VEHICLE CRASHWORTHINESS VIRTUAL ASSESSMENT: STUDY UNDER ANNEX 8, UN R21.01 REQUIREMENTS

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ABSTRACT

The automotive industry is constantly seeking to improve safety and optimize vehicle design, which requires accurate prediction of occupant response during collisions. Numerical simulation is a widely used method to assess/investigate occupant kinematics and injury risk, but its reliability depends on how well it correlates with physical testing. This paper presents a comparison between vehicle occupant CAE simulation and physical test results. Factors affecting the numerical results, such as the level of model details and input parameters, are discussed. Comparison between numerical and experimental tests based on Annex 8 of Regulation UN R21.01 are presented, among recommendations to enhance the numerical representation of physical testing. Overall, this paper highlights the role of research and development to achieve high levels of confidence of numerical simulation when compared to physical testing and suggests key aspects in order to further develop the numerical assessment of vehicle crashworthiness performance.

INTRODUCTION

Computer-aided engineering (CAE) and virtual testing allow manufacturers to simulate various scenarios a vehicle may encounter, such as crashes, driving conditions, and environmental factors. Virtual testing offers efficiency and cost-effectiveness by evaluating vehicle and component performance, in most cases without the need for expensive physical testing. It enables manufacturers to assess design options, make improvements, and reduce the need for costly physical prototypes. This iterative process speeds up development and leads to better-performing and safer vehicles [2].

Evolution in virtual simulation technology continues the improvement of its accuracy and capability. These tools enhance the accuracy and realism of virtual testing, enabling simulations that closely resemble real-world conditions. This makes virtual testing an increasingly valuable tool for vehicle approval process. Manufacturers can use these simulations to refine designs and evaluate the impact of changes more efficiently. Advancements in computing power allow for faster and more complex simulations, enabling manufacturers to test more scenarios and evaluate a wider range of design options. These technological advancements contribute to the creation of better-performing and safer vehicles during the vehicle development process [3].

Currently the approval framework regulation (EU) 2018/858 of the European Parliament, sets the requirements for the approval and market surveillance of motor vehicles and their trailers and components. It applies to all vehicle categories, including cars, buses, trucks, and trailers, with the goal of ensuring safety, environmental protection, and technical harmonization [1]. This regulation includes provisions for the conformity of production, requiring manufacturers to ensure compliance with type approval requirements throughout the production process.

The Annex VIII of Regulation (EU) 2018/858 establishes the conditions for the use of virtual testing methods in the approval process by a manufacturer or a technical service. The scope includes a list of 19 different regulatory acts with provisions concerning the use of virtual testing. At the request of the manufacturer, and subjected to the agreement of the approval authority, virtual testing methods may be used as alternative to the physical test but always following the specific conditions indicated in Appendix 2 of this annex.

The computational tools must be validated before the use for the vehicle homologation purpose. Within the Regulation, the Appendix 3 shows the flowchart of the validation process explaining how the manufacturer shall proceed.

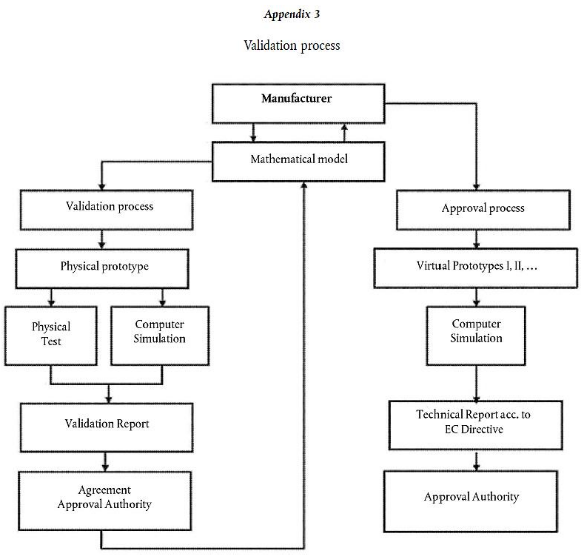


Fig 1. Flowchart from Appendix 3, Annex VIII, Regulation (EU) 2018/858 [1].

The figure 1 shows two main columns. The column of the left shows the validation process that the calculation tool shall submit. This validation is based on the assessment of the mathematical model by verifying the quality and evaluating the comparison of results between computer simulation and the physical test. The validation report and the agreement from the approval authority will be granted if the result deviation between simulation and test are accepted. In the other hand, the column on the right shows the approval process of the vehicle. Depending on the specific conditions of each of the 19 different regulatory acts, two alternative or complementary type approval approaches based on virtual testing can be applied: *Full virtual testing* and *Hybrid virtual testing*. *Full virtual testing* approach means that the results obtained from virtual testing fully covers all technical requirements necessary for the approval process. In addition, *hybrid virtual testing* approach means that results obtained from virtual testing are not still validated and need to be compared with some physical test. [6]

DEFINITION OF THE TEST

Annex 8 of Regulation UN R21.01 includes some technical requirements outlined for head impact testing in vehicles, focused on the evaluation of the head impact protection system within the passenger interior space of the vehicle. This annex provides an alternative to the static procedure defined in Annex 1 by proposing a dynamically determined head impact zone for vehicles. Manufacturers may choose to use Annex 8 by demonstrating, through an accepted procedure, that a dynamic head impact zone is relevant for their vehicle type. If Annex 8 is adopted, manufacturers must ensure that the vehicle's restraint system, including safety belts, airbags, and load limiters, prevents head impact in the reference zone during frontal impacts.

In order to assess the effectiveness of the protective system, sled tests are conducted with adult dummies representing occupants of various sizes, positioned according to manufacturer specifications. These tests involve a fixed rigid barrier at an impact speed of at least 48.3 km/h, with different angles ranging from 0° to ±30°. The dynamically determined head impact zone is evaluated for each dummy, considering potential contact between the dummy's head and non-glazed surfaces within the vehicle's interior. The manufacturers have the option to conduct physical test by using a vehicle or sled sample, or to conduct simulations to determine the dynamic head impact zone, which is typically smaller than the determined head impact zone [4]. The head impact zone encompasses all non-glazed surfaces of the interior, which could come into contact with a spherical head of 165 mm diameter. This zone is located in front of the seat H-point, determined using a device called H-point machine, and positioned 25.4 mm above the seat. The non-glazed surfaces of the head impact zone include the outer surfaces of the instrument panel (IP) and console [4] For the fulfilment of the regulation it is necessary to assure that all surfaces within the head impact zone are smooth and free of protrusions or sharp edges that may pose injury risks to occupants. Additionally, any padding or protective measures used in this area must be tested and proven to be effective in providing adequate head injury protection. The compliance evaluation involves measuring and analyzing head displacement of the dummy, and these values must be within the specified limits to demonstrate compliance with the regulation.

Lap and shoulder belt force measurements play a crucial role in assessing the safety performance of a vehicle's interior fittings. These measurements are obtained during frontal impact sled tests and are used to evaluate the restraint system's ability to protect occupants from head and chest injuries. In the test, a dummy is secured in the seat using the lap and shoulder belt. The sled is then accelerated and rapidly decelerated to simulate a frontal collision. The installed load cells store the recorded lap and shoulder belt forces. Chest compression and deflection are also important evaluated criteria during sled test. Chest compression measures the distance between the sternum and spine at the point of maximum chest deformation, with the allowed maximum compression varying based on seating position and dummy size. Similarly, chest deflection measures the displacement of the sternum from the initial position to the position of maximum chest deformation. Moreover, these additional data from measurements give more inputs to enhance simulations and improve the result comparison with physical tests, enhancing the model fidelity [5].

SPECIFIC TECHNICAL REQUIREMENTS

For the use of virtual testing, it is important to create a methodology that covers all the technical aspects of the model construction and establish standardized procedures. These are the key steps necessary to consolidate the validation of virtual methodology under requirements of UN R21.01 [4]:

1. Standardized modeling methodology definition: To establish a set of guidelines or standards for the modeling process and for the postprocess results. This ensures consistency across simulations and simplifies replication of the modeling construction. Develop a template or base model that serves as a starting point for the modeling construction. This template should include the necessary features, components, pre-defined contact definitions, material properties, and boundary conditions required for the specific simulation. [7]
2. Model quality procedure: To define a checklist document that will allow us to verify the model. To prepare detailed step-by-step procedures for the modeling construction process, addressing each technical requirement. To provide clear instructions on component positioning, contact interactions, kinematic considerations and friction specifications. This documentation will be used as a reference guideline for future simulations, ensuring consistency and facilitating the maintenance of established standards.
3. Verification and Validation: To perform verification and validation exercises to ensure the accuracy and reliability of the model construction. To compare simulation results with experimental data or known reference cases to validate the modeling approach. To adjust the methodology as necessary based on findings to achieve thorough validation and verification.
4. Continuous review and Improvement: Continuously review and enhance the methodology based on research, feedback, lessons learned, and technological advancements. Incorporate new techniques, tools, or best practices to improve the modeling process and ensure alignment with industry standards. After any new update of any aspect related with the methodology, the manufacturer shall inform to the approval authority. Depending on the extent and influence of this update, that could be major or minor change, the technical service could require different conditions to validate the new version.

General Motors (GM) has developed a comprehensive methodology that effectively address all technical requirements for consistent modeling construction in virtual simulations. With a strong emphasis on quality and precision, standardized guidelines and procedures have been established that govern the entire modeling process. This methodology encompasses crucial aspects such as accurate component positioning, creation of precise contact criteria, meticulous consideration of kinematic factors, and the inclusion of appropriate frictions within virtual simulations. By adhering to these guidelines, the virtual models accurately represent real-world scenarios and generate reliable results.

To ensure consistency across various simulations, GM has implemented a template-based, which provides a standardized starting point for modeling construction, incorporating pre-defined contact definitions, material properties, and boundary conditions. By using this template, engineers can rapidly and consistently create models that meet the required technical specifications. Furthermore, significant importance is placed on documentation, capturing step-by-step procedures for the modeling process in meticulous detail. This comprehensive documentation serves as a valuable reference, guiding engineers through each stage of the modeling construction while ensuring adherence to established standards. Additionally, regular verification and validation exercises are conducted to confirm the accuracy and reliability of the modeling approach, thereby instilling confidence in the methodology.

Continuous improvement is a core principle at GM, and constant evaluation of the methodology is conducted to incorporate new techniques, tools, and industry best practices. This commitment to ongoing enhancement ensures that the modeling construction methodology remains at the forefront of technological advancements, allowing for the delivery of precise and consistent virtual simulations.

PROCEDURE OF CASE SELECTION

For the identification and selection of the most severe conditions, considered as worst-case, a systematic method is employed from the full simulation matrix involving different dummy percentiles and angle orientations. The goal is to identify combinations that result in the most severe conditions for each percentile dummy. For example, at least three worst cases are chosen, one for each percentile dummy.

During the analysis of results, metrics related to occupant safety, such as head impact criteria (HIC) and acceleration, are carefully evaluated for severity. The simulation results are then ranked based on the severity of these metrics. This ranking helps identify combinations with the highest potential risk or injury, considering predetermined threshold values or safety limits defined by regulatory requirements.

Any combinations that exceed these criteria are considered as potential worst-case scenarios.

Prioritization is crucial, considering available resources, time, and cost constraints. The combinations are further prioritized based on factors such as regulatory compliance, real-world relevance, and impact on occupant safety. The most critical worst-case scenarios receive higher priority for validation testing.

By following this method, the worst-case scenarios for validation testing are chosen based on identifying combinations that represent the most severe conditions for each percentile dummy. Physical validation testing of these scenarios provides assurance regarding the accuracy, reliability, and overall safety performance of the vehicle. The minimum dynamic gap between the head and the head impact zone is a significant factor considered in this study.

PROCEDURE FOR MODEL QUALITY ASSESSMENT

In order to ensure correct simulation results, it is essential to implement a model quality assessment template. This template is used as a model checklist to verify that all the necessary requirements are being fulfilled throughout the model construction and simulation process. By regularly using this tool, simulation engineers can confidently validate the accuracy and reliability following the methodology.

One crucial aspect of the model checklist template is the revision of input parameters. This includes reviewing the spatial discretization, ensuring an appropriate level of detail in the model, and validating the accuracy of material properties assigned to various components. Additionally, this template addresses the verification of boundary conditions to confirm they accurately represent the real-world operating conditions. It also verifies the correct implementation of contact definitions and friction coefficients between components. On the other hand the output revision section of the template focuses on validating the accuracy of the simulation results, comparing position and velocity to expected values and real-world behavior. The simulation time is also checked to confirm it falls within an acceptable range, providing a reasonable representation of the physical event. Furthermore, the energy balance is evaluated to ensure conservation of energy throughout the simulation process, verifying the overall fidelity of the results.

By systematically employing the quality assessment template, engineers can effectively review and assess the critical aspects of their simulations. Regular utilization of the template helps identify any potential errors or discrepancies early in the process, enabling timely corrections and ultimately leading to improved simulation outcomes. Overall, the quality assessment template is an indispensable tool within the methodology, since it provides a structured approach for evaluating input parameters and output results, certifying that all requirements are met and confident results are obtained. By incorporating such a template, organizations can enhance the reliability and credibility of their simulations while driving continuous improvement in their modeling practices.

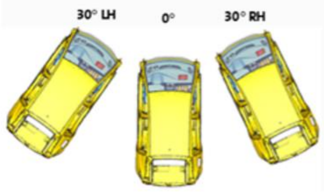
MODEL COMPARISON: VIRTUAL VS PHYSICAL

Using an example to conduct a comprehensive analysis, a small sedan car, has been selected as the subject vehicle for this study. Our aim is to compare and evaluate the behavior of the dummy occupants when subjected to the specific load conditions outlined in Annex 8 of Regulation UN R21.01. By focusing on this car model, we can gain valuable insights into the performance and safety aspects of this vehicle model under the prescribed test scenarios, contributing to a deeper understanding of its crashworthiness and potential areas for improvement.

The comparison of kinematic behavior and measurements of the head between test and simulation involves assessing the response of the driver and passenger dummies under different acceleration and directions, for this study: 0 degrees, +30 degrees, -30 degrees, in virtual simulations. First, the driver dummy is simulated considering the specified acceleration directions according to table 1 and presented the minimum gap between head and vehicle for 95% dummy in positive 30 degree and zero degree. The same assessment was simulated for passenger, where results can be seen at table 2.

Table 1: The minimum gap between head and vehicle for driver

Load case



Gap between head and vehicle

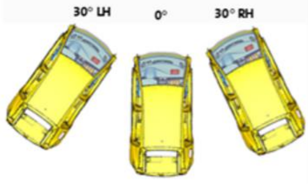
Dummy	Driver		
	Pos 30 º	0 º	Neg 30 º
5%	110 mm	161 mm	135 mm
50%	83 mm	54 mm	72 mm
95%	19mm	18 mm	51 mm

Source: General Motors

The simulation considers the dynamic behavior of the dummy and the surrounding environment, including the vehicle interior and its components. By applying the defined acceleration values, the output from simulation generates the kinematic data plot of the head of the dummy, catching its movement and interaction with the surrounding environment. Concurrently, physical tests are conducted using actual driver and passenger dummies only in the case that minimum gaps were identified by simulation. Through high-speed cameras, motion capture systems, the kinematic behavior of the head during the test is recorded and analyzed, as show at Figure 1 and 2, where passenger test versus simulation comparison at positive 30º load case.

Table 2: The minimum gap between head and vehicle for passenger

Load case



Gap between head and vehicle

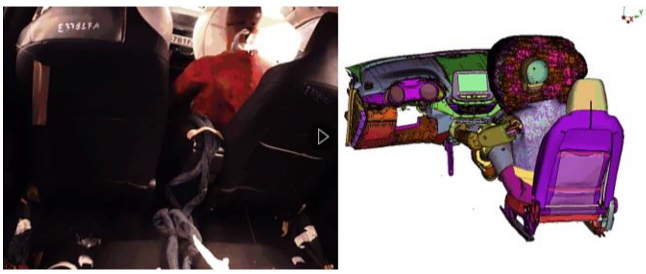
Dummy	Passenger		
	Pos 30 º	0 º	Neg 30 º
5%	170 mm	163 mm	146 mm
50%	160 mm	85 mm	109 mm
95%	113 mm	29 mm	76 mm

Source: General Motors

Figure 1 shows the comparison between physical test results and simulation data for the positive 30º simulation, specifically focusing on the interaction between the initial dummy position and the deployment of the airbag system. The figure allows a direct comparison with the corresponding test results, aiding to assess the accuracy and reliability of the simulation in capturing the dynamics and behavior of the dummy and airbag system during the positive 30º scenario.

Figure 2 shows the comparison for the positive 30º simulation involving the passenger, with a specific emphasis on evaluating the minimum gap between the passenger and the surrounding vehicle components. It is possible to observe how well the simulation replicates the real-world conditions and captures the concerned interactions. The minimum gap analysis is crucial for assessing the potential risk of occupant injury and validating the effectiveness of the vehicle's protective systems.

Figure 2: Test versus simulation comparison at positive 30º simulation for initial dummy and air bag interaction, t=95ms.



Source: General Motors

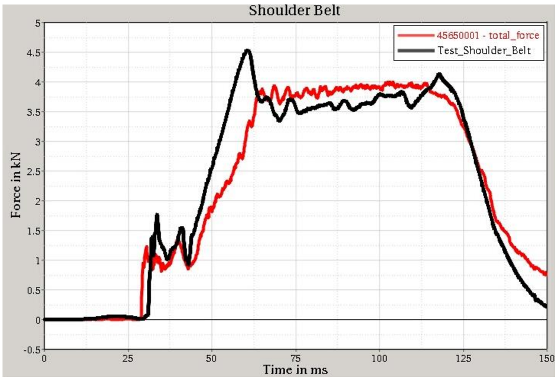
Figure 3: Test versus simulation comparison at positive 30º simulation passenger at minimum gap, t=135ms.

Source: General Motors

The comparison between test and simulation involves evaluating various parameters, such as head displacement, rotation, and contact with the vehicle's interior trims and components. Visualization techniques, such as overlaying the simulated and experimental head movements, can also help in the comparative assessment. However, the analyses should not be limited to visual aspects, but rather output variables of the numerical and physical tests.

For instance, the comparison of shoulder force reaction between the test and simulation results, shown at figure 4, and for head acceleration in the figure 5 revealed a strong model capability to reproduce the dynamic response in both scenarios. The measured shoulder force values obtained from the physical tests had a slope similar to the obtained numerically. This demonstrates that the simulation methodology is accurately predicting the biomechanical response of the occupants in various impact scenarios. To have a model with high capability to reproduce the physical test is crucial for assessing the effectiveness of safety measures, such as restraint systems, and evaluating the potential for injury to the shoulder region.

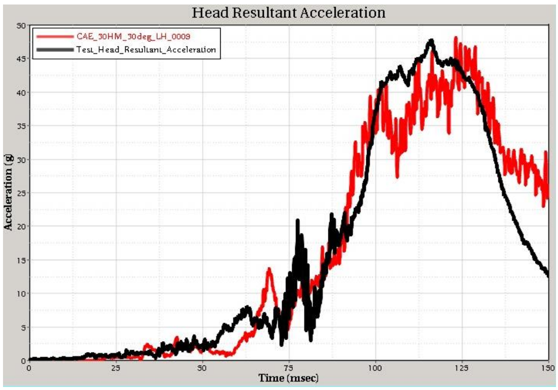
Figure 4: Test vs. simulation Shoulder force positive 30º simulation for passenger



Source: General Motors

By comparing the output from the physical tests and simulations, a comprehensive evaluation was performed. The comparison involved analyzing the trends, magnitudes, and consistency of the measured values for each parameter across different acceleration directions and dummy percentiles. This analysis allowed for an assessment of the simulation's accuracy and its ability to predict the dynamic behavior of the dummies in various impact scenarios.

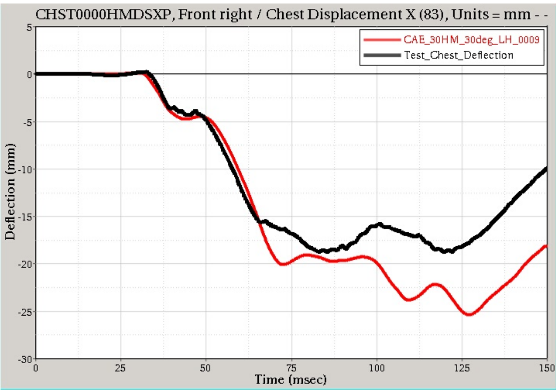
Figure 5: Test vs. simulation head acceleration positive 30º simulation for passenger.



Source: General Motors

Figure 6 shows chest displacement measurements and the comparison between physical test and simulation, black and red, respectively. The simulation results show a higher magnitude of chest displacement compared to the physical test. This deviation captured the worst-case scenario modeled in simulation. If simulation were a nominal case, further analysis and investigation would be required to identify the contributing factors contributing and refine the simulation model accordingly. It is crucial to understand the reasons behind chest displacement variations in the simulation to ensure accurate representation and assessment of occupant safety.

Figure 6: Chest displacement for +30º. Physical test vs. simulated worst case scenario (passenger).

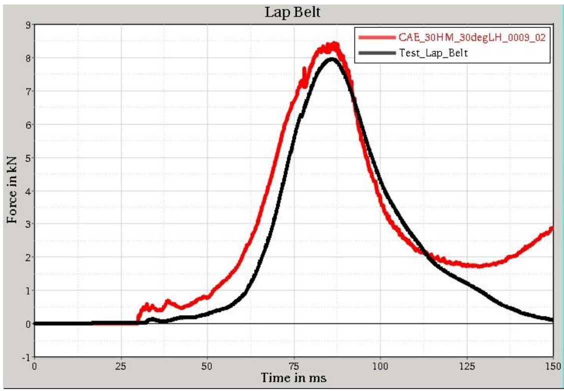


Source: General Motors

In contrast, Figure 7 illustrates the comparison of lap belt forces between the test and simulation. Remarkably, the lap belt forces recorded in both the test and simulation show a striking similarity, with the simulation results slightly higher than the test values. This close agreement suggests that the simulation model accurately captures the behavior and interaction of the lap belt with the occupant during the evaluated scenario. The slight discrepancy in the magnitude of the lap belt forces could be attributed to factors such as variations in belt material properties or differences in the modeling of belt geometry. Nevertheless, the overall agreement between the test and simulation for the lap belt forces demonstrates the effectiveness of the simulation in predicting and assessing the restraint system performance.

It is essential to understand the reasons behind the observed deviations by refining simulation model or check test conditions, setups and variations sources. In general, a physical test result can be considered a “snapshot” of system, that can variate on production. Indeed, a simulation model performed by CAE tool, has the capability to represent many “snapshots” on the system and can be used to represent nominal conditions and worst cases, considering, for example, materials and dimensional variations. Integrating those variations, GM seeks to reach a stable solution, with models that take the conservative side and are capable to evaluate the occupant safety and informing design improvements for different test scenarios.

Figure 7: Test vs. worst-case simulation lap belt force for +30º simulation (passenger).



Source: General Motors

MODEL CONTROL AND TRACEABILITY

The development and approval process of vehicle simulations for ECE R21.01 compliance requires addressing concerns regarding model control and traceability. Technical services play a crucial role in verifying compliance and ensure transparency and integrity in the simulation process. This section provides an overview of measures that can be implemented to address these concerns while fostering confidence in the simulation results.

To establish the traceability of model revision, comprehensive documentation should be provided, detailing the simulation model's development process. This includes the methodology used, assumptions made, input data sources, and any modifications or adaptations applied. Clear model documentation enables technical services to assure the quality of simulation and if the results are according with

Regulation requirements. Hence, the whole process can lead to the preparation of the validation report valid for the approval process.

Implementing a version control is essential for tracking changes to the simulation model over time. By maintaining a clear record of revisions, updates, and the rationale behind each change, it becomes easier to identify the approved version of the model. This ensures that any modifications made to the model can be traced and reviewed as necessary, demonstrating a commitment to transparency and control.

Verification of the model construction following the methodology and the validation of the results against physical test data are critical to ensure accuracy and reliability. By comparing simulation results with experimental data, technical services can assess the model's performance and its ability to predict real-world behavior. Documenting the validation process, including the test data used, comparison metrics, and outcomes, provides evidence of the model's fidelity and strengthens confidence in its results.

A robust quality assurance process should be implemented to ensure compliance with regulations and internal standards. Regular audits and checks should be conducted to verify adherence to the approved methodology and guidelines. This includes assessing spatial discretization, material properties, boundary conditions, contact criteria, and friction used in the simulations. Upholding strict quality assurance protocols ensures the accuracy and consistency of the simulation results.

Implementing robust data security measures is crucial to address concerns about unauthorized modifications or access to the simulation model. This involves controlling access, secure storage, backup systems, and monitoring for any unauthorized changes. By safeguarding the integrity and security of the simulation model data, the risk of manipulation or tampering is minimized, providing reassurance to technical services.

The generation of an unique serial number to each approved simulation model enhances traceability and control. This input and output model control uses cryptographic algorithms such hash functions or digital signatures that ensures the integrity and authenticity. The technical services can use a verification tool to verify that the models were not manipulated compared to other simulation runs.

APPROVAL DOCUMENTS

When it comes to the validation of the virtual method and the approval process using virtual results, manufacturers are required to prepare certain essential documents. These documents are crucial in demonstrating the reliability and accuracy of the results obtained by virtual testing.

These are the main steps for documentation creation:

1. *Description of methodology:* First part of this documentation delivered by the manufacturer is the description of simulation methodology. This document includes details such as the objectives of the validation, the scope of the validation study, the specific test cases to be conducted, and the acceptance criteria for determining the validity of the method. This includes information about the geometry, material properties, and boundary conditions incorporated into the model. The model description should also specify any simplifications or assumptions made during the modeling process.
2. *Validation of the methodology:* The simulation tool used by the manufacturer shall be previously validated by the technical service. The methodology document shall contain the evidence of a correct result comparability between the virtual test and physical test. The evidence will be based on the quality of the virtual model which has followed the methodology and the raw data obtained from physical test.
3. *Validation of the model to be approved:* Once the manufacturer has validated the simulation tool, then it is possible to deliver results performed by virtual test valid for the type approval of the vehicle. In this case the manufacturer shall be sure that the model to be approved is following the same methodology already validated.
4. *Documentation system for model traceability:* To address concerns about model traceability, the manufacturer should establish a comprehensive documentation system. This system tracks any change applied to the simulation model, including updates, modifications, or refinements. It ensures that the model's evolution can be traced back, allowing for transparency and control over the original model.

By preparing these essential documents, the manufacturer and the technical service can have the necessary evidence to support the validation of their virtual testing method and the approval of the vehicle model. These documents demonstrate the thoroughness and reliability of the virtual approach, providing confidence in approval authorities and technical services supervising the approval.

CONCLUDING REMARKS

The aim of this study was to evaluate the behavior of dummy occupants in a small sedan car under specific load conditions requested by Annex 8 of Regulation UN R21.01. The comparison between the test and simulation results was focused on assessing the kinematic behavior and measurements of the head, shoulder belt, and lap belt for different dummy percentiles and acceleration directions. After performing several simulations, a matrix showing all results was necessary to select a worst case. As shown in table 1, one different dummy percentile was selected, each one representing a different acceleration orientation. Then, these 3 candidates were compared with specific physical tests by the analysis of differences in distance and acceleration.

Figures 2 and 3 showcased the interactions between the dummy occupants, airbags, and vehicle components during the positive 30º simulation scenario. These visual comparisons demonstrated the simulation's accuracy and reliability in capturing the dynamics and behavior of the occupants in real-world conditions.

Figures 4 and 5 indicated the comparison of shoulder belt and head acceleration between the test and simulation results, revealing the simulation's ability to accurately predict the biomechanical response of the occupants. It also confirmed the effectiveness of the simulation methodology in evaluating safety measures and assessing the potential for injury.

Moreover, Figure 6 highlighted a disparity in the chest displacement measurements obtained from the test and simulation data, reflecting the worst-case scenario of input parameters. To improve the simulation's accuracy in representing occupant safety, further analysis and refinement of the simulation model are always required to identify the factors contributing to eventual discrepancies.

On the other hand, Figure 7 demonstrated a close agreement between the test and simulation results for lap belt forces, with the simulation values slightly higher than the test values. This agreement indicated an accurate representation of the lap belt's behavior and its interaction with the occupants, highlighting the simulation's effectiveness in predicting and assessing the performance of the restraint system.

To enhance the reliability of the simulation methodology, it is crucial to investigate the reasons behind the observed discrepancies in chest displacement and refine the simulation model accordingly. By addressing these differences, the simulation methodology can become an even more valuable tool for evaluating occupant safety, guiding design improvements, and optimizing restraint systems for various crash scenarios.

In summary, the comparison between the test and simulation data provided valuable insights into the behavior and interactions of dummy occupants in that Chevrolet small sedan. This study contributes to a deeper understanding of crashworthiness and identifies potential areas for improvement. The findings can aid in the development of safer vehicles, advancement of vehicle safety standards and to follow regulation requirements.

REFERENCE

[1] Regulation (EU) 2018/858 of the European Parliament and of the Council of 30 May 2018 on the approval and market surveillance of motor vehicles and their trailers, and of systems, components and separate technical units intended for such vehicles, amending Regulations (EC) No 715/2007 and (EC) No 595/2009.

[2] G.F. Wallace et al., Structural optimization of automotive components applied to durability problems, SAE 2003-01-3547

[3] Khanna, S., "Improving Vehicle Performance in Offset Deformable Barrier Crash as per ECE R94 via Computer Aided Engineering," SAE Technical Paper 2009-01-0351, 2009, https://doi.org/10.4271/2009-01-0351.

[4] Regulation No 21 of the Economic Commission for Europe of the United Nations (UN/ECE) Uniform provisions concerning the approval of vehicles with regard to their interior fittings.

[5] The vehicle frontal impact safety evaluation and design method based on the coupling effect between crash pulse and restraint system characteristic J. Zhang, D. Wang, Y. Jim, L. Wu, H Zhou. International Journal of Vehicle Design 2018, inderscienceonline.com, https://doi.org/10.1504/IJVD.2018.100097

[6] Cordero, R., García, J., EU project, Implementation of virtual testing in safety regulations, IMVITER. Document D2.1.

[7] Laso, M. Beaugonin, Muriel. Lancashire, R. D'Addetta,GA. Mayer, C. Klein, C. EU Project, OSCCAR Deliverable D4.1 "Virtual environment check tool and documentation".