

EURO NCAP VIRTUAL TESTING - CRASHWORTHINESS

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ABSTRACT

The European New Car Assessment Programme (Euro NCAP) began using numerical simulations in its vehicle ratings in 2009. Virtual testing with human body models was first used in the assessment of vehicles equipped with deployable pedestrian protection systems. In 2019, Euro NCAP created the Virtual Testing Crashworthiness (VTC) working group. This working group is supported by Euro NCAP, Euro NCAP's members along with industry representatives from both the European Automobile Manufacturers Association (ACEA) and the European Association of Automotive Suppliers (CLEPA). The far side occupant assessment was selected as the first load case for this work. The objective of this paper is to introduce the procedures defined by the Virtual Testing Crashworthiness working group and present the results generated within the two pilot test series.

In addition to the standard load cases defined in the current far side assessment protocols, robustness load cases were defined with varying impact angles and seat heights. Simulations of the specified load cases were performed by the car manufacturers with their internally developed and validated vehicle models. Two series of physical far side sled tests were performed in accordance with the Euro NCAP Far side occupant sled test procedure with the corresponding vehicles. These test series were used to evaluate the validity of the vehicle models and the capabilities of the simulation models to predict the trends observed within the tests. Processes and acceptance criteria were established to ensure that the simulation models are as representative as possible of their physical counterparts while protecting the intellectual property of the car manufacturers and suppliers. The validated vehicle models are used in a series of robustness simulations.

The physical sled test results from the pilot phase showed reasonable test scatters, even when using two different WorldSID dummies, and were shown to be a suitable test result to be used for validation of the vehicle models. The developed procedure was applicable within the pilot tests. The ISO Scores, used as objective validation metrics, were comparable between standard and the new robustness load cases, indicating that the procedure and the model used were robust. Further room for improvement of the assessment procedure was identified, specifically regarding the acceptance criteria of signals with low amplitudes.

The current study outlines the procedures for introducing virtual testing of occupant safety into consumer information. When viewing vehicle safety ratings from a consumer perspective, it is acknowledged that computer simulations cannot completely replace physical testing. However, a combination of physical and virtual testing offers a powerful and flexible assessment of vehicle safety. The robustness load cases will be assessed in the future based on the virtual tests only and complement the existing far side occupant assessment in the final vehicle rating.

INTRODUCTION

Automotive design engineers have been using advanced computational models for many years to study and optimize crash performance over a vehicle and its components with minimum crash testing. While computer-aided engineering (CAE) has become increasingly more popular and sophisticated in the industry, its use in regulations and consumer protection is still uncommon. The European New Car Assessment Programme (Euro NCAP) began using numerical simulations in its 2009 vehicle ratings for pedestrian protection. Human Body Models (HBM) were first used to assess vehicles equipped with deployable pedestrian protection systems, and this was where the first certification procedure for virtual human models was developed [1]. Building upon this work, Euro NCAP created the Virtual Testing Crashworthiness (VTC) working group in 2019 and tasked it with developing a virtual test and assessment procedure for application in other impact scenarios for future Euro NCAP ratings.

Virtual testing is a way to add broader scope and robustness to the existing Euro NCAP assessments without increasing the physical test burden. Where limitations in physical test equipment or physical test scenarios exist, virtual testing offers a way of providing a more comprehensive and real-world-like assessment to complement the existing test procedures.

The work of the VTC group began by considering a number of different crash scenarios that could be applied in a virtual environment. To limit complexity, full scale impacts were not considered. Although subsystem tests are more complicated to model than the current pedestrian impact tests, they are not as difficult as full-scale tests. The Euro NCAP Far side occupant assessment was selected as the pilot case for this work. The relevance of far side accidents for injuries of vehicle occupants is well known [2–4], and culminated in the introduction of far side protection into the Euro NCAP ratings in 2020 [5].

The current Euro NCAP assessment of far side occupant protection has identified limitations of the WorldSID 50th percentile male dummy in this specific impact configuration [6–8]. To overcome these hardware issues and to have a more robust evaluation that considers a greater variety in the evaluated test scenarios, this load case was deemed a suitable candidate for application to virtual testing.

This paper introduces the procedures defined by the working group and presents the results generated within the two physical pilot testing phases conducted by the group. A comparison of the CAE and physical tests is presented within this paper along with prerequisites for the CAE models, including dummy model certification requirements.

METHOD

For a consumer rating programme, it is essential that Euro NCAP has confidence in the models being evaluated to ensure that simulation outputs are trustworthy, robust and can be applied practically to the different assessments.

Based on previous research [1, 9, 10] and discussions with different stakeholders, the following procedure was defined, which is shown graphically in Figure 1:

- 1.) To gain trust in the used WorldSID simulation model, the models must meet certain qualification requirements for virtual testing. Criteria are defined at three different levels, starting with fulfilling the current ISO 15830 standard in terms of mass properties, external dimensions, range of motion, sensor locations and dynamic qualification procedures. Secondly, the kinematic behaviour of the lumbar spine and neck is checked (as limitations in the current WSID certification for these regions were identified) and compared to hardware tests. On the third level, the full-scale dummy response is validated by means of sled tests on a simplified seat. [11]
- 2.) Simulations of the predefined simulation matrix consisting of two far side validation load cases and additional virtual testing load cases are performed by the vehicle manufacturer (VM) with their in-house calibrated virtual vehicle models and the qualified WorldSID model. The results are shared with Euro NCAP in a prescribed format via a specific upload portal. The datasets have to include all specified information and to fulfil the specified quality criteria.
- 3.) After step 2 is completed, physical sled tests of the two validation load cases are performed, and test results are submitted to Euro NCAP.
- 4.) Euro NCAP compares the hardware sled test results and simulation-based predictions with each other to validate the VM's virtual model of the vehicle environment (including seat, seatbelt, airbag, centre console). By this means Euro NCAP can establish the necessary trust in the VM model, without physically requiring access to the model.

- 5.) If the validation results of step 4 are sufficient, i.e. hardware and simulation results closely match, this step (5) can be skipped. If the validation results are not sufficient, the VM must provide evidence showing this was caused by the specific hardware test conditions, deviating from simulation parameters. The simulations of the two standard validation load cases may be repeated with adjustments to prescribed boundary conditions from the sled tests. The boundary conditions are limited to initial positions (node coordinates of dummy, seat and belt) as well as adaptations to the measured crash pulse. The repeated simulations for these validation load cases are again shared with Euro NCAP. If validation criteria are still not fulfilled, the results submitted in step 2 are not considered for the assessment, otherwise step 6 follows.
- 6.) The results from the virtual testing load cases submitted in step 2 are considered for the vehicle rating.

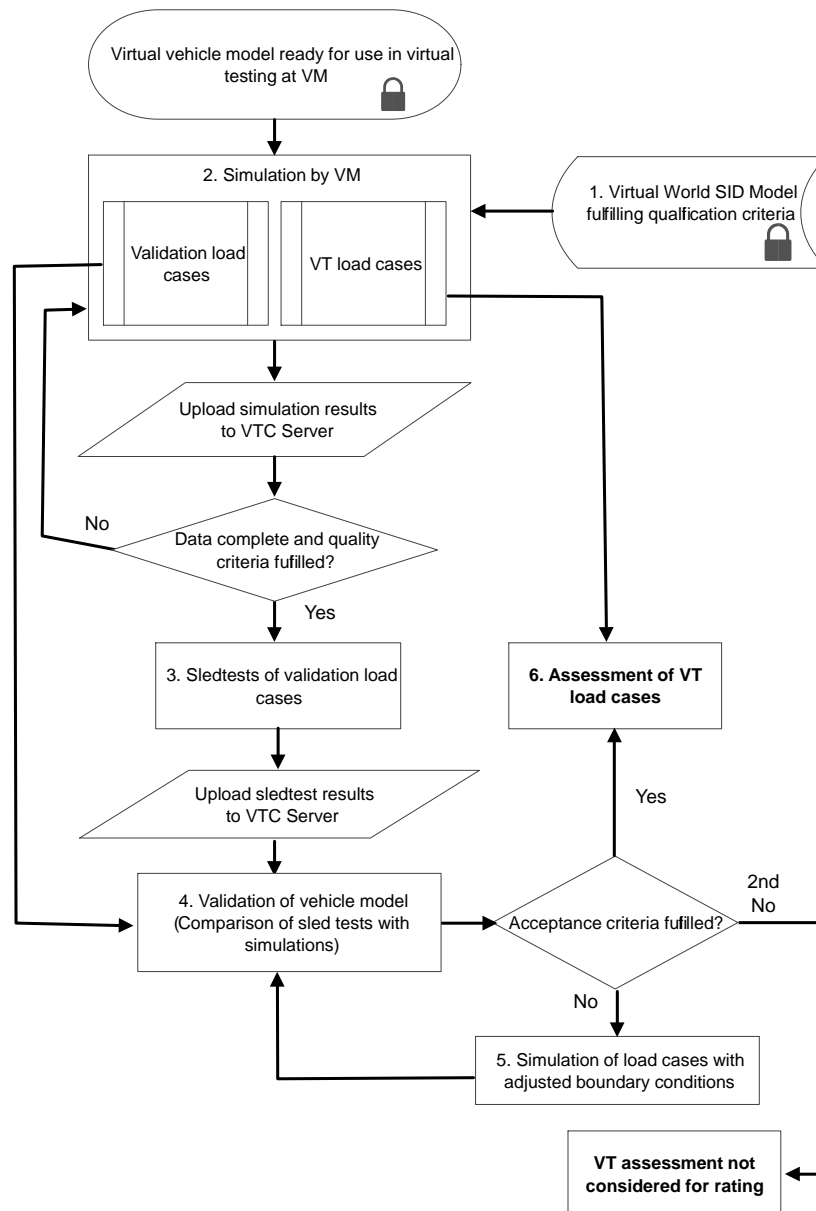


Figure 1: Overview of the developed virtual testing procedure

The procedure was applied in two pilot test phases with different complexity (one with and one without centre airbag) from two different car manufacturers. Additional validation tests were performed within the pilots, to analyse the performance of the simulation models outside of the standard validation load cases.

Simulation setups

The vehicle models are calibrated in advance and VMs must have confidence that the model is ready to predict occupant responses in far side test cases. No modifications of the vehicle models are allowed during the virtual testing procedure. All material models and settings are kept constant apart from boundary conditions, such as the

initial position of the seat, initial seat deformation, belt routing and load curves describing the sled acceleration, especially in the last step of the procedure where simulations are rerun after the tests.

The qualified WorldSID model was positioned in the calibrated vehicle environment in line with the Euro NCAP Far side testing protocol [12]. The Dummy model was settled in the seat, so that no in-physical spring-back occurs at the simulation start and realistic contact forces are present (initial displacement of H-Point in z-direction should be <10mm in first 5 ms).

The following quality criteria were defined for the simulations:

- Max. Hourglass Energy of full setup < 10% of max. internal energy.
- Max. Hourglass Energy of all WorldSID components < 10% of max. internal energy of WorldSID.
- Max. mass added due to mass scaling to the total model is less than 5 % of the total model mass at the beginning of the run.
- Less than 10 mm H-point z-disp. in first 5 ms of the simulation (5 ms after t0).
- Simulation time needs to exceed time of maximum head y-displacement*1.2.

Load cases

Load cases were defined based on the analysis of real-world crashes within the range of useful application possibility of the WorldSID. To assess the robustness of the far side occupant protection, the vertical seat position and the impact angle were varied. The overall matrix is summarised in Table 1. Load case 1 and 2 are part of the current far side assessment and supposed to be used as validation load cases in future assessments. Within the two pilots, additional sledtests were performed to investigate the validity of the simulation models within a wider range of scenarios. Those are supposed to be assessed in future assessments virtually only to prove that the occupant protection works robustly.

Table 1: Load case matrix describing the robustness load cases, validation load cases and additional validation load cases simulated / tested within the two pilots

	Pulse	Impact Angle	Seat position x (fore/aft)	Seat position z (height)	Test-data Pilot 1	Test-data Pilot 2	Validation load case
1.	Pole	75	reference	reference	x	x	x
2.	AEMDB	75	reference	reference	x	x	x
3.	Pole	60	reference	reference	x	x	
4.	Pole	60	reference	uppermost	x	x	
5.	Pole	65	reference	reference	x		
6.	Pole	75	reference	uppermost	x	x	
7.	Pole	90	reference	reference	x	x	
8.	Pole	90	reference	uppermost			
9.	AEMDB	60	reference	reference	x	x	
10.	AEMDB	60	reference	uppermost			
11.	AEMDB	75	reference	uppermost			
12.	AEMDB	90	reference	reference	x	x	
13.	AEMDB	90	reference	uppermost			

Airbag deployment times and pre-tensioner settings were consistent between simulations and tests and fulfilled the criteria defined in the far side testing protocol for both pulses.

In the analysis of results of this paper, we focus on the load cases where test data is available for both pilots to enable comparison. Simulation results were available for the remaining load cases.

Laboratory tests

Sled tests were performed of the load cases highlighted in Table 1 in accordance with Euro NCAP far side protocol [12] The WorldSID was positioned in the vehicle as close as possible to the simulation specifications provided from the vehicle manufacturer.

Data processing

For the head excursion evaluation, the lateral displacement (global y-direction) of the head CoG is considered. To assume the outside are of the head, which should be compared to the vertical lines, 80 mm distance from the head

CoG to the outer surface of the head are assumed, which corresponds to half of the distance between the two head targets in lateral (y) direction of the Wold SID. All injury criteria are calculated according to Euro NCAP Technical Bulletin 021.

ISO Scores were calculated according to ISO/TS 18571 standard [13] including the latest corrections of the standard, with a python library developed by TU Graz, which is available open-source (<https://openvt.eu/validation-metrics/ISO18571>).

To summarise ISO Scores of multiple axis to one sensor score, the individual scores were weighted per axis based on its amplitude according to

Equation 1:

$$Score_{Sensor} = \frac{\max(|Sensor_x|) \cdot ISO_{Sensor_x} + \max(|Sensor_y|) \cdot ISO_{Sensor_y} + \max(|Sensor_z|) \cdot ISO_{Sensor_z}}{\max(|Sensor_x|) + \max(|Sensor_y|) + \max(|Sensor_z|)}$$

whereby the maximum channel values $\max(|Sensor_i|)$ are based on the testing signals, as they are seen as “ground truth”.

Data is processed on a Euro NCAP hosted VTC server, where processing is performed directly after the data upload and simulation and testing results are automatically merged and all quality and acceptance criteria are checked.

RESULTS

Repeatability of results

The pole reference load case (75° and seat in reference position) was tested in both pilots three times, whereby one test was repeated and in one, a different dummy was used. The differences in resulting injury metrics are shown in Figure 2 and Figure 3 and compared to the prediction from the simulation. Highest differences within the tests were observed upper neck moments in both pilots. In Pilot 1, remarkable differences were also observed for the lower neck moments, where the highest deviations between simulation-based predictions and test results were observed. In Pilot 2, the lumbar spine y force and x moment also showed higher deviations than the other metrics. Head excursions were in both pilots the most critical injury metric (highest percentage of lower performance threshold) and showed only small test scatter (difference <2%).

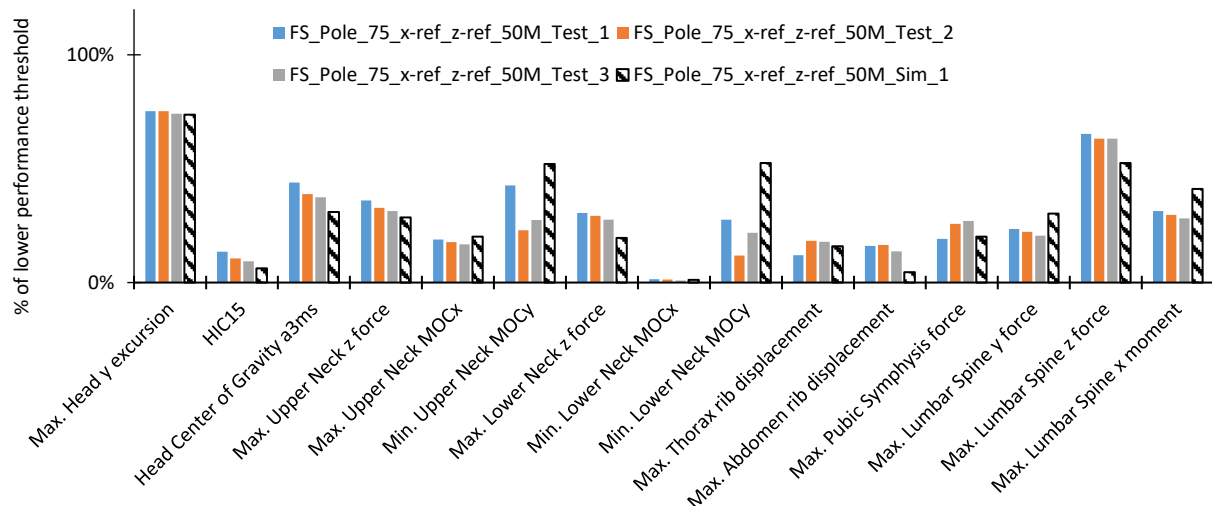


Figure 2: Injury criteria deviation between repeated tests with the same and different dummy in Pilot 1

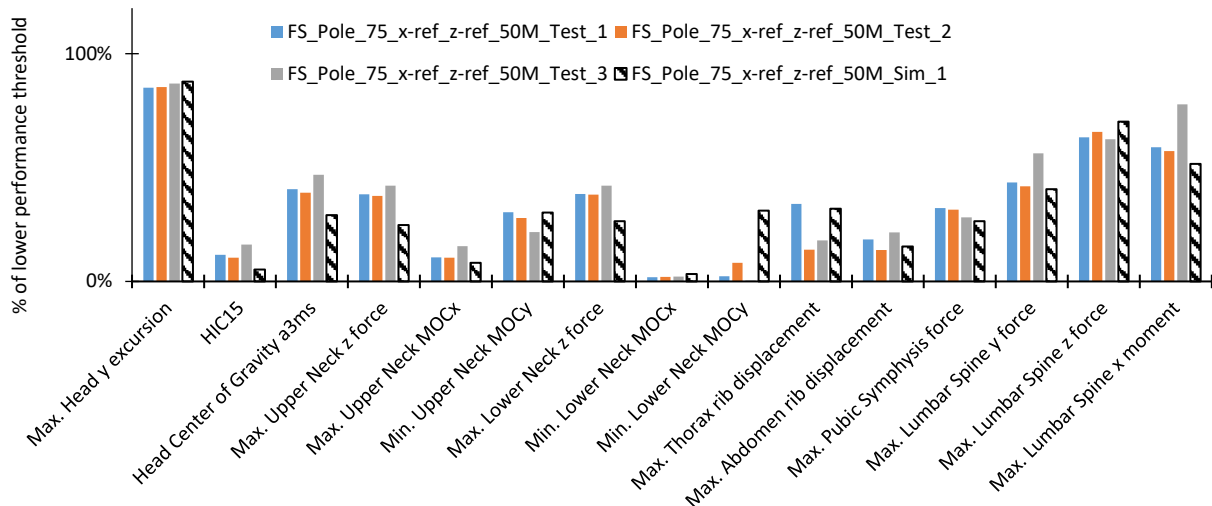


Figure 3: Injury criteria deviation between repeated tests with the same and different dummy in Pilot 2

The amplitude weighted ISO Scores per sensor ($Score_{sensor}$) for the two pilots are shown in Figure 4 and Figure 5, where the signals from the simulation of the load case were compared to the three repeated tests respectively. The use of a different dummies caused differences in ISO Scores. However, when comparing the different sensors with each other, the trends of which sensors showed the highest / lowest scores were the same among the three different tests. Highest differences in ISO Scores between the three tests were observed for the rib deflections.

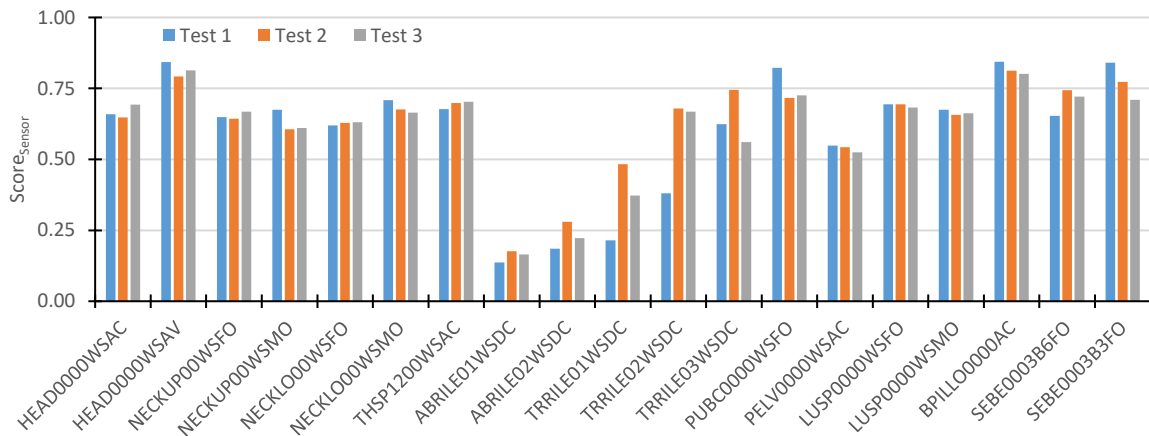


Figure 4: Sensor scores for pole 75 degree load case in Pilot 1 for the 3 different repeated tests (test 3 was performed with a different dummy; test 1 was included in the later comparisons)

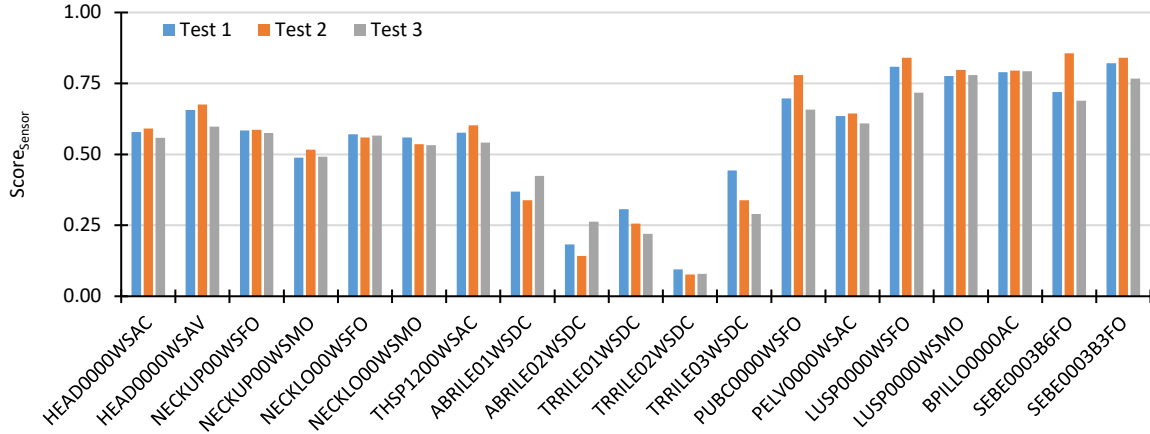


Figure 5: Sensor scores for pole 75 degree load case in Pilot 2 for the 3 different repeated tests (tests 1 and 2 were performed with a different dummy; test 3 was included in the later comparisons)

Validation results over different use cases

The $Score_{Sensor}$ values of the robustness load cases (tested only within the pilot phase) were in general similar to those of the standard validation load cases with only single outliers for isolated channels (especially rib deflections). The $Score_{Sensor}$ for the load cases with uppermost seat positions were lower compared to the standard seat position.

In both pilots, lowest $Score_{Sensor}$ values were observed for the rib deflections.

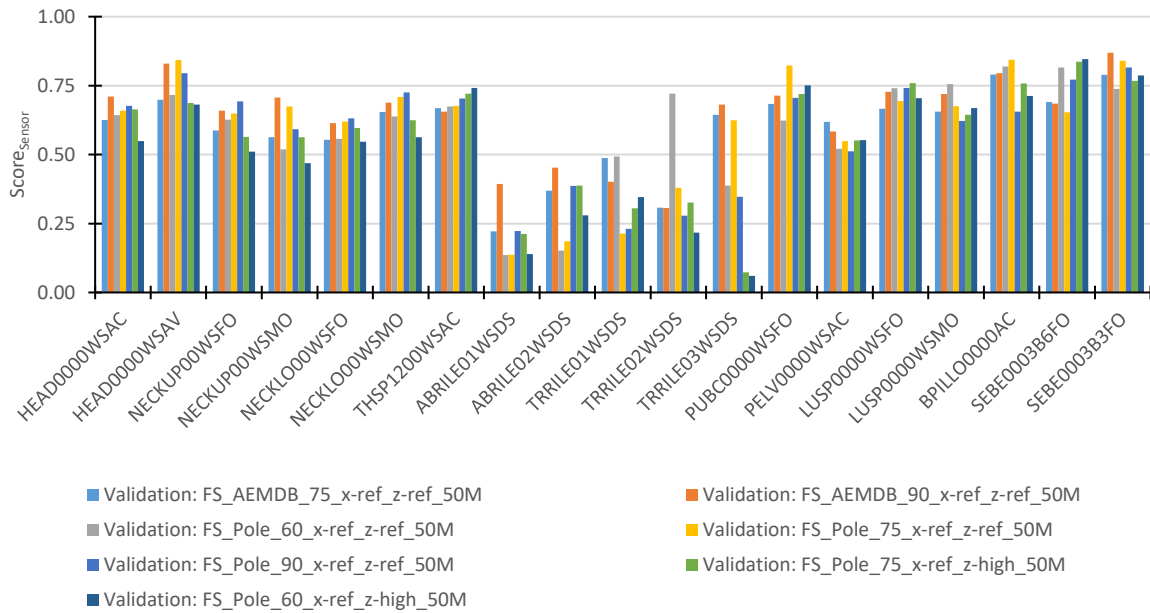


Figure 6 Sensor scores for the different channels and load cases from Pilot 1

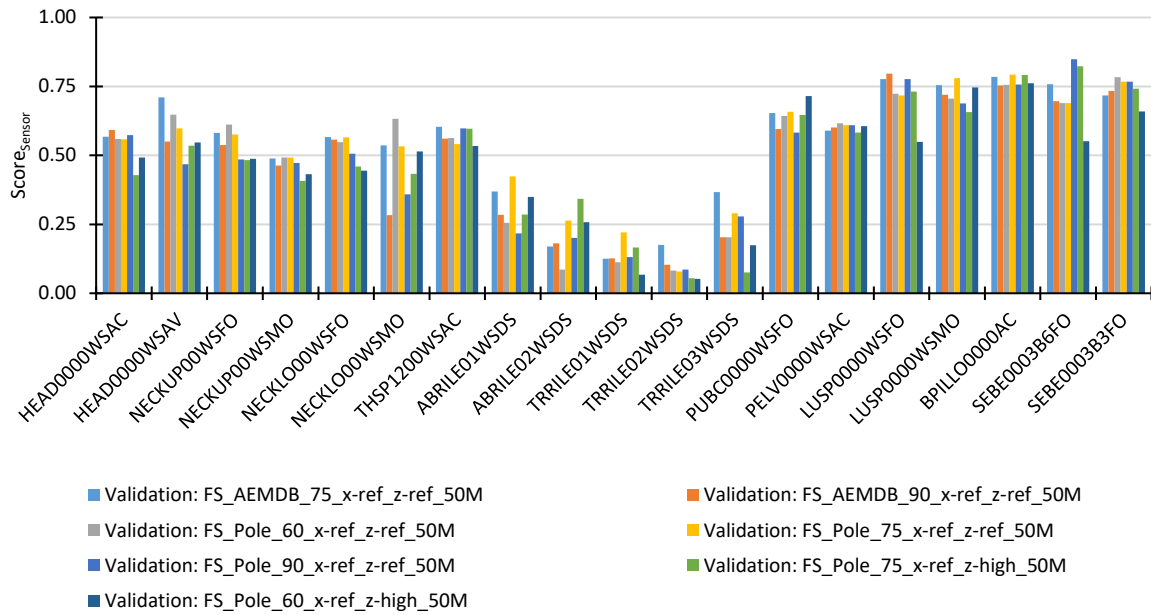


Figure 7: Sensor scores for the different channels and load cases from Pilot 2

As a metric to validate the overall kinematics, the weighted sensor scores of the accelerometers of the head CoG, T12 and the pelvis were averaged for each load case. These averaged acceleration scores (mean_acc) are summarised in Table 2. They were higher than 0.58 (fair according to ISO standard [14]) in all cases in the first pilot. In the second pilot, values of the averaged acceleration scores below 0.58 were observed for the load cases with uppermost seat position, in which significant deviations between simulations and tests were also observed in the qualitative comparison of videos and animations as well as the standard pole 75 degree impact when compared to Test 3 (values >0.6 were observed for the other 2 tests for this load case).

Table 2: Mean Score_{sensor} from head, T12 and pelvis accelerometer for all load cases in two different pilots

Pulse	AEMDB	AEMDB	Pole	Pole	Pole	Pole	Pole
Angle	75	90	60	75	90	75	60
Z-position	reference	reference	reference	reference	reference	uppermost	uppermost
Mean acc Score Pilot 1	0.64	0.65	0.61	0.63	0.63	0.65	0.61
Mean acc Score Pilot 2	0.59	0.58	0.58	0.57	0.59	0.54	0.54

Due to the higher complexity of the second pilot, the ISO Scores were lower compared to the first pilot, which can be seen also in Figure 8, where the ISO Scores per sensor for the two standard load cases of the two pilots are compared.

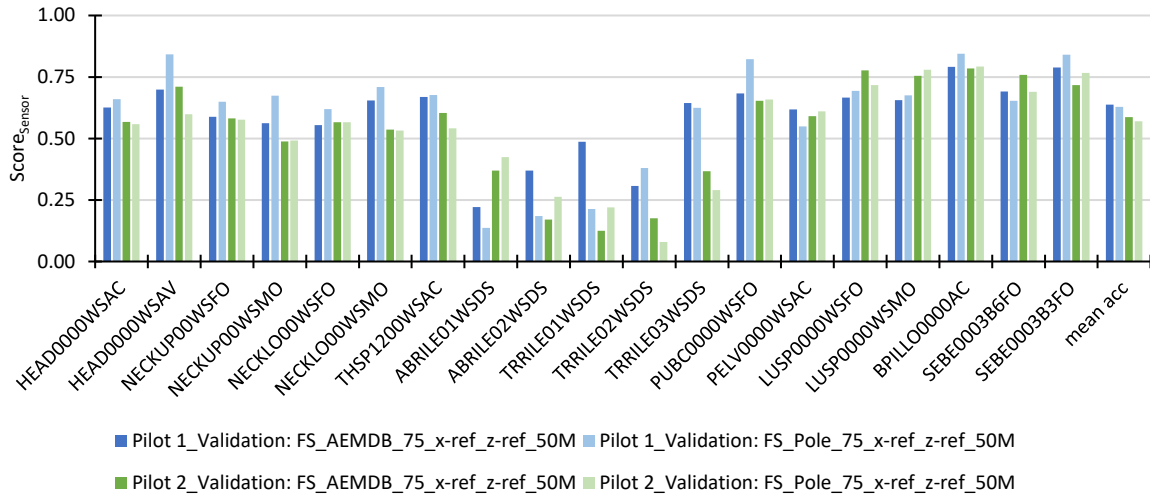


Figure 8: ISO scores for the different channels and load cases from Pilot 1 & 2 for the load cases which are going to be used for validation of the vehicle models in the final procedure

Assessment results over different load cases

The cars analysed in the pilot phase were shown to protect the occupants robustly over a wide range of loading scenarios, which is shown in Figure 9 and Figure 10 for both pilots and for simulation-based predictions (transparent) as well as the performed sled tests. Rib displacements were very low over all load cases as well as HIC and the neck x moments. None of the lower performance thresholds was exceeded in the analysed load cases within the tests. Higher head excursions (within the orange zone for the simulations) were observed in the second pilot for the load cases with higher seat position, whereby the simulations were more sensitive to that change than the tests. The load case with the highest head excursion was the 75° Pole impact from the second pilot in the uppermost seat position, which was true for simulations and tests. No such sensitivity on the seat height adjustment was observed in the first pilot.

Deviations between predicted injury metrics from simulations and the laboratory tests were highest for the neck moments MOCy in both pilots. In the first pilot, these deviations were observed for the upper and lower neck, while they were only prominent for the lower neck in the second pilot.

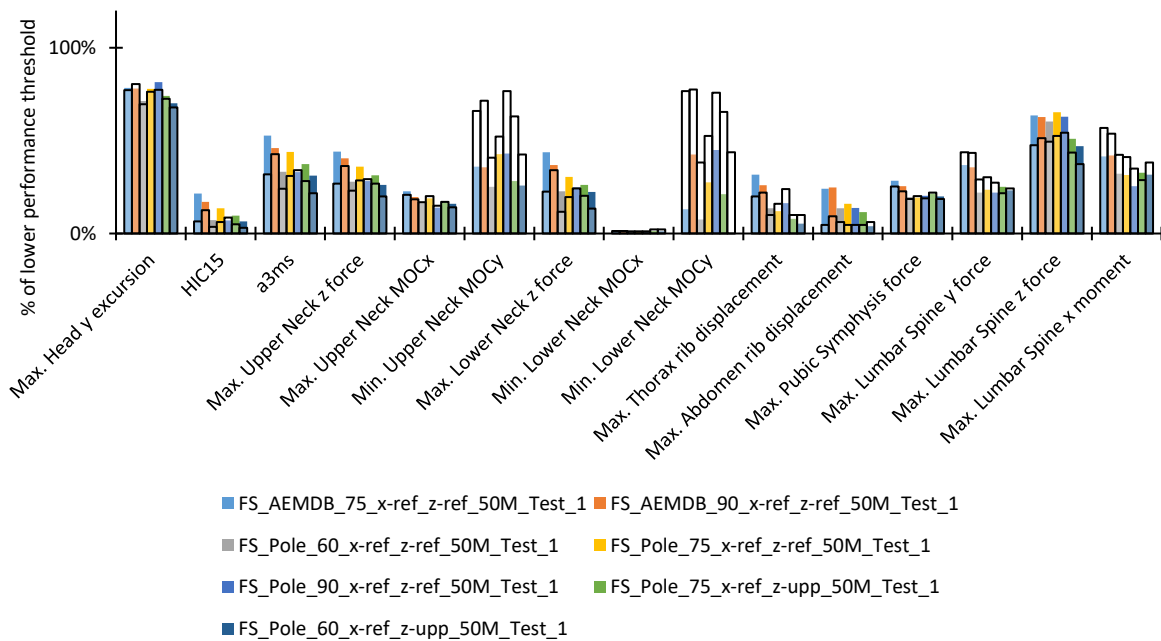


Figure 9: Injury criteria for the different load cases relative to threshold for Pilot 1 from tests (coloured bars) and simulations (white transparent bars with black frame)

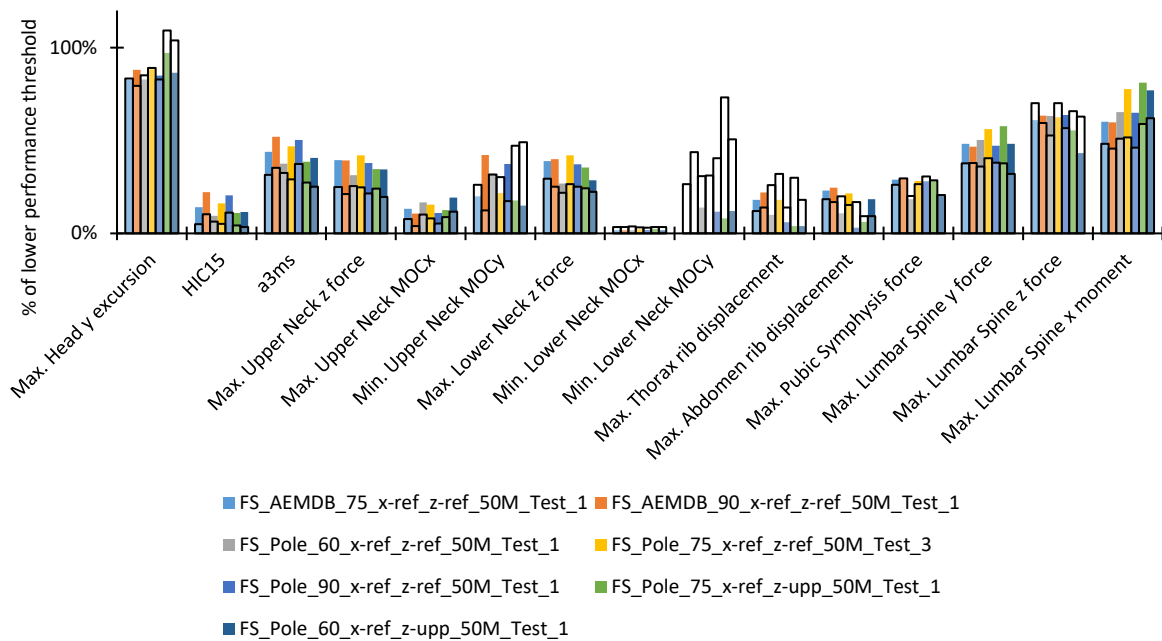


Figure 10: Injury criteria for the different load cases relative to threshold for Pilot 2 from tests (coloured bars) and simulations (white transparent bars with black frame)

DISCUSSION

Euro NCAP has developed the first procedure for virtual testing of occupant safety that can be used in a standardised consumer information testing protocol. The procedure was applied in two pilot phases and a protocol and related tools have also been drafted. The current procedure focuses on robustness of occupant protection systems and utilises virtual models of WorldSID as occupant

Model validation

Throughout the development of the procedure, the definition of appropriate acceptance criteria and the levels that those criteria must meet were the most challenging aspects to establish. It is these criteria that will determine if a CAE model represents the physical tests sufficiently and can be used for virtual testing. It therefore underpins the confidence that exists in the model for the further assessments and load cases to be evaluated.

While simulations may offer greater repeatability and reproducibility over physical testing, one cannot expect simulation results to be closer to test results than the individual test results are to each other. Therefore, when defining acceptance criteria, scatter from physical testing has to be considered when defining how strictly they should be defined for different sensors.

Another component of this includes the results from the WorldSID model qualification procedure, as these demonstrate the predictive capabilities of the WorldSID model itself. One particularly problematic area is the WorldSID lumbar spine. This is not certified at a component level in hardware testing and the loading it receives in a far side impact results in kinematics that are not representative of what would be seen in the full dummy thorax certification test. To address this challenge, a new component test setup was introduced in the WorldSID qualification level two requirements [11].

In addition, limitations of the WorldSID dummy on the prediction of rib fractures in far side crashes are known from previous studies. The dummy rib loadings were well below the rib higher performance limits, with the result that comparisons of low values (in terms of % difference) between hardware and CAE can be unreliable and might also be the reason for the low ISO Scores for these channels.

Acceptance criteria have been adopted to reflect the importance of the measure and the reliability of the anticipated values.

A multi-stage approach was drafted for this purpose:

1. Plausibility check: The ISO Score for each individual sensor of the specified list is calculated. The checking of all signals with an ISO Score <0.5 for plausibility (check e.g. for polarity and unit errors) is highly recommended.
2. Sensor check: The single ISO Scores are summarised to $Score_{\text{Sensor}}$ according to equation 1 and are only checked if they are critical for the overall interaction (seatbelt forces, B-pillar acceleration, dummy accelerations and head rotational velocity). Other signals are added when they exceed a relevant amplitude.

3. Kinematics check: The averaged Score_{Sensor} of the head, T12 and pelvis accelerometer is calculated and checked.
4. Injury criteria check: deviation between test and simulation are checked and compared to the lower performance threshold.

The thresholds for each step and the “relevant amplitude” for step 3 are currently still in discussion and will be further refined during the monitoring phase. Within the monitoring phase it is also planned that other settings than the ones specified in step 5 of the process shown in Figure 1 can be adjusted if justified and documented as additional set of results.

Limitations

In the current VTC procedure, every load case that was simulated could be also tested in a laboratory. This has the advantage that validation tests could be performed in the event of any doubts concerning the accuracy of the prediction. At a later stage, when human body models are used as occupant models instead of virtual dummy models, this validation will not be possible. Therefore, the quality and traceability of simulation models used in the different steps will play an essential role [15], which was not considered in the current study.

The developed procedures have currently, only been applied to two different vehicles, whereby only one of these had a centre airbag. Further data will be collected in the course of a monitoring phase to fine-tune the developed procedure and especially acceptance criteria if needed. Also, the load cases only represent relatively small variations (impact angle, seating height) of the official sled test configuration. With more experience, larger variations, such as replacing mid-sized male percentile WorldSID with a small female WorldSID model could be considered.

It was identified that significant deviations between simulations and tests were observed for the rib displacements. This might be caused by the low displacements measured. In the dummy certifications, minimum rib displacements are 35 mm, while rib displacements in the pilots were mostly in the range of 10 mm. The WorldSID dummy was originally designed for near-side and the limited sensitivity for capturing rib loadings in far side scenarios has been observed in previous studies [6–8].

Outlook

When viewing vehicle safety ratings from a consumer’s perspective, it is acknowledged that computer simulations cannot completely replace physical testing. However, a combination of physical and virtual testing offers a powerful and flexible assessment of vehicle safety. This also allows for advancements that are not open to evaluation by physical testing.

In the first phase of work, the virtual WorldSID model was used for the representations of the car occupants. In future, virtual testing with human body models will also be considered for addressing diversity and enhanced injury prediction capabilities.

The developed procedure for virtual testing with WorldSID models to improve the robustness of the assessments, will be applied for monitoring from 2024 onwards in the Euro NCAP far side assessment and will be fully in force from 2026 onwards.

All that has been learned from this load case will be transferred to other load cases. As indicated in the Euro NCAP 2030 roadmap [16], virtual testing is intended to be also implemented for frontal and whiplash protection assessments with a special focus on the diversity of the vehicle occupants.

CONCLUSIONS

A procedure was developed to enable virtual assessment of occupant safety to improve the evaluation robustness by considering different loading conditions and seat adjustments. It was observed that the validity of the vehicle models was good and comparable among the different load cases considered. The definition of a pass/fail validation criterion proved to be challenging, which is why a multi-step approach was developed. It was observed that the magnitude of signals plays an essential role and that it is challenging for simulations to predict low amplitudes outside of the design range and for sensors in which higher test scatters were also observed.

The presented procedure is an important first step, pathing the way for future applications of virtual testing to further progress towards real-world safety assessment.

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