HBM-based VT procedure with a 50-percentile female HBM a new validation device (Figure 12) which is correctly representing the interaction between test tool and the seat could be used for validation of the vehicle environment simulation model. The reflections presented here are somewhat comparable to what was defined as objective for the development of the so-called “Biofidel” dummy (producing traces on a vehicle exterior during impact that are typical for those of a real pedestrian rather than for an ATD).

Figure 10 Example for a ballast dummy: BART (Source: http://ballast-test-dummies.com)

Figure 11 50-percentile female neck model (Source: Östh et al., IRCOBI 2017, [7])

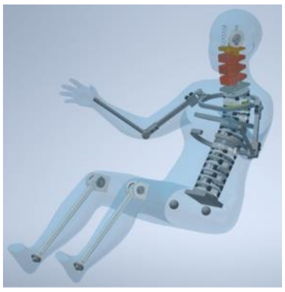


Figure 12 Example for a validation device for 50-percentile female rear impact seat validation from the project VIVA II (Source: http://crashscene.se/f50flogard)

The selection or definition of validation test cases and selection of an appropriate validation device has to be done once every time before the introduction of a new HBMs based VT load case in a regulatory or consumer testing procedure. Theoretically, it needs to be proven at this stage that the validation device can serve for environment validation with any restraint system. In reality, this selection and decision will hold for known restraint/interior systems and will need to be carefully re-evaluated if new systems are presented. To evaluate, if a validation test with proposed validation device, which could be a standard ATD, is sufficient for this specific load case, it is proposed to perform matching tests or simulations with the proposed validation device and the HBM in the homologation load case.

The HBM of course needs a sufficient validity for such an analysis step. As this step is however expected to be run by a group of experts (once within the introduction process of a VT load case), no further implications to the HBM application are discussed within this deliverable. The whole-body kinematics and interacting forces between the occupant and vehicle environment should be analysed. The effect of possible observed differences on relevant injury criteria should be evaluated to decide whether a validation with the proposed validation device is reasonable and sufficient. Otherwise another more appropriate validation load case on subsystem level or another (new) validation device might be necessary. Additional measurements to assess the load distribution between occupant and vehicle environment might also be needed.

Adjustment or modification of the validation process (load case and validation device) might be necessary, if new homologation load case results in new protection principle resulting in very different vehicle environment (new restraint systems), which requires new validation load cases/devices to show the correct interaction between occupant and environment.

3.2.3 Selection of validation channels

The objective of the extended model validation is to ensure the virtual components (e.g. belt, airbag) are loading the HBM in the correct way reflecting the loading and interaction with the HBM like the real vehicle components. Thus, the relevant validation measurements that have to be compared between test and simulation should be in the first place the loads (e.g. belt loads) acting between these components and the occupant.

Additional measurements that are usually not recorded in a standard sled test to quantify the loading between the occupant and environment should be considered for the future, (e.g. airbag pressure, seat forces). However, it might be difficult to measure these signals in a production vehicle as it has to be assured that the vehicle safety systems performance is not influenced by the measurements. Also, more advanced measurements like pressure distribution between the validation device and the vehicle components could be considered for the future for a more robust validation.

By the validation procedure it has to be assured that the interaction between occupant and restraint (e.g. belt sliding) and resulting load distribution within the occupant is correct. For this purpose, the following measurement might also be needed in the validation procedure:

- internal ATD measurements (e.g. IR-TRACCS, clavicle loads)
- tracking of belt movement
- load / pressure distribution measurements

The focus should be placed on the body regions that will be of main interest for the HBM-based injury assessment. Body regions that are not used for the HBM-based injury assessment should also be considered, but only with the focus of correct load transmission.

Furthermore, kinematic measurements should be considered, if it is feasible to take the measurements during the test. If possible, target tracking should be evaluated. Alternatively, the whole-body kinematics could also be assessed by acceleration of relevant body parts.

For each selected validation device and validation channel, it can be discussed if only the relevant loading direction or resultant has to be considered. For example, in a frontal impact load case only some of the x-direction ATD signals might be relevant whereas in an oblique homologation load case also the lateral direction of ATD signals might have to be considered.

3.2.4 Workflow and responsibilities of involved parties in an environment certification process

The objective of the certification procedure (phase 2) as shown in Figure 9 is to ensure that the simulation model of the vehicle environment is sufficiently validated to be used for Virtual Testing with a human model in the new load case. To ensure a similar level of trust in the whole VT procedure compared to a real testing-based procedure the definition of a clear work flow and responsibilities of the involved parties is necessary. This might be different between regulatory testing for type approval or consumer testing.

Option A: A very strict procedure would follow these steps in sequential order (see Figure 13 upper part of the flowchart):

1.) The OEM has to improve the simulation model up to a level that it is sufficiently validated to be used for Virtual Testing. At this stage the model status must be frozen. It has to be assured that exactly this version of model (see section 3.2.5) will later be also used in the homologation/assessment simulation (Phase 3). With this model all defined validation simulation should be carried out by the OEM. The detailed simulation results for all validation load cases should be provided in an agreed data format. Together with the data a report could be provided to show the level of validation.

2.) In a next step technical service or an accredited consumer testing lab would carry out all or selected real validation tests. Another option could be witnessed tests, which are carried out by the OEM or an accredited lab.

3.) In a third step, based on an objective correlation procedure the validation status of the vehicle environment model should be confirmed by clearly defined criteria (see section 4). After that the environment model can be labelled by a Consumer Testing organization (NCAP) or technical service/type approval authority as certified for use in Phase 3 of the VT procedure.

Option B: To reduce the effort for the Consumer Testing organisation/technical service/type approval authority and to simplify the procedure (see Figure 13 lower path through the flowchart), it would also be possible to certify the vehicle environment model based on a validation report summarizing the internal validation work done by the OEM during the vehicle model development (Phase 1). In Phase 2 the technical service or expert at a consumer testing organization would check the validation report and confirm the certification of the model for VT testing based on the report. Technically, this is somewhat comparable to what is called Self Certification in the sphere of responsibility of the NHTSA. However, this procedure would allow less credibility and trust compared to the previously described approach.

A possibility could be to go for Option B in general, but on a case by case decision keep open the possibility to carry out validation tests by the technical service or consumer testing lab (as described in Option A) to confirm the results presented in a validation report. However, for this approach also clear pass or fail criteria (as proposed in section 4) would be needed.

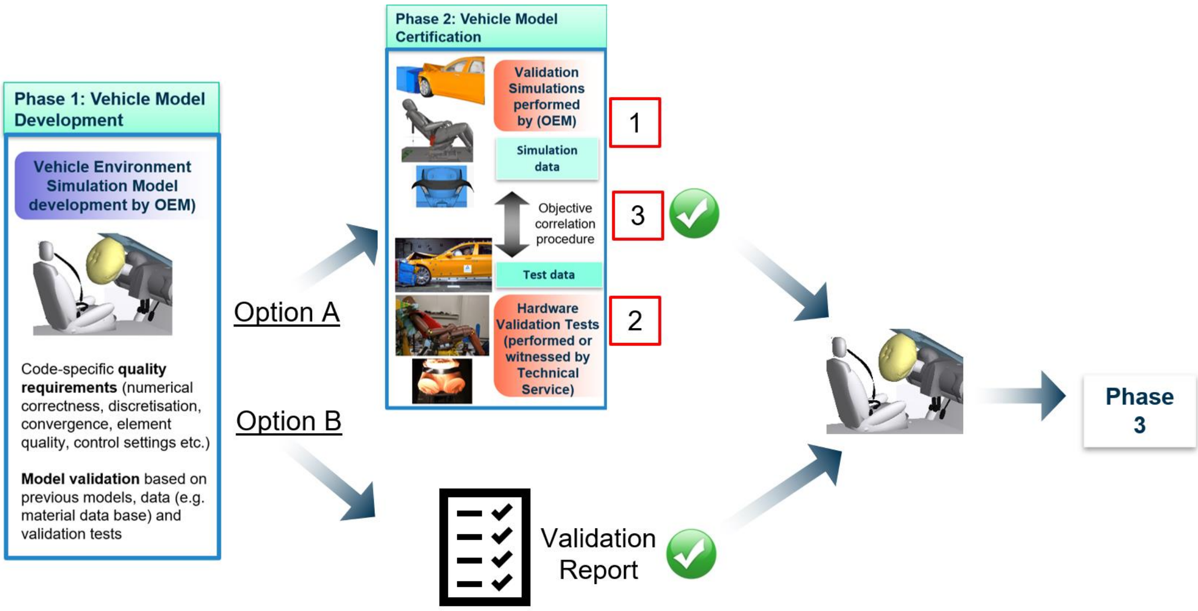


Figure 13 Different options for vehicle environment model certification workflow

3.2.5 Model version control

Currently (following the IMVITER proposal and Euro NCAP approach) the vehicle environment model as well as the HBM, will not be shared outside the companies. In this kind of VT process the quality and validity of the models will be checked and finally approved for further use for VT by a certification procedure. For the vehicle model this will be based on a validation testing-based procedure described within this report. After certification of the vehicle model it has to be made sure, that the same model is used in the whole validation process and eventually for VT-based assessment or type approval

This can be done or is currently done on a basis of trust and based on OEM internal documentation systems. However, if HBM-based Virtual Testing will be used in a homologation of type approval process also an IT-based level of “labelling” (such as check sum, encryption or similar) might be needed. The models could get a kind of “certified” label and the vehicle manufacturer has to guaranty that exactly this model will be used within the whole virtual consumer test or homologation procedure.

Different options to ensure this requirement should be further investigated. After a model (HBM or vehicle/interior) is certified it could be encrypted or “locked” in a way that it cannot be further modified without permission which might result in a re-certification or update of the certification report. Another option could be that the model receives a unique labelling. All simulation results (output data/plots/reports) which are generated with exactly that model would automatically carry that label. It might be also possible to automatically generate some kind of “hash” code from simulation input file, which is always provided together with outputs/results and reports. This “hash” technology is also used in the block-chain method and proposed for cyber security of HAVs.

Eventually, the technical feasibility of all possible proposals within the different IT environments and codes of different OEM has to be considered. It also has to be made sure that it is still possible to work with the model. After certification of the vehicle (environment) model and certification of the HBM, it is still necessary to combine both models in a VT procedure to define the assessment or homologation load case simulation. For example, it has to be possible to modify the geometry to position the HBM in a seat according to a standardised procedure. This still has to be possible if the version control is done by e.g. encryption of the models.

In the following an example for VPS is shown on how to add relevant parts of the input to the result file itself.

The so-called stripped input option, which is active by default in the VPS solver, may help assert that the correct input has been used. The stripped input including the input header is embedded in the ERF result file upon initialisation of the solver. It contains all relevant definitions such as part and material cards and can be reviewed with the free HDFView tool as shown in Figure 14. Nodes and elements are excluded from the stripped input though with the aim to limit the size of the result file.

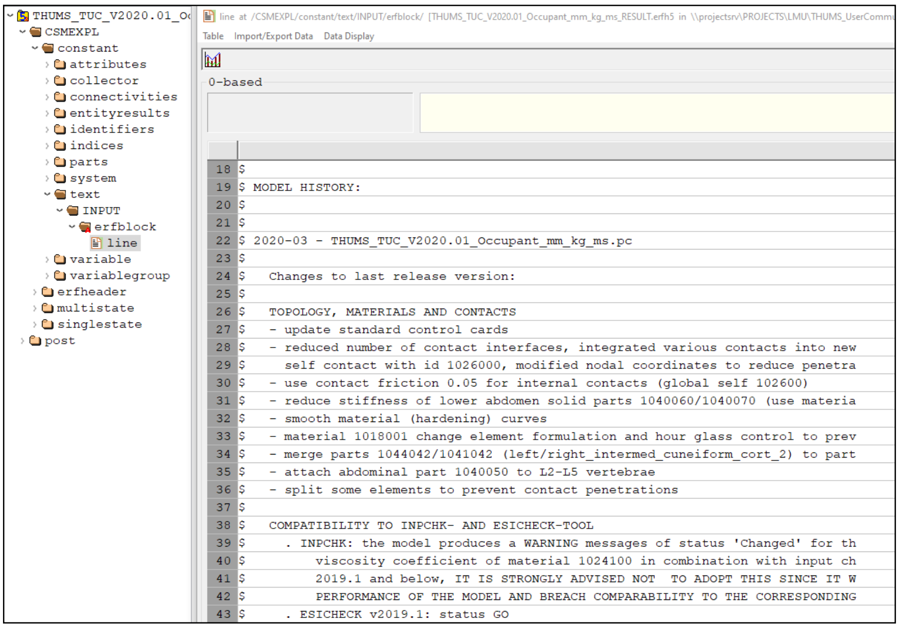


Figure 14 Example display of the ERF result file and its embedded stripped input with HDFVIEW

For further verification of the input files other tools may be utilised for quickly comparing and highlighting relevant differences between inputs. As an example, the Model Compare tool from the Visual Crash for Pam/Dyna (VCP/VCD) pre-processor can be named. In Figure 15 a typical configuration prior to and a result after a comparison are shown. In the GUI various entities such as nodes and elements can be de-selected in order to speed up the comparison. The result from comparison can be interactively investigated by collapsing and expanding the individual sections on the different keywords. One noticeable advantage of this tool is that the inputs can be compared independent of the order of keywords in the files. In a VT process, this could potentially be considered to elucidate issues with failures to ensure model freeze.

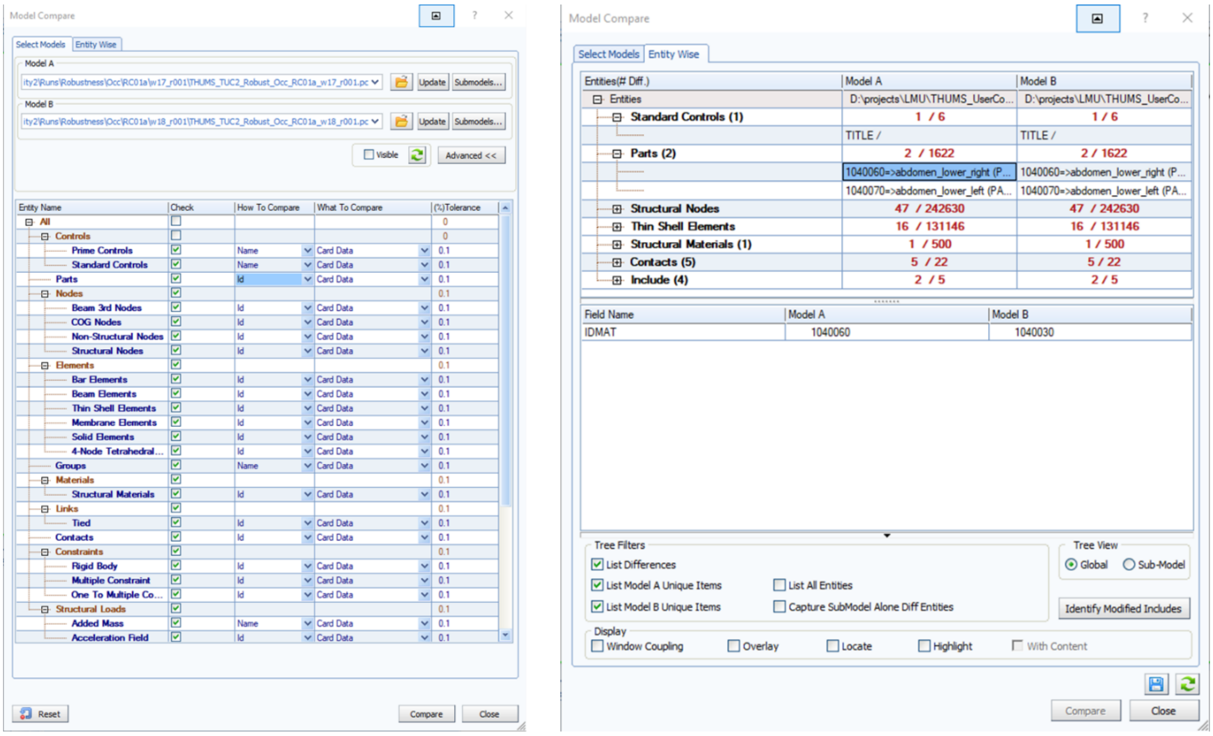


Figure 15 Example of the model compare tool from visual crash for pam

3.3 Application to OSCCAR homologation test case

The OSCCAR project focuses on potential future interior concepts in combination with future accident-relevant scenarios for highly automated vehicles. The reflection on such concepts includes the assessment of the protection of occupants under those conditions. One of the core objectives of the project is the demonstration of a potential VT process for systems related to occupant protection, which is realised within the homologation test case. The consequences of a potential frontal impact in a forward-facing seating position with reclined seat back are to be assessed in this demonstration. For the reasons given above, Virtual Testing with HBMs is complementing physical testing.

It is assumed that in the future the assessment of occupant safety will include both, a seating position considered as standard these days and a position with reclined seatback. While for the standard position a real test procedure with an ATD is applied, simulations with HBMs will be used for assessing risks in the position with reclined seatback in case the ATD cannot be positioned in such a position or is not considered as valid.

Using HBMs might allow analysing the risk of submarining on a more biofidelic level. Furthermore, with HBM simulations it will be possible addressing the mechanical behaviour of the involved body structures and tissues directly, which would not be feasible with an existing standard ATD. For example, strain-based assessment of rib fracture risk will be possible to be used instead of deflection-based ATD chest injury criteria which might not be precise for this kind of loading. Due to limitations of the ATD chest instrumentation, it might not be feasible or not possible at all to calculate the ATD-based criteria. In a next step also, the estimation of lumbar spine injury risk will be possible when HBM-based criteria for this kind of injury will become available.

The OSCCAR homologation test case includes a test setup with a highly reclined seating position resulting in a thoracic angle of 48°. The crash configuration is a full-frontal loading direction with a 50 km/h deceleration pulse. For assessment an HBM representing a 50%ile male occupant is used (see Figure 16).

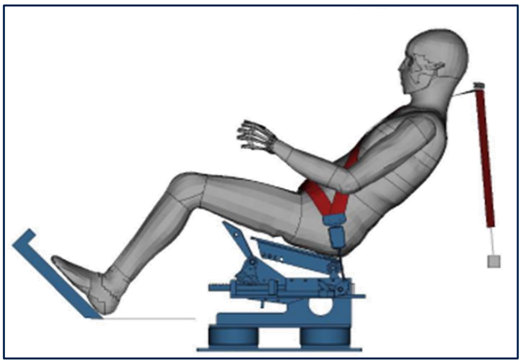


Figure 16 OSCCAR homologation demonstrator

3.3.1 Validation load cases and validation device for OSCCAR homologation test case

To ensure a baseline validation of the vehicle environment model a sled load case in a standard upright seating position with a standard ATD is used. A frontal sled test with the same 50 km/h pulse as in the homologation test case is performed. The THOR-50M is used as a validation device. The ATD is positioned in an upright seating position with a target thorax angle of 23° (see Figure 17).

Additional validation tests are needed representing the restraint interaction with the virtual test tool in the new loading condition. The preferred option for this kind of validation test would be a sled test with the validation device put in the exact same loading conditions as in the assessment loading conditions with a thoracic angle of 48° (Figure 18).

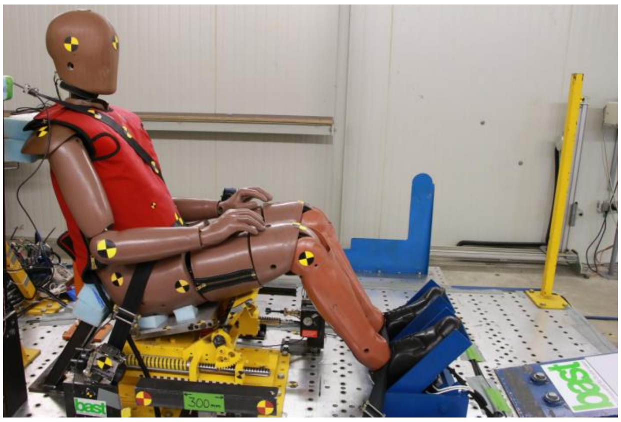


Figure 17 Sled test setup with THOR-M 50 in standard seating position (Thorax angle 23°) – for ATD-based injury assessment and baseline validation of the vehicle environment

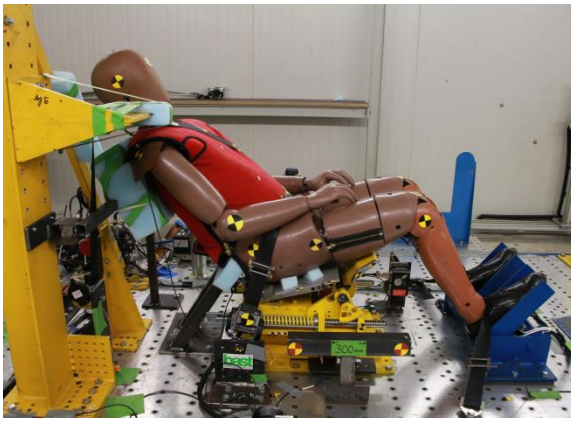


Figure 18 Sled test setup with THOR-M 50 in reclined seating position (Thorax angle: 48°) – only to be used for validation of the vehicle environment in Virtual Testing

The applicability of currently used standard ATDs like THOR or Hybrid III in sled tests for validation of a highly reclined position also implies certain limitations. In any case the biofidelity of internal ATD measurements in a reclined position is questionable. Thus, the measurement signals of the standard ATD will be used only as a validation device in comparison to the virtual ATD, but not for the injury assessment. This will be done with a virtual test tool, the HBM, by Virtual Testing in the new loading condition.

3.3.2 Selection o/f validation channels for OSCCAR homologation test case

For the OSCCAR homologation test case sled tests with THOR were proposed as validation tests as described in the previous section 3.3.1. In order to compare the output from validation tests and validation simulations, measurements were selected following the method from section 3.2.3. The measurement channels proposed for the OSSCAR validation tests are summarised in Table 1.

To validate the belt system the belt loads B3 and B6 should be compared. Furthermore, the retractor pay-in and pay-out need to be considered. To assess the similarities of occupant kinematics the accelerations of relevant body segment of the validation device should be compared (Head Center Of Gravity (C.o.G), T1, T4, T12 and pelvis). As the OSCCAR homologation test case is a straight frontal load case, only the x- and z-components of the acceleration channels will be assessed. Lateral components would only be needed for an oblique load case.

Furthermore, to assess the kinematics of head C.o.G, shoulder, elbow and knee target marker data from videos analysis will be compared to the simulation results. To ensure correct load transfer between the environment and occupant as well as resulting load transfer within the validation device, also some forces and moments are proposed to be recorded for validation (neck, thoracic spine, femur). To assess the correct interaction between the shoulder belt and the upper body of the occupant, it is proposed to compare IR-Tracc resultant measurement and clavicle loads.

Because one focus of the homologation test case will be assessing submarining risk, also the iliac loads should be compared. Furthermore, the test and simulation should agree in parameters relating to occurrence of submarining.

Region	Location	Load	Signal
Belt	Shoulder Belt (B3)	Force	F_{B3}
	Lap Belt (B6)		F_{B6}
	Retractor (B1)	Pay-in/out (Displacement)	D_{B1}
Head	Head C.o.G.	Acceleration	AC_x
			AC_z
		Relative displacement w.r.t. environment (Kinematics)	$D_{x,\ rel.}$
			$D_{z,\ rel.}$
Neck	Upper Neck	Force	F_x
			F_z
		Moment	M_y
Thorax	T1	Acceleration	AC_x
			AC_z
	T4	Acceleration	AC_x
			AC_z
	T12	Acceleration	AC_x
			AC_z
	Shoulder	Relative displacement w.r.t. environment (Kinematics)	$D_{x,\ rel.}$
			$D_{z,\ rel.}$
	Upper Left IR-TRACC	Resultant Displacement	UL_{Res}
	Upper Right IR-TRACC		UR_{Res}

	Lower Left IR-TRACC		LL_{Res}
	Lower Right IR-TRACC		LR_{Res}
	Clavicle	Force	$F_{x, inner}$
			$F_{z, inner}$
			$F_{x, outer}$
			$F_{z, outer}$
	Thoracic Spine	Force	F_x
			F_z
		Moment	M_y
Upper Extremities	Elbow	Relative Displacement w.r.t. environment (Kinematics)	$D_{x, rel.}$
			$D_{z, rel.}$
Pelvis	Pelvis	Acceleration	AC_x
			AC_z
		Angular Velocity	AV_y
		Submarining	Yes/No
	Iliac	Force	F_x
		Moment	M_y
Lower Extremities	Femur	Force	F_z
	Knee	Relative displacement w.r.t. environment (Kinematics)	$D_{x, rel.}$
			$D_{z, rel.}$

Table 1 Channels for the validation of the environment of OSCCAR homologation test case

3.3.3 Evaluation and discussion of proposed OSCCAR validation load cases and device

Sled tests in upright and reclined seating posture with THOR-M50 were proposed for validation of the vehicle environment for the OSCCAR homologation test case. The tests were performed within WP2 Task 2.4. Results are reported in D2.5. [8]. For the tests it was possible to position the THOR in the same position w.r.t. to thorax angle as the HBMs in the homologation test case even for the reclined position. Furthermore, it was also possible to perform the tests with the same deceleration pulse like in the homologation test case without any unusual observation during the ATD tests. No damages to the ATD were observed.

However, even though the ATD could be positioned in the same position that is desired for the homologation test case, it does not necessarily mean that the whole-body kinematics and the interaction between restraint system as well as seat and the test tool are represented in a biofidelic way. Indeed, the ATD was not designed and validated for this seat position.

This leads to the open question whether the interaction of THOR with vehicle environment (including possible new protection systems) and resulting load distribution is sufficiently representative of the HBM in this new test case. Recent publications ([9], [10]) indicate that there are differences in kinematics for reclined seating postures between THOR and PMHS. Based on that it could be expected that also the resulting loadings between THOR as the validation device and vehicle environment are not correctly representing the loads between restraints and a human surrogate or

HBM and finally the represented human occupant.

To further investigate this issue as suggested in section 3.2.2, matching simulations were performed with a THOR-50M model and an HBM (THUMS V5) in the reclined position validation load case (Figure 19). To define the matching positions the focus was on aligning the pelvis, lower extremities and upper body. The influence of remaining differences in head position and lower arms should not have only negligible influence on the evaluated results. The results of this study are shown and discussed in the following.

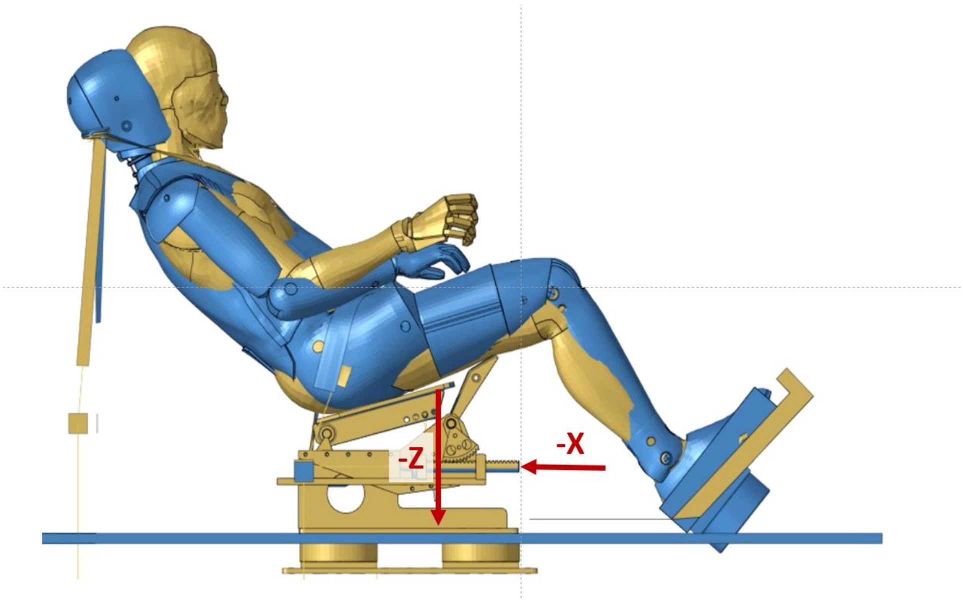


Figure 19 Matching simulations with THUMS V5 and THOR-50M model in reclined position validation load case

As shown in Figure 20 the deflection of anti-submarining ramp (X) is significantly less for the HBM (~50%) than for THOR. The seat pan deflection (Z) is comparable. Belt forces (Figure 21) are slightly higher for the HBM except the outer anchorage belt force B6, which is significantly lower (~1.5 kN) in the HBM simulation. The difference in belt forces and anti-sub-ramp deflection might be due to different pelvis kinematics and or buttock to seat interaction (see Figure 23, which shows a pelvis excursion for THOR approximately higher by 50 mm than the HBM).

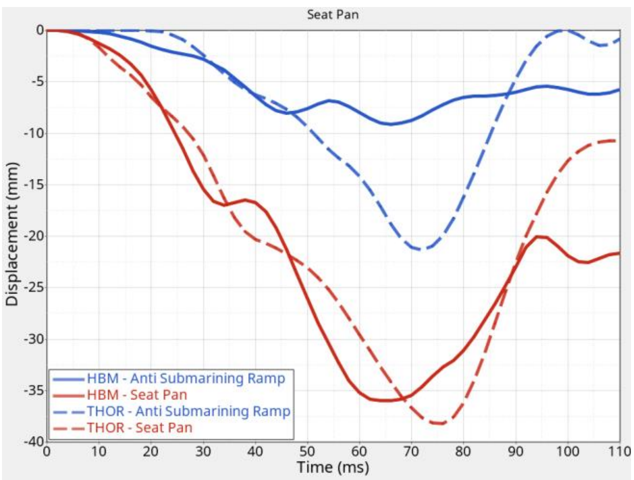


Figure 20 Seat Pan (z) / Anti Submarining Pan deflection (x)

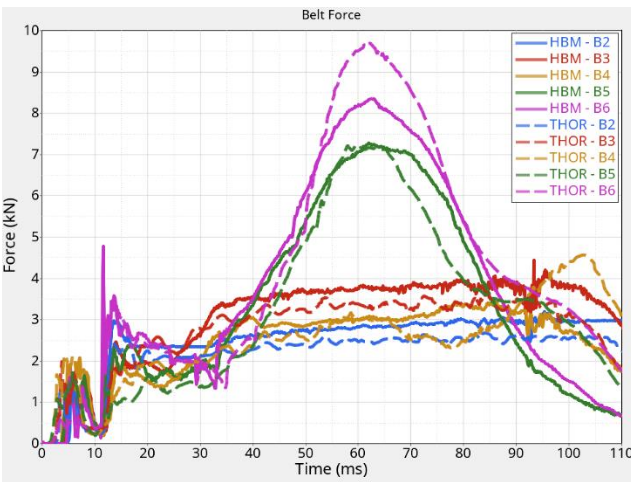
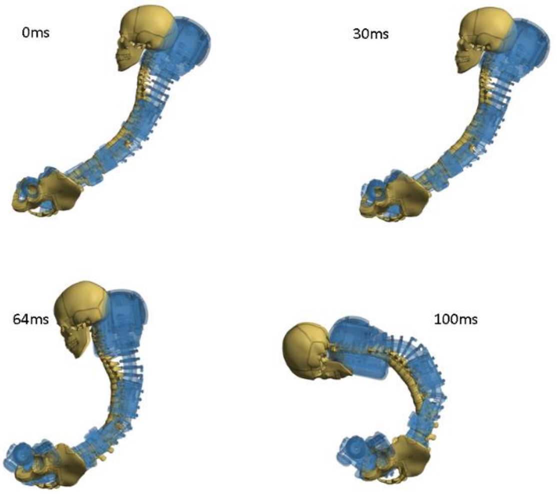


Figure 21 Belt Forces

The kinematics of the HBM and THOR during the forward displacement as well as the kinematic trajectories are shown in Figure 22 and Figure 23. The flexion of the spine developed by the ATD is less and delayed compared to that one of the HBM. In contrast the HBM does not show this behaviour. Forward displacement of the pelvis and of the lumbar spine are greater for the ATD. The forward displacement of the pelvis of the ATD is approximately 50% larger, which requires to check for a possible tendency of submarining. Less forward displacement of the pelvis in HBM is compensated by a greater flexion around T12 and leads to a greater forward displacement of T1 and head than for the ATD.



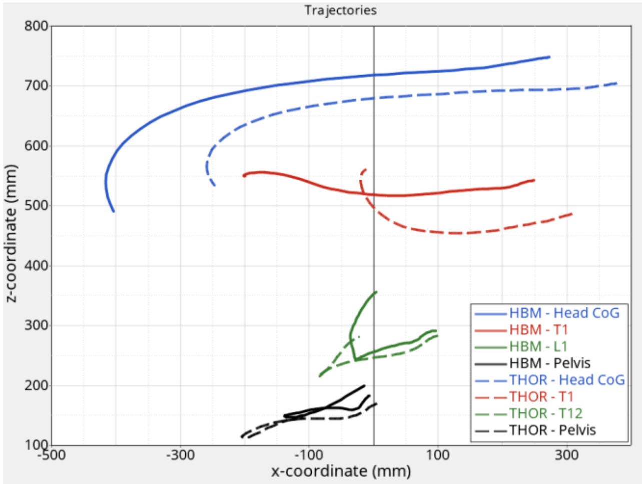


Figure 22 Comparison of occupant kinematics HBM (yellow) vs. THOR ATD (blue)

Figure 23 Kinematic trajectories HBM vs. ATD

In conclusion, these first results indicate that basically different kinematics were observed between ATD and HBM. The load on the restraint system in the pelvic area is different. Thus, the transferability of validation results with the ATD as validation device to the validity of the environment model for VT with an HBM is questionable. More simulations and a reliable methodology how the responses can be proven or falsified is needed. It should be further discussed under which circumstances the results regarding the validation are transferable. Furthermore, the influence of friction and also of the belt position on submarining should not be neglected.

At this stage it has to be mentioned that the HBM might not be sufficiently valid for this new seating position, which is a major limitation of this study. It is recommended to repeat the HBM simulations of this study after the validation level of the HBM has been improved based on PMHS tests in this new seating positions.

These observation lead to the question if there is need for a (new) validation device for this load case that is more representative of the HBM kinematics and resulting interaction with new restraint concepts? It should also be investigated if other dummies like e.g. Hybrid III or THOR-AV could be more appropriate for vehicle environment validation. On the other hand, question should be discussed whether a simpler validation device would be sufficient or even better for environment validation.

Additional component or subsystem tests might also be an option to further validate on a robust level the interaction between restraints and HBM in the extremely reclined seat position. Additionally, to conventional component tests that are used to validate seat and belt simulation model new component validation tests might be needed. For example, a component test could be performed with an isolated ATD pelvis. With such a component test different pelvis angles and belt angles relatively to the pelvis could be investigated to increase the robustness of validation in the relevant loading condition.

To address the validation of pelvis-to-seat interaction, a dedicated validation test could include a device mimicking the surface of human buttocks with a rather stiff surface. This device, being applied on the seat cushion with normal and tangential forces forcing it to slide forward on the seat, would allow to compare the mechanical response of seat model and physical seat in submarining-relevant loading conditions. The conditions to be used need to be identified from parametric studies - numerical or physical ones.

Additionally to the question whether validation with a standard ATD is sufficient, another issue could be relevant. A belt model developed and validated with a standard ATD model might not work in the same robust way in combination with a human model. Some issues related to that were observed related to a belt system in the homologation test case with an HBM within WP4 that was validated within Task 2.4 based on ATD sled simulations.

Finally, considering that a validation procedure should make sure that the environment simulation model can be used for VT with HMBs in a robust and reliable way it might be necessary to define the validation load cases and a new validation device more representative of the HBM loading in the homologation test case.

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4 OBJECTIVE METHOD FOR COMPARING EXPERIMENTAL TEST DATA AND MODEL RESPONSE

To certify a vehicle environment model for Virtual Testing (see Phase 2 in Figure 9), an objective method for comparing experimental test data and model response in the defined validation load case is needed. For clarity, such comparison between an experimental result curve and a simulation result curve is a goodness-of-fit analysis. Y-values from both curves at same X-values can be analysed for their correlation.

4.1 Requirements for objective rating for virtual testing

As explained in section 3.1.2 the reliability of the validation procedure in a VT-based homologation process is crucial. Failure within the validation process is no option for the OEM, because there is no RT-based backup option.

The vehicle environment validation requirements for an HBM-based VT procedure might be different compared to validation requirements usually applied for CAE model validation used for vehicle development. Within a vehicle model development process, a CAE model might be only used to predict tendencies between design variations. Furthermore, under-prediction of results might not be an as critical in some phase of the design process. However, within a VT process a more exact quantitative prediction of tests results will be needed leading to the need of more objective comparison procedures.

This leads to the following requirements for a validation-based certification procedure for a vehicle model to be used in an HBM Virtual Testing process:

- Pass/fail criteria are needed to objectively distinguish between the responses of a valid and a non-valid model
- The criteria should be stringent enough to assure the correct validation of vehicle environment to guarantee the same level of trust in a full VT procedure like in a real testing-based procedure
- On the other hand, the validation procedure has to be achievable to make sure it is possible to pass the criteria of the vehicle environment validation with reasonable efforts.

4.2 Description of objective rating metric

An objective rating metric for the validation load case should include:

- Determination of the goodness of fit between two non-ambiguous signals of a simulation and the corresponding physical test of a dynamic system (vehicle safety applications)
- Unambiguous thresholds for rating
- Standardised method.

The most important characteristics for an ideal metric for the determination of the goodness of fit are according to Barbat [11]:

(1) Objective – produces same result regardless who conducts the assessment,

(2) Generic – reflects differences in the full distribution of the simulation and experimental outcomes and key features like phase, magnitude, and slope,

(3) Robust – produces consistent results with different sampling rates, symmetric – produces same result when the experiment and simulation outcomes switch,

(4) Symmetric – produces same result when the experiment and simulation outcomes switch,

(5) Simple – easy to understand and use,

(6) Contains clear physical meaning and Subject Matter Experts (SMEs)' knowledge,

(7) Under uncertainty – accounts for data uncertainties in both the experiments and numerical simulations.

Within the project IMVITER an extensive review of available metrics was done [12]. In OSCCAR, two promising methods were selected. On the one hand the widely spread CORA method and on the other hand the metric defined and standardised in ISO/TS18571:2014(E).

4.2.1 CORrelation and analysis (CORA)

CORA [13] can be used to assess the goodness of fit between two non-ambiguous signals. Two independent sub-ratings are used within the CORA overall rating, a corridor rating and a cross-correlation rating (Figure 24).

The **cross-correlation metric** analyses the characteristics of signals and is divided into three sub-metrics:

- The **phase shift sub-metric** measures the phase lag between the two analysed time histories.
- The **size sub-metric** compares the square of the areas between the curves and the time axis.
- The **shape sub-metric** rates the difference in the shape of the two time-history curves.

The cross-correlation rating is the sum of the individual weighted sub-ratings.

The **corridor matric** evaluates the deviation between two signals in terms of their fit into an automatically generated corridor around the reference curve.

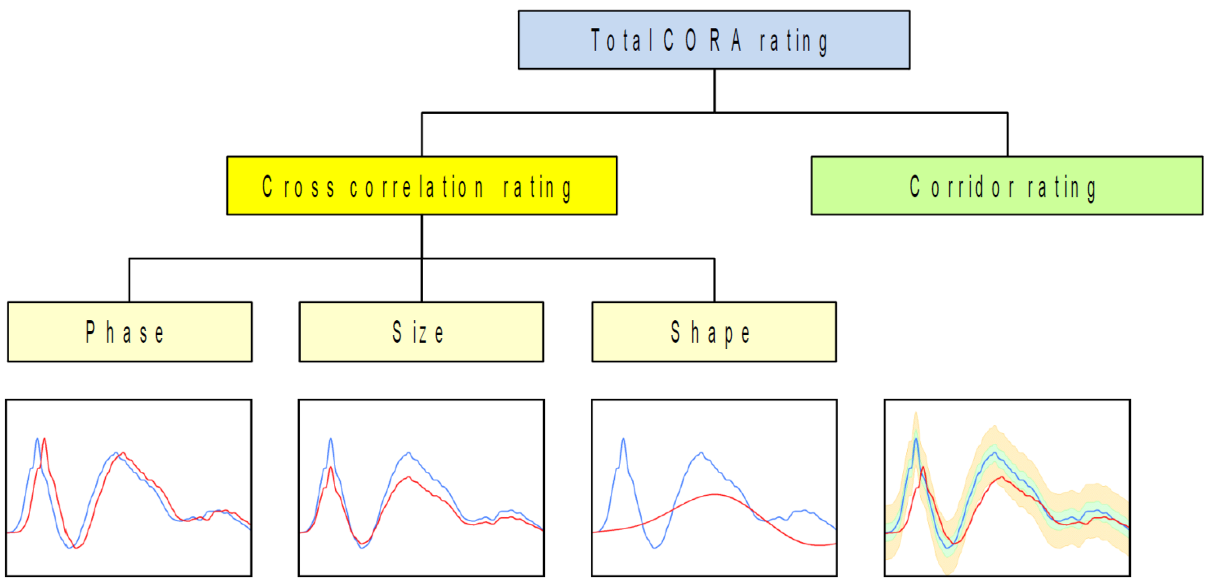


Figure 24 CORA rating scheme [20]

The results of the cross-correlation and the corridor rating are finally summed up to the total CORA rating by using individual weighting factors for each metric. The result of each sub-rating and the overall rating is a number between zero and one. The higher this value is, the better the match.

A phase shift can lead to very poor results in the corridor rating thus the cross-correlation method is used to compensate this disadvantage.

Besides the rating of a single signal, CORA can be used to determine the overall score of a load case with different sub-load cases consisting of different signals.

The CORA metric assumes some requirements for the signals to be evaluated. The signals must be non-ambiguous and defined in the whole evaluation interval. Both have the same number of data points in the evaluation interval thus the same sampling rate for the signals is needed. Using the CORAplus software, signals with different sample rate can be used and are re-sampled internally.

Special care must also be taken in the choice of the evaluation interval. Only the part of the signal relevant to the load case should be considered to avoid distortion of the rating.

The CORA rating uses a huge number of parameters which can be used to fine-tune the rating and adapt it to specific needs. Changing these parameters may have a significant impact on the final rating. Consequently, this leads to uncertainties in the classification of results. The score cannot be assigned to a qualitative assessment or grade and no threshold can be defined since the parameters are not standardised.

4.2.2 ISO/TS18571:2014(E) metric

The ISO standard defines validation metrics and evaluation procedures, to determine the goodness of fit between two non-ambiguous signals calculated from a physical test and a computational model for applications in the field of vehicle safety.

The ISO TC22/SC10/12/WG4 “Virtual Testing” Working Group selected four validation metrics for dynamic responses (CORA, EEARTH, model reliability metric and Bayesian confidence metric) based on the above-mentioned characteristics for an ideal metric for a more detailed investigation. Based on the findings a new combined objective rating metric based on CORA corridor metric and **E**nhanced **E**rror **A**ssessment of **R**esponse **T**ime **H**istories (EEARTH) metric was developed. This combined metric has been proposed and adapted for the ISO standard (ISO/TS18571:2014(E)).

The ISO rating combines four metric ratings:

- The **corridor sub-metric** (same as CORA corridor metric but with fixed parameters, see 4.2.1) determines the deviation between curves with the help of automatically generated corridor so call “inner corridor” and “outer corridor”, each of constant width.
- The **phase shift sub-metric** is based on EEARTH and measures the phase lag between the two analysed time histories.
- The **magnitude sub-metric** (based on EEARTH) is a measure of discrepancy in the amplitude of the two time histories.
- The **slope sub-metric** (based on EEARTH) calculates the difference in the slope of the two time histories curves.

The sub ratings for phase, magnitude and slope analyses the same characteristics of signals as CORA cross-correlation rating but use different calculation methods.

The score for each sub-metric ranges from zero (no correlation) to one (best correlation).

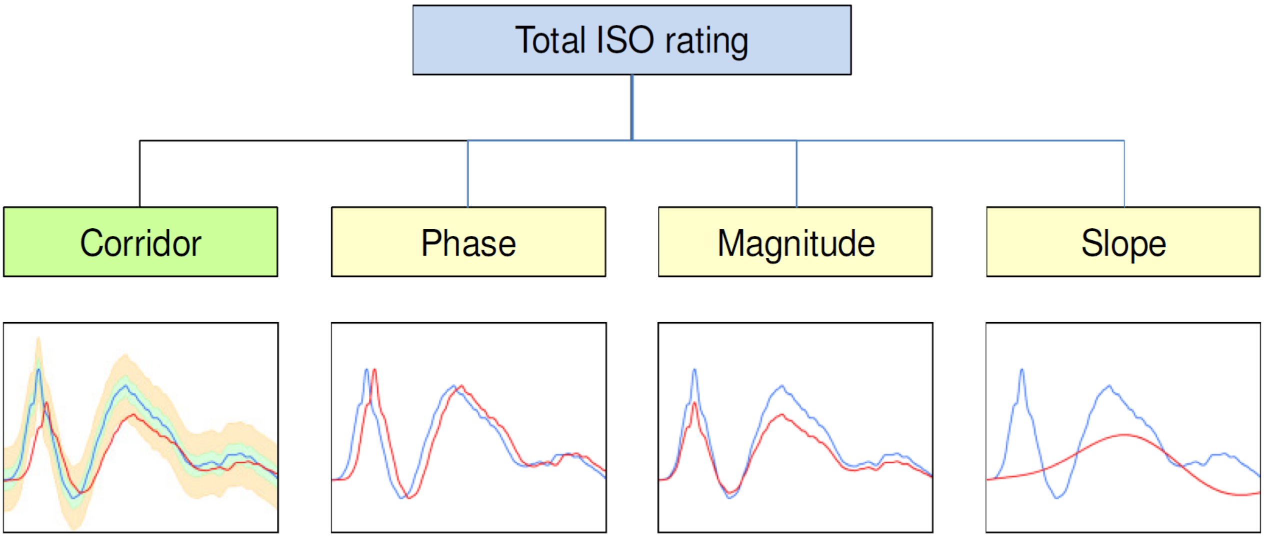


Figure 25 ISO 18751 rating scheme [6]

Based on the scores of each sub-metric the final overall objective rating is calculated by summing up the sub-ratings each multiplied by an individual fixed weighting factor (see Table 2). Besides the weighting factor, various other parameters, which e.g. in CORA can be modified by the user, are fixed in this ISO standard. The structure of the overall ISO metric is shown in Figure 25.

Sub-metric	Weighting factor
Corridor	0.4
Phase	0.2
Magnitude	0.2
Slope	0.2

Table 2 ISO 18517 Weighting factor

The final overall rating ranges from zero to one, with the higher the score, the better the correlation. Finally, the rating is assigned to appropriate grades as shown in the table below.

Rank	Grade	Rating R	Description
1	Excellent	R > 0.94	Almost perfect characteristics of the reference signal are captured
2	Good	0.80 < R <= 0.94	Reasonably good characteristics of the reference signal are captured, but there are noticeable differences between both signals
3	Fair	0.58 < R <= 0.80	Basic characteristics of the reference signal are captured, but there are significant differences between the two signals

Rank	Grade	Rating R	Description
4	Poor	R <= 0.58	Almost no correlation between the two signals

Table 3 Sliding scale of the overall rating acc. to ISO 18571

When applying the ISO method, various pre-requisites must be considered and fulfilled. If this is not done, the validity of the method is no longer ensured. The test and CAE signal must have the same starting and end point, same sampling rate and filtering class. The signals have to be synchronised. The ISO metric was validated with 10kHz signals. Consequently, the grades shown in Table 3 are no longer valid when using other sampling rates.

In addition, special care must be taken when selecting the interval of evaluation. The focus should be on the relevant time interval (e.g. skip pre- and post-crash phase). The minimum length of 10ms has to be considered.

The ISO metric is validated for non-ambiguous time history signals of forces, accelerations, velocities and displacements in all kind of passive vehicle safety tests and corresponding CAE.

The ISO rating is only valid for the comparison of two signals and not for a whole test. The overall ISO sliding scale is no longer valid, if more than two signals are compared. The ISO rating cannot be applied for any sub-metric.

4.2.3 Applicability for a vehicle environment model certification procedure

In general, both above mentioned objective rating methods, CORA metric as well as ISO 18571 metric, seem suitable for assessing the validity of the CAE model in a validation load case. Both were developed to compare two non-ambiguous curves. This includes typical time-history signals from tests and simulation. In ISO 18571, the scope is even further limited to signals of physical test and CAE model in the field of vehicle safety, which corresponds exactly to the test case in OSCCAR. Since many parameters of the CORA metric are not fixed, the global meaning of the CORA score is unclear and a threshold for a good correlation cannot be defined easily.

Within the IMVITER project two steps were proposed to establish a threshold (acceptance level) for a validation criterion [12]:

1. Assess the capability and sensitivity of the metric to detect different levels of similarity between curves. This knowledge can be obtained by comparing the results provided by that (mathematical) metric and those provided by a SME (Subject Matter Expert) group when assessing a certain set of curve pairs [14]. Pairs of curves can be taken corresponding testing and simulation in validation process covering the full range of possible similarity levels. Some curve pairs could be generated in in a synthetic way, introducing controlled theoretical modifications, i.e. scaling or offset.

2. Establish the metric threshold for validation acceptance will come from consensus within the SME group, looking at the evaluation scales coming from the first stage and setting a fixed value. This decision should be further validated with additional trial cases, adapting the threshold value if necessary. A practical method to define threshold values for validation metrics is possible when results from test repetitions are available Then, by comparing curves from different test repetitions, an idea of expected metric value for good similarity can be derived.

For the ISO method, the rating scale is already defined. In this crucial point, the fixed parameters defined in the ISO 18571 and the rating scale, which is validated against the typical vehicle safety test signals, are advantageous.

Nevertheless, there are also some critical points when applying ISO 18751 metric. Most of the signals for kinematic evaluation are acquired via video target tracking. But usually the video recordings in vehicle safety testing have a sample rate significantly below 10kHz. In the case of the analysed test load case the video recordings have a sampling rate of 1 kHz. The ISO 18571 metric however requires a frequency of 10 kHz. Thus, the rating of the signals derived from target tracking with less than 10 kHz is, at least, questionable. Another issue is that the target may be obscured while filming. That means that data points are partly missing in the evaluation interval and the pre-requisites of both metrics, CORA and ISO18571, are not fulfilled and a rating might not be possible. In future, a measurement method for kinematics is needed that minimises the risk of missing data points in the evaluation interval and has a sample rate of 10kHz, unless rating methods are adapted accordingly. Alternatively, it could be discussed if comparison of peak values is sufficient for kinematic validation measurements.

4.3 Acceptance criteria for validation considering test scatter

A realistic validation procedure should consider the test scatter. The sources and amount of scatter in the relevant validation tests should be identified. Based thereon, validation acceptance criteria should be defined.

4.3.1 Identification and quantification of test and simulation scatter

To select appropriate acceptance criteria, it has to be considered that there is no RT-based alternative. The criteria need to be defined in a way that the requirements are on the one hand side demanding enough to ensure the necessary trust in the VT process but on the other hand still achievable. To ensure the achievability of the requirements test scatter should be taken into account.

Three sources of possible test scatter in validation sled tests were identified:

1.) Scatter in the test procedure (test execution) e.g. pulse, positioning of the validation device, seat belt installation

Test parameters like crash pulse will show variation between tests and test labs. Furthermore, the positioning of the validation device and other test parameters e.g. belt routing on the ATD chest will show some variation between tests, even if a standardised procedure described in a protocol or regulatory document is followed. This will result in a difference between test and simulation, which needs to be considered.

The acceptable variation of test parameters is usually defined by tolerances in a test protocol (e.g. H-point tolerance, impact velocity variation). Some parameters are possibly not quantified in sufficient detail, which is required for a VT validation procedure, e.g. belt path variation, but only defined by a quality procedure in test protocol. If the variation of the relevant parameters is relevant for a certain validation channel it might be needed to quantify the variation of this parameter in a dedicated test program with repeated tests and detailed documentation of the parameter variation.

Within OSCCAR Task 2.4, repeated validation tests have been performed. Some parameters related to validation device positioning and belt routing are available (see D2.5). Further studies including higher number of repeated tests in one configuration are planned within OSCCAR.

2.) Scatter of the validation device

Even though dummies are certified to make sure the impact response is comparable, the ATD certification corridors allow a certain scatter of relevant ATD measurement channels. The expected test scatter of the ATD measurement channels, which will be used for environment model validation could be identified from the corridor width from the respective ATD certification tests. Furthermore, ATD R&R (Repeatability and Reproducibility) studies (sled test, component tests) reported in literature should be considered to get an overview of the scatter.

For the OSCCAR homologation test case, the THOR is used for assessment of the vehicle environment validation. For the THOR various R&R studies are available, which are reporting the variation of relevant ATD channels in repeated tests or between different THOR dummies (e.g. [15], [16]).

3.) Scatter of vehicle environment/vehicle components/restraints

Relevant parts of the vehicle environment (e.g. restraint system and seat components) will show differences in terms of mechanical response due to variation within the production process. The scatter within the vehicle parts can be related to the following effects [17]:

- Geometry related scatter (Divergence between designed and manufactured geometry) or material parameter scatter, instability problems (bifurcation), assembly conditions
- Material related scatter (Differences in manufacturing process, variance in supplier charges, environmental influences)

For some parts the variation might be high especially between different production batches. It is essential for a VT process that information about the scatter of vehicle environment components are gathered and provided by the vehicle manufacturer or supplier of the respective parts.

4.) Numerical scatter

Simulation scatter also exists and should be reduced as much as possible. According to Ullrich et al. 2020 [17] numerical scatter must be smaller than physical scatter to allow the identification of the physical scatter and make sure the simulation results are only affected by physical scatter. Only if numerical scatter is kept as small as possible VT-based assessment can be used in a reliable way with similar trust as in real testing.

Proper solver techniques and modelling techniques can help to minimize the numerical scatter which may differ between different solvers. In case a solver shows numerical scatter using different hardware or different general launching settings (e.g. number of CPU or parallelisation mode) these parameters need to be prescribed during the whole VT process (including validation simulations and assessment/type approval simulations)

4.3.2 Possible ways to consider test scatter in the validation procedure

1.) Scatter in validation test procedure and validation device

Whereas the scatter in vehicle components falls in the influence sphere of the vehicle manufacturer, the first two above-described sources of scatter (validation test procedure and validation device) can be influenced by considering the requirements for the selection or definition of validation load case and the validation device. Those two sources of scatter should be as low as possible. A selection of a simpler validation load case e.g. sled test instead of full-scale test or sub system test instead of or in addition to a sled test could be done, if the test scatter turns out to be too high for an achievable validation procedure in a certain load case.

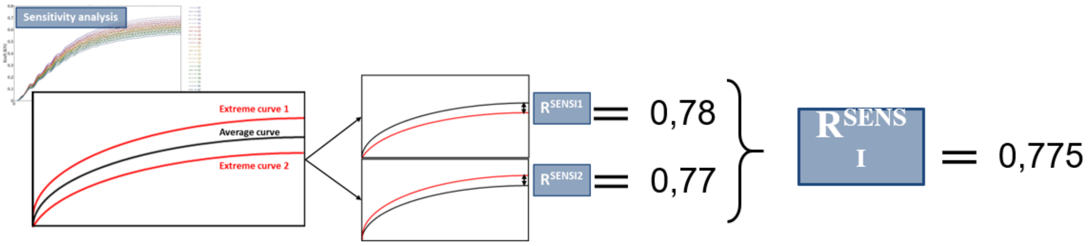
Furthermore, the validation device and related validation channels should be selected in a way that the validation criteria enable a robust validation of the vehicle environment to provide sufficient trust in the whole VT procedure and at the same time are achievable with reasonable effort.

Once the validation tests including the validation device are specified, the effect of test scatter on the individual validation channels should be identified as mentioned above by information from literature or repeated test in the validation load cases. This can be supported by a CAE parameter study to identify the mainly relevant input parameters on each validation output channel.

Parameter studies evaluating this for other load cases and potential validation tools are available in the literature. For an example in study by Heil and Tejero [18] the effect of various parameters on output measurements in sled test with the THOR dummy was analysed. However, for a new Virtual Testing load case a specific validation procedure needs to be defined, including the validation load cases, validation device and validation channels. Based on that in many cases also a specific test campaign to investigate test scatter will be needed.

Based on that individual acceptance criteria per validation channel should be defined. With the ISO rating and considering the test data scatter per channel, it could be decided whether an excellent, good or fair rating is realistic to apply. Another approach could be an updated ISO rating for each channel considering the variation. With the CORA method the information about test data scatter could be used to define the parameters and set an individual threshold for each channel.

A proposal how to consider variation of test data in a rating is provided by Fuchs (2018) [19]. Fuchs proposed to adapt the rating depending on the variation of the response of a validation parameter in experimental tests. The factors representing the agreement between the average curve and the lower/upper bounds are combined to one mean. This mean is then multiplied with the initial rating values, yielding the adapted rating values. Thus, to achieve an excellent rating a lower metrics value (0.79 instead of 0.94) would be needed. An example is shown in Figure 26 .



Grade	Initial Rating	Adapted Rating
Excellent	R^{VAL} > 0,94	R^{VAL} > **0,79**
Good	R^{VAL} > 0,80	R^{VAL} > **0,68**
Fair	R^{VAL} > 0,58	R^{VAL} > **0,49**
Poor	R^{VAL} ≤ 0,58	R^{VAL} ≤ **0,49**

Figure 26 Example how to consider variation of response in experimental testing in rating (reaction force at anterior rib end) according to Fuchs (2018) [12].

2.) Scatter in vehicle component response

In real testing-based type approval and assessment procedures the vehicle manufacturer takes the vehicle component scatter into account by a robust design including a safety margin with respect with some specific requirements (e.g. ATD injury reference values). Even a vehicle with a worst-case performance of the relevant component would have to fulfil the requirements.

To ensure the same in a full VT procedure, the following process is proposed (see Figure 27). For the simulation of the validation load cases an upper and a lower setting of relevant vehicle environment component parameters should be used. If in best case available, even a distribution of input parameters could be used in a stochastic simulation.

A corridor should be provided based on the simulations an upper and lower output (or output distribution) of validation channels. The corresponding output channel from the real validation test would not have to match exactly one deterministic simulation output, but be within the corridor to be accepted as validated. Possibly also metrics like ISO or CORA could be used to assess the signals. Finally, it will be challenging to combine this approach with the above-mentioned acceptance criteria (e.g. CORA or ISO metrics) considering the scatter of validation test and validation tool.

The same upper lower and lower parameters would also have to be used in the vehicle environment model in homologation/assessment simulation (phase 3). Evaluation of influence on injury prediction should be analysed to decide, if it is necessary to base the assessment on the resulting worst-case performance or (on the long run) on a distribution.

For a start, this procedure would use what is already done in today's development process (robust design with safety margin to account for component scatter) and transfer it to the VT world. In subsequent developments, it is seen to be suitable to quantify component scatter in further detail.

The descriptions in this chapter give a general idea based on a one-dimensional consideration of component scatter. In future research projects, a procedure reasonably addressing several sources of scatter should be developed.

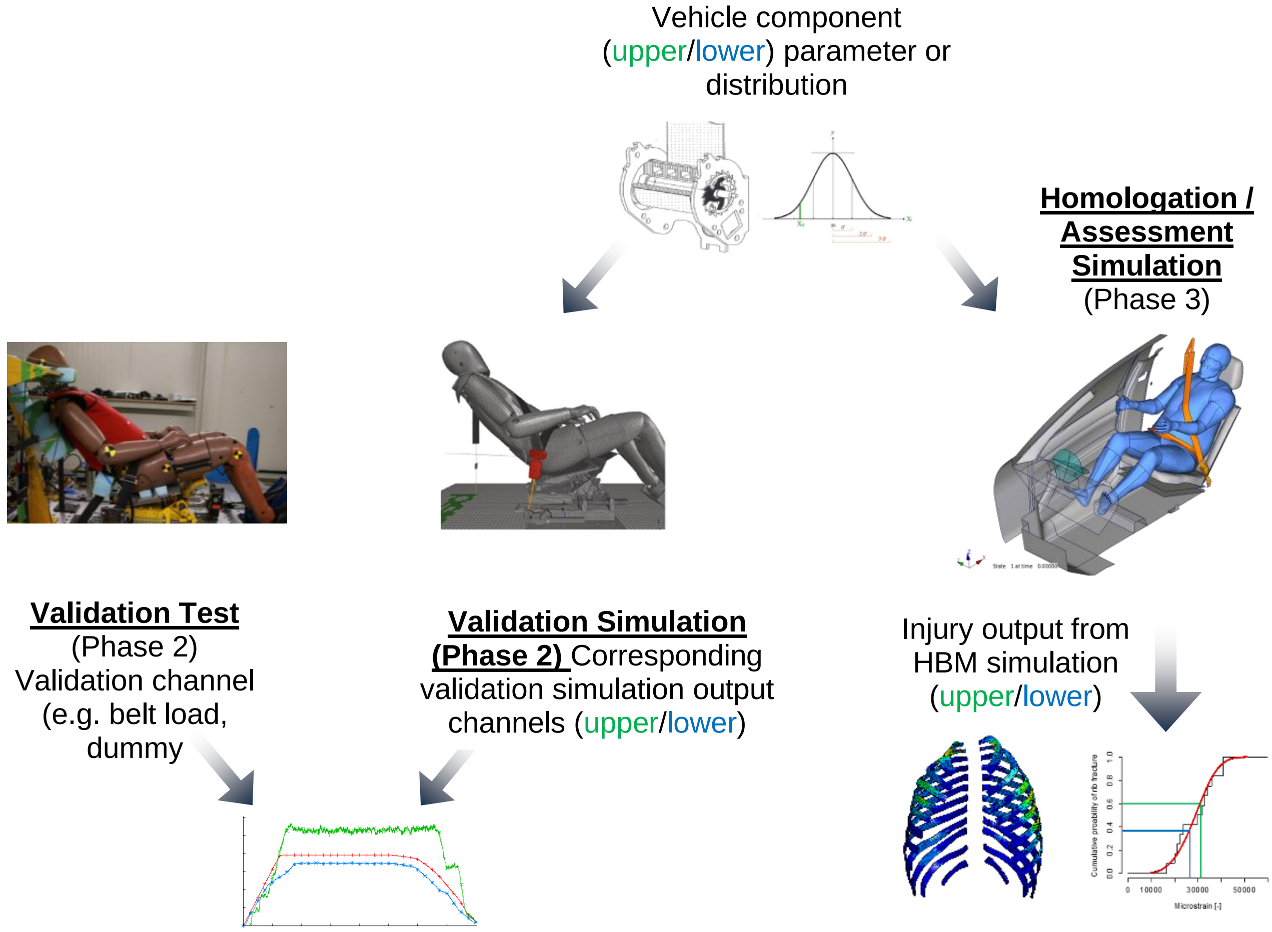


Figure 27 Possible procedure to consider vehicle component scatter in a VT test procedure

5 CODE-INDEPENDENT REQUIREMENTS FOR PRE-PROCESSING AND POST-PROCESSING

5.1 Introduction

As simulations are the only means of homologation/assessment in a specific (sub-) load case if Virtual Testing with HBMs is applied (no fallback option), the credibility of those simulations is of highest importance. The considerations and recommendations worked out in the following can be used in two ways to increase such credibility. They can serve the simulation engineer as guidance to strengthen his/her quality assurance. The second way is to use the considerations and recommendations as certification requirements when simulations are to be accepted in a VT process.

Requirements for pre- and post-processing aim to verify robustness, stability and quality of the results independent of the solver code used. The requirements should be defined in a way that they are applicable in any crash code to ensure that all final results in a VT process are code-independent. The requirements defined in this task should serve as input for WP 4. They are worked out for Finite-Element solvers in this chapter but can in parts serve for similar considerations with a multi-body solver.

Pre-processing requirements consist of checks for:

- mesh quality
- connectivity
- appropriate material models
- control settings, on local and global level
- solver output messages after initialisation
- initial time step and initial contact work of the model
- mass report including added mass from time step control

Post-processing requirements consist of checks for:

- energy balances including total, kinetic, internal and hourglass components
- stable time step and mass increase over run time
- plausibility of requested signals (i.e. initial peaks)
- plausibility of animation

In addition, definitions such as unit systems, element formulations and controls, mesh size, material formulations and contact definitions should be compatible in the context of consistency over various load cases and models to ease integration and exchange of sub-models. This ensures compatibility between vehicle environment models in validation, certification and homologation phases with other models, e.g. the model of the validation device and the HBM.

Checks for quality should be applied any time a change to the simulation input is made. In case that automated check tools are not available or not applicable the user should document the checks applied in a form of a check list or report.

5.2 Code-Independent requirements for pre-processing

In the following some requirements for pre-processing are exemplary elaborated in detail.

5.2.1 Control parameters definition, local versus global level

The influence of globally defined control options must be checked. Ideally options defined on local card level are not overwritten by global definitions. In this case a change of the global control header after distribution of models does not influence the results. In case that global definitions overwrite local definitions, unconventional or not widely used settings should be avoided. It is highly recommended to use harmonised global control setting for all models and components (i.e. vehicle environment, HBM).

5.2.2 Simulation time step control

Prior to running the simulation, a data-check simulation should be performed to preliminarily check and confirm the time step after initialisation as well as the initially added mass resulting from time step control. In addition, at this stage artificial energies should be checked (i.e. contact energies).

The initial timestep should correspond to the target time step defined in the time step control block.

The initially added mass resulting from the time step control should be orders of magnitudes lower than the total mass. Furthermore, the added mass per part should also be significantly lower than the physical mass of this part. This accounts especially for moving or not fully constrained parts, where the added mass would influence the kinematics. Setting up limits of percentage of total/part mass are one possible way for the user to reliably monitor this.

5.2.3 Element formulation and element mesh

Element formulation for 1D/2D and 3D entities should be chosen considering aspects of stability, robustness and desired quality of results.

Under-integrated elements can be chosen to reduce the computational efforts. While doing so some numerical aspects have to be considered.

- Appropriate hourglass control and viscosity parameters should be assigned depending on material properties.
- For 3D solid parts the number of through thickness elements should be noticeably higher than just one element, otherwise the bending stiffness of this region is considered insufficient. In this case it is recommended to utilize fully integrated element formulations.

Fully integrated elements can be chosen when hourglass prevention or bending stiffness of a part is assumed to be insufficient otherwise. It is advised to monitor the computational cost of a model. Generally, fully integrated elements require a higher quality of the mesh to avoid instabilities.

The model mesh should be chosen such that **mesh quality criteria** are met. Due to the nature of finite element approaches these criteria influence the accuracy of the solution and usually consist of thresholds for internal element angles, element edge length, element time step, maximum distortion from CAD. Furthermore, some criteria are specific for 2D or 3D elements such as

- 2D elements: warpage angle, skewness, taper, aspect ratio
- 3D elements: Jacobian

In addition, 2D under-integrated elements should not have more than one free edge in order to not trigger hourglass modes. To fulfil this criterion a local split of quadrilateral into triangular elements or a local refinement should be considered.

5.2.4 Contact modelling

In terms of modelling contacts, various aspects should be checked, such as

- Completeness of contact selection - No missing contact between entities, no matter if these belong to the same part or to different parts - this is also a requirement for post-processing
- Correct contact types utilised
    - Use edge contacts to avoid contact hooking
    - Choose symmetric or un-symmetric contact types, e.g. for car-to-car or car versus rigid wall scenario
    - Apply properly the interaction of different contact types i.e. use the same friction values and avoid many overlaying contacts
- Meaningful friction coefficients
- No edge intersections for edge contacts, no perforations for node-to-segment contacts
- No initial penetrations
    - Unless these result from a pre-simulation
    - In case that automatic penetration removal is active it should be checked that the minimum remaining contact thickness is noticeable higher than zero in order to avoid local failure of contacts

5.2.5 Robust modelling with respect to launch parameters and solver version

As mentioned in section 4.3.1 numerical scatter needs to be minimised to be able to assess physical scatter by simulation. In case significant numerical scatter is observed, the root cause should be analysed. As illustrated in Figure 28 numerical scatter can be reduced by either modelling techniques or solver techniques.

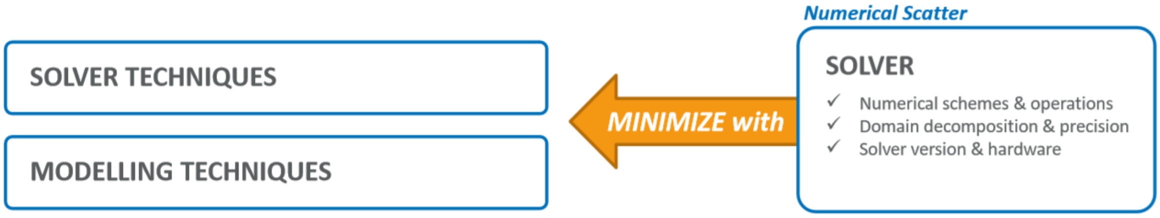


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Figure 28 Scheme to minimize unphysical numerical scatter with proper solver or modelling techniques

If proper modelling is applied robust solver techniques should not show significant influence to results by a variation of the solver launching parameters such as

- Shared- or distributed-memory processing mode (SMP / DMP)
- Single or double precision solver
- Number of CPU cores and domains in DMP mode

An example of improper modelling with respect to numerical scattering can be e.g. crossing material curves or material curves with zero slope as depicted in Figure 29. In such cases, the response from the solver for specific loading conditions is undetermined and scattering and even stability issues are likely to occur.

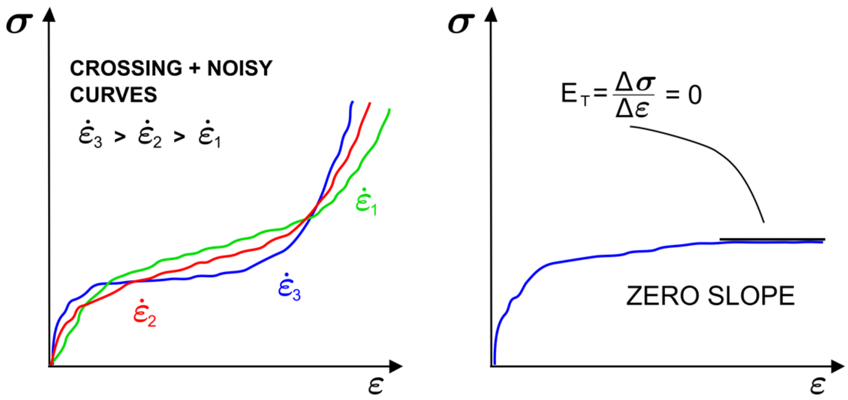

Figure 29 Example for unfavourable definition of material curves with respect to numerical scattering

In case of integrating pre-validated components or models the user should verify the solver version and the corresponding control setting that have been used. The influence of a change in solver version should be assessed to avoid unexpected results i.e. caused by changes in default values. In this regard also release notes of solvers should be carefully read.

In case that components require specific solver versions this should be clearly documented ideally through a respective solver keyword.

5.3 Code-independent requirements for post-processing

Some numerical quantities should be evaluated in every simulation independent of the code in order to check numerical stability and plausibility of results.

5.3.1 Global energy and other time histories

The control of the global energy balance is one of the important points to be checked in each simulation. Usually, the following main components should be considered:

- Total energy
- Global internal energy
- Global kinetic energy
- Global hourglass energy
- External work, damping work
- Simulation time step
- Added mass from time step control (initially and dynamically added)

The following plot shows a typical example for the global energies. In case that there is no external work the total energy should remain constant whereas the total hourglass energy should not exceed a threshold of 5-10 percent from the total energy. In case of a noticeable maximum hourglass energy in the global energy plot, the ratio of hourglass to internal energy should be checked on part level. Parts with a high ratio have to be checked and analysed in detail to overcome a deformation dominated by zero energy modes (hourglass modes). A possible measure in such cases could be the change of the hourglass prevention method from stiffness to velocity-based approach.

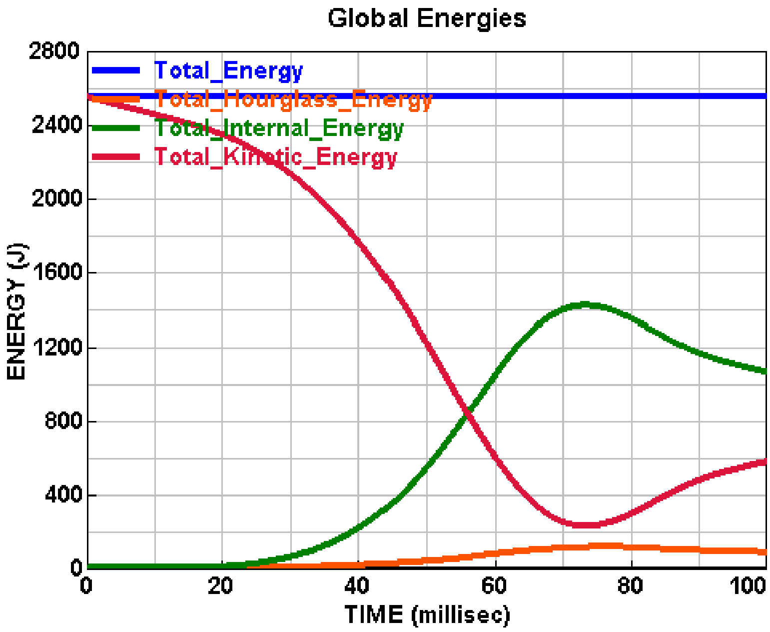

Figure 30 Global energy plot example

Additionally to the global energies, the time histories of the simulation time step and the total added mass over time indicate whether results of a simulation are numerically stable and physically plausible. Strong drops in time steps may indicate an instability and need special attention. The added mass over time should stay low compare to the total mass of the model to keep artificial inertia effects on a low level.

5.3.2 Plausibility of animation

Even with previous checks being unobtrusive, checking the result animation for plausibility should be considered especially when major changes have been applied to the simulation input.

A focus should lie on aspects such as

- Insufficient contact definitions
  - parts perforating each other
  - contact hooking, edge contact problems
- “Flying” parts, insufficient connectivity
- Hourglass deformation patterns
- Unphysical deformation modes

6 DISSEMINATION, EXPLOITATION AND STANDARDISATION

The procedures and concepts developed in OSCCAR related to HBM-based Virtual Testing focusing on a validation of the vehicle environment model have been presented at several workshops and conferences. Furthermore, the information was shared in Working Group meetings related to VT in consumer testing and regulation. This will be continued at further event and meeting related to this topic. Finally, the report will be publicly available at the OSCCAR webpage.

Results and findings of Task 5.1 were presented at the following conferences, workshops and Working Group meetings:

- Euro NCAP Working Group on Virtual Testing Crashworthiness (VTC), continuously since June 2019
- 12th VDI conference on vehicle safety, November 2019, Berlin
- OSCCAR VIRTUAL IRCOBI pre-conference workshop, September 2020
- Carhs Symposium on Human Modelling in Automotive Engineering, November 2020
- HBM4VT expert group meetings, since December 2020

Dissemination, exploitation (planned):

- THUMS User Community (TUC), dissemination planned by LMU supported by BASt, 2021
- IRCOBI pre-conference workshop, BASt, LMU, September 2021
- Dissemination of results of D5.1 and D5.2 planned by ESI Group in one the conferences ESI Forum 2021 or Automotive CAE Grand Challenge 2021
- Mercedes Benz will disseminate the results of Task 5.1 in the automotive industry through meeting of the ACEA Working Group Task Force Bio
- A conference presentation related to Task 5.1 results by BASt is requested for the Aachener Karosserietage, 21. – 22. September 2021

Additionally, the presented procedures and concepts related to vehicle environment validation will be exploited internally by the project partners involved in Task 5.1. BASt is involved in Euro NCAP Working Groups and will be involved in future Working Groups related to VT and will use the results to define further VT standards.

BASt is planning some internal workshops with road restraint systems certification experts to transfer the results to other regulatory fields of application beyond the automotive sector. Furthermore, discussions between BASt and German regulators, type approval authorities and technical services are planned to exploit the results for standardisation in the field of VT. BASt will be involved in a Workshop organised by Bosch to start projects related to Virtual Testing by the VDA FAT Arbeitskreis 27 „Simulationsmethoden und Virtuelle Validierung“. A first workshop was planned 2020, but cancelled due to COVID-19 and will be rescheduled 2021.

Mercedes-Benz exploit the results internally for vehicle safety development to be prepared for possible future vehicle safety requirements in terms of VT in consumer testing and regulations. The results of this task have been disseminated by a WP4/W5 workshop in June 2020 and a WP5 workshop in December 2020 within OSSCAR to other project partners. Based on that, several project partners will further use the results and findings from Task 5.1 for internal discussions and their individual exploitation plan as described in the OSCCAR exploitation plan.

Results of the Task 5.1 including this deliverable will be the basis for deliverables within WP6, focusing more specifically on paving the road for transfer of this knowledge to application areas and standardisation-related activities.

7 CONCLUSIONS

The main objective of Task 5.1 was to provide guidelines for a standardised procedure for vehicle environment model validation. Following the distinction of several phases in a Virtual Testing process as proposed within IMVITER, HBM-based VT as the only means of homologation/assessment in a (sub-) load case should involve three phases. While the first phase serves internal model development by the OEM (which is comparable to what is done without VT), the second phase focuses on providing prove of the validity of the models. Calibrating models is not acceptable in this phase. With a successful completion of phase 2, the models can then be admitted to phase 3, in which they serve as the only base for assessing the protection offered to the occupant. Even if, on a global level, this HBM-based VT is only complementing existing physical testing, there is no fallback option for the specifically addressed (sub-) load case, which creates high requirements to be checked for in phase 2.

The selection of appropriate validation tests, requirements to choose or define an appropriate validation device, were proposed including the specification of relevant validation channels. The proposal was discussed related to the OSCCAR homologation test case, which consists of an occupant in a reclined seating position. For this new load case a validation procedure based on sled testing with the available THOR ATD was analysed and discussed. A set of validation channels was also proposed. The selection procedure for validation channels can also be applied to other HBM load cases in the future.

The suitability of sled tests with the THOR ATD as validation load case and validation device was analysed. Based on observed differences to HBM simulations and recent findings, the suitability of THOR as the only validation device for this load case is questionable. Further research to investigate the suitability of other standard ATDs as validation device for this or similar load case will be needed. Based on that, the development of a specific new validation device and validation test for this new load case might be needed.

Available metrics to compare test and simulation results for model validation and admittance criteria were reviewed. The focus was on the metrics CORA (CORrelation and Analysis) and ISO/TS18571. In general, both metrics seem to be suitable for the purpose needed here. However, for CORA it is needed to define parameters and threshold based on further research. For the ISO rating it is necessary to decide which rating would be acceptable for each individual validation channel or model that should be admitted to Virtual Testing considering real test scatter.

First ideas and concepts how to address scatter to define reasonable admittance criteria were discussed. The main sources of scatter in validation testing (test procedure, validation device and scatter in vehicle environment components) were described. Proposals were made how to address scatter in a validation procedure. Based on that, further work it is needed to identify the best way to consider scatter defining reasonable and achievable criteria to admit a vehicle environment model to a Virtual Testing procedure. The influence of numerical scatter should be considered.

The recommendations summarised in chapter 5 are relevant for the simulation engineer, who is integrating or utilizing modelling components representing the occupant's environment. Moreover, they are also important for developers of HBMs and tests or validation setups.

It is important to note that, although automated procedures and tools supporting the quality control of simulation parameters can provide a substantial time saving, there is no substitute for careful result evaluation by the simulation engineer. The responsibility for adequate decisions on modelling parameters remains his duty. This should be considered in any practice-oriented reflection on VT procedures. Based on that it should be finally the obligation and responsibility of the vehicle manufacturer to deliver a simulation model for VT that fulfils all appropriate state-of-the-art requirements also going beyond the above listed minimum criteria to be checked to ensure credibility of the results.

In the end, all above mentioned concepts are not only relevant for the simulation engineer who develops a model, but could also serve as guidelines to define requirements for all stakeholders who are eventually responsible to decide whether a simulation model can be admitted for VT. The definition of responsibilities within a detailed description of the steps of the whole process should be part of any new VT procedure in regulation or consumer testing.

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