Ref. Ares(2020)13669 - 03/01/2020

Upscaling **P**roduct development **S**imulation **C**apabilities exploiting **A**rtificial inte**L**ligence for **E**lectrified vehicles

D5.4 Load cases for the full vehicle models to be used within the UPSCALE project

M. Andres (VW), A. Dumon (ESI), C. Jiménez (IDIADA), Ch. Breitfuss (ViF), S. Menegazzi (CRF)

10/2019

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement Nº 824306.

Project Details

PROJECT TITLE	Upscaling product development simulation capabilities exploiting artificial intelligence for electrified vehicles
PROJECT ACRONYM	Upscale
GRANT AGREEMENT NUMBER	824306
INSTRUMENT	RIA
CALL	LC-GV-2018
STARTING DATE OF THE PROJECT	November, 1ST 2018
PROJECT DURATION	42 Months

The UpScale Project

UPSCALE is the first EU project with the specific goal of integrating AI (artificial intelligence) with traditional physics-based Computer Aided Engineering to reduce the development time and increase the performance of electric vehicles (EVs).
Nowadays High-Performance Computing (HPC) and Computer Aided Engineering (CAE) play a decisive role in vehicle development processes, thus the two most HPC and CAE intensive parts of the development, which are vehicle aero-thermal and vehicle crash performance, have been chosen as use cases for the endeavour.
Through the combined effort of universities, research laboratories, European automotive OEMs, software companies and an AI-SME specialized in machine learning (ML), the UPSCALE, project will provide a unique and effective environment to produce novel AI-based CAE-software solutions to improve the competitiveness of the automotive industry.

The UpScale Consortium

PARTICIPANT Nº	PARTICIPANT ORGANISATION NAME	COUNTRY
1 (Coordinator)	**IDIADA AUTOMOTIVE TECHNOLOGY SA (IDIADA),**	Spain
2	VOLVO PERSONVAGNAR AB (Volvo Cars)	Sweden
3	VOLKSWAGEN AG (VW)	Germany
4	CENTRO RICERCHE FIAT SCPA (CRF)	Italy
5	ESI GROUP (ESI GROUP)	France
6	ENGYS LTD (ENGYS LTD)	United Kingdom
7	Kompetenzzentrum - Das Virtuelle Fahrzeug, Forschungsgesellschaft mbH (VIF)	Austria
8	VRIJE UNIVERSITEIT BRUSSEL (VUB)	Belgium
9	ECOLE NATIONALE SUPERIEURE D'ARTS ET METIERS (ENSAM PARISTECH)	France
10	ALGORITHMICA TECHNOLOGIES GMBH (ALGORITHMICA)	Germany
11	F INICIATIVAS I MAS D MAS I SL (F-INICIATIVAS)	Spain

Document Details

DELIVERABLE TYPE	Other
DELIVERABLE Nº	D5.4
DELIVERABLE TITLE	Load cases for the full vehicle models to be used within the UPSCALE project
NAME OF LEAD PARTNERS FOR THIS DELIVERABLE	Volkswagen AG
VERSION	04
CONTRACTUAL DELIVERY DATE	Month 12
ACTUAL DELIVERY DATE	Month 12
DISSEMINATION LEVEL	Public

ABSTRACT

This report describes the load cases used for the full vehicle simulation models in order to generate input data to the training of the ROM and AI models associated with the prediction of short circuit risk of the battery cell and with the treatment of contact and stiffness. The load cases are parameterized in order to create various different loads acting on the batteries within the vehicles which consequently generate different deformation modes of the battery cells. By setting up parameterized load cases, the necessary amount of input data is easily achieved. Furthermore, validation tests are set up immediately when choosing parameter combinations that have not been used for training.

Revision History

The following table describes the main changes done in the document since it was created

REVISION	DATE	DESCRIPTION	AUTHOR (ORGANIZATION)
R01	28.10.2019	First draft	M. Andres (VW)
R02	28.10.2019	Review	C. Breitfuss (ViF)
R03	29.10.2019	Second draft	S. Menegazzi (CRF)
R04	29.10.2019	Third draft	A. Dumon (ESI)
R05	29.10.2019	Merge of previous drafts	M. Andres (VW)
R06	31.10.2019	Review	A. R. de Liébana (IDIADA)

Disclaimer

Table of contents

Acronyms and abbreviations

AE-MDB	Advanced European Mobile Deformable Barrier
AI	Artificial Intelligence
BiW	Body-in-White
CAE	Computer Aided Engineering
D	Deliverable (within the UPSCALE project)
DoE	Design of Experiment
EV	Electric Vehicle
FE	Finite Element
FMVSS	Federal Motor Vehicle Safety Standards
MDB	Mobile Deformable Barrier
NCAP	New Car Assessment Programme
NHTSA	National Highway Traffic Safety Administration
ODB	Offset-Deformable Barrier
PGD	Proper Generalized Decomposition
ROM	Reduced Order Model(ing)
VPS	Virtual Performance Solution
WP	Work Package

1 Executive Summary

This report describes the load cases used for the full vehicle simulation models in order to generate input data to the training of the ROM and AI models associated with the prediction of short circuit risk of the battery cell and with the treatment of contact and stiffness. The load cases are parameterized in order to create various loads acting on the batteries within the vehicles which consequently generates different deformation modes of the battery cells.

To produce data which is useful for training a ROM or AI model predicting the risk of short circuit in a battery cell, the meso-scale cell model described in D1.5 require relatively large deformations of the battery cell coating, as an internal short circuit will appear mostly after fracture of a separator foil, see [1], [2]. For this reason, the deformations acting on the batteries need to be enlarged. As the vehicles are designed, such that a crash, legal or consumer, will not deform the battery to high, adjustments to the FE full vehicle simulations are needed. On one hand, the vehicle models themselves could be adjusted, e.g. by reducing the sheet thicknesses of important components within the body in white or by removing reinforcements of components. On the other hand, the load cases could be adjusted by increasing the total energy of the system. This can be achieved e.g. by increasing the mass and / or the velocity of a barrier or by increasing the velocity of the vehicle. Besides an increased impact to the battery could be achieved e.g. by changing the size of a barrier or pole or by moving the point and / or angle of impact.

The authors decided to follow the second approach, i.e. the change of the load cases instead of changing the vehicle models. This decision was made due to several reasons. First of all, changing the vehicle model has a higher risk of erroneous simulations. Furthermore, by changing the vehicles geometry a comparison between two different simulations is not valid anymore. By setting up parameterized models, the necessary amount of input data for the training of the ROM or AI models is easily achieved. Moreover, validation tests are set up immediately when choosing parameter combinations, that have not been used for training. Finally, the non-linear behaviour of the vehicles or batteries deformation depending on a linear change of load case parameters can be identified.

At this point the authors again want to emphasize, that the results of the full vehicle simulations may not be used in order to assess the safety or performance of one of the vehicles provided in D5.2 and D5.3 or even a real vehicle which may look similar. First of all, the load cases are adjusted in such a way, that no legal or consumer test may be valid anymore. Second, the vehicles themselves are not based on real vehicles as they only exist as FE models for research reasons. Furthermore, a comparison with existing vehicles, whether they are now available or in the future, is strictly prohibited.

The report is first describing the load cases that are used within this project as well as their corresponding parameterization in chapter 2. The load cases are based on the existing load cases, that are the Euro NCAP AE-MDB side impact, the Euro NCAP ODB frontal impact, the Euro NCAP side pole impact and the FMVSS305 MDB rear crash. Chapter 3 is dedicated for the discussion on possible risks and their elaboration. Finally, conclusions and recommendations are made in chapter 4.

The objective of this task was to provide load case models for full vehicle simulations which can be used to create the input data to the meso-scale battery cell models as described in WP1. An adequate amount of different load cases was delivered in time.
To assess if the presented models are sufficient in order to feed the ROM / AI models, the next steps will need to be made within the project. The first is to create the input for the meso-scale cell models using the presented simulation models and second to run the meso-cell models in order to create the input to the ROM / AI models. If the amount of data turns out to be insufficient for training the ROM / AI models, modifications related to this task will need to be performed. Some possibilities for modification are already presented in chapter 3 of this report.

2 Definition of the parameterized load cases used for the full vehicle simulations

In this chapter the load cases on vehicle level are presented. In order to generate as many different loads acting on the battery as possible, load cases from all three categories, i.e. frontal impact, side impact and rear impact, are chosen. For creation of large deformations of the battery cells housing, the total energy of the system is increased. This is achieved by parameterization of the load case relevant variables, e.g. the mass of a barrier or the velocity. Every of the following sections describes first the base load case as it is defined by the corresponding legal or consumer testers and then gives an overview of the parameters that are respectively changed for changing the deformation modes of the battery cells. As a full vehicle crash behaves highly non-linear, it is insufficient for each load case to just use the interval bounds of each parameter to get the minimal, respectively maximal deformation. Therefore, a Design of Experiment (DoE) will be set up to define a simulation campaign for every load case. If the amount of data appears insufficient, further DoE maybe performed additionally.

As the presented tests are designed mainly for occupant safety assessment, the parameters of the load cases are changed within the UPSCALE project in order to assess the safety of the battery of an EV. First, the parameters are changed to increase the deformation of the battery housing to create input data for the training of the ROM or AI models described in WP3. Second, parameter combinations that have not been used for training are used for validation of the ROM or AI models.

2.1 Euro NCAP AE-MDB side impact adjusted for the project

The following description has been taken from the Euro NCAP website see [3] and the subsequent sites therein.

Side crashes account for the second highest frequency of death and serious injuries. Compared to a frontal impact, there is very little space inside the vehicle interior in which to absorb energy and severe injuries to the head and the chest are common.

In Euro NCAP’s test, a deformable barrier is mounted on a trolley and is driven at 50km/h into the side of the stationary test vehicle at right angles. A side impact dummy representing an average male is put in the driver's seat and child dummies are placed in child restraint systems in the rear.

The test ensures that there is adequate protection of the critical body regions. This has driven the strengthening the structures of vehicles around the B-pillar (between the doors), the fitment of side impact or curtain airbags in cars but also the development of less obvious energy-absorbing structures in seats and door panels. The timing and deployment of airbags must be very carefully controlled to ensure that they provide the greatest protection possible.

The FE model of the Euro NCAP AE-MDB side impact is shown in Figure 1. The point of impact provided by Euro NCAP is visualized in Figure 2.

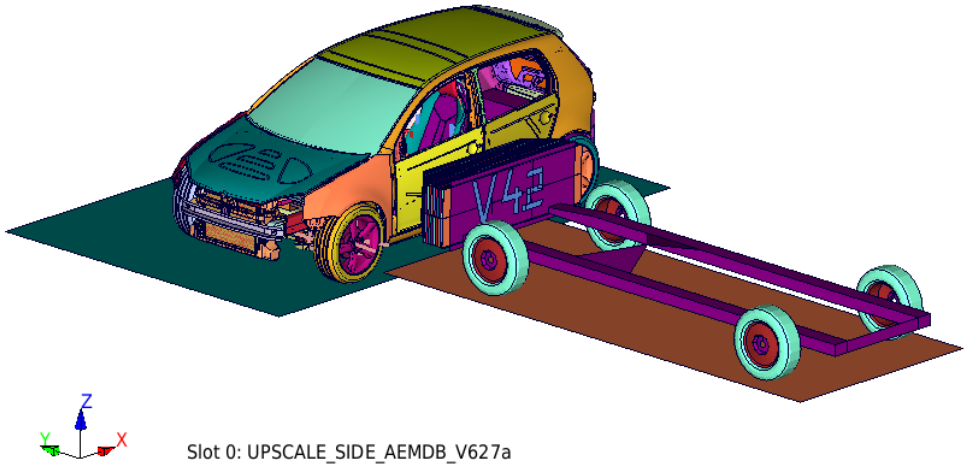

Figure 1: FE model of the Euro NCAP AE-MDB side impact

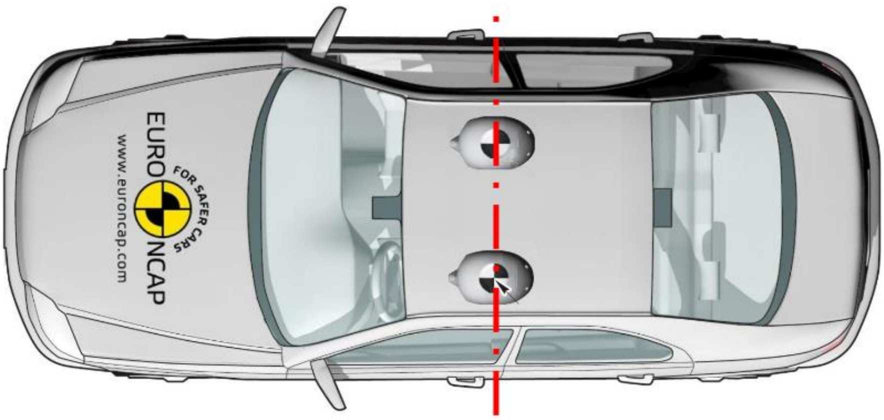

Figure 2: Euro NCAP AE-MDB side impact reference line from [4]

For the Euro NCAP AE-MDB side impact test the parameters defined in Table 1 have been changed.

Table 1: Parameters of the adjusted Euro NCAP AE-MDB side impact test

Base Load Case	Adaptation	Range
Euro NCAP side impact AE-MDB at 90°	Add mass to barrier	50-500 [kg]
	Increase velocity of barrier by	2-25 [m/s]

	Scale width of barrier by factor	0.5-1.5 [-]

To realize a fast and script based execution of the DoE the load case parameters have been defined as python variables (PYVAR Card) in the VPS main execution file. Details on the definition of a PYVAR Card are described in D5.1. The python variables are depicted in Figure 3. A visualization of the scaled barrier can be found in Figure 4.

```
PYVAR / 1000
NAME Load case paremeters
$ Parameters to change the side AEMDB load case
initial_velocity_of_barrier = 13.88
additional_mass_of_barrier = 0.0
scale_width_of_barrier = 1.5
$ auxiliary variables
invel = initial_velocity_of_barrier
addmas = additional_mass_of_barrier
scalew = scale_width_of_barrier
END_PYVAR
$          NODE    VELX0    VELY0    VELZ0   VANGX0   VANGY0   VANGZ0    IFRAM    IRIGB
$#        IDNOD    VELX0    VELY0    VELZ0    VANX0    VANY0    VANZ0     IFRA    IRIGB
INVEL /       0       0. <invel>       0.       0.       0.       0.        0        0
NAME Initial velocity Barrier
        GRP 'INVEL_Impactor'
        DELPART  9700004
        END
$
NODE  / 80000000          1250.0               0.0               0.0
TRSFM /
NAME Scaling width of Barrier
        GRP 'DEFOELEMENT'
        END
        SCAL  80000000 <scalew>   1.0   1.0
        END
$              ID    MASS
NSMAS /      1000<addmas>
NAME Adding mass to Barrier
        GRP 'DEFOELEMENT'
        GRP 'BARRIEREWAGEN'
        END
```

Figure 3: Section of the VPS input deck to create the load case parameters of the Euro NCAP AE-MDB side impact

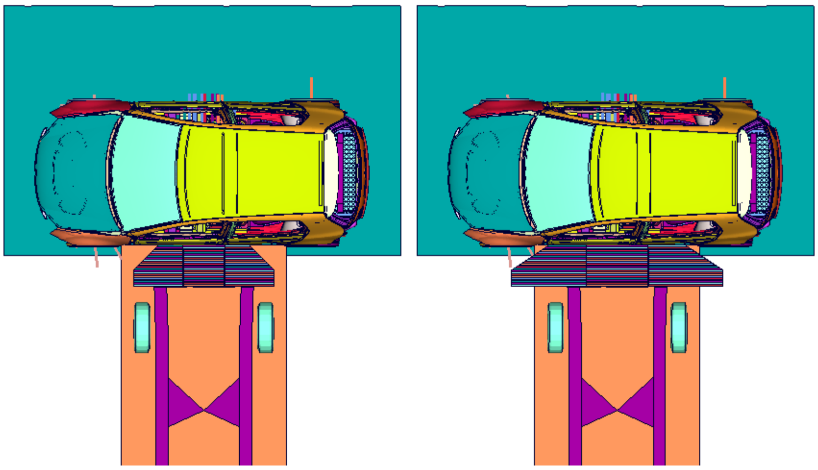

Figure 4: Comparison of the barriers, scaled by factors (left: 1.0, right: 1.5)

2.2 Euro NCAP ODB frontal impact adjusted for the project

The following description has been taken from the Euro NCAP website see [3] and the subsequent sites therein. The reference configuration is depicted in Figure 5.

Frontal crashes are responsible for more deaths and serious injuries than any other accident type. A typical scenario is a head-on collision between two oncoming cars at moderately high speeds. In most collisions of this type, only a part of the vehicle front width structure is involved, i.e. the two colliding vehicles are offset.

In the full-scale test, the car is driven at 64km/h and with 40 percent overlap into a deformable barrier which represents the oncoming vehicle. The test replicates a crash between two cars of the same weight, both travelling at a speed of 50km/h. Two frontal impact dummies representing the average male are seated in the front and child dummies are placed in child restraints in the rear seats.

In this crash, the vehicle structure is put to the test. Limited structural engagement may expose occupants to increased intrusions. Crash forces have to be efficiently directed to parts of the car where the energy can be efficiently and safely absorbed. The front crumple zone must collapse in a controlled way, leaving the passenger compartment as undeformed as possible. Rearward movement of the steering wheel and the pedals must be limited if serious injuries are to be avoided.

Figure 5: Euro NCAP ODB frontal impact reference configuration from [3]

For the Euro NCAP ODB frontal impact test the parameters defined in Table 2 have been changed. The parameterization is achieved in the same way as for the previous section by using python variables within the main VPS execution file.

Table 2: Parameters of the adjusted Euro NCAP ODB frontal impact test

Base Load Case	Adaptation	Range
Euro NCAP ODB frontal impact at 40% overlap	Increase initial velocity of vehicle by	2-20 [m/s]
	Change overlap of barrier from	20% - 80%

The adapted initial velocity applies to the vehicle except for the wheels, where the velocity is translated to the rotational velocity according to the diameter of the wheels. The changed overlap of the barrier will, on purpose, lead to large variations of the deformation mode. The range of the overlap is shown in Figure 6. Note, that the small width of the barrier will lead to critical deformations for some values of the overlap parameter, as the barrier may miss both frontal longitudinal members.

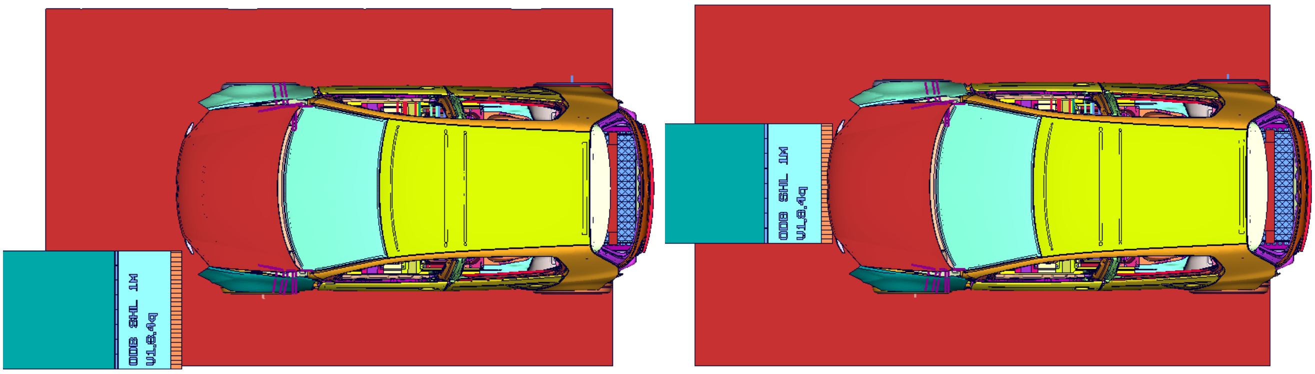

Figure 6: Minimal (20%) and maximal (80%) used overlap of the Euro NCAP ODB frontal crash barrier

2.3 Euro NCAP side pole impact adjusted for the project

The following description has been taken from the Euro NCAP website see [3] and the subsequent sites therein. The reference configuration is depicted in Figure 7.

Some side impacts involve a vehicle travelling sideways into rigid roadside objects such as trees or poles. Often this is the result of a loss of control on the part of the driver, owing to speeding, misjudgment of a corner or because of a skid in slippery conditions. Such accidents are severe and the frequency of death or serious injury is high.

In Euro NCAP's test, a car is propelled sideways at 32km/h against a rigid, narrow pole. The car is placed at right angles to the direction of motion, or as is done from 2015 onwards, at a small angle away from the perpendicular. A single average male side impact dummy is placed in the driver's seat.

This is a very severe test of a car's ability to protect the driver's head. As the loading on the car is so localized, deformation can be very high and the pole can penetrate deeply into the passenger compartment. Without effective protection, the pole would strike the head resulting in serious injuries. Head protection airbags – often curtain airbags mounted above the side windows but sometimes seat-mounted thorax/head airbags – have become a common solution but great care is needed to ensure effective performance of such devices.

Figure 7: Euro NCAP pole side impact reference configuration from [3]

For the Euro NCAP side pole impact test the parameters defined in Table 3 have been changed. As for the Euro NCAP AE-MDB side impact test the variables are parameterized by python variables in the main VPS execution file. Note, as this load case is using five parameters, it is favorable to be used for D5.5 in task 5.1 of WP5 which is the creation of a ROM for a parameterized load case using PGD.

Table 3: Parameters of the adjusted Euro NCAP side pole impact test

Base Load Case	Adaptation	Range
Euro NCAP side pole impact at 75° impact angle	Change x-position of impact point by	±0-500 [mm]
	Set impact angle to	60-90 [°]
	Increase initial velocity of vehicle by	2-15 [m/s]
	Scale diameter of pole by factor	0.5-1.5 [-]
	Shorten pole in z-direction by factor	0.25 – 1.0 [-]

By shortening of the pole in z-direction the load acting on the vehicles bottom components is increased. For a factor above 0.5, the pole will not hit the roof frame, further decreasing the factor will lead to even higher loads, as components within the door, as the door side impact bar will be missed in addition. An example of a parameterized Euro NCAP pole side impact model is shown in Figure 8.

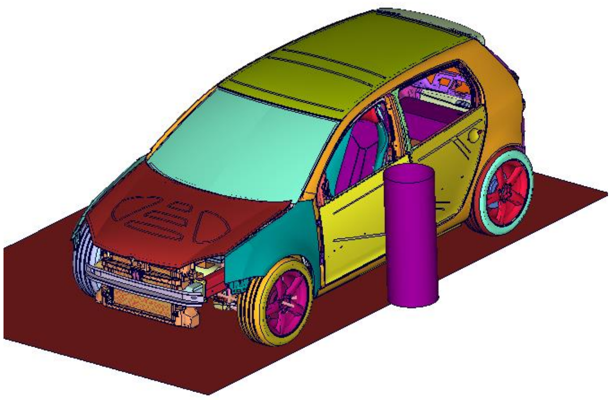

Figure 8: Parameterized Euro NCAP side pole impact, pole diameter is scaled by factor 1.5, height of the pole is scaled by factor 0.5

2.4 FMVSS305 MDB rear impact adjusted for the project

The following description has been taken from the NHTSA website see [5] and the subsequent sites therein. The reference configuration is depicted in Figure 9.

FMVSS No. 305 specifies performance requirements for limitation of electrolyte spillage, retention of propulsion batteries, and electrical isolation of the chassis from the high-voltage system during the crash event. This standard applies to vehicles that use electricity as propulsion power.
Vehicles will be tested to the requirements of FMVSS 305 which may be any single moving deformable barrier crash at any speed up to and including 80km/hr, rear impact with 70% overlap toward either side of the vehicle (passenger car, MPV, truck, or bus under 4,536 kg GVWR (10,000 pounds).

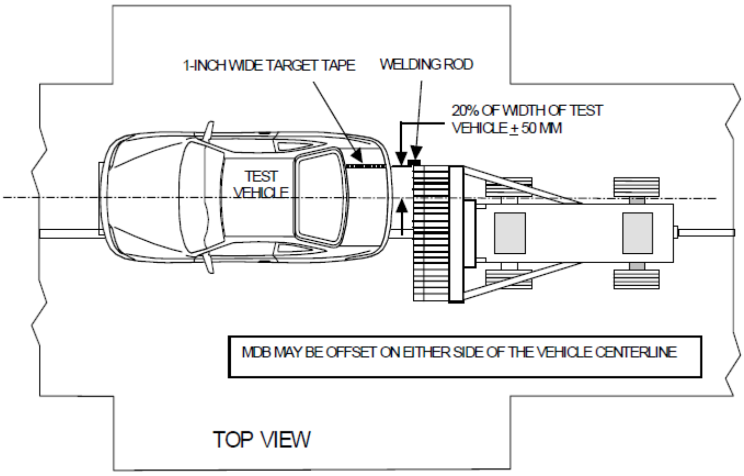

Figure 9: FMVSS MDB rear impact test reference configuration from [5]

For the FMVSS305 MDB rear impact test the parameters defined in Table 4 have been changed. The approach is the same as for the previous sections. An example of the model is shown in Figure 10.

Table 4: Parameters of the adjusted FMVSS305 MDB rear impact test

Base Load Case	Adaptation	Range
FMVSS305 MDB rear impact with 70% overlap	Add mass to barrier	50-500 [kg]
	Increase speed of barrier	2-15 [m/s]
	Change overlap of barrier to	20% - 80%

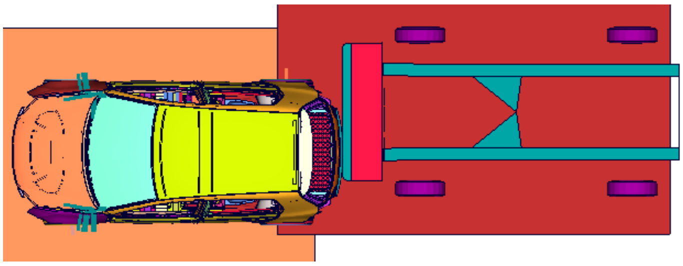

Figure 10: FE model for the FMVSS305 MDB rear impact test

2.5 FMVSS214 MDB side impact

The following description has been taken from the NHTSA website see [6] and the subsequent sites therein. The reference configuration is depicted in Figure 11.

This final rule incorporates a dynamic pole test into Federal Motor Vehicle Safety Standard (FMVSS) No. 214, “Side impact protection.” To meet the test, vehicle manufacturers will need to assure head and improved chest protection in side crashes. It will lead to the installation of new technologies, such as side curtain air bags and torso side air bags, which are capable of improving head and thorax protection to occupants of vehicles that crash into poles and trees and vehicles that are laterally struck by a higher-riding vehicle.[1]

[1] https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/fmvss/214_Side_Impact_final_Aug_30_2007.pdf

The peculiarity of this testing protocol is the 27° oriented MDB barrier.

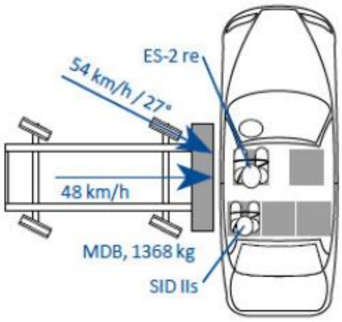

Figure 11 FMVSS Std.214 side impact

2.6 TRIASS 15 rear impact with rigid barrier

The TRIASS 15 rear impact provides a crash case involving a rigid wall barrier impacting all the rear compartment of the car, see Figure 12. The test permits to evaluate the rear bumper compartment and to evaluate the intrusion on the rear side of the vehicle.

Table 5: Parameters of the adjusted TRIASS 15 rear impact with rigid barrier test

Base Load Case	Adaptation	Range
TRIASS 15 rear impact	Increase speed of barrier	0-20 [m/s]

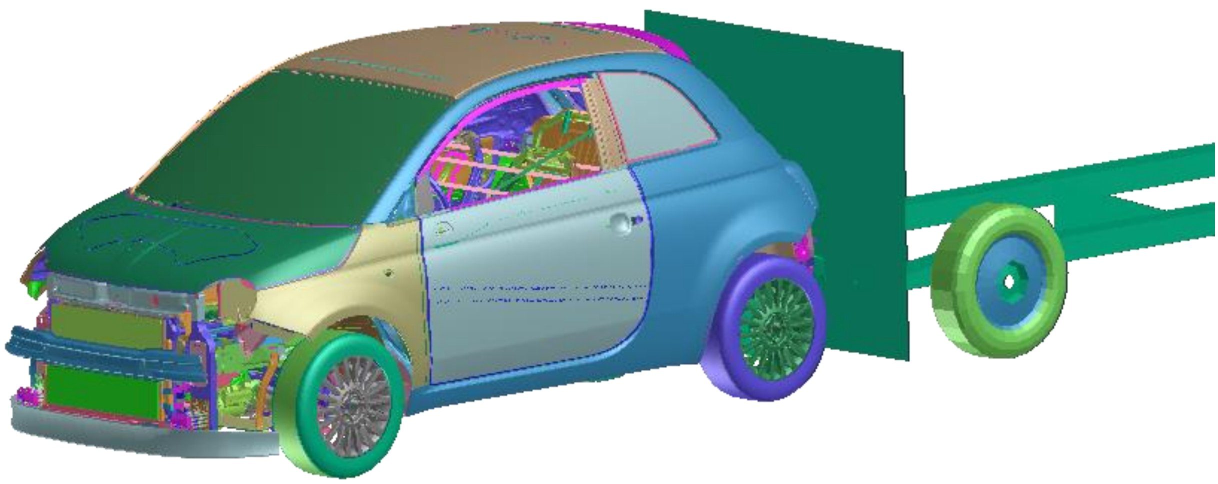

Figure 12 TRIASS 15 with Rigid Barrier Rear Impact

The rear impact involves the battery case on the rear side and could involve the battery pack. The impact will present a higher energy transmission to the vehicle with reference to the deformable barriers. To increase the level of intrusion of the barrier and the harshness of the impact it will be increased the impact velocity as shown in Table 5 and consequently the amount of energy that will be dissipated during impact.

3 Possible risks and elaboration on the risks

The presented load cases will be used for creation of input data, that is used within the meso-scale battery cell models of WP1, see D1.5. Within full vehicle simulations the risk of using wrong models, e.g. in the sense of missing connections or contacts within the model, is always present. As the model outputs will be exchanged and thus checked twice or even more by the project partners, errors in the model are supposed to be identified early, such that the corrected simulation data can be produced quickly.
Furthermore, as the load cases are all parameterized, it cannot be ensured, that some contact formulations will be stable within every simulation, depending on different parameter combinations. These simulations will be identified, checked carefully and if possible re-simulated with improved contact settings.
Another risk is related to the lack of impact on the battery pack, in particular in the front impact cases also with small overlap. Those cases may not damage the central and rear part of the vehicle considering the standard test velocity. The first option would be to increase the impact speed, in this way the deformation due to the impact would increase the intrusion in the vehicle Body-in-White (BiW). It could be that also by increasing the speed of impact the re-bounce of the vehicle could avoid severe damage of the battery pack. It could then be lowered the number of front impact simulated in favour of the side and rear impacts.
Finally it could be criticized that the same base load cases are used for AI validation and quality checking. If the pursued validation procedure may cause reasonable doubts about the approximation quality of the ROM or AI models, further load cases on vehicle level could be applied, e.g. the small overlap barrier frontal impact test, see Figure 13.

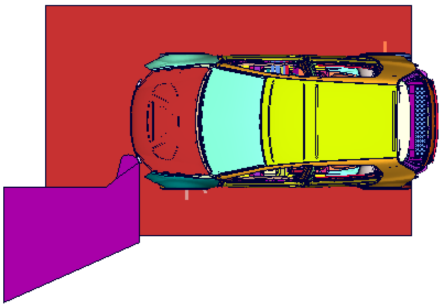

Figure 13: FE model of the Small Overlap Barrier frontal impact

4 Conclusions and recommendation

The load cases used for the full vehicle simulations were presented. All load cases are parameterized such that a fast and automated creation and simulation of various test cases is made possible. For future work it is highly recommended to follow the strategy of parameterizing the load cases as presented here, since the set up for an appropriate ROM or AI model to exchange some high-fidelity model cannot be carved in stone. Every feature or behaviour, especially when it is highly non-linear will need different settings of input data.

The parameterization also allows for further simulation campaigns or DoE to enrich the input data. An estimation of possible error of the AI model and distance to the training set would also be useful to know if the input should be enriched.
Load cases that could not deform the battery pack also with the increased severity in the boundary conditions presented in this Document should be removed by the training phase but still referred in case of future progress in the battery pack design and installation strategy.

5 Figures

6 Tables

7 References

[1] S. F. Heindl, C. Breitfuss, C. Ellersdorfer, F. Feist und W. Sinz, „Method for Predicting Li-Ion Cell Reactions due to Mechanical Crash Loads,“ in *AVL Advanced Simulation Technologies International User Conference*, Graz, 2015.

[2] Y. Xia, T. Wierzbicki, E. Sahraei und X. Zhang, „Damage of cells and battery packs due to ground impact,“ *Journal of Power Sources,* Bd. 267, pp. 78-97, 2014.

[3] Euro NCAP, 06 2019. [Online]. Available: https://cdn.euroncap.com/media/53146/euro-ncap-side-test-protocol-v81.pdf.

[4] Euro NCAP, 09 2019. [Online].

[5] NHTSA, 10 2019. [Online].
[6] NHTSA, 08 2007. [Online]. Available: https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/fmvss/214_Side_Impact_final_Aug_30_2007.pdf.