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FIMCAR
XIV – Potential of Simulation Tools towards the Evaluation of Compatibility

frontal impact and compatibility assessment research

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CONTENT

EXECUTIVE SUMMARY

For the assessment of vehicle safety in frontal collisions compatibility (which consist of self and partner protection) between opponents is crucial. The use of simulation tools is the only way to a realistic and wide coverage (w.r.t. the real accident situations that may happen on the road) of car-to-car compatibility issues with acceptable costs.

This report reviews the use of Virtual Testing (VT) in today's European vehicle and product type approval, and the on-going work for future implementation of VT in vehicle type approval and rating. The modelling requirements and validation process are discussed both regarding barrier models and car models. Combined with the experience from the use of simulation tools in the FIMCAR project, a 4-step roadmap for implementation of VT tools in the compatibility development is proposed.

Step 1

2013-2020: further evolution of GCMs concept (Generic Car Models) and consequent availability of first agreed/recognised reference VT model family for regulatory and/or rating application, with associated definition of verification and validation procedures. Convergence towards PGCMs concept (Parametric Generic Car Models) for this type of virtual tool and on the dimensions/typology of the simulation run matrix required for VT evaluation of car-to-car configurations. PGCMs equipped with generic restraint systems and occupant models are then capable of providing realistic biomechanical responses. Crash simulation is used to identify the worst case configurations of vehicles for physical testing.

Step 2

2020-2025: first ratings and/or voluntary agreements for compatibility purposes, i.e. interim regulatory purposes focused mainly on car structural responses and including car-to-PGCMs virtual crash configurations. Behaviour of vehicle occupants (real cars and PGCMs) analysed indirectly i.e. through indicators like OLC (Occupant Load Criterion) or other similar criteria as minimum requirement, with the possibility to provide occupant responses (use of real car and/or PGCMs equipped for biomechanical response). VT is accepted for type approval model variations based on previously approved vehicles (i.e. physical testing).

Step 3

2025-2030: first full vehicle-crash regulations (type approval and even self-certification) for car-to-car compatibility based on full VT (structural behaviour and dummy biomechanical response based on PGCMs). Physical testing is still required for new vehicle registrations.

Step 4

2030-2040: VT maturity reached, with type approval based on full system simulations (structural and biomechanical behaviour included, with human body models (HBM) as occupants of specific car and PGCM opponents involved and enhanced injury criteria taken into account in the protocol).

1 INTRODUCTION

1.1 FIMCAR Project

For the real-life assessment of vehicle safety in frontal collisions, the compatibility (described by the self-protection level and the structural interaction) between the opponents is crucial. Although compatibility has been analysed worldwide for years, no final assessment approach was defined. Taking into account the EEVC WG15 and the FP5 VC-COMPAT project activities, two test approaches have been identified as the most important candidates for the assessment of compatibility. Both are composed of an off-set and a full overlap test procedure. However, no final decision was taken. In addition another procedure (tests with a moving deformable barrier) is getting more and more in the focus of today's research programmes.

Within this project different off-set, full overlap and MDB test procedures will be analysed to be able to propose a compatibility assessment approach, which will be accepted by a majority of the involved industry and research organisations.

The development work will be accompanied by harmonisation activities to include research results from outside the consortium and to early disseminate the project results taking into account recent GRSP activities on ECE R94, Euro NCAP etc.

The FIMCAR project is organised in six different RTD work packages. Work package 1 (Accident and Cost Benefit Analysis) and Work Package 5 (Numerical Simulation) are supporting activities for WP2 (Offset Test Procedure), WP3 (Full Overlap Test Procedure) and WP4 (MDB Test Procedure). Work Package 6 (Synthesis of the Assessment Methods) gathers the results of WP1 – WP5 and combines them with car-to-car testing results in order to define an approach for frontal impact and compatibility assessment.

1.2 Objective of this Deliverable

The objective of this deliverable is to analyse the potential of simulation tools towards the evaluation of compatibility. The report reviews the on-going activities in Europe regarding implementation of simulation tools in type approval- and rating procedures, and analyse/discuss how to implement compatibility into this on-going process.

1.3 Structure of this Deliverable

This report starts with an overview of activities towards Virtual Testing before and parallel to the FIMCAR project. This review is followed by a summary of the FIMCAR experience with numerical simulation w.r.t. structural assessment of cars with a focus on the FIMCAR car models used. Furthermore general requirements on models for Virtual testing (i.e., model verification and validation) are discussed. Chapter 4 presents a proposal how to assess frontal impact compatibility based on Virtual Testing. Finally this proposal is discussed w.r.t. to the road map presented by the IMVITER project that was running in parallel to the FIMCAR project.

2 BACKGROUND

2.1 Historical Evolution

Recently, changes in the EC type approval process related to the implementation of Virtual Testing (VT) have been introduced, so that now an appropriate regulatory framework is available to gradually implement the use of the numerical simulation for a wider variety of current and new regulatory acts. This situation in Europe is the result of intensive work conducted on the subject mainly in the last decade, with a special attention paid to the automotive safety aspects. The following list provides a historical review of the main activities to apply simulations in regulatory activities.

2001 - EU FP5 Project VITES (Virtual Testing for Extended vehicle passive Safety) starts to pave the way by evaluating the potential use of VT in regulations (Development of virtual testing procedures, guidelines and objective criteria for the evaluation of numerical models quality, including corresponding software tools – 3 years duration)

2002 – A technical working group (CEN/TC226/WG1/TG1/CME) was initiated in 2002 to investigate the use of computer simulations for the type approval of road equipment, specifically regulation EN-1317.

2004 - EU FP6 Integrated Project APROSYS (Advanced PROtection System) continues the studies on the subject with the aim to develop possible approaches and deliver practical demonstrators (Sub Project 7 on Advanced Virtual testing – 5 years duration). First Generic car Model versions (GCMs) are developed and used within this project.

2004/2005 – ISO TC22/SC10 WG4 and EEVC Working Group 22 on Virtual Testing are established

2005 - 'CARS 21 High Level Group' considers that the introduction of VT can provide more flexibility and reduce costs. The Group proposed to replace 38 EC directives with international UN/ECE regulations without any loss in the level of safety and environmental protection. Furthermore, it identified also 25 directives and UN/ECE regulations where self-testing and virtual testing could be introduced to reduce costs for industry. In particular it recommended introducing virtual testing in the following directives:

77/389/EEC (towing hooks)

77/649/EEC (forward vision)

78/318/EEC (wash/wipe for geometric requirements)

78/549/EEC (wheel guards)

92/114/EC (external projections of cabs)

(1)UNECE R-21 (for the geometric requirements of interior fittings)

UNECE R-26 (exterior projections)

UNECE R-46 (for the field of rear vision)

UNECE R-48 (installations of lighting)

UNECE R-55 (couplings; only with regard to geometric requirements)

2007 - Article 11 (3) of Directive 2007/46/EC: provides the possibility to use VT for regulatory purposes.

2008 - In order to go ahead with the recommendations of CARS 21 in the area of regulatory simplification, the Technical Committee – Motor Vehicles (TCMV) in its 4th meeting, sets up a calendar for a Sub-Group made of Stake-holders with the purpose of bringing forward a structured proposal on the implementation of VT before end of 2009.

2009 – The Sub-Group starts working with the initial list proposed in the final report of CARS 21. Physical phenomena addressed in the initial list were only pure geometric requirements.

2009 – At the APROSYS Final Event, demonstrators of possible approaches about implementation of VT in regulations/ratings are presented, with a special attention paid to pedestrian protection applications.

2009 – IMVITER Kick off meeting. The project aims to help and support in the definition of upcoming virtual type approval procedures. It was agreed to address three levels of complexity regarding the physical phenomena involved in each test. Physical phenomena are addressed in the initial list of pilot cases, from static (towing hook and seat belt anchorages) to complex dynamic tests (pedestrian head and leg form impacts).

2009 – There is a legislative proposal which collects the work of the Sub-Group of TCMV. In this proposal the number of cases and the physical phenomena involved has increased. Physical phenomena in the final list: pure geometric requirements, static and also dynamic cases.

2009 – FIMCAR kick-off meeting: within the project, a second generation of GCMs is developed for the virtual study of compatibility aspects, together with Parametric Car Models (or PCMs); numerical simulations involving such car models are extensively used to support definition and refinement of new proposals of frontal impact test configurations (through car-to-barrier and car-to-car numerical simulations).

2010 – COMMISSION REGULATION 371/2010 replaces Annexes V, X, XV and XVI to Directive 2007/46/EC, including the lists of Regulatory Acts for which a manufacturer may be designated as technical service and the conditions required to virtual and self-testing methods.

2011 – ISO releases new technical documents developed by the CEN/TC226/TG1/WG1/CME group describing the requirements for numerical simulations in type approval of road equipment covered in EN-1317.

2012 – IMVITER Final Event: the results of the project, on the four selected pilot cases, are presented to the public. These include also a roadmap for VT implementation in regulations.

2.2 Review of CAE in Vehicle and Product Type Approval/Rating

In the automotive sector, the following regulations/standards provide for the possibility for applying numerical simulation (or Virtual Testing) results:

ECE Regulation 66: Uniform provisions concerning the approval of large passenger vehicles with regard to the strength of their substructure.

EN-1317: Road restraint systems: Proposal for approving certain products by simulation using grading system identifying the combination of testing and simulation used in the type approval.

ISO 13232: Test and analysis procedures for research evaluation of rider crash protective devices fitted to motorcycles.

Directive 2007/46/EC: Framework directive for motor vehicles type approval and EC Regulation 371/2010 (Annexes V, XVI)

The last Directive (dated 5 September 2007) establishes a framework for the approval of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles and, together with the Commission Regulation (EU) No 371/2010 of 16 April 2010, opens the door to use computer simulations, instead of conducting physical tests, for the type approval process. In particular, the ANNEX XVI (Specific conditions required from virtual testing methods) describes the general requirements that need to be satisfied when virtual testing is used. Within its Appendix 1, general conditions required from virtual testing methods are fixed:

- The virtual test pattern: a common scheme shall be used as basis structure for describing and conducting Virtual Testing;
- Fundamentals of computer simulation and calculation: Mathematical model, Validation process of the mathematical model and Documentation;
- Tools and support: access to appropriate software and respect of confidentiality.

Within Appendix 2, Specific conditions concerning virtual testing methods are recalled:

- List of regulatory acts: currently, Virtual Testing can be used mainly for geometrical related issues and identification of test conditions. Typically the geometrical prescriptions are verified virtually through CAD. CAE can be used for some quasi-static loading cases (e.g. towing hooks, front underrun protection systems) and for one dynamic load case (buses and coaches rollover). In the following, the tables contained in Appendix 2 are presented (Table 1 to Table 3).

Table 1: List of regulatory acts indicated in EC Reg. 371/2010-Appendix 2.

1. **List of regulatory acts**

No	Regulatory act reference	Subject
3.	Directive 70/221/EEC	Fuel tanks/rear protective devices
6.	Directive 70/387/EEC	Door latches and hinges
8.	Directive 2003/97/EC	Indirect vision devices
12.	Directive 74/60/EEC	Interior fittings
16.	Directive 74/483/EEC	Exterior projections
20.	Directive 76/756/EEC	Installation of lighting and light signalling devices
27.	Directive 77/389/EEC	Towing hooks
32.	Directive 77/649/EEC	Forward vision
35.	Directive 78/318/EEC	Wash/wipe
37.	Directive 78/549/EEC	Wheel guards
42.	Directive 89/297/EEC	Lateral protection
49.	Directive 92/114/EEC	External projections of cabs
50.	Directive 94/20/EC	Couplings
52.	Directive 2001/85/EC	Buses and coaches
57.	Directive 2000/40/EC	Front underrun protection

Table 2: Specific conditions for VT methods, from EC Reg. 371/2010-Appendix 2.

Specific conditions concerning virtual testing methods

1. **List of regulatory acts**

	Regulatory act reference	Annex and paragraph	Specific conditions
3.	Directive 70/221/EEC	Annex II (Rear underrun protection) Point 5.4.5.	
6.	Directive 70/387/EEC	Annex II Point 4.3.	
8.	Directive 2003/97/EC	Annex III All provisions in Sections 3, 4 and 5.	Prescribed fields of vision of rear-view mirrors.
12.	Directive 74/60/EEC	Annex I All provisions in Section 5 (Specifications).	Measurement of all radii of curvature and of all projections except for those requirements where a force has to be applied in order to check compliance with the provisions.
		Annex II	Determination of the head-impact zone.
16.	Directive 74/483/EEC	Annex I All provisions in Section 5 (General specifications) and Section 6 (Particular specifications).	Measurement of all radii of curvature and of all projections except for those requirements where a force has to be applied in order to check compliance with the provisions.
20.	Directive 76/756/EEC	Section 6 (Individual specifications) of UNECE Regulation No 48.	The test drive provided for in Point 6.22.9.2.2 shall be performed on a real vehicle.
		Provisions of Annexes 4, 5 and 6 to UNECE Regulation No 48.	
27.	Directive 77/389/EEC	Annex II, Section 2	
32.	Directive 77/649/EEC	Section 5 (Specifications) of Annex I.	
35.	Directive 78/318/EEC	Annex I	Point 5.1.2. Measurement of the swept area only.
37.	Directive 78/549/EEC	Section 2 (Special requirements) of Annex I	
42.	Directive 89/297/EEC	Annex I Point 2.8.	Resistance under a horizontal force and deflection measurement.
49.	Directive 92/114/EEC	Annex I All provisions in Section 4 (Specific requirements). Regarding N_1 vehicles, the provisions referred to in item 16 of this Appendix shall apply.	Measurement of all radii of curvature and of all projections except for those requirements where a force has to be applied in order to check compliance with the provisions.

Table 3: Specific conditions for VT methods, from EC Reg. 371/2010-Appendix 2 (cont. of Table 2).

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	Regulatory act reference	Annex and paragraph	Specific conditions
50.	Directive 94/20/EC	Annex V "Requirements for mechanical coupling Devices"	All provisions of Sections 1 to 8 included.
		Annex VI Point 1.1.	Strength tests on mechanicals couplings of simple design may be replaced by virtual tests.
		Section 4 of Annex VI "Testing of mechanical coupling devices"	Points 4.5.1. (Strength test), 4.5.2. (Resistance to buckling) and 4.5.3. (Resistance to bending moment) only.
52.	Directive 2001/85/EC	Annex I	Point 7.4.5. Stability test under the conditions specified in the Appendix to Annex I.
		Annex IV Strength of superstructure	Appendix 4 — Verification of strength of the superstructure by calculation.
57.	Directive 2000/40/EC	Section 3 of Annex 5 to UNECE Regulation 93.	Resistance under a horizontal force and deflection measurement.

In Appendix 3, the Validation process is outlined, through the use of a general flowchart (see Figure 2.1).

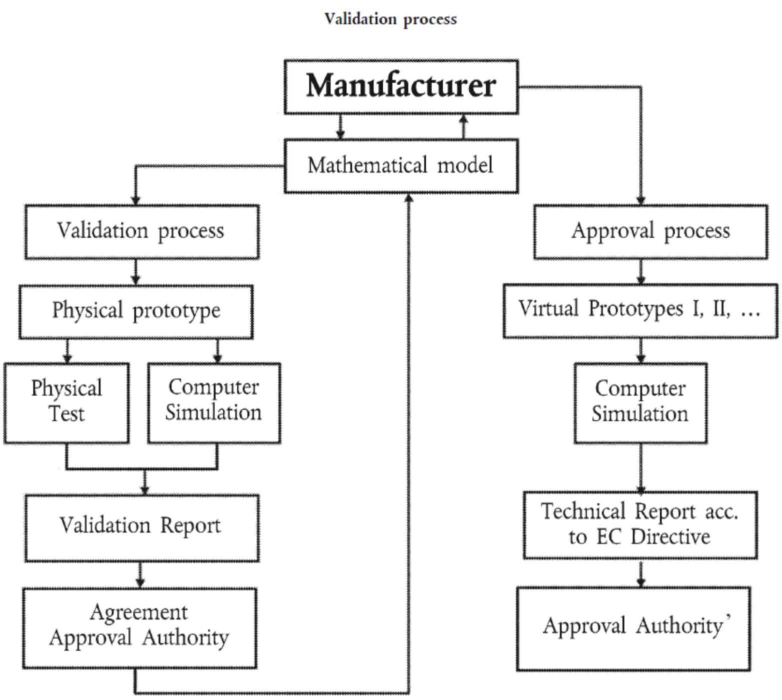

Figure 2.1: The general flow chart as defined within EC Reg.371/2010-Appendix 3.

Despite the given reference, this flowchart, together with the other general conditions required from virtual testing methods contained in ANNEX XVI of EC Directive 371/2010 [EC 2010] leaves several questions open, e.g. [Cordero 2012]:

- Does the manufacturer have to give a simulation model to the Technical Service? (Confidential information is included in simulation models!)

- Does the Technical Service have the necessary code(s)?
- How are simulation models predictability assessed?
- What differences between simulation model predictions and test results can be acceptable?
- Is a physical prototype really necessary?
- What is the benefit of VT if both test and simulations are to be conducted?
- What kind of test should be carried out? Do the same parameters need to be measured for validation purposes?
- Who should run the model?
- Which codes can be used? Commercial or in-house developed ones?

The IMVITER project worked on all these aspects and generated a step forward in terms of general procedural flow chart, detailed flow charts and corresponding written virtual testing procedures for type approval, by applying them on a selection of regulatory pilot cases, including pedestrian protection (head and leg form impacts) as the most complex dynamic load case.

More details about these evolutionary steps are given in Chapter 3.

3 SIMULATION TOOLS IN CRASH TESTING

3.1 Modelling Requirements

In general, a model is used to describe a specific and limited image of the real world. Two main characteristics can be found in a model: abstraction and idealisation. Thereby abstraction is the process of reducing unimportant details and idealisation is the process of isolating the important details. This is typically referred to as simplification process. Often the purpose of a model is the variation of parameters to investigate their influence on a system's response and to get a common understanding of specific mechanisms. To be sure that the model is suitable, a model has to be verified and validated. Thereby verification is the process of confirming the approach in which the model was created. Within the verification process the limits of a model and the intended field of applications have to be defined. After the modelling process has finished, a confirmation is needed to ensure that the model behaviour is the same as the original or at least comparable to it. This process is called validation. Only if these requirements are fulfilled the model provides verified and validated responses.

3.2 FIMCAR Car Models

Within the FIMCAR project two different modelling approaches for the development of FE car models were used. The GCM (Generic Car Models) were developed by CRF (Centro Ricerche FIAT S.C.p.A.) and the PCM (Parametric Car Models) developed by TUB (Technische Universität Berlin). The two types of models are available for three different crash solvers: LS-DYNA, PAM Crash and RADIOSS. In this way, it is possible to include the detailed car models of the OEMs (which are partners of the consortium) into the virtual test program. A short overview about the two modelling approaches will be given in the following sections. More details can be found in [Stein 2013/2].

3.2.1 GCM - Generic Car Models

The GCMs used in FIMCAR were derived from the GCMs developed by CRF within the research project APROSYS [Puppini 2009], through the implementation of huge modifications and improvements. In total five different models of three different vehicle classes (super mini, small family car and executive) were generated (see Figure 3.1). Two additional variants, with respect to the original architectures of super mini and small family car, were in fact introduced by the addition (super mini) or removal (small family car) of a lower load path.

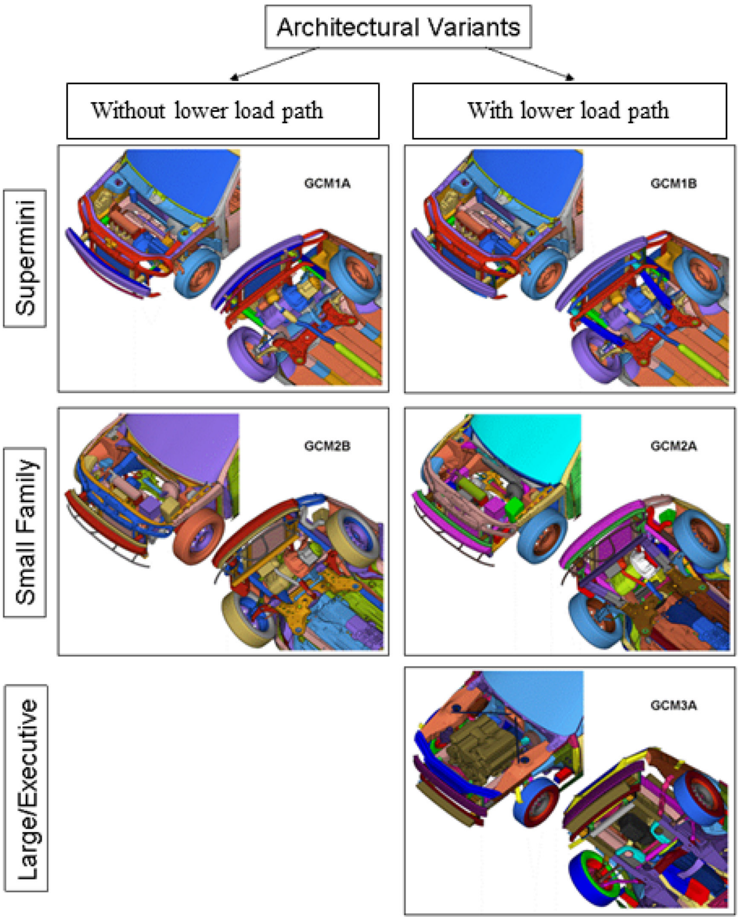

Figure 3.1: Architectural variants of GCMs.

The modelling was controlled by the following two main parameters: high level of detail (comparable to models of OEMs) and a generic topology of structures and parts of typical vehicles that can be found on the roads of the corresponding vehicle class. To fulfil the first requirement especially the front structures of the GCMs were modelled with fine mesh. Thus the models consist of about 600,000 elements. Although the structures are generic they are modelled to ensure realistic (i.e. representative of the European fleet) crash behaviour with respect to crash pulse, intrusion behaviour, energy absorption management and collapse modes.

The validation of the GCMs was performed for the US NCAP (rigid wall, 56 km/h, 100% overlap) and old ams (rigid wall, 55 km/h, 50% overlap, 15° wall inclination as conducted by the German automotive magazine “auto motor und sport”) configuration.

The main tasks of the GCMs within FIMCAR were to analyse the crash behaviour in the different frontal impact test configurations, to compare these results with responses from car-to-car simulations and to serve as common bullet vehicles against the OEM models.

3.2.2 PCM – Parametric Car Models

To investigate the influence of different front structure topologies and the impact of the assessment metrics to the front structures the PCMs were developed to overcome the aims of structural interaction. Normally to modify the structure of a finalised FE model is a complicated and time consuming exercise. Morphing tools or manual transformations of the mesh is time consuming and can cause numerical instability. To avoid these problems the PCMs approach uses an implicit parametric design of one CAD model that allows fast modifications of the structures. In this way, position as well as shape and size of the most important crash structures can be changed in an efficient way. Finally, an automatic mesh algorithm generates meshes and additional FE information needed to create computable FE models without further pre-processing [Stein 2011].

In contrast to the GCMs, one of the main requirements of the PCMs was the shorter calculation time. To comply with this, the PCMs were simplified. For example, all parts of the powertrain were merged to one rigid part, and crash relevant parts like cross beam, longitudinal side members and sub frame were modelled with respect to realistic crash behaviour (see Figure 3.2)

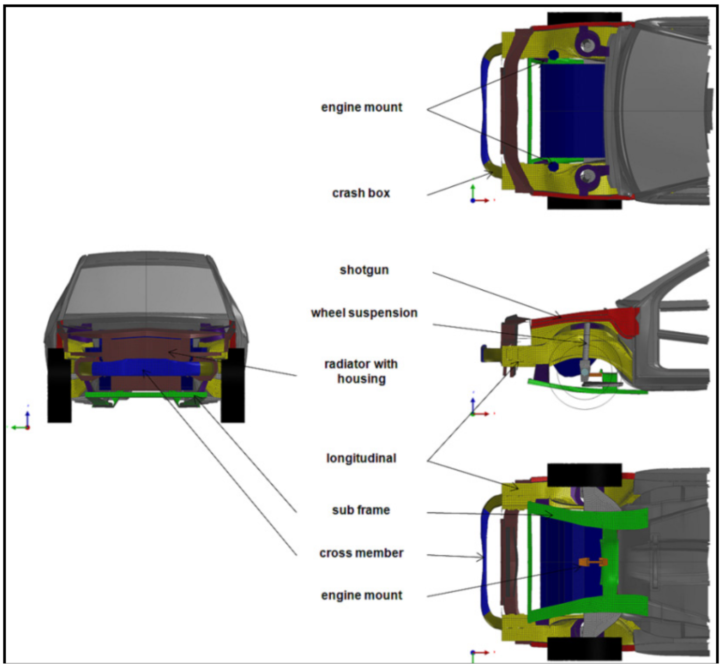

Figure 3.2: Front end structures of the PCMs.

During the first part of the FIMCAR project, three different vehicle classes (super mini, large family car and executive) were modelled. To reduce the computational effort, the mesh size was set to an edge length of 15 mm. The final number of elements is about 200,000 for each vehicle model.

The models were validated for the US NCAP configuration (rigid wall, 56 km/h, 100% overlap), where the crash pulse of the compartment was the main criterion. The pulses were compared (duration, peak and average deceleration) with real crash pulses of cars of the corresponding vehicle class.

The main tasks of the PCMs within FIMCAR are sensitivity analyses of the topology of structures in car-to-car crashes and robustness analyses of the test configurations and their corresponding assessment metrics.

3.2.3 Requirements for Vehicle Models

Both modelling approaches are results from the definitions given in Chapter 3.1. Regarding the intended field of applications the GCM approach should allow in-depth analyses of the structural interaction of the main EAS (Energy Absorbing Structures) and the under bonnet components. Due to the high level of detail w.r.t. the number of different modelled components and their connections to each other, the number of models is fixed (in total 5 different GCMs were available within FIMCAR). To overcome this limitation the PCMs were simplified vehicles based on a full parametric CAD model that allows fast design changes to analyse the influence e.g. of the topology of the EAS. Even though there are big differences between the two approaches, common requirements were used to create the models. On the one hand, the same validation criteria were used. Typical characteristics like acceleration pulse and force-deflection curves were used to generate a crash behaviour of the corresponding vehicle classes, see [Stein 2012]. On the other hand, model specific parameters in particular the mesh size (10mm – 15mm) were defined to ensure the interaction of GCMs and PCMs with the detailed models of the OEMs. Furthermore, both models guarantee numerical stability at least for the crash scenarios used for the validation process.

However, no common agreed procedure was used for verification and validation of the models. The following section summarises some recommendations of requirements for future modelling of vehicles for use, amongst other, within legislative framework.

3.2.4 Future Requirements for Vehicle Models

Taken into account the great efforts currently on-going in the field of VT it seems to be merely a matter of time until standardised vehicle models will be used to extend today's crash regulations. W.r.t the experiences made within FIMCAR the combination of both GCM and PCM approaches seems to be promising to provide vehicle models that can be used to overcome limitations of solver dependent FEM models as well as models of different manufactures, see Chapter 3.4.

The following requirements for a combination of GCMs and PCMs can be used for the verification and validation process:

Verification:

- Topology of main EAS as well as crash relevant parts (e.g. engine, wheels, radiator and cooler) can be derived from the VC COMPAT and IMPROVER structural databases. In that way, different generic vehicle classes can be created to represent the actual European vehicle fleet in terms of mass, dimensions and structural concepts. A parametric design of either a CAD model or an FEM model provides the possibility to update the models continuously depending on the evolution of the vehicle fleet.
- The stiffness (or force) level of a structure is controlled by two main parameters, geometry and material. The main objective of the crash relevant structures is to absorb the crash energy. Using reverse engineering the contribution of the absorbed energy can be estimated by analysing detailed vehicle models (provided by NCAC or OEMs). Taken into account the total amount of energy that needs to be absorbed (depending on the crash configuration) the stiffness of the structures can be defined. Low and high speed crashes (e.g. repair cost crashes like RCAR bumper test and Euro NCAP) provide information about strain rate dependencies of the materials.

Validation:

- Generic crash responses w.r.t different vehicle classes need to be specified analogue to the creation of generic structures average crash pulses and deformation behaviours can be used to validate the corresponding vehicle models of each vehicle class. Objective assessment tools and corresponding thresholds can ensure validated models independently from the chosen crash solver.

The database developed within FIMCAR offers a good starting point. A large number of tests provide data for baseline crash behaviours for different crash scenarios. In combination with the structure database established in VC-COMPAT, baseline topologies of the EAS can be modelled. However, to model appropriate representatives of the European fleet, more data is needed. One way to collect these data could be to monitor crash pulses and deformation behaviour as well as the topology of the structure concepts during the homologation process of future vehicles.

Other important points are modelling parameters already mentioned, like mesh size, materials, contacts and parameters ensuring numerical stability. At this time no thresholds can be defined to specify these parameters. Further research is needed to answer these open questions.

3.3 Deformable Barrier Models

Two new deformable barrier types were investigated within FIMCAR: the progressive deformable barrier (PDB) and a deformable element in front of a full-width barrier (FWDB). Compared to the test configuration used in ECE R94 and EURO NCAP, the new test configurations are intended for analysis of the partner protection potential of the tested car. In case of the PDB, the deformation pattern of the barrier is primarily used to analyse load spreading. In case of the FWDB, the deformable element is used to prevent engine dump and to activate the front structures in a more realistic way then it is done in a full-width rigid barrier test (FWRB). Furthermore, the forces applied to the wall are measured by load cells. The assessment metrics require minimum forces in specific areas of the wall in both test configurations the deformable element is crucial for the assessment of the vehicle. The main properties that influence the final deformation pattern of the PDB are the stiffness and strength of the honeycomb as well as the cladding sheet. In terms of the FWDB, the deformable element is responsible for some minor load spreading effects and therefore for the load distribution measured on the wall.

3.3.1 Today’s Requirements for FE Barrier Models

In Europe, the same deformable barrier (ODB) is used in regulation and consumer tests for frontal impacts. The specification and detailed description of the barrier is given in [ECE 2010]. In addition to the geometrical data, material type and stiffness of the barrier as well as the certification process is described. This certification process requires different specimens to be extracted from the barrier for tests by dynamical loading. In this way the stiffness of the honeycomb block is validated and the barrier can be certified.

For the development of the FE barrier model, geometry, material type and (axial and shear) stiffness of the honeycombs are essentially the only requirements that are needed to be fulfilled to create a validated model. In terms of the ODB, this is sufficient due to the fact that neither the barrier deformation nor the barrier forces are analysed after the crash. Additionally, in house requirements of the provider or the OEM itself can be defined.

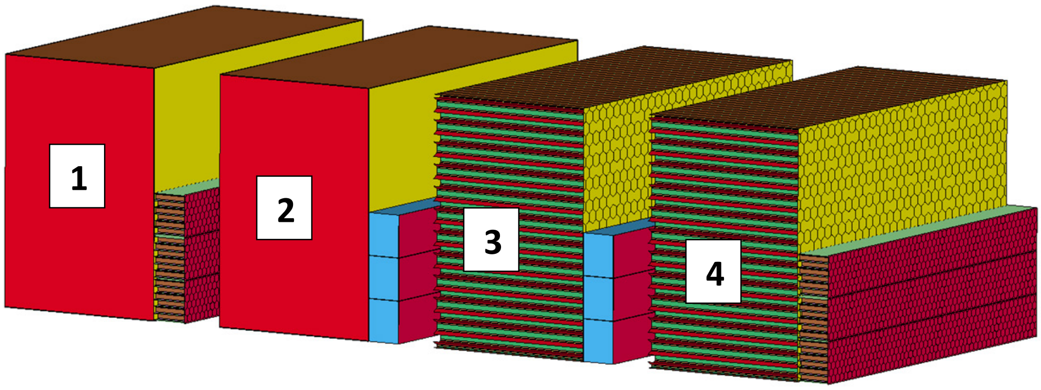

Figure 3.3: Different ODB FE barrier model designs [Bala 2003].

Table 4: Comparison of different ODB FE barrier models [Bala 2003].

Barrier Number (See *Figure 3.3*)	Main Block	Bumper Block	Number of Elements
1	Solid elements	Shell elements	193,655
2	Solid elements	Solid elements	64,119
3	Shell elements	Solid elements	380,973
4	Shell elements	Shell elements	1,504,793

Different fields of application lead to different modelling approaches to simulate the behaviour of the honeycombs. Between the trade-off of accuracy and time consumption, the user must decide which model design is the best for the intended application. Figure 3.3 shows different designs of the ODB as provided by the LS-DYNA crash solver [Bala 2003]. Depending on the design the number of elements, as one of the most important criterion in FEM simulation, increases dramatically with the level of detail. The level of detail changes dramatically when the element type changes from solid to shell elements and the complexity of the barrier model becomes the same order of magnitude as a full vehicle model. Comparisons of element model and barrier modelling are presented in papers like [Yasuk 2008].

3.3.2 Requirements for PDB model

Due to the fact that there was no commercial FEM model of the latest PDB version available, a new model was created by GME [Stein 2012] within the FIMCAR project. Within the development, the standard procedure of barrier modelling was used. The first version of the barrier showed a very good correlation of the acceleration pulse of the colliding vehicle. As described above the validation was only done with respect to geometrical requirements and material characteristics, in particular the axial loading of the honeycomb blocks. This model (PDB v1) was used for some initial runs with the PCMs. The preliminary results showed that correlation of the deformation behaviour of the barrier model with the real barrier was very poor. One of the identified problems was that the lateral stiffness of the barrier model was too soft. Thereby the honeycomb blocks moved to the left during the rotation of the vehicle around the right edge of the PDB, Figure 3.4. Another problem was the created footprint. The deformation pattern of the barrier showed no correlation with typical footprints of real cars of the corresponding vehicle class (executive car). However, due to a lack of suitable PDB metrics no objective assessment could be done. Based on the subjective assessment of the deformation behaviour and the footprint, it was decided that the quality of PDB version 1 was not sufficient for the use within FIMCAR.

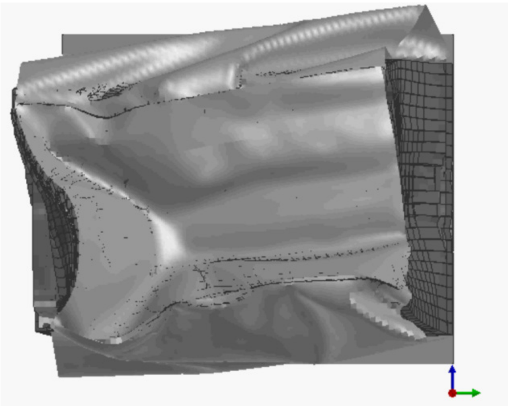

Figure 3.4: Deformation behaviour of PDB model version 1.

A second model was created (PDB v2) with respect to the identified problems. Within this validation process, the focus was the creation of realistic deformation behaviour of the honeycombs. Therefore the lateral stiffness and the rupture were fitted to test data coming from the two certification tests (trolley with rigid plate and tubes) for the barrier and finally validated with real crash test data. The following simulations show a good correlation of the barrier model in terms of deceleration pulse and deformation pattern of the barrier, Figure 3.5.

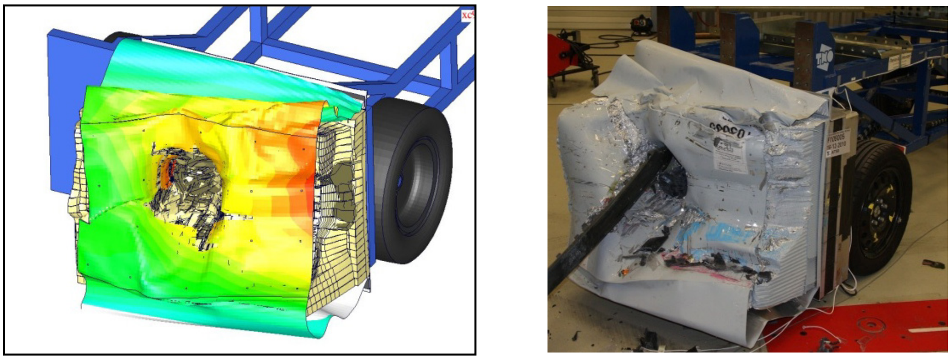

Figure 3.5: Comparison of PDB version 2 model with real crash test.

3.3.3 Summary and Conclusions

Different barrier models were used within FIMCAR. On one hand, the ODB FEM model, which is a de facto standard tool in the product development process and new barrier models like PDB and FWDB. Due to the fact, that the new deformable elements are used differently than in the past (i.e., barrier deformation pattern for PDB and force transfer through the barrier for FWDB) the model quality needs to fulfil additional requirements compared to today. These are:

- Load spreading
  - Information about lateral stiffness of honeycombs
  - Force transmission through rivets, intermediate plates or glued connections
- Rupture of material
  - Exact thresholds for material rupture needed
  - Rupture mechanisms need to be identified

Two different scenarios seem to be capable to address the requirements needed for barrier modelling:

1. Expanded certification process

A specific number of dynamic test configurations need to be specified. The tests shall load the barrier with realistic loadings (e.g. energy, structures). A specific number of thresholds need to be fulfilled addressing requirements like load spreading, deformation pattern as well as today's standard requirements.

2. Specific definitions of material characteristics

A detailed confirmation of the validated barrier model in terms of material behaviour (honeycombs and cladding/intermediate plates) and connection characteristics (glued and rivet connections) need to be provided. The final validation can be done by a specific test where either a predefined deformation pattern has to be created or a specific amount of load spreading is allowed.

Both scenarios are suitable to provide enough data for a barrier modelling process. Dynamic tests have the advantage that boundary effects like the trapped air in the honeycombs, are taken into account as well. Furthermore, realistic loads provide the benefit that the barriers behave during the certification in the same way as they do in real crash test.

The most important conclusion is that the minimum requirements for barrier models are not sufficient to create the new barrier models investigated in FIMCAR. New requirements need to be defined to ensure a realistic behaviour of any FEM barrier model.

3.4 Different Crash Solvers

Today, several commercial crash solvers are available and are used by the industry. Within FIMCAR, all FEM models should be made available for the three crash solvers (LS-DYNA, PAM Crash and RADIOSS) used by the industrial partners of the consortium. For the modelling process, a specific knowledge of the used crash solver is necessary. Basically the modelling approach is the same, but particular numerical effects (e.g. hourglass and shear lock effect, mass adding) require solver specific controls to handle the effects and to ensure stable calculation and valid results. Furthermore, there are no commercial tools available which can reliably "translate" models from one solver into another. The geometrical definitions such as the translation of nodes, elements and the corresponding parts do not cause problems. Definitions of more software specific parameters for materials, contacts, constraints and loads are problematic however. The treatment of kinematic options also differs between the solvers. These entities have to be defined manually and is very time consuming and prone to errors. Another problem that has an influence on the results is the computer and its hardware components. Solving the FEM generated numerical algorithms depends on the interaction of the hardware components. Especially the last point is influenced by multi CPU clusters. The following three main parameters are responsible for the quality of the results of different solver:

- Knowledge of solver dependent controls to handle numerical effects
- Knowledge of solver specific definitions to set up model characteristics
- Influence of hardware used for the calculation

Within the modelling process, all of these three main parameters were taken into account. Within FIMCAR, no thresholds were defined for the validation of the models for the different crash solver, Figure 3.6. The comparison of the results was made subjectively according to a standard validation process (real world – model) and engineering judgment. The following section deals with the possibility of objective assessment of crash solver responses.

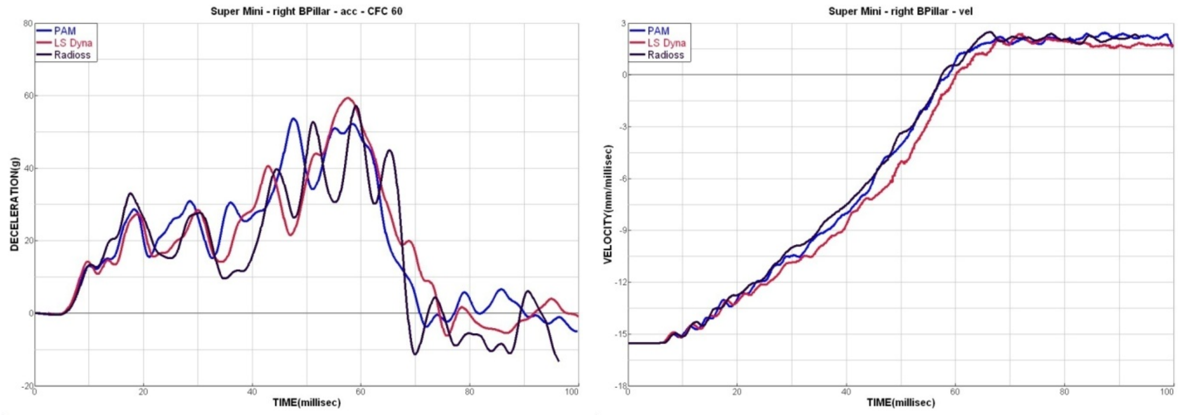

Figure 3.6: Comparison of crash solver responses (PCM Super Mini; left side – deceleration; right side velocity).

3.5 Objective Response Assessment

The growing role of FEM simulations in the product development process requires tools for the objective assessment of measurements in particular for the validation process of FEM models. Different approaches are available to compare signals against each other:

- Comparison of specific values of a signal (e.g. maximum peak at specific time)
- Comparison of curve characteristics in a predefined interval

While the comparison of specific values is less difficult, the assessment of the correlation of the whole curve with the original one is very complex. Several possibilities exist that were used in different fields of applications (e.g. curve fitting, signal analysis) to make an objective assessment of two curves. The following list gives an overview about commonly used methods:

- Corridor methods
- Cross correlation method
- Least square method

3.5.1 Corridor Method

This method uses corridors to assess the correlation of two curves, Figure 3.7. Different rating levels can be used to weight the distance between the curves [Gehre 2009]. At least one corridor needs to be specified. The width of the corridor can be set up to different values (e.g. +/- root mean square deviation, +/- x-% of average of each point or of the maximum peak value, user defined values).

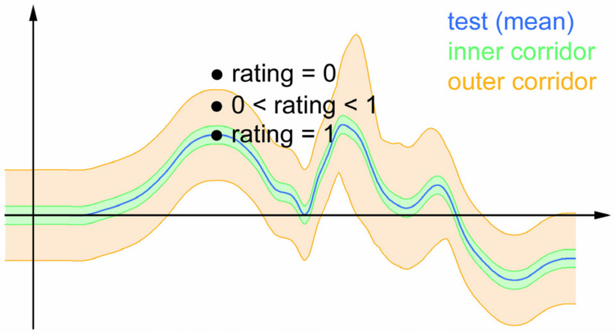

Figure 3.7: Corridor method with two corridors using three rating values [Gehre 2009].

3.5.2 Cross Correlation Method

Basically this method is used in fields of signal analysis. Separate analyses can be made and independently compared against each other: phase shift (see Figure 3.8), size of area under the curve and shape of the curve.

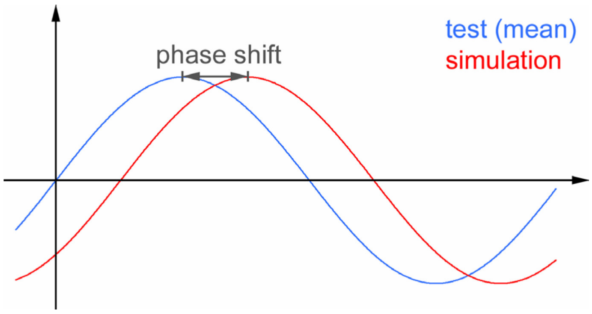

Figure 3.8: Example for cross correlation – phase shift [Gehre 2009].

3.5.3 Least Square Method

Optimisation tools commonly use this method for curve fitting optimisation. The goal of this method is to minimise the sum of the residual difference between an objective curve and the original curve. As well as values calculated by corridor and cross correlation method, the sum of the residuals can be used as an indicator of the correlation of two curves.

Many individuals and organisations have developed software to perform the comparisons of different curves. The NCHRP 22-24 [Ray 2010] project developed a Matlab[1] based script that uses a variety of metrics to compare curves with the specific application to road restraint systems.

3.5.4 Summary

The objective assessment of curves e.g. within the validation process of FEM models can help to improve the model quality and can reduce the effort needed for the validation. Furthermore these tools offer the potential to compare different crash solver against each other. Special models addressing numerical effects and their treatment by the solver can be used to adjust the solver settings. Objective curve assessment can provide thresholds that need to be fulfilled before the settings can be used in the final model. In that way, it is possible to exclude the influence of the solver from the model response. As already mentioned, the identification of appropriate thresholds is crucial before the objective assessment can be applied.

[1] Matlab is a product of The MathWorks (www.mathworks.com)

3.6 Model Verification and Validation

The general flowchart elaborated within IMVITER (Figure 3.9) evolved the flow chart of Regulation 371/2010 into a clearer version based on 3 phases: model verification, model validation and type approval [Eggers 2012].

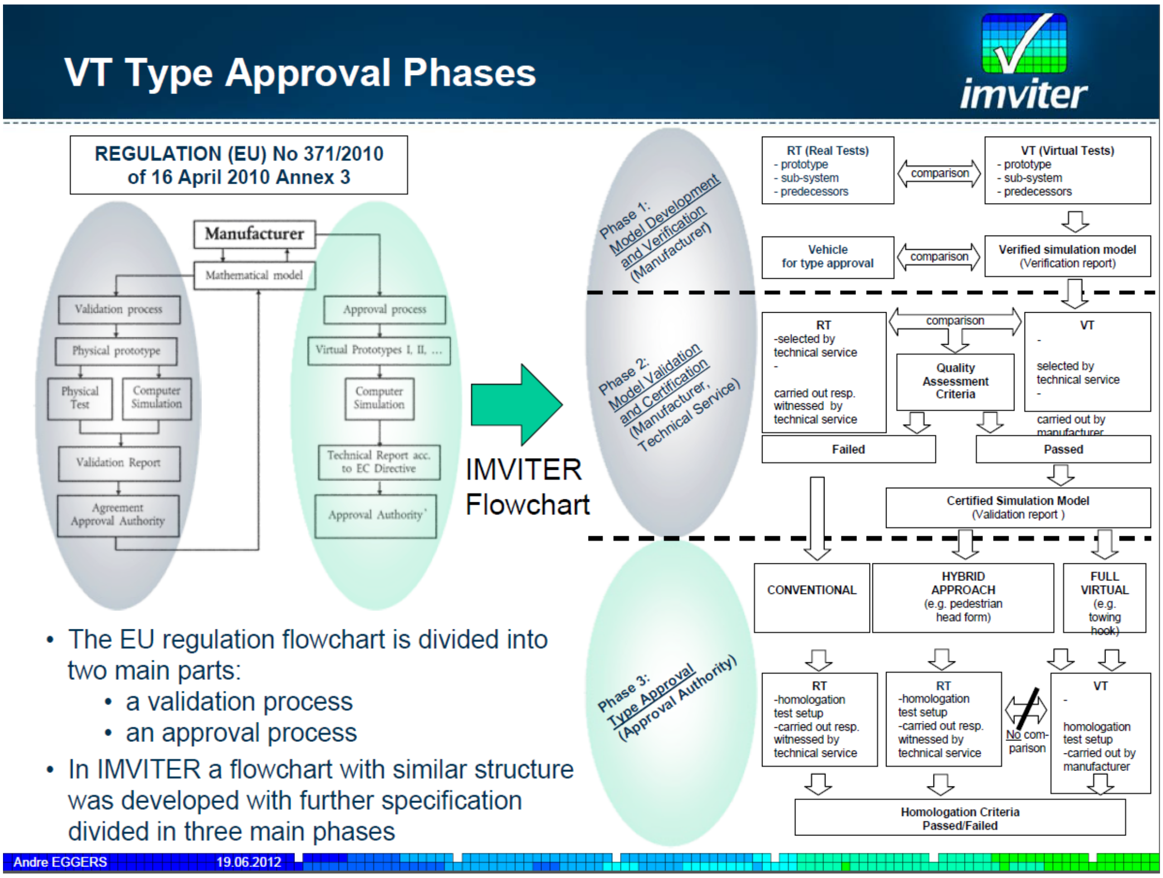

Figure 3.9: Type Approval Phases according to [Eggers 2012].

The type approval phase can follow 3 approaches (in addition to the conventional case with real testing only):

Full VT: Type approval technical requirements are assessed only with VT.

Hybrid VT: Type approval technical requirements are assessed with a combination of physical test and VT.

Extension of Approval (EoA) based on VT: A vehicle is type approved based on simulation predictions obtained from a model, which is obtained from a predecessor model previously validated, and with small modifications.

The numerical model is validated in Phase 2 against real testing results: the model is accepted when the proper validation criteria (metrics, with threshold values depending on the specific application) are satisfied (then ensuring an adequate level of overlap between numerical and virtual outputs, for the specific test set-up/configuration concerned).

All the phases described in the detailed procedures or flowchart have to be summarised at the end within reports that have to be approved by the Technical Service. These reports need to include a minimum amount of information in order to prove the verification and validation of the involved models (phase 1 and phase 2 of the general IMVITER flow-chart respectively), so that they can be accepted and used for the Type approval (phase 3). In practice, the model verification report is used for the identification of the model, i.e. proving that the virtual product/tool actually represents the real one. The model validation report describes the model ability to reproduce the reality, i.e. assesses the predictability of calculation results. In this report, the results of simulation runs are compared to the ones from the reference experimental test and judged according to the selected metrics/validation criteria. For each presented calculation, a check of the loading conditions (set-up) and of the numerical correctness (e.g. energy balance, added mass, etc.) associated to the corresponding run also has to be passed and this is called verification of the run. So the model validation report always provides the evidence about verification of calculations and validation of their results. The general reporting approach defined within IMVITER is summarised in Figure 3.10 [Puppini 2012]

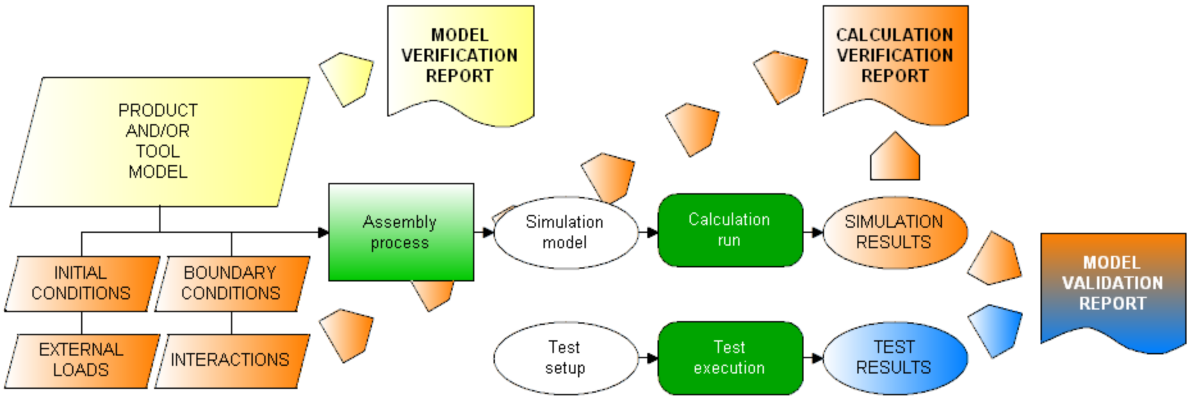

Figure 3.10: Reporting approach according to IMVITER [Puppini 2012].

IMVITER delivered report templates for the pilot cases that were studied and these represent the main synthesis of the virtual testing procedures and a basic reference for each future implementation of VT in regulations.

Several metrics were suggested in the past and are then available for the objective comparison of results required by the model validation phase. Some of them were preliminarily proposed in IMVITER (together with the threshold values for the pilot case concerned) for the validation of the model results and then included within validation report templates.

ISO-TC22-SC10-WG4 on Virtual Testing is currently active on the elaboration of an ISO standard for the objective comparison of two signals. The release of such a reference standard on metrics will probably lead to an update of the criteria preliminarily proposed in IMVITER for its pilot cases, other than creating a new basis for criteria considered in future VT regulation developments.

Pedestrian protection is currently not included among the regulatory acts in which the use of virtual testing is allowed. An in depth study on this specific pilot case was performed within IMVITER and the corresponding results will form the basis for future evolution/refinements of the current Regulation.

Euro NCAP rating has introduced the possibility to use numerical simulation results within the pedestrian protection evaluation “box”. This option is already considered within the forthcoming new Pedestrian protection Protocol (version 6.0 from February 2012) for the assessment of vehicles with active bonnets, where the numerical simulations, involving standing pedestrian models of different sizes, will be required to identify the ‘hardest to detect' pedestrian and support the choice of test tool. The simulations will concern the pedestrian statures that result in head contact with the bonnet and acceptable numerical models and codes are specified in a dedicated Appendix.

For the evaluation of the head-to-bonnet impacts according to the so called Grid Method, the OEM is required to provide Euro NCAP Secretariat with HIC or corresponding colour data detailing the protection offered by the vehicle at all grid locations on the bonnet (defined through an appropriate geometrical procedure). These predicted values or colours can be the results of numerical simulations and shall be provided before any test preparation begins. The predicted level of protection offered by the vehicle is verified by Euro NCAP by means of testing of a sample of randomly selected grid-points and the overall prediction is corrected accordingly, i.e. through the application of a correction factor generated by comparing the outcome from the randomly selected test locations with the predicted results supplied in advance for the same points. Only data that results in a correction factor between 0.500 and 1.500 are accepted and where this is the case, the headform score will be based on the predicted data score with the correction applied.

The Grid Method represents a first practical application/implementation (with additional elaborations) of the possible virtual testing approaches proposed within APROSYS (overall map of predicted VT results generated in advance on a series of points evenly distributed within the impact areas of the vehicle and made available) and presented in occasion of its Final Event [Puppini 2009].

4 FRONTAL COMPATIBILITY EVALUATION

4.1 Introduction

Numerical (FE) simulation is a reliable tool for the assessment and optimisation of car design and facilitates reduced testing efforts. Each OEM largely relies on this tool during its product development process. For this reason, only with simulation tools a realistic and wide coverage of car-to-car compatibility issues (w.r.t. the real accident situations that may happen on the road) can be reached with acceptable/sustainable costs. Real car-to-car tests are very expensive and only provide information at specific sensor locations or areas observed in film coverage. For this reason, car-to-car compatibility was identified as one of the fields with higher potential towards VT applications, with benefits in terms of enhanced real world safety [Puppini 2009].

Numerical simulation offers a resource to address the complexity introduced with new frontal impact requirements as well as offers extended evaluation of compatibility beyond the physical tests. The remainder of this chapter discusses the types of possible simulations to assess compatibility and the technical challenges for their implementation. In the following, VT is defined as the use of numerical simulation models to reproduce real tests for regulatory purposes, according to the definition given within IMVITER project [Cordero 2012]. While not all numerical simulation activities are VT, e.g. the ones like model development and its internal use for design purposes, VT can be considered as the common area between numerical simulation and legislation. The latter can also represent more general standards like internal industry or those used as a reference for voluntary agreements and/or ratings. In other words, only numerical models that pass appropriate and agreed verification and validation procedures and are then certified by regulatory bodies (through their Technical Services) can be used for VT (where the results of the numerical simulations performed with such certified models are used for assessing the compliance with regulatory prescription/requirements).

4.2 Implementation Options

Compatibility is an issue exceeding the borders of the vehicle fleet of one manufacturer, as real car-to-car impacts occurring in the entire vehicle fleet. Confidentiality and use of different software codes make it impossible to simulate crashes between car models of different OEMs. Due to this important limitation, for an OEM the only practical way to proceed to evaluate its products' performance is to use a virtual common target vehicle – or better a number of common target vehicles – that is not restricted by confidentiality or commercial interest.

Within FIMCAR this way was addressed through the generation and use of Generic Car Models (GCMs) and Parametric Car Models. The concept of GCMs was born and already successfully applied within the past APROSYS project but a second generation of these models was specifically developed for the use towards frontal impact compatibility issue.

In general, when examining the use of virtual testing tools for compatibility aspects, typically full car crash simulations are considered, that can be classified w.r.t. the different type of impact configurations (numerical set-up) involved:

a) Specific vehicle-to-barrier(s)
b) Specific vehicle-to-itself (car-to-car)
c) Specific vehicle-to-other specific vehicle of different class (same OEM)
d) Specific vehicle-to-common/standardised reference vehicle of same class (GCM approach)
e) Specific vehicle-to-common/standardised reference vehicle of different class (GCM approach)

Again in general, simulation tools or Virtual Testing for compatibility evaluation can be seen under 3 different macro-perspectives/scenarios:

1) For vehicle design/development purposes
2) For "interim" regulatory purposes (compliance to voluntary agreements and/or ratings)
3) For regulatory purposes (vehicle type approval)

Vehicle design/development is nowadays largely based on simulation tools and the inclusion of compatibility aspects is not posing particular operational problems. Impact configurations of type a) are normally considered within the virtual activities supporting the product design & development phases during the standard product development process (PDP) adopted by OEMs. Configurations of type b) and c) are also considered/explored by OEMs but only for specific verifications of the vehicle overall crash behaviour and/or research purposes and not an integrated part of the systematic design approach. Current industrial crash simulation procedures/practices are ready to deal with typical compatibility aspects and scenario 1) is the one with the short term applicability. Configurations of type d) and e) are feasible also within this scenario, provided that representative generic car models are made available and agreed/recognised within the industry as the reference tool for this type of crash simulation based compatibility analyses.

The second scenario ("interim" regulatory purposes), can be seen as an extension of current industrial procedures/practices for full car crash simulation but on a voluntary agreement basis and/or on requests coming from new rating protocols. The time frame for this could be the medium term perspective. The definition of a VT standard focused on compatibility needs an appropriate period of discussion for convergence towards a procedure that is agreed within appropriate TWGs (Technical Working Groups), and then to be applied on a voluntary basis by OEMs or within a rating protocol. This voluntary (or independent, in case of ratings) characteristic is the factor that could speed up the development of such a VT standard w.r.t. a classical regulatory act. This scenario could involve obviously all the previously mentioned crash configurations, from a) to e).

The third scenario, i.e. VT within the regulatory purposes, requires the OEM to strictly follow predefined procedures to ensure that the models adopted to produce the results are adequately predictive. This means that the virtual models are verified and validated against real results, through the use of appropriate correlation criteria/standards (introduced in Chapter 3). It has already been highlighted that such types of approaches have been/are studied in dedicated international projects/working groups (i.e. IMVITER, ISO WG4). The complexity levels considered to date, however, are still far from the full car crash configuration necessary for frontal impacts, so the scenario 3) appears to be the most difficult to be implemented. The most complex type approval procedures considered within the IMVITER project were pedestrian head and leg form impacts where no complex material behaviour (local and global buckling, material failure, etc.) are significant in the dynamic event.

Full car FE structural analysis is widely applied within industry but testing is still essential for the manufacturers to have confidence in the product's performance. Better damage and rupture modelling is needed for predictive structural analysis. Component tests help to validate models locally but an experimental full system response may still disclose unexpected failure modes in different scenarios. Therefore VT for type approval applications vs. compatibility aspects seems to be still a very complex case, even for the classic crash configuration of type a). For these reasons, scenario 3) is seen as a more long term perspective where all the crash configurations (a) to e) can be involved.

The previously discussed classifications and contents can be organised in a matrix in order to visually identify the level of potential application. Colour coding is used to show the difficulty of the issues.

In Table 5, the situation described in the previous paragraphs is presented using the following colour code: green=currently feasible/short term perspective; yellow=medium term perspective; orange=long term perspective).

Table 5: Matrix showing the level of potential application of VT for compatibility purposes.

		Scenarios		
		1) For vehicle design /development purposes	2) For "interim" regulatory purposes (compliance to voluntary agreements and/or ratings)	3) For regulatory purposes (vehicle type approval)
Numerical test set-up	a) Specific vehicle-to-barrier(s)		X	
	b) Specific vehicle-to-itself (car-to-car)		X	
	c) Specific vehicle-to-other specific vehicle of different class (same OEM)			
	d) Specific vehicle-to-common/standardised reference vehicle of same class (GCM approach)		X	
	e) Specific vehicle-to-common/standardised reference vehicle of different class (GCM approach)			

The last two cells of scenario 1) column are indicated in yellow because the availability of agreed/recognised representative generic car models as reference tool still needs some additional steps forwards, w.r.t. GCMs used within FIMCAR. Moreover Scenario 1) is related to common/normal industrial internal activity performed by OEMs within their PDPs, as already mentioned. In this case, the discussion of VT potential for compatibility assessment has not been addressed to date. This document is not focused on this scenario but rather on the other two as defined in the beginning of this chapter.

According to this and to the experience done with VT applications in FIMCAR, the area (cells) of the matrix indicated with an “X” are then the ones on which the following considerations are mainly based.

Scenario 2) involves, other than a target car model (specific real vehicles but even GCMs/PCMs), the model of the specific barrier type concerned (FWRB, FWDB, (M)PDB, ODB): in view of VT application, the models of tool concerned need to be verified and validated, too, according to common procedures/templates that need to be defined and agreed. Within FIMCAR different barrier models were used in certain configuration simulations (FWDB and PDB) by different partners, even if the level of equivalence between them were not assessed against a common validation and verification procedure (V&V). A preliminary V&V certification of this type will be required in the future. It is believed that this procedure can be defined and agreed within a relatively short time window (i.e. compatible with the medium term perspective), as barrier model verification and validation process is already today done at different sites according to similar procedures and only aspects like common reference experimental results and correlation criteria/metrics for the model acceptance need to be shared and formalised.

Scenario 2 is an area where the numerical simulation can support the selection of “worst case”. In the FIMCAR-proposed compatibility approach two load cases should be tested, both Full Width Deformable Barrier (FWDB) and Offset Deformable Barrier (ODB). The main objectives for the FWDB test are a compatibility metric and high cabin acceleration driven dummy criteria. The car configuration that represents the worst case for the FWDB metric could be the smallest powertrain version (the powertrain that loads the deformable barrier latest in a FWDB test), and the option level that gives the lowest curb weight. This may not be the same configuration that produces the worst case for dummy loading as the dummies may have a longer ride down distance. For the ODB test, the objectives are to test structural integrity and intrusion driven dummy criteria. The worst case car configuration should be the powertrain version and option level that creates the highest intrusions in the driver compartment area.

Internal discussions within the FIMCAR consortium have resulted in the decision to identify a worst case vehicle configuration for the FWDB and ODB test separately. Thus, crash simulation can be used to demonstrate the worst case vehicle configuration prior to the homologation testing to be approved by a technical service. Crash simulation can thereby supplement the test data if the vehicle and barrier models can be verified and validated through acceptable procedures.

FIMCAR adopted the concept of GCMs by developing new improved versions and using them extensively in the numerical simulation activities involving the car-to-car crash configurations (numerical set-up a), b) and d)). The approach followed in this activity already contains all the main elements that a future V&V procedure for certified common opponent vehicle models should implement/formalise. The GCM development process was driven by the following requirements:

- To represent typical vehicles of the actual European vehicle fleet, in terms of mass and dimensions

- To evaluate the occupant severity level through appropriate readings of the vehicle crash pulse (no restraint system and dummy models on board of GCMs/PCMs) => OLC (Occupant Load Criterion)
- To be available in all codes used by FIMCAR OEMs (LS-DYNA, RADIOSS, PAM-Crash)
- To ensure numerical stability (stable time steps, energy conservation and added masses) in all the main crash configurations considered
- Capable to interact with OEM detailed models, i.e. that can be easily included inside virtual car-to-car test set up involving a real car model as opponent
- High level of detail, similar to the one of detailed OEM models (around 600,000 to 700,000 elements each), i.e. fine mesh, especially for what concerns the vehicle front structure and all relevant under bonnet lay-out components implemented
- Realistic crash behaviour during the collision types considered, i.e. adequate deformation of the front-end structures with correct interaction of the under bonnet lay-out components, contained occupant compartment intrusion levels and realistic vehicle crash pulses
- To have main rails with an adequate overlap w.r.t. the “part 581 common interaction zone”
- To be properly instrumented, in order to permit the monitoring of relevant structural parameters/indicators
- Validation towards the achievement of a good overlap with real US NCAP pulses (“realistic” behaviour) and equivalent model responses among the different codes (LS-DYNA, RADIOSS and PAM-Crash)

The formalisation of the way to obtain such certified virtual common reference car models and the corresponding availability of these first generation of reference tools, agreed/recognised on a wider scale, seems to be feasible in the medium term as demonstrated by the successful application of GCMs in the FIMCAR project. The FIMCAR applications even take into account further evolution of GCMs simulation output and metrics to judge their level of realistic behaviour or representativeness (e.g. average values of public available crash pulses as reference curves for objective metric applications, corridors derived from the specific class real curve envelopes, etc.). There is also a great potential w.r.t. harmonisation, as this type of approach (availability of common opponent models) is something considered also outside EU. The In the US a fleet of FE models was developed by NCAC that represents a similar way to provide common opponents for VT. The main difference between the US and EU approach was that the NCAC models are reverse engineered models of available car models while GCMs are virtual car models with no physical counterpart. Both approaches can coexist in the future and be integrated with each other. Past car crash compatibility studies in the US have seen a relevant use of NCAC models to complement the real car-to-car crash test programs [Patel 2009, Stein 2013/1, Park 2009].

Any reference generic models family, once adopted as a tool for VT based evaluations, has to be updated periodically in order to reflect the fleet evolution. This is undoubtedly a huge task (models architectures, code versions etc.), with associated costs and efforts that can be probably managed only by dedicated institutions and/or accredited companies having this by mandate and/or core business.

An important step forward can be the convergence/integration of the two approaches used within FIMCAR, i.e. GCMs and PCMs. Detailed GCMs can be based on a parametric CAD geometry (like PCMs), permitting relatively fast changes of architecture and/or ”jumps” between adjacent classes, other than an easier updatability (in order to take into account fleet evolutions), while maintaining an high level of detail in the models. This evolutionary step is called PGCMs.

The number of reference models (vehicle classes represented) cannot become extensive in order to maintain feasible dimensions for the simulation run matrix required for VT evaluation of car-to-car configurations. A manageable/sustainable range could be 4 classes: Supermini, Small Family, Large/Executive, and SUV. For this reason, the number of car-to-car crash configurations to be considered in a procedure has to be limited to a minimum (e.g. one closing speed, two horizontal, and two vertical offsets).

5 DISCUSSION

Several road maps considering the introduction of VT in regulations have been presented in the past decade: Advanced Passive Safety Network (APSN) in 2004 and 2006, CARS21 in 2005, IRCOBI in 2006 and APROSYS in 2009 [Puppini 2009]. All of them dealt with the general aspects summarised in the following list, even if with some differences in the type of approach and/or focus (e.g. more emphasis on expected time for certain VT phases introduction/implementation than on their details or vice-versa):

- Development of standardised model validation procedures and tools
- Evaluation of model/simulation quality/predictability
- VT acceptance as assessment method in regulations
- Expansion of regulatory test configurations with VT
- Implementation in regulation/ratings (first on simpler cases and then on more complex ones, with integrated approaches)
- New advanced VT tools (dummy and especially human body models, with improved injury criteria and potential to cover a much wider range of occupants, in terms of size, age and gender)

In the following section, however, the IMVITER Roadmap for VT implementation is introduced and reviewed.

This is the latest roadmap that was released (June 2012) by a research project that ran in parallel with FIMCAR and that made a significant step forward on the subject. Considerations about the specific case of VT vs. compatibility aspects will be then made on the basis of this up-to-date document [Seibert 2012].

Figure 5.1 shows the roadmap presented at the IMVITER Final Meeting (19th June 2012). As it can be seen from the figure, it is expected that Real Testing (RT) and Virtual Testing (VT) will coexist in the future but, from 2018-2020 on, a growth in the proportion of VT in regulation is foreseen. An increasing and relevant presence of full VT based type approvals is predicted from 2030 onwards.

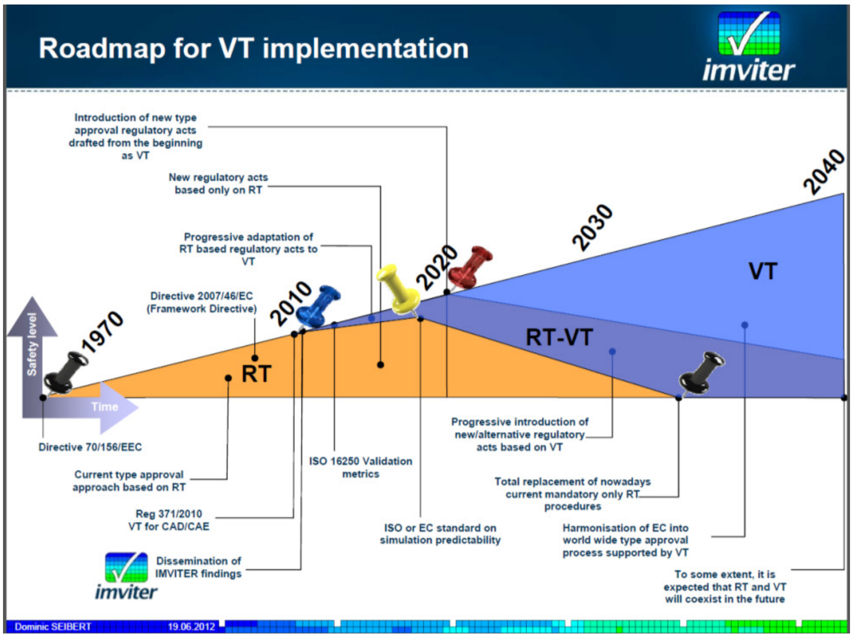

Figure 5.1: IMVITER roadmap for VT implementation [Seibert 2012].

The use of VT towards compatibility aspects can be positioned within this roadmap. A time frame for integrating VT into full vehicle VT is presented below with the potential for full certification by simulation identified.

Step 1

2013-2020: further evolution of GCMs concept and consequent availability of first agreed/recognised reference VT model family for regulatory/rating application, with associated definition of verification and validation procedures/templates. Convergence towards PGCMs concept for this type of virtual tool and on the dimensions/typology of the simulation run matrix required for VT evaluation of car-to-car configurations. PGCMs equipped with generic restraint systems and occupant models and then also capable of providing realistic biomechanical responses. Crash simulation is used to identify the worst case configurations of vehicles for physical testing.

Step 2

2020-2025: first ratings and/or voluntary agreements for compatibility purposes, i.e. interim regulatory purposes focused mainly on car structural responses and including car-to-PGCMs virtual crash configurations. Behaviour of vehicle occupants (real cars and PGCMs) analysed indirectly (i.e. through indicators like OLC or other similar criteria) as minimum requirement, with the possibility to provide occupant responses (use of real car and/or PGCMs equipped for biomechanical response). VT is accepted to type approve model variations based on previously approved vehicles (i.e. physical testing).

Step 3

2025-2030: first full vehicle-crash regulations (vs. type approval and even self-certification) for car-to-car compatibility based fully on VT (structural behaviour and dummy biomechanical response on PGCMs). Physical testing is still required for new vehicle registrations.

Step 4

2030-2040 Type approval based on full system simulations (structural and biomechanical behaviour included, with HBMs as occupants of specific car and PGCM opponents involved and enhanced injury criteria taken into account in the prescriptions).

The above mentioned four steps for VT implementation vs. compatibility aspects, obviously, have to face some obstacles/difficulties: the main ones are indicated in the following Table 6 and Table 7.

Table 6: VT implementation steps & obstacles.

Roadmap step	Description	Obstacles	Possible solutions
*Step 1: **2013-2020***	*Specification of vehicle model requirements for use in type approval support actions (i.e. worst case selection)- Further evolution of GCMs concept: PGCMs equipped with generic restraint systems and occupant models* *- First agreed/recognised reference VT models family for regulatory/rating application* *- Convergence on the dimensions/typology of the simulation run matrix required for VT based evaluation of car-to-car configurations*	*-Agreements between industry and rulemaking bodies on model properties and criteria that are not design restrictive* *-huge and then expensive task (different models architectures, different code versions, etc.)* *- need of periodical update of VT models reference fleet, according to evolutions in real fleet and in numerical simulation techniques state of the art (SotA)* *- long process to obtain agreement on common VT tools and procedures*	*- dedicated public funded projects* *- dedicated institutions and/or accredited companies having the PGCMs maintenance as mandate and/or core business* *- activation of specific international technical working groups elaborating the VT procedures and reaching the necessary agreement*
*Step 2: **2020-2025***	*- first ratings and/or voluntary agreements for compatibility purposes, including car-to-PGCMs virtual crash configurations* *- main focus on vehicles structural behaviour* *- occupant behaviour: indirect evaluation through indexes (like OLC) as minimum requirement; available option for direct evaluation through occupant models*	*- difficulties/delays in completing the previous Step 1* *- complexity of VT procedure, i.e. complex models, complex templates to report all results, high amount of CPU time needed to perform the required simulation matrixes*	*- keep complexity level under control, by focusing on procedures/requirements sounded with the SotA of the period* *- automation of the procedures (integration within Product Data Management Systems)* *- continuously improving performances within HPC field (High Performance Computing)*

Table 7: VT implementation steps & obstacles (continued).

Roadmap step	**Description**	**Obstacles**	**Possible solutions**
Step 3: ***2025-2030***	*- first full vehicle-crash regulations (type approval /self - certification) for car-to-car compatibility based on fully on VT* *- structural behaviour and at least dummy biomechanical response on PGCMs*	*- difficulties/delays registered in previous step 2* *- differences in VT procedures for different regulatory approaches (type approval and self-certification) in different areas of the World*	*- harmonization of VT procedures (within the overall process of harmonisation of type approval procedures and world- wide regulations*
Step 4: ***2030-2040***	*- type approval based on full system simulations* *- structural and biomechanical behaviour included* *- HBMs as occupants of specific car and PGCM opponents* *- enhanced injury criteria in the prescriptions*	*-possible relevant changes in the real fleet mix, with the presence of new vehicle concepts (e.g. Full Electric Vehicles) becoming comparable/ predominant w.r.t. traditional cars, with associated changes in the overall compatibility picture/problem and needed safety countermeasures*	*- more lean and flexible rule/regulation making processes (update/extension of existing procedures)* *- timely generation of new PGCMs providing appropriate reference models for the new vehicle classes (e.g. REVMs, Reference Electric Vehicle Models)* *- integration of Active-Preventive safety systems effects within VT procedures*

6 SUMMARY

The objective of this deliverable was to analyse the potential of simulation tools towards the evaluation of compatibility. A historical recap and a review of the on-going activities to implement simulation tools in automotive type approval and rating processes was performed. Extensive work is on-going in Europe within this subject. The EC founded IMVITER project aimed to help and support in the definition of upcoming virtual type approval procedures. The outcome from IMVITER combined with the experience from the use of simulations tools in FIMCAR was used as a base for the analyses and discussions on how to implement compatibility in the virtual type approval processes.

A roadmap with a 20-30 years perspective is proposed with the evolutionary steps towards a type approval based on complete system simulations, including both structural and biomechanical evaluation. The obstacles and their possible solutions are discussed for each step. However, obstacles still remain to be solved before a complete type approval can be possible, but the use of simulation tools is the only way to a realistic and wide coverage (w.r.t. the real accident situations that may happen on the road) of car-to-car compatibility issues with acceptable costs.

7 GLOSSARY

ams	auto motor und sport (German automotive magazine)
EAS	Energy Absorbing Structure
FE	Finite Element
FWDB	Full Width Deformable Barrier
FWRB	Full Width Rigid Barrier
GCM	Generic Car Models
HBM	Human Body Model
HPC	High Performance Computing
NCAC	(US) National Crash Analysis Centre at George Washington University
ODB	Offset Deformable Barrier
OLC	Occupant Load Criterion
PCM	Parametric Car Models
PDB	Progressive Deformable Barrier
PDP	Product Development Process
PEAS	Primary Energy Absorbing Structure
PGCM	Parametric Generic Car Models
REVM	Reference Electric Vehicle Model
SEAS	Secondary Energy Absorbing Structure
SotA	State of the Art
TCMV	Technical Committee – Motor Vehicles
V&V	Verification and Validation
VT	Virtual testing

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