Facilitating Virtual Testing at an Industrial Level with Simulation Data Management

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1 Introduction

From an industrial or productive standpoint, the scale of simulation models, the number of involved simulation model components, and the complexity of the utilized processes with a vast amount of data are at a level that is challenging to manage manually. The introduction of virtual testing adds to the complexity of the development process and the quantity of data to be handled. Consequently, the use of a Simulation Data Management (SDM) system for this purpose can be advantageous or even indispensable.
The introduction of virtual testing can be accomplished in several steps. The initial step is the automation of data preparation, encompassing both input data and produced result data for both the OEM and the testing authority. Subsequent steps involve the implementation of individual processes and security mechanisms against data manipulation. This paper primarily addresses the initial step and outlines a methodology for achieving the objective of safeguarding against data manipulation and intellectual property (IP) infringement by OEMs.
An automated process has been implemented to enable virtual testing for LS-DYNA FEM models managed in an SDM system. One of the goals of this process is to automatically hash individual model parts each time the CAE engineer runs a simulation and to preserve this information (the hashes). This information is then used in an automatically generated report from the results and serves as a fast way to identify unallowed, intended or not, changes to the model parts that must not change between different simulated load cases. The hashing process, the management of the hashes, as well as the report creation was completely automated. Furthermore, the required ISO-MME data, necessary for submission to the Euro-NCAP web portal, is also prepared automatically, thus making it as simple as possible to follow the required procedures. The requirements for the data to be delivered to the testing authority should not add any additional workload to the CAE engineer. This can be achieved by utilizing an SDM system to oversee both the FEM model data, the methodologies employed in its development, and to automate the entire process.
With such a process in place, it is possible to argue that it can be easily manipulated. Consequently, all the potential process steps that could facilitate such data manipulation must be safeguarded against such manipulation. This will be the focus of further investigations and the further development of the implemented process.

1.1 EuroNCAP Virtual Testing workflow / Motivation / Goals

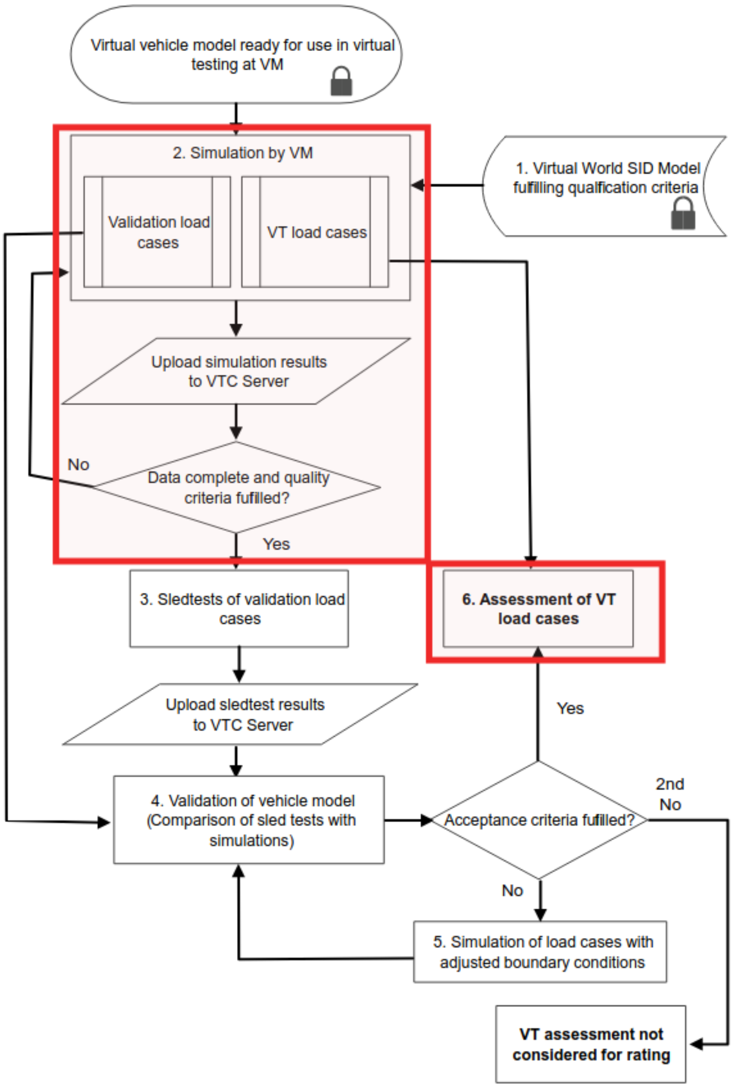

Fig.1: Overview of EuroNCAP VTC Process [1]

In [1] EuroNCAP describes the workflow for virtual testing involving both the OEM and the testing authority. The diagram above provides an overview of the workflow, including the generation and exchange of simulation data. In step 2 the OEM prepares the simulation results for two validation and six evaluation or virtual test (VT) load cases and sends them to the testing authority, in this case EuroNCAP. The total of eight simulation results must come from simulation models in which most of the model parts must be kept unchanged between them. According to [1] only “Crash pulses, orientations and seat positions are to be adjusted”. All other parts such as material cards, control settings, elements, everything from the dummy model except the nodes and so on will be referred to in this text as "static model parts". Only when the results of all eight simulations are complete and meet certain quality criteria can the process continue. After the sled test validation, the simulation results for the six virtual test load cases are considered by the testing authority for its final rating. With this in mind, the OEM's CAE engineers are likely to want to:

- assure the result data is complete
- assure the quality criteria from EuroNCAP for the acceptance of the data are met
- assure all simulation results come from models in which the static model parts are not changed
- assure the EuroNCAP rating criteria for the six VT load cases are acceptable

Until all these requirements are met, it is likely that some of the eight load cases will be simulated several times, i.e. within the OEM, step 2 of the EuroNCAP workflow will be repeated several times until the conditions required after step 2 and in step 6 are met. An effective workflow and automation of this iterative process is crucial for the productive implementation of virtual testing. Therefore, the objectives and use cases of this work are as follows:

- Use of an SDM tool to support collaboration and consistent documentation through version control
- Automatic hashing of relevant static model parts during the process with minimal user interaction
- Optimize job submission and result data preparation (post-processing)
- Automated result data preparation and report generation
- Easy and fast way, e.g. with an automatic report, to check the 4 requirements listed above (data completeness, data quality criteria, static model parts, evaluation criteria)
- Easy and fast way to export the required result data for submission to the testing authority

2 Setup in the Simulation Data Management System

There are many reasons why it makes sense to set up the entire EuroNCAP vehicle restraint system design workflow in an SDM system. On the one hand, an SDM system provides centralized access to all data and processes for everyone involved in the development process, and on the other hand, the structured storage of all data ensures consistency and complete documentation. In addition, the extensive automation of processes allows for a significant increase in efficiency when using simulation for development. Especially in the area of "virtual testing", critical steps that should run as error-free as possible, such as the hashing of static model parts, can be covered by automation and thus lead to reproducible results. In this thesis, the SDM system SCALE.sdm was used for the management of the simulation models and the automation of the processes, as well as for the visualisation of the results and the generation of reports. In addition, the requirements and thresholds for the different evaluation criteria and requirements were addressed in the project management. The following chapters provide a brief description of the implementation.

2.1 Definition of Requirements

One of the first things to do when setting up a project in SCALE.sdm is to think about the requirements and objectives and define them in the project management of the SDM system. For EuroNCAP these may be the values for the evaluation criteria (Fig.2:) and the values for the data set quality criteria for acceptance by EuroNCAP (Fig.3:).

6.3 Table 7.: EuroNCAP VTC (10)				
	✔	Head a3ms	-∞ ≤ x < 80.00	80.00 ≤ x < ∞
	✔	Abdomen compression	0.000 ≤ x < 65.00	65.00 ≤ x < ∞
	✔	Chest compression	0.000 ≤ x < 50.00	50.00 ≤ x < ∞
	✔	Head excursion	0.000 ≤ x < 80.00	80.00 ≤ x < ∞
	✔	Head HIC (15 ms)	-∞ ≤ x < 700.0	700.0 ≤ x < ∞
	✔	Lumbar Fy	0.000 ≤ x < 2.000	2.000 ≤ x < ∞
	✔	Lumbar Fz	0.000 ≤ x < 3.500	3.500 ≤ x < ∞
	✔	Lumbar Mx	0.000 ≤ x < 120.0	120.0 ≤ x < ∞
	✔	Pubic symphysis force	0.000 ≤ x < 2.800	2.800 ≤ x < ∞
	✔	Neck moment y	0.000 ≤ x < 50.00	50.00 ≤ x < ∞
Static bending, NVH (1)				

Fig.2: EuroNCAP requirements

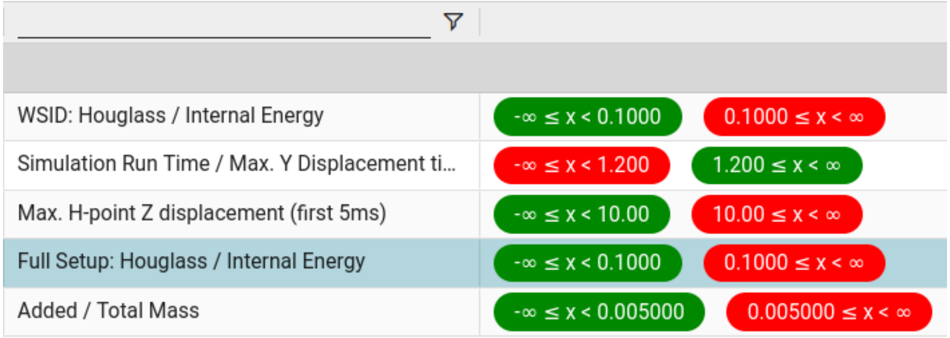

Fig.3: EuroNCAP quality criteria

These requirements and their configured limits can then be used in the subsequent evaluation in the reports of each test, either physical or simulation.

2.2 Managing model input data

To ensure an efficient workflow, effective collaboration, and easy traceability of changes, it is best practice to organize the simulation model into modular components. There are no strict rules for this, but it usually means separating the model into modules (components) that should or could be developed and simulated separately. This allows individual modules (components) to be developed by different team members on the one hand, and the same module to be used in many load cases on the other.

The management of the model input data for this work was done within the model management of SCALE.sdm. The input data was divided into components such as master, dummy, seat and so on, but it also contains scripts and processes for pre- and post-processing. Fig.4 shows an overview of the folder-like structure of the data.

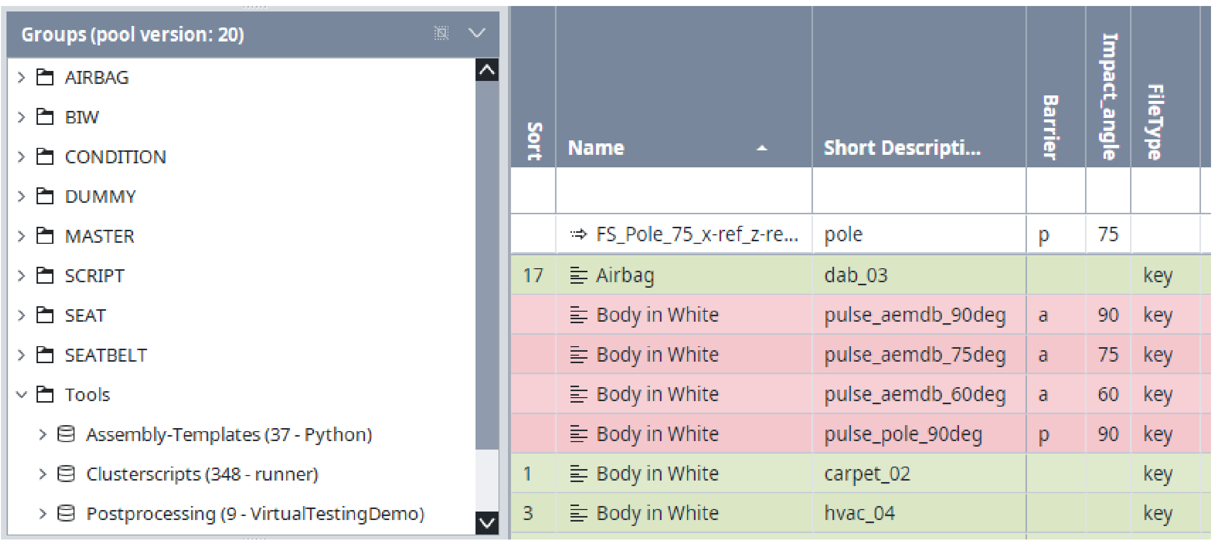

Fig.4: Input data in SCALE.sdm

The different EuroNCAP load cases are defined as run-configurations in SCALE.sdm. Run-configurations are configurations that define which components and parameters are to be used for a specific simulation. The assignment of specific components (e.g. includes) or parameter values (e.g. for "time to fire") to a particular simulation run is done through attributes assigned to these entities and referenced by the Run Configuration. Matching these will automatically determine the correct content that is required. If set up correctly, this approach allows many components to be used in all required load cases without having to manually reassign them to new load cases. The load cases for the EuroNCAP test cases as defined in SCALE.sdm are shown in Fig.5:.

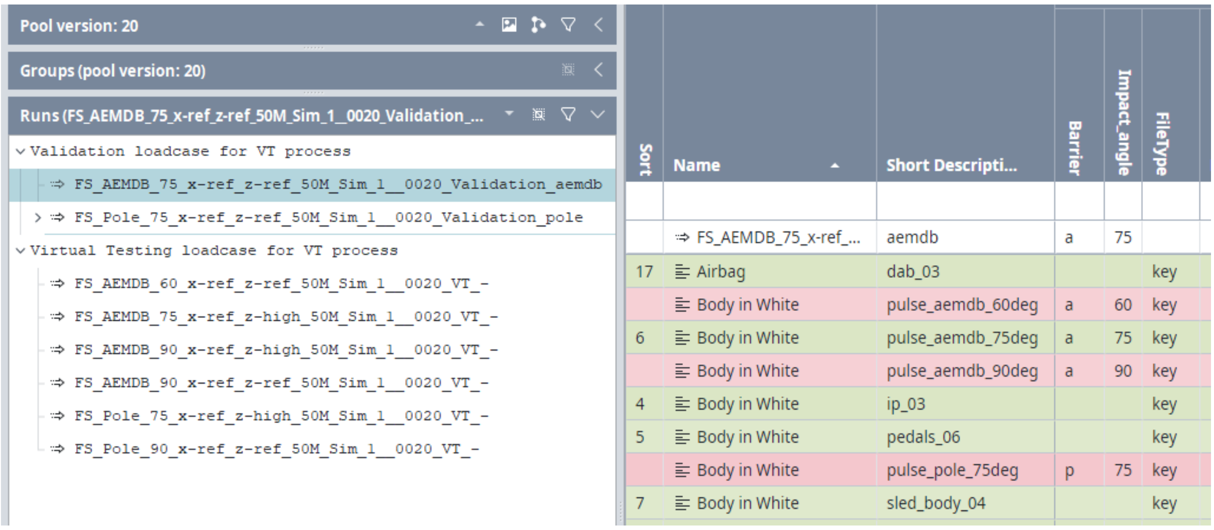

Fig.5: Load cases defined as Run Configurations in SCALE.sdm

The version control feature allows multiple team members in different locations to work together. All users can work on the data at the same time and create new versions, which can then be merged into versions containing the different changes. Fig.6: shows how this is handled in the SDM system. In version 14, User A prepared the validation runs and submitted them to EuroNCAP. In the subsequent versions 16 to 19, users A and M continued to optimize the other load cases required for the EuroNCAP rating, with user A concentrating on the z-ref load cases and user M on the z-high load cases. Then, in version 20, user M merged their efforts to produce a 'status' version containing both optimizations, the results of which could be sent to EuroNCAP.
By applying a very strict version control in SCALE.sdm, it is also ensured that every change is thoroughly captured and documented. This is probably also very important for "virtual testing" to document what has changed between validation runs and subsequent runs of other load cases during development. SCALE.sdm has several different tools for handling and documenting versions, as shown in Fig.6::

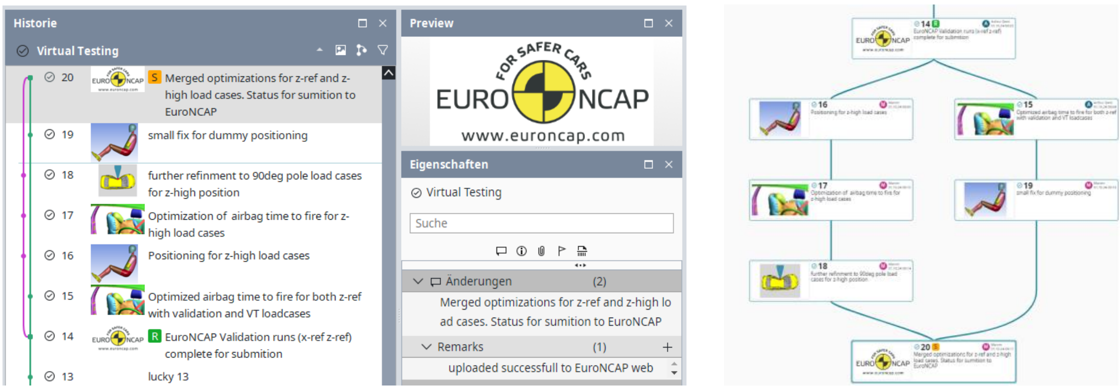

Fig.6: Version control in SCALE.sdm – left: rail graph for navigation – right: history graph for overview

Another important aspect of an SDM-system is the full automation of the simulation job, which typically includes post-processing jobs to automatically extract all relevant key values, curves, images and videos required for rapid evaluation of the simulation results. The submission and monitoring of simulation jobs is tightly integrated in SCALE.sdm and detailed job progress feedback can be viewed in the 'Jobs Monitor' as shown in Fig.7:

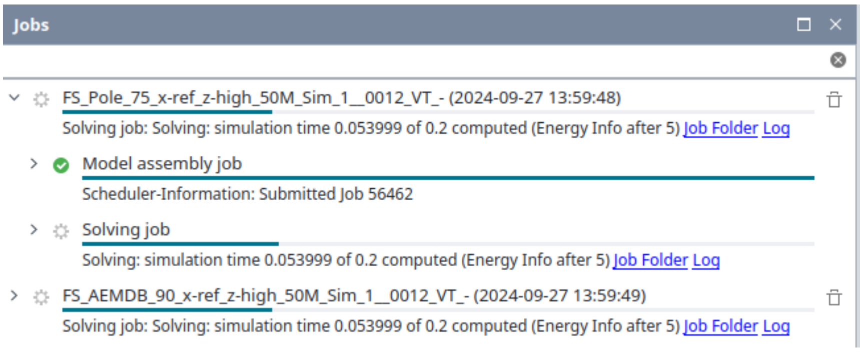

Fig.7: Job progress feedback in SCALE.sdm

As SCALE.sdm is solver independent, it provides an application programming interface (API) for managing model data when submitting to the HPC cluster or when assembling a load case locally. The term for this in SCALE.sdm is assembly-template. In the following section, the assembly-template used for LS-DYNA models and for the hashing process is briefly described.

2.3 Solver specific assemble (LS-DYNA Template and STATIC BLOCKs)

The assembly templates in SCALE.sdm are Python scripts that can access the content or so-called assembly context for any load case through a python module. In the case of the LS-DYNA assembly template used in this work, the following operations were automated with it:

- Writing out keyword files as individual files
- Writing out master and control files into one master file
- Writing out metadata to specific files
- Replacing parameters with their specific load case values
- Computing and writing out the hashes for the static model parts
- Executing cluster- and user- scripts depending on the environment

In case of the static model parts, a yet non existing LS-DYNA card syntax was assumed. These cards would mark the static model parts similar to the LS-DYNA PGP encrypted blocks. The assumed format could be as follows:

```
$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
$-----BEGIN STATIC KEY BLOCK: dummy content 1 -----
*CONTROL_ACCURACY
         0         2         0         0
*CONTROL_CONTACT
       0.0       0.0         1         2         1         0         1         0
         0         0         0         0       0.0         1         0         0

...
   5000268   5000263   5000263         0   5000263         0         0         0
$
$----- END STATIC KEY BLOCK -----
$
$ ==========
$ NODE cards
$ ==========
$
*NODE
 5000001      -146.83640     -0.21606500       766.60809       0       0
 5000002      -149.25600     -0.19832100       773.21039       0       0
 5000003      -151.81239     -0.18168300       779.76093       0       0
```

Fig.8: Assumed format for static model parts

The content between these lines must be exactly the same for all 8 simulations where the results are submitted to the testing authority. This means, for example, that the definition of the control cards, elements, parts and materials of the dummy must remain unchanged, but the node coordinates are

outside the block and can be changed for positioning purposes. To ensure this, the hashes of these "static model parts" are automatically calculated by the assembly template during job assembly and stored with the result data in SCALE.sdm. The hash of such a static model part is a short and unique string that changes whenever any data within that block is changed. These hashes are then used in the automated web report to give users a quick overview of which 'static model parts' have changed.
The hashing-based methodology implemented in this work was inspired by [2], where a similar approach was implemented. This work also went into more detail and focused on possible mechanisms against data manipulation.

2.4 Process Scripts for Postprocessing

In SCALE.sdm, all key-values, curves, images and videos required for assessment are automatically extracted from the raw result data after solving on the HPC system. In the example set up here for EuroNCAP load cases, the required result data is extracted using software tools from Arup, including Reporter and d3plot, as well as Python scripts. The aforementioned tools and scripts are executed in batch automatically after solving on the HPC in a subsequent job through the queuing system. The extracted raw data is then stored in the ISO-MME format and uploaded to SCALE.sdm, where it is accessible to all users for various types of evaluation and assessment.
The scripts used for this process to extract the result data are managed in SCALE.sdm together with the simulation input data. They are versioned together with the simulation input data, ensuring a clear audit trail of which scripts have been used with which data.

2.5 Interactive web report for evaluation

In addition to static reports in PDF or PowerPoint format, the SCALE.sdm Web Client provides users with the ability to create and customize interactive web reports, tailored to their specific requirements. The Web-Client also enables users to access all simulations stored in the SCALE.sdm system from any web browser. The web reports offer the unique possibility to interactively select and deselect multiple results, either from simulations or physical tests, and compare them instantly.
In this example for EuroNCAP, a web report was created with the primary objective of verifying the requirements and criteria outlined in chapter 1.1. It provides a rapid, comprehensive overview of all the simulation results selected by the user.

2.5.1 Legend with overall status

The web report begins with a legend and an overall status overview. In case that multiple simulations have been selected, the legend is a valuable reference tool. The overall status provides the user with a rapid assessment of whether the result data for the selected simulations meet the required quantity and quality criteria.

Legend

	Test Name	Overall	# Invalid Result Criteria	# Mismatched Parts	# Invalid Rating Criteria	# Channels	# Videos
	FS_Pole_90_x-ref_z-ref_50M_Sim_1__0013_VT_-	Not Ok	0	-	2	115	6
	FS_Pole_75_x-ref_z-high_50M_Sim_1__0013_VT_-	Ok	0	0	0	115	6
	FS_Pole_75_x-ref_z-ref_50M_Sim_1__0013_Validation_pole	Ok	0	0	0	115	6

Fig.9: Legend and overall status in web-report

If any of the quality or quantity criteria are not met, the corresponding simulation result will appear in red and the user can proceed to the corresponding section of the report to check the details of what is missing, or which criteria are not met.

2.5.2 Quality criteria of data for EuroNCAP

The Quality Criteria section contains several assessments for the simulation required by EuroNCAP to meet specified limits. If these limits are not met, the uploaded data will not be accepted by EuroNCAP. In addition to these quality criteria, this section also contains the number of channels and videos required. If any of these channels or videos are missing, the simulation result will also not be accepted. If more than one simulation is selected, the results are displayed in columns so that they can be compared.

Quality Criteria for EuroNCAP

Result	Limit			
Full Setup - Maximum Hourglass Energy < 10% of Maximum Internal Energy	≤ 0.1	0.01943	0.01871	0.001888
WSID Dummy - Maximum Hourglass Energy < 10% of Maximum Internal Energy	≤ 0.1	0.02882	0.02759	0.005757
Maximum Added Mass (%) < Total Model Mass at the beginning of the simulation	≤ 0.005	5.016e-4	5.016e-4	5.016e-4
Z Displacement (mm) in the first 5 ms of the simulation	≤ 10	4.2	4.2	
(Time of Maximum Head Y Displacement) + 20% < Simulation Time	≥ 1.2	1.5	1.5	
Number of Mandatory Channels	115	115	115	**61**
Number of Mandatory Videos	6	6	6	6

Fig.10: EuroNCAP Quality criteria for three selected simulations in a web-report in SCALE.sdm

Such a quality criterion will only have a green background if all selected simulation results meet the criteria. Yellow is used if only some of the selected runs are OK, and red if none of the selected results meet the corresponding criteria.

2.5.3 Report on "static model parts"

The automatic process described in Chapter 2.3 creates hashes for each model part that is effectively marked as not to be modified. In this part of the report these hashes are used to compare the status of the static model parts between the selected runs. This means that this section of the report is only useful if at least two simulation results have been selected. The first selected result is used as the basis for comparison. If the hashes of the other selected simulations differ from the base simulation, this will also be considered as a problem for the upload to EuroNCAP.

Validation of Static Model Parts

Part			
carpet part 1	...30321	...30321	...30321
carpet part 2	...1817a	...1817a	...1817a
biw column (full)	...de3eb	...de3eb	...de3eb
biw hwac (full)	...bc2df	...bc2df	...bc2df
biw ip03 (full)	...1c29f	...1c29f	...1c29f
biw pedals (full)	...083d7	...083d7	...083d7
sled part 1	...51d71	...51d71	...51d71
sled part 2	...88c9c	...88c9c	...88c9c
contact_05 (full)	...d86e2	...d86e2	...d86e2
control_02	...36e3e	...36e3e	...36e3e
dummy content 1	...1670a	**...9592a**	...1670a
dummy content 2	...5414c	...5414c	...5414c
seat part 1	...813c9	...813c9	...813c9
seat part 2	...3ca67	...3ca67	...3ca67
seat belt content	...61b01	...61b01	...61b01
seat belt part 2	...df543	**...467cf**	...df543

Fig.11: Static model parts comparison in EuroNCAP web report for 3 different simulations

In the example shown above, the "static model parts" of three simulations are compared. The first selected simulation, shown in the first column of hashes is the reference or base simulation that was used for the validation run that was submitted to EuroNCAP. The hashes of the "static model parts" of the other simulations are shown in the other columns. If the hash of a "static model part" in one of the simulations differs from the simulation of the validation run, this is indicated by a red background color. If a simulation differs in one or more "static model parts" from the simulation from the validation run, this would not be accepted by EuroNCAP.

2.5.4 Rating criteria of EuroNCAP

Even if all 8 simulation results meet the quality and quantity criteria for uploading to the testing authority, the OEM's ultimate goal is to also receive a good rating from the testing authority. Therefore, it is also necessary to check the values used by EuroNCAP for the rating before uploading the simulation results. This is the purpose of the third section of the report. TODO: correct units for a3ms, float formating...

Rating Criteria EuroNCAP

Assessment Criterion	Limit			
HIC15	≤ 700	169	33.67	143.8
A3ms	≤ 80	43.31 G	23.76 G	41.9 G
Upper Neck Fz	≤ 3.74	0.296 kN	0.465 kN	0.192 kN
Upper Neck MxOC	≤ 248	21.9608 N m	142.298 N m	24.4736 N m
Upper Neck MyOC	≤ 50	22.7058 N m	46.3669 N m	14.2845 N m
Lower Neck Fz	≤ 3.74	0.154 kN	0.054 kN	0.115 kN
Lower Neck Mx(base of neck)	≤ 248	6.24678 N m	0.496497 N m	4.60146 N m
Lower Neck My(base of neck)	≤ 700	11.7259 N m	7.50386 N m	5.74929 N m
Chest compression	≤ 50	0.0	0.0	0.0
Abdomen compression	≤ 65	0.0	0.0	0.0
Pubic Symphysis force	≤ 2.8	0.0	0.0	0.0
Lumbar Fy	≤ 2	0.423 kN	**2.07 kN**	0.404 kN
Lumbar Fz	≤ 3.5	0.126 kN	1.01 kN	0.106 kN
Lumbar Mx	≤ 120	5.95886 N m	**120.588 N m**	8.51914 N m
Head excursion	≤ 80	44.3 mm	45.8 mm	45.6 mm

Fig.12: Key results for rating in the web-report

In this example it can be seen that based on the values in the rating for the second simulation, the rating is unlikely to be as desired. It may therefore be appropriate to delay the upload to EuroNCAP and improve the model by further optimizing the restraint system using simulations.

2.5.5 Chanel plotter for all channels required for EuroNCAP

All channels available for test or simulation can be reviewed in the Channel section. As there are many channels, the user can first select the location of the sensor, then the parameter being measured and the axis of the measurement. The plot then compares the selected channel from all selected simulations and immediately adds the result of newly selected simulations.

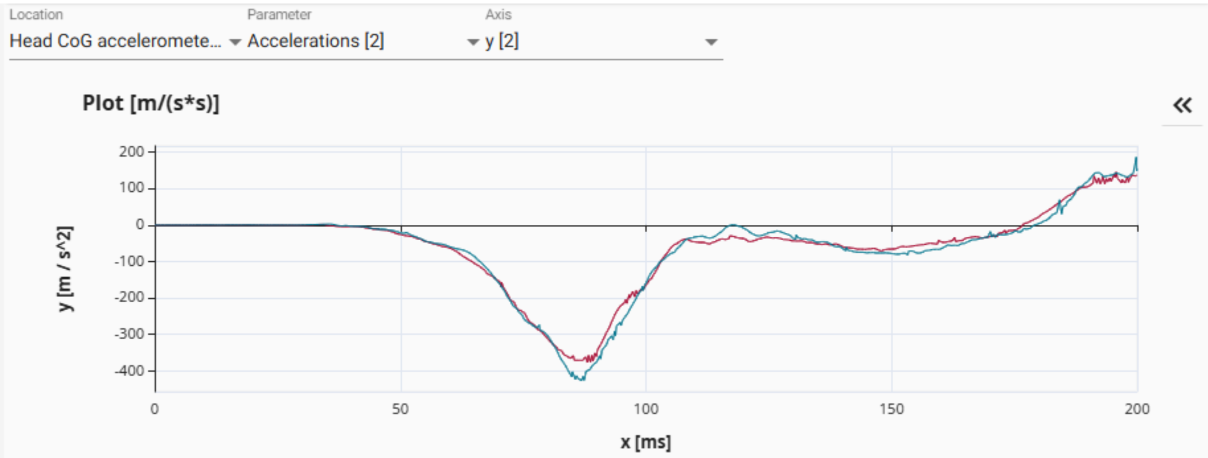

Fig.13: Channel navigation in web-report

If some of the required channels are missing, this is also easy to recognize as the missing channels are highlighted in the selector according to the EuroNACP requirements.

Fig.14: Channel navigation in web-report

In the example above, it is easy to identify the missing channel or category of channels thanks to the different highlighting colors and the number of simulation results containing that specific channel in square brackets.

2.5.6 Videos required for EuroNCAP

The EuroNCAP rating requires the submission of 6 videos from exact camera positions and perspectives. These videos can be viewed side by side in the last section of the report for the selected simulations. The videos are played synchronously and there is a common slider to adjust the position in the video for all videos at the same time.

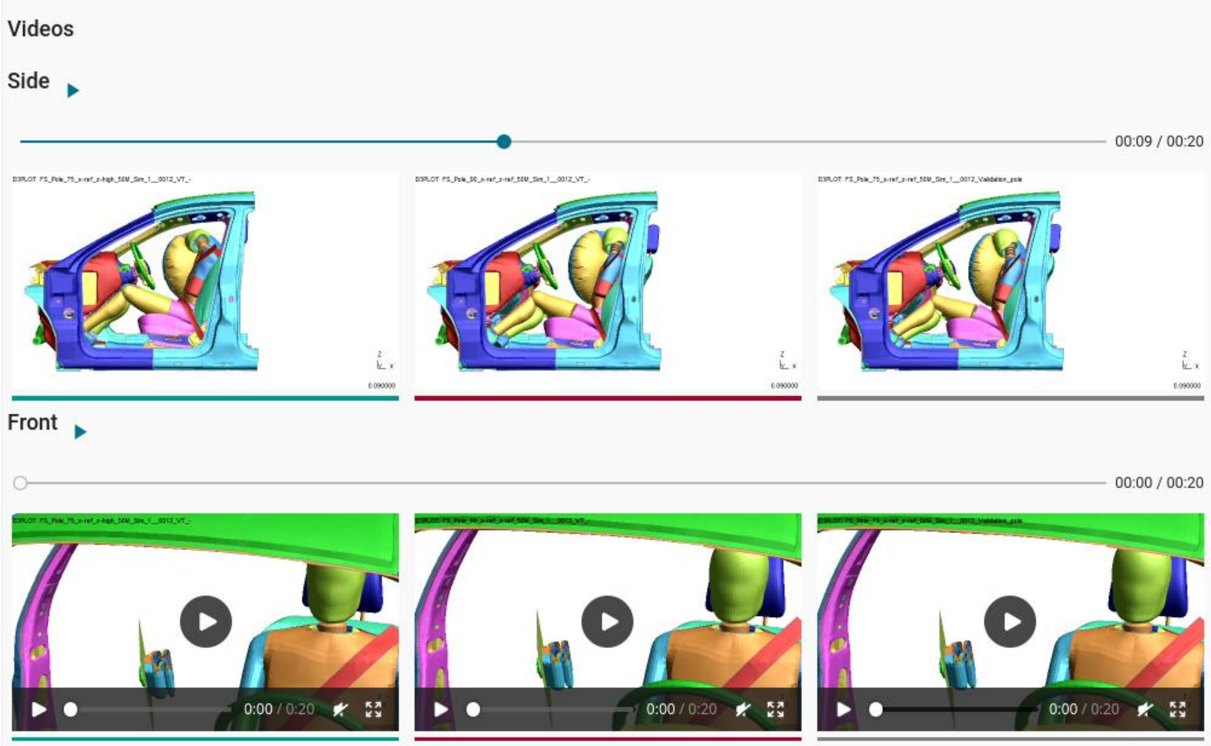

Fig.15: Video navigation in web-report

2.6 Data transfer from the SDM-System to the EuroNCAP WebPortal

The simplest method for data delivery to EuroNCAP is to export the result data for the required simulation in ISO-MME format from SCALE.sdm. This function is integrated in SCALE.sdm as an addon. It is used to export all required result data per simulation as a tar archive. The exported ISO-MME data can then be uploaded to the EuroNCAP website.
Another, perhaps even more user-friendly and automated solution would be to extend such an addon with an automatic upload function to the EuroNCAP website.
In case of new or different requirements for the result data format in the future, such addons can be written or extended relatively quickly without the need to update the installed SCALE.sdm instance.

3 Thoughts on possibilities of safeguarding against data manipulation

Up to this point, we have only demonstrated how an SDM system can be used to make the virtual testing workflow as simple as possible for the end user. However, there is still the problem that it is not trivial to ensure that the hashes for the static model parts actually belong to the simulation data that was actually used in the solving. And the integrity of the generated result data is not necessarily guaranteed either. Although the hashes that are automatically generated in the process implemented in the SDM system for the static model parts are useful information for quickly seeing whether relevant model components have remained the same between simulations, it cannot be ruled out that they have been manipulated at some point in the process. The same applies, of course, to the result data which ends up in the form of values, curves and videos in the ISO-MME data set submitted to EuroNCAP. It is not easy to check whether this result data has been generated with the simulation data that is specified.
One way to overcome the problem would of course be for the OEMs to make their complete simulation data available to EuroNCAP together with the results. In this case, it would be possible to run the simulations in house at EuroNCAP and it could be clearly confirmed that the results also match the data and which components of the simulation data have been altered. However, OEMs are not really a fan of this idea, as it would require them to disclose a lot of their classified data on vehicle projects under development.
Another approach would be to work with signatures instead of hashes. In contrast to hashes, a signature also ensures that the signed data was as it was when it was signed and that can be verified by any party by using the public key of the signer. If a trusted party signs both the input and output data that belong together with a cryptographic key at the time they are available, it can be assumed that these data also belong together and have not been manipulated. Only the party who has the private key can sign the data but anyone can verify the signature by using the corresponding public key. In case of LS-DYNA it is already common practice that users can encrypt blocks of data of their simulation models and a PGP-Key, that presumably is embedded in LS-DYNA, is used to decrypt that data. The same key could also be used by LS-DYNA in order to sign every block of "static model parts" and write the signatures into a report (e.g. into the d3hsp file). The same needs to be done also for all relevant output data and the corresponding signatures should also be included in the report.

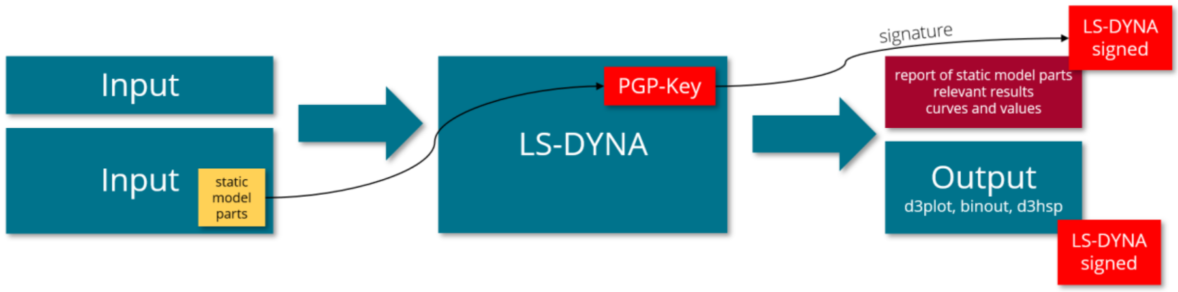

Fig.16: Using LS-DYNA encryption for signing static model parts and relevant output

The drawback of above-mentioned approach is that even if the simulation inputs of the validation runs are signed, they could still be "tuned" input files that are manipulated to produce results that match the desired physical results. Without disclosure of the actual inputs, it will be difficult for the certification authority to validate that the input files used by LS-DYNA are actually valid simulation models that have not been manipulated. Another point is that this approach would need to be adapted by any other solver that OEMs are using for their virtual development. Also, Ansys would still need to implement the proposed signing functionalities directly in LS-DYNA.

4 Summary

In this work we have tried to show how a simulation data management system can be used to support the tasks required for virtual testing. In addition to the benefits for collaboration in the development of restraint systems or by increasing efficiency in the creation of simulations, it should also be shown that SDM systems offer advantages, as all changes are systematically recorded and documented. In addition, the integration of the automatic creation of hashes for “static model parts” and their presentation and evaluation in automatically generated reports makes it possible to quickly record and check the results and whether they are sufficient for the requirements of EuroNCAP.

5 Literature

[1] EuroNCAP: EUROPEAN NEW CAR ASSESSMENT PROGRAMME, https://cdn.euroncap.com/media/77236/euro-ncap-vtc-simulation-and-assessment-protocol-v10.pdf 18 May 2023, page nb. 3

[2] Esma Galijatovic, Maria Eichlseder, Simon Franz Heindl, Corina Klug: Integrity of virtual testing for crash protection, https://www.frontiersin.org/journals/future-transportation/articles/10.3389/ffutr.2022.914489/full 30 November 2022

[3] Dr. Ferenc Leichsenring, Dr. Martin Liebscher, Marko Thiele - SCALE GmbH: Simulation Data Management Systems: The Foundation to Integrate ML and Data Analysis Techniques automotive CAE Grand Challenge 2024