Crash simulations of electric cars in the EVERSAFE project

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1 Introduction

EVERSAFE is a Swedish-German project funded by the Seventh Framework Programme ERA-NET Transport Electromobility+ that has been initiated in 2012 [1]. The overall aim of the project is to provide recommendations for improved safety regulations and to find out about research needs for electrically propelled vehicles. Both active and passive safety issues have been addressed within the project. Although full electric vehicles are the main focus, results of the project are also applicable to other electric vehicle variants including hybrid electric vehicles, fuel-cell electric vehicles and plug-in hybrid electric vehicles [2].

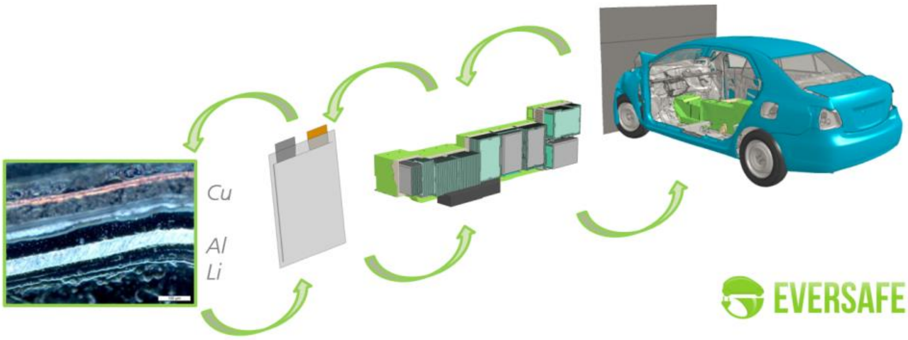

Fig.1: EVERSAFE project: from cell model to full car crash simulations.

This paper focuses on the passive safety part of the project including cell level component tests as well as comprehensive simulations evaluating battery vulnerability (Fig.1). Partners involved in the passive safety part are the Fraunhofer Institute for High-Speed-Dynamics (EMI), the Fraunhofer Institute for Chemical Technology (ICT), the German Federal Highway Research Institute (BASt), the Swedish Transport Research Institute (VTI), and Volvo Car Corporation (VCC).

2 Method

2.1 Li-Ion pouch cell characterization and testing

A set of experiments was dedicated to microscope analysis and tensile tests of Li-ion battery cells. Samples were directly cut into the cell and used for tensile tests, both on layer and on entire thickness levels, as shown in Fig.2. A numerical model of the cell structure was then constructed using the mechanical information obtained from the different components.

Fig.2: Tensile tests performed on pouch cells and on each layers.

Following the material characterization, several mechanical abuse tests were conducted on fully loaded cells. As presented in Fig.3, these tests consisted in:

- Shear test with a sharp blade. This test is designed to investigate what could happen in a vehicle crash when a sharp metal sheet penetrates a module and cuts a cell.
- Penetration tests according to SAE J2464 (thin metallic nail penetration) and also according to in-house procedure which consists of a penetration by a round plastic pin. This test was performed to investigate the influence of non-conductive penetrators.

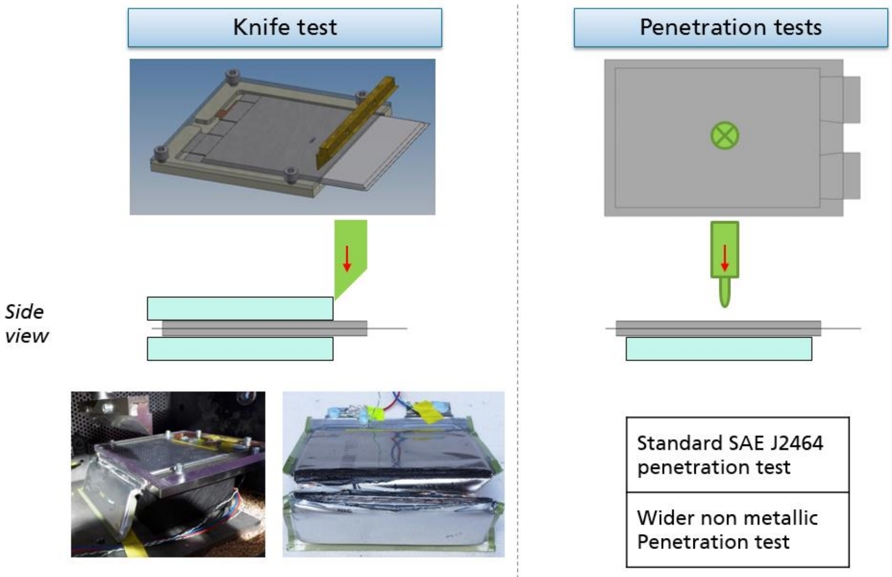

Fig.3: Mechanical abuse tests performed on Li-ion pouch cells: shear test with a knife (left) and penetrations tests according to standard and in-house test (right).

2.2 Battery pack model

Based on literature study, especially on the Gidas database [3], the work was oriented on the tunnel area which is presented as the statistically safest place for a battery. A detailed FEM tunnel battery pack has been developed with 192 pouch cells divided in 8 modules. Pouch cells could be considered as a worst case, as they don't have a rigid protective surrounding like prismatic or cylindrical cells. The mass of the whole pack is 198 kg which fits with current battery concepts. For computational efficiency, each cell model is limited to 2000 elements. An overview of the model can be seen in Fig.4.

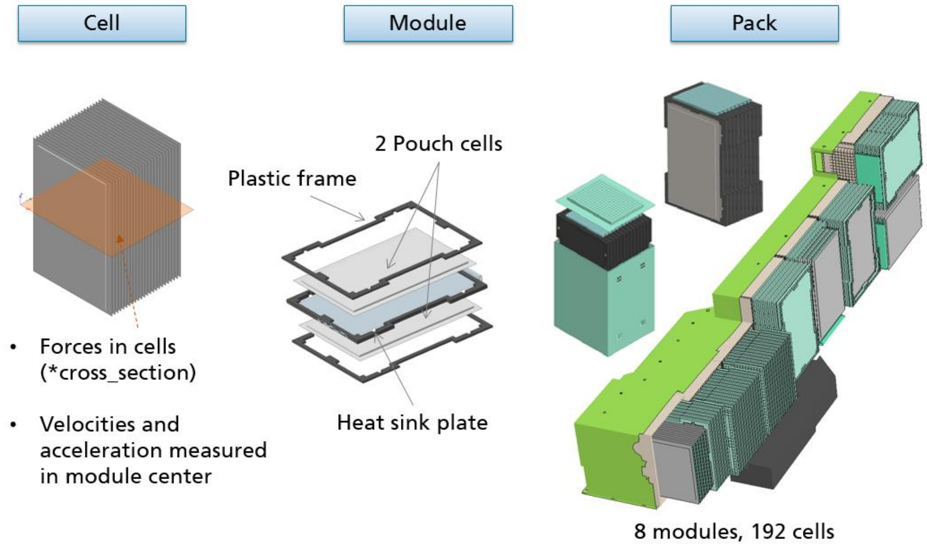

Fig.4: Battery pack model developed.

The 600,000 elements battery pack was then fitted into the vehicle model. For this purpose, the position of the front seats in the vehicle model had to be changed slightly and the tunnel area was modified.

2.3 Vehicle modifications and validations

As reference vehicle the model of the Toyota Yaris developed by NCAC [4] was selected. Some work has been done to improve this model. Here is a short summary of these adaptations:

- Reference load cases (frontal and side crash) were investigated to identify the weak points of the model.
- Contact problems were solved, especially concerning side crash simulation against MDB.
- Loose parts were connected.
- Recommendations from DYNAmore (control cards) and from literature (e.g. improved tire models) were incorporated to make the model more stable and accurate.

As a result, the model showed a good numerical stability concerning frontal, rear and side impacts and all other scenarios of interest, as no element in the vehicle caused the calculation to terminate. The energy components were checked to prove that no nonphysical energy (hourglass) is developed. The resulting model, without detailed battery, consists of 1 million elements.

The validation of the model was made using available test data. The acceleration peaks recorded in the vehicle's b-pillar in simulation were compared to a range of tests involving super-minis, small family cars and SUVs. The comparison of the acceleration peaks for frontal Fig.5, side barrier Fig.6 and side pole impacts Fig.7 confirmed that the Yaris is a suitable small family car model.

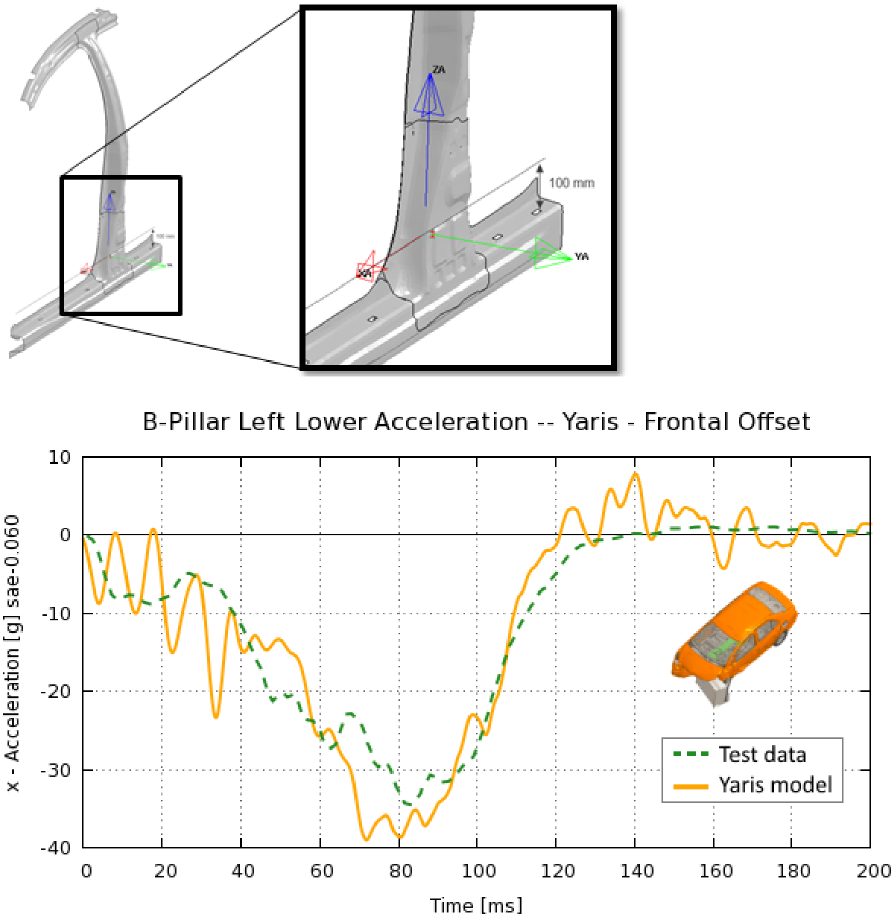

Fig.5: Crash pulse of Euro NCAP frontal offset simulation for Toyota Yaris model. Measurement is performed in the B-pillar. The orange curve denotes the numerical results; the green curve denotes test data of small family class vehicles.

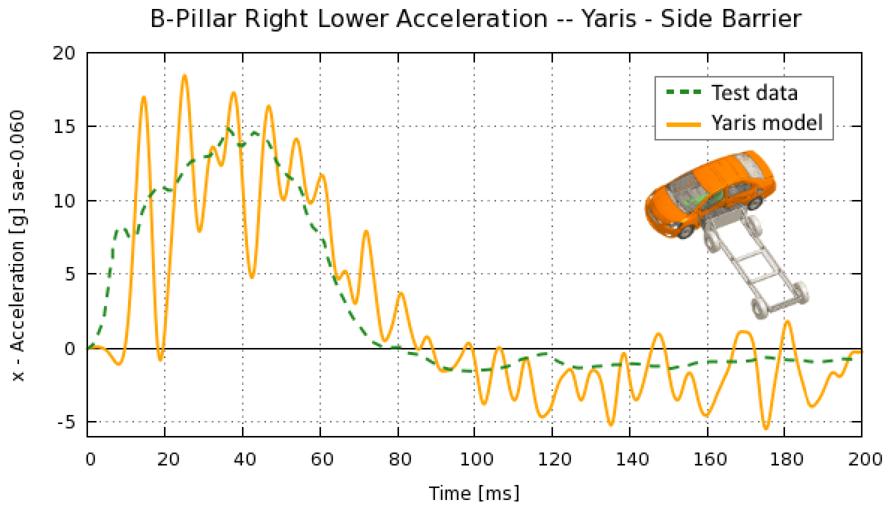

Fig.6: Crash pulses of Euro NCAP side barrier simulation for Toyota Yaris model. The orange curve denotes the numerical results; the green curve denotes test data of small family class vehicles.

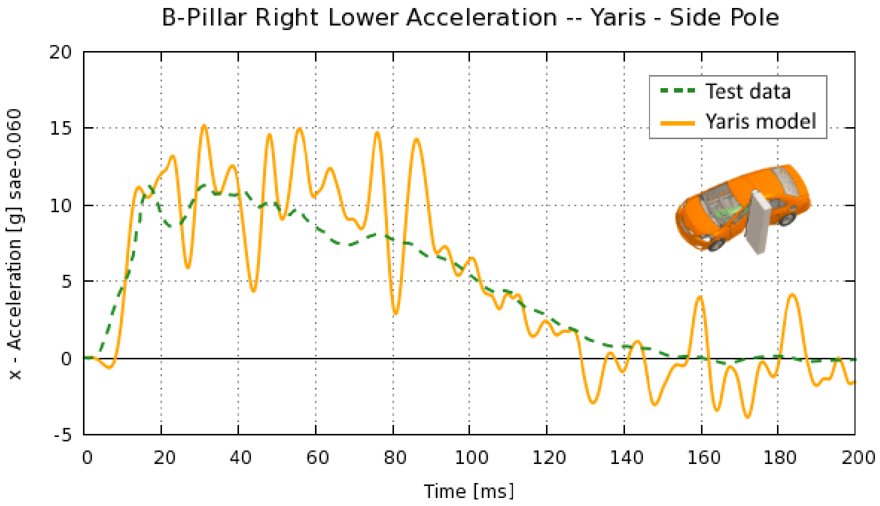

Fig.7: Crash pulse of Euro NCAP side pole simulation for Toyota Yaris model. The orange curve denotes the numerical results; the green curve denotes test data of small family class vehicles.

For the purpose of integrating the battery pack into the Yaris vehicle model, the position of the front seats had to be changed slightly and the tunnel area was modified (200 spot-welds moved). The initial frontal aggregates (fuse box, battery, windshield washing container) were left but the engine was removed to get closer to a 1GEV configuration.

2.4 Vehicle crash simulations

The Yaris 1GEV (first Generation Electric Vehicle) was subjected to 14 different load cases. Most of them are represented in Fig.8. Some of the scenarios were analyzed additionally with slightly modified parameters such as different crash velocities or impact angles.

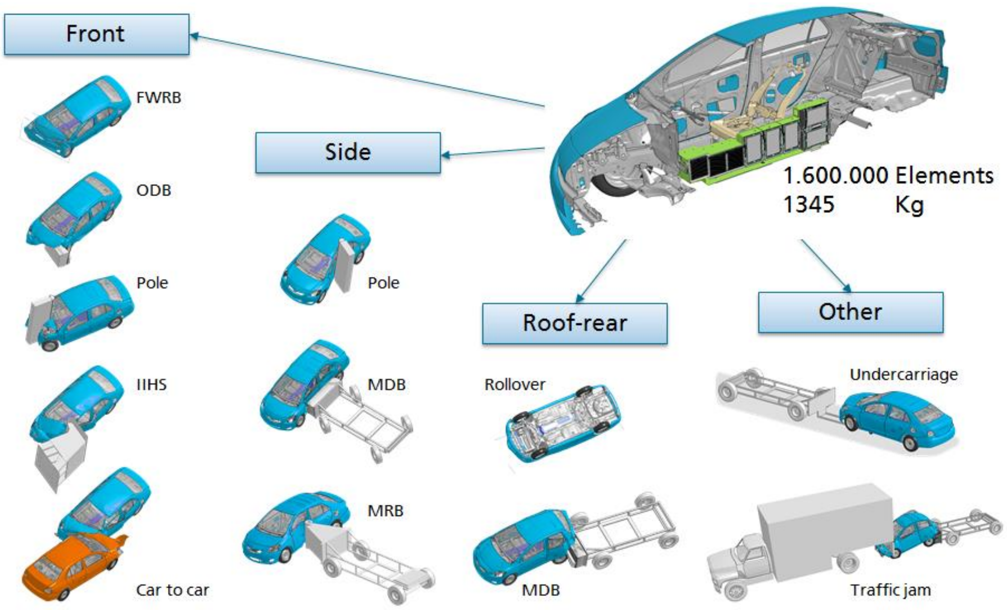

Fig.8: Crash simulations performed in the EVERSAFE project.

Many of the test conditions are standard test conditions specified in regulations or consumer testing and are not described in detail in this report. These tests are usually used by the manufacturers as design requirements, hence one can expect a good vehicle response for all of them.

2.4.1 Non-typical scenarios

If most of the simulation load cases are well defined in official crash test protocols, four simulations that have been created in EVERSAFE which consist in a frontal pole impact, an undercarriage impact, a moving side pole barrier impact and a traffic jam crash required some additional description. It has to be noted that these configurations have not been validated yet in international working groups and viability for experimental test conditions has not been proven.

Front pole impact

The front pole impact is a centered crash at 50 km/h on a rigid pole. This type of crash requires significant lateral cross members to direct loads from the bumper into appropriate parts of the vehicle frame, Fig.9.

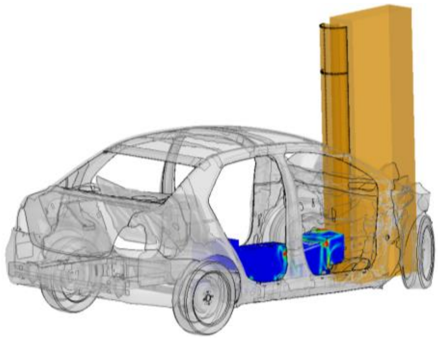

Fig.9: Front pole impact simulation for the 1GEV model developed within the project.

Undercarriage impact

Little literature is available for predicting damage to the battery pack due to a ground impact. Xia and Wierzbicki [5] proposed a scenario where a rotating object of debris gets stuck between the ground and the battery and hits the battery severely due to its own rotation whereby a direct impact to the battery is established.

The test case designed in EVERSAFE involves a rigid mass that the vehicle runs over. The tunnel configuration of the battery developed in the project benefits from a higher ground clearance than a so called "floor battery". Consequently, a tunnel battery usually is protected by the front axle of the vehicle, Fig.10.

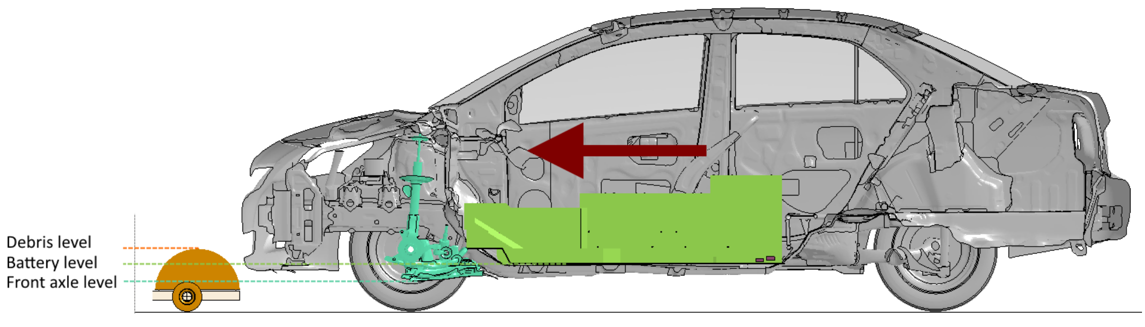

Fig.10: Undercarriage impact simulation, level differences between debris, battery and front axle.

However, in order to simulate an impact from underneath onto a floor battery configuration, it was decided for reasons of efficiency to use again the Yaris 1GEV model. To approach the conditions of a floor battery (lower ground clearance than tunnel battery), the vehicle's front axle has been removed from any contact constraints, so that the tunnel battery configuration was exploited to the potential severe loads due to an underground impact that could be seen in case of a floor battery (*Undercarriage_noFA* simulation).

Moving side pole barrier

To validate the theoretical developed experimental crash test configuration (aiming to apply a similar amount of energy to the vehicle under test as in the Euro NCAP side pole test) involving the Mitsubishi iMiEV (test performed at BASt) the Yaris model was used under comparable conditions. The test consisted of a movable barrier (mass of 2,050 kg) equipped with a front pole and driving at a velocity of 35 km/h. The simulations confirmed the initial calculations concerning the amount of absorbed energy, see Fig.11.

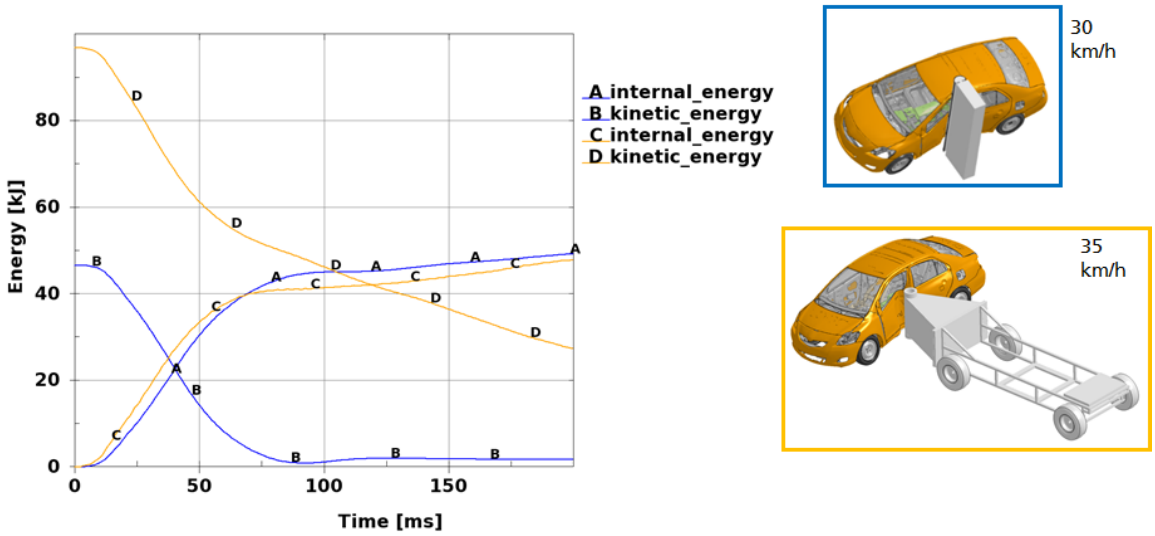

Fig.11: Very similar amount of deformation energy between Euro NCAP Side Pole (A curve) and reverse test performed (C curve).

Traffic jam

The traffic jam impact is a severe, multiple collision where a vehicle is rear-ended and then rolls into a heavier vehicle. The test speed, mass, and multiple impact setting exceed current safety standards. This condition was performed experimentally by BASt on the BMW i3 (Bergisch Gladbach, August 2014). See [1] for more information.

3 Results

3.1 Cell Model

The cell model was developed at both a detailed and simplified level as shown in Fig.12. The main components are the envelope (aluminum + plastic coating), the electrodes (copper, aluminum), and the plastic separator. The microscope analysis allowed a precise determination of the different layer thicknesses. Coating on the electrodes (lithium and graphite) was not represented is these models.

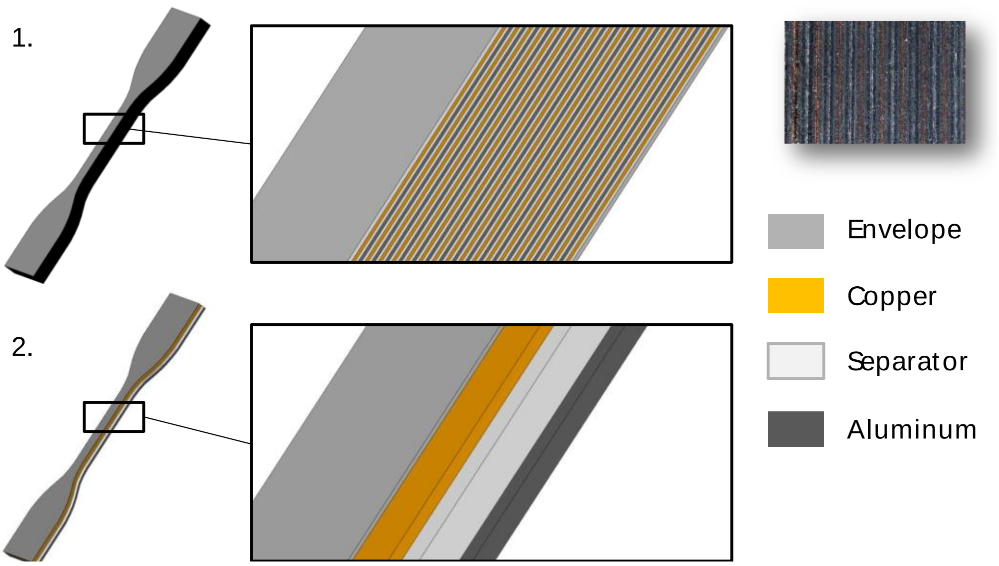

Fig.12: Numerical Model of Battery Cell (1-Detailed, 2-Simplified).

The model was validated against the mechanical tests with reasonable results as shown in Fig.13. Electrodes inside the cell fail first, followed by the aluminum inside the pouch casing and then by the separator. The last element to fail is the cover coating.

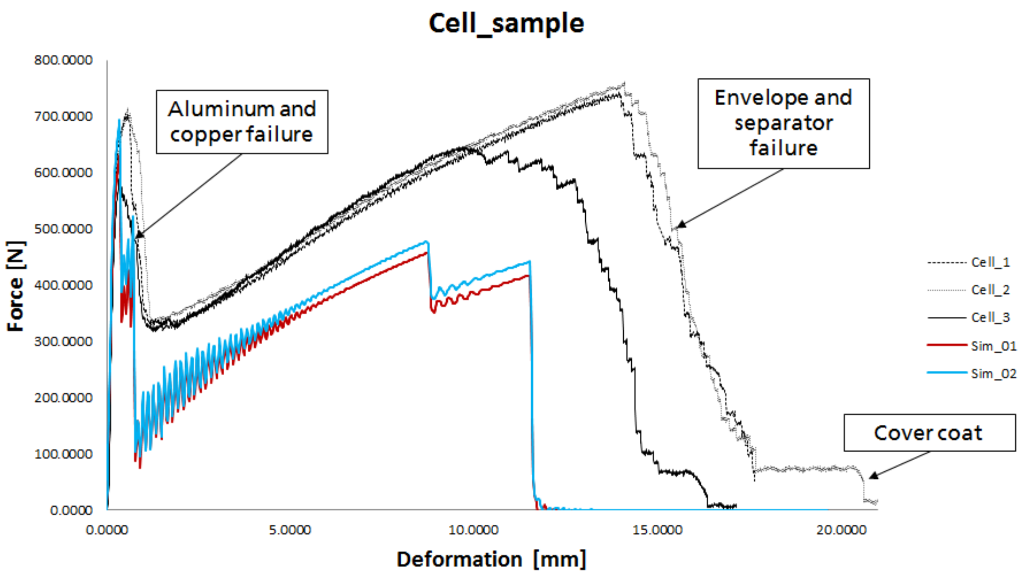

Fig.13: Validation of the cell model.

This detailed model was not used yet in full car crash simulations as it must be merged into a unique material, to avoid too many elements in the battery model. However this model allowed a better understanding of the failure mechanisms on the cell, in particular the constraints that leads to a separator failure and thus to short-circuit.

The mechanical abuse tests lead to unexpected results, as an internal short circuit and resulting thermal activity was not observed in many cases. The shear tests as well as the penetration tests according to the standard procedure SAE J2464 were not leading to a thermal runaway, in contrast to the penetration test with wider penetrator. The different failure thresholds for the materials may explain the robust behavior. The simulation model allowed to understand the failure mechanism and to explain these results, see Fig.14.

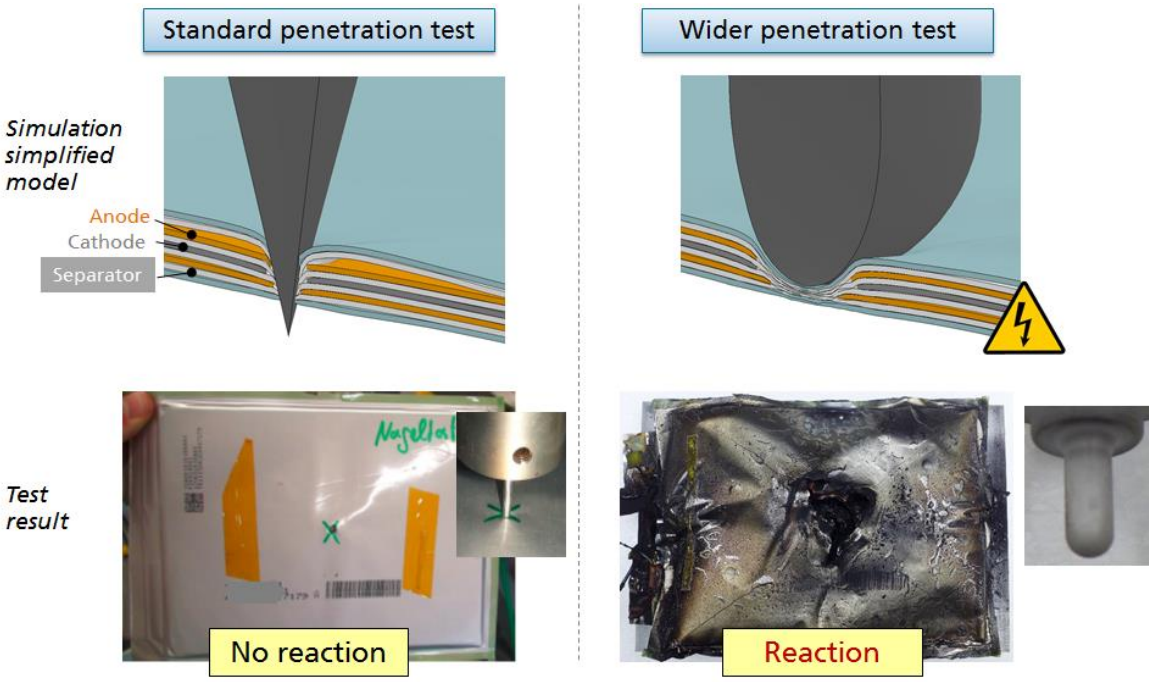

Fig.14: Differences in failure mechanism between standard penetration test (left) and wider penetrator (right), simplified simulation model.

The outer case (coating) of the pouch and the separator are essentially made of plastic, i.e. non-conducting materials. As they are more ductile, they deform easily with the shape of the intruding structure and electrically isolate it from the remainder of the cell, thus reducing the likelihood of an internal short circuit in the case of a thin nail penetrator (standard procedure). In the case of the non-standard test, the pin is compacting the cell locally until the separator film is so thin, that a contact between electrodes happens.

3.2 Vehicle Simulations

The results of the simulations performed on Yaris 1GEV were aggregated to identify worst cases for the vehicle model used. Two criteria were retained for this assessment:

- The maximum plastic strain of the battery housing
- The maximum acceleration peak in the battery pack

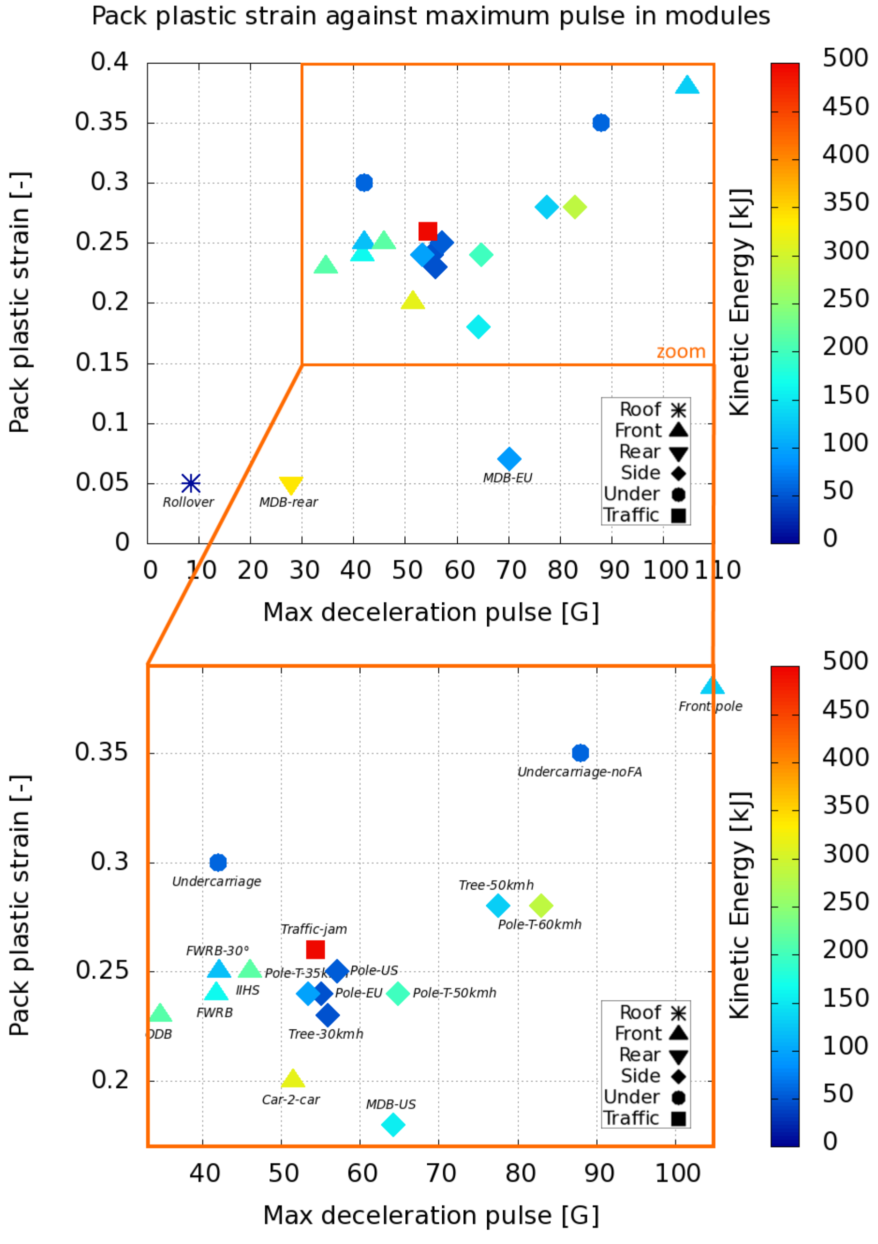

Fig.15: Simulation results in terms of battery pack plastic strain and maximum acceleration recorded in the modules, comparison between the different scenarios. The initial kinetic energy involved in each load case is also represented.

Following results can be observed in Fig.15:

- The most severe accident scenarios both in terms of the acceleration peak in the modules and the plastic deformation of the pack occur when there is direct contact or deformation of the battery structures, see especially the front pole impact (*Front-pole*).

- The comparison of the undercarriage impact with (*Undercarriage*) and without protection (*Undercarriage-noFA*) highlights the possibility of reducing the crash severity in such an accident scenario. In the latter case, the front axle avoids a direct impact onto the battery pack and thus reduces the acceleration peak in the battery by 52%.

- Rollover and rear impact scenario (*MDB-rear*, 80 km/h) are the least challenging tests for this type of electric car configuration.

- The crash severity does not correlate with the amount of kinetic energy involved in the accident. For example, the most severe scenario represented by the front pole impact (*Front-pole*) has a far lower amount of kinetic energy compared to the rear impact scenario (*MDB-rear*) which is not critical for the battery.

- Despite the important amount of initial kinetic energy, compatibility simulation (in the sense of frontal car to car crash with 40% overlap) with this concept doesn't belong to the most challenging simulations.

The following sections provide details for the worst case scenarios as well as unconventional load cases.

<u>Front pole scenario</u>

The frontal pole impact was identified to be the most severe impact in terms of the acceleration pulse and the deformation with regard to the high voltage battery package. Fig.16 shows how high the pulse in this special configuration is in comparison to the other scenarios.

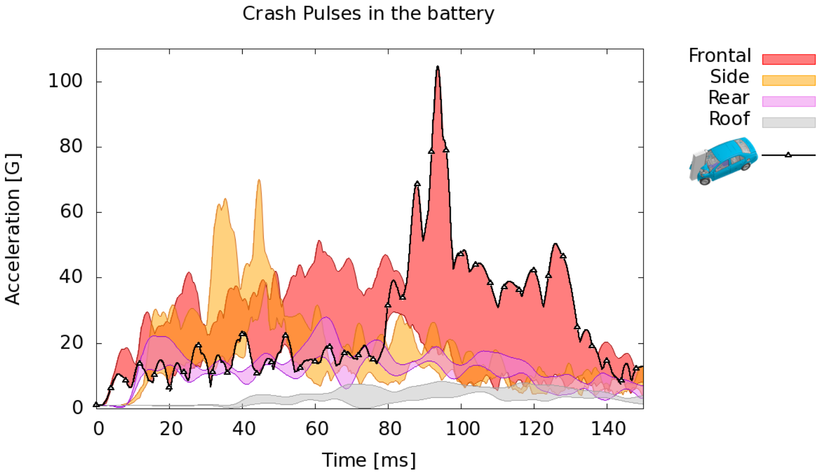

Fig.16: Acceleration corridors in the battery for frontal, side, rear and roof scenarios. Worst case scenario (front pole impact) is represented.

The most severe acceleration is characterized as following:

- Maximum peak at 105 g.
- Time duration at 70 g (2/3 of the maximum): 3.9 ms.

The reason for a high acceleration is that the pole only hits the bumper (in blue in Fig.17) as crashworthiness structure before impacting directly the firewall and the battery behind. No significant energy was dissipated by the vehicle in this process. This can be attributed to the lack of frontal pole impact test requirements and the modification of the ICE (Internal Combustion Engine) vehicle into an electric vehicle. In its original configuration, the pole would have struck the drivetrain.

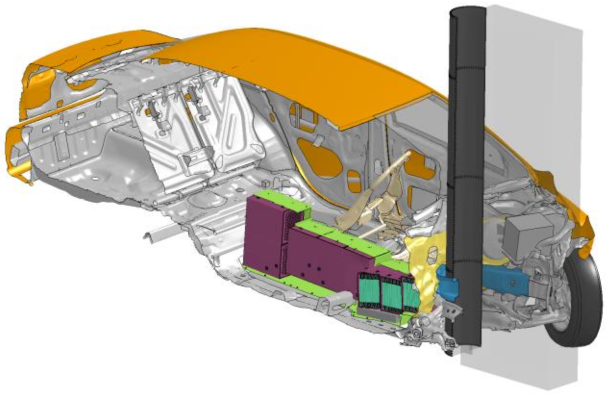

Fig.17: Front pole impact with 50 km/h. This scenario was found to be the most severe for the battery in terms of maximum forces in cells and maximum accelerations in the modules.

Undercarriage impact scenario

Undercarriage simulations showed that the vulnerability of a floor battery placement can result in very high loads inside the battery depending on the impact size, shape and speed. Due to time and practical reasons constructing the undercarriage impact barrier, this type of crash was not tested experimentally. However such undercarriage impact is assessed as critical, especially for vehicle concepts without sufficient protective structures in front of the battery pack. The characterization of the road debris (size, stiffness) and the definition of the scenario conditions are difficult parts of the stated research and a parametric study involving a variation of the ground clearance, of the impact velocity and of the debris type clearly needs further investigation.

Traffic jam situation

The maximum acceleration peak recorded in the B-pillar-left for this simulation is of 34 g (Fig.18) which is far under the maximum peak recorded in the BMW i3 test conducted at BASt. One can conclude that the whole structure of the i3 including the battery is much stiffer than the Yaris model used in simulations.

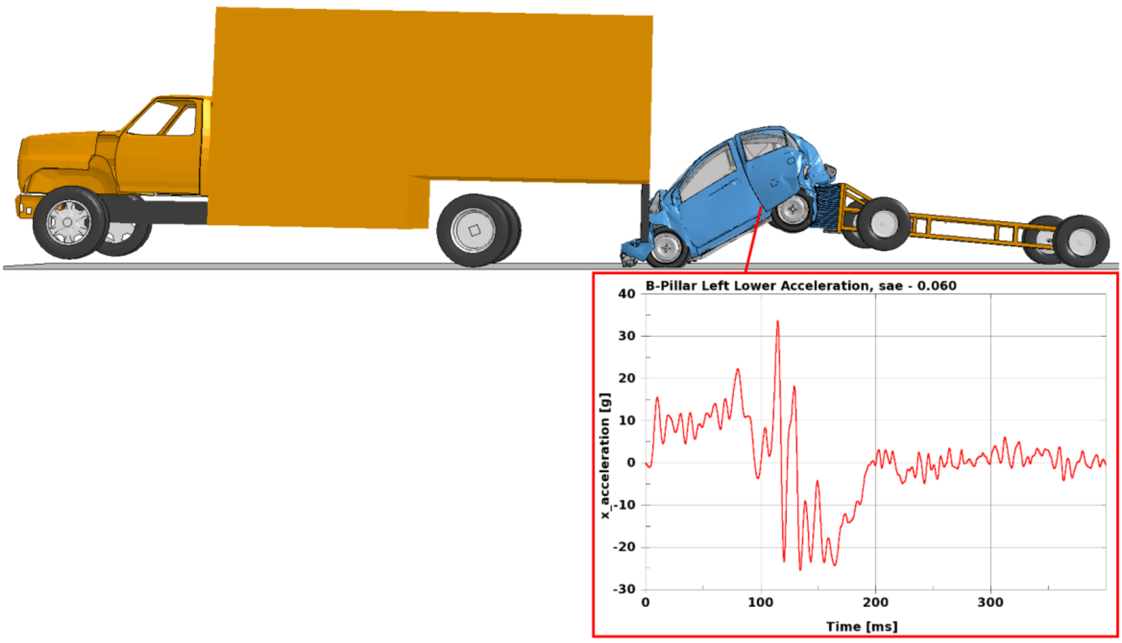

Fig.18: Simulation of a traffic jam accident.

4 Conclusions

The following conclusions regarding the crash safety of electric vehicles can be made based on the simulations performed in the EVERSAFE project (note: a 1GEV with a tunnel battery model was used):

On cell level

- The modelling of the cell allowed a better understanding of the different failure steps and the definition of a short-circuit criterion. The differences in results between the SAE J2464 penetration test and its variant (wider penetration) could be explained.

On battery/vehicle level

- Simulations based on current crash test regulations constituted a basis to compare with non-typical load cases and evaluate their severity.
- It was possible to identify precisely the part of the battery which was damaged most.
- For all simulated crash scenarios, none case led to intrusion into the battery.
- The worst case was identified as the front pole impact, where the maximum acceleration has reached 105 g in the front module and 70 g (2/3 of the maximum) during 3.9 ms.
- Non standardized undercarriage impact simulations have been performed which indicated severe loading to the HV battery and thus, would require further research.
- The amount of initial kinetic energy in the crash scenario does not directly correlate with the pulse severity in the battery.

5 Discussion

The simulations performed in EVERSAFE constitute a comprehensive overview of standardized as well as non-standardized crash load cases that cover a wide spectrum of accident scenarios. Although simulations were done with a 1GEV, these results give general guidance towards scenarios that are most challenging to battery packs placed centrally in the tunnel. The results from this task were used to support the development of general recommendations in the project. For alternative battery pack placements, similar studies may need to be performed before such recommendations can be made, as the severity of a given load case may strongly differ, depending on the vehicle concept, Fig.19.

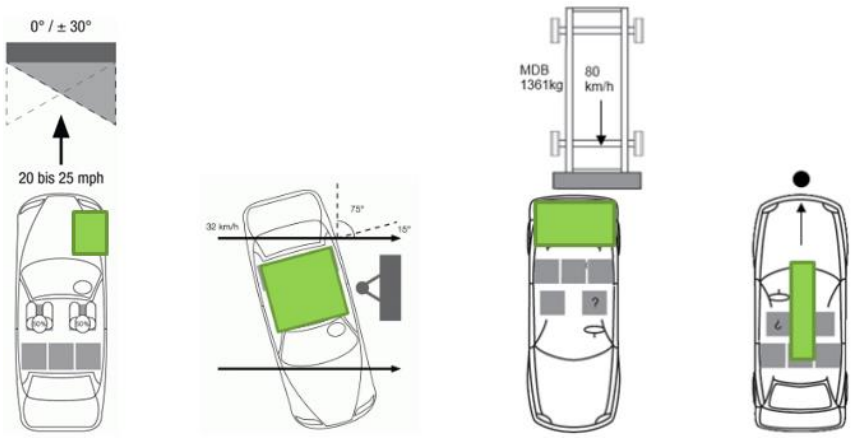

Fig.19: Results about the most critical scenario might strongly differ depending on the battery placement (green).

Some of the load cases investigated are intended to provoke direct damage to the battery and may not represent practical design conditions.

The severity assessment method developed allows the comparison of crash severity between different accident scenarios. However, it remains to be confirmed if the maximum acceleration in the battery pack is a suitable criterion to assess about the crash severity. Concerning the robustness of the battery against acceleration tests, it could be supposed that every cell on the market can overcome an acceleration peak of 150 g during 6 ms, as it is required by transport regulations. However, these tests are theoretically performed with unloaded cells and the behavior of loaded cells by such accelerations should be investigated. Results from the BMW i3 test (45 g) indicated not any thermal activity.

Some cases of fires in experimental tests by OEMs were mainly due to cable or surrounding electronic component failures. Such a level of detail has not been reached in the Yaris 1GEV model but should be an area of concern for further studies.

The conclusions drawn from crash simulations on the modified 1GEV (Yaris) must be made carefully as the new model is no longer a true production vehicle and there is no validation proof for its performance. However it is a useful surrogate until such 2GEV models can be made available to research projects. The Toyota Yaris Sedan was not designed specifically as platform for electric vehicles, hence caution should be taken to interpret the simulation results. One example is the worst case with the frontal pole impact. An under view of the front structure deformation between the Yaris model and the C30 1GEV model in this type of accident highlights the important difference in intrusion, see Fig.20.

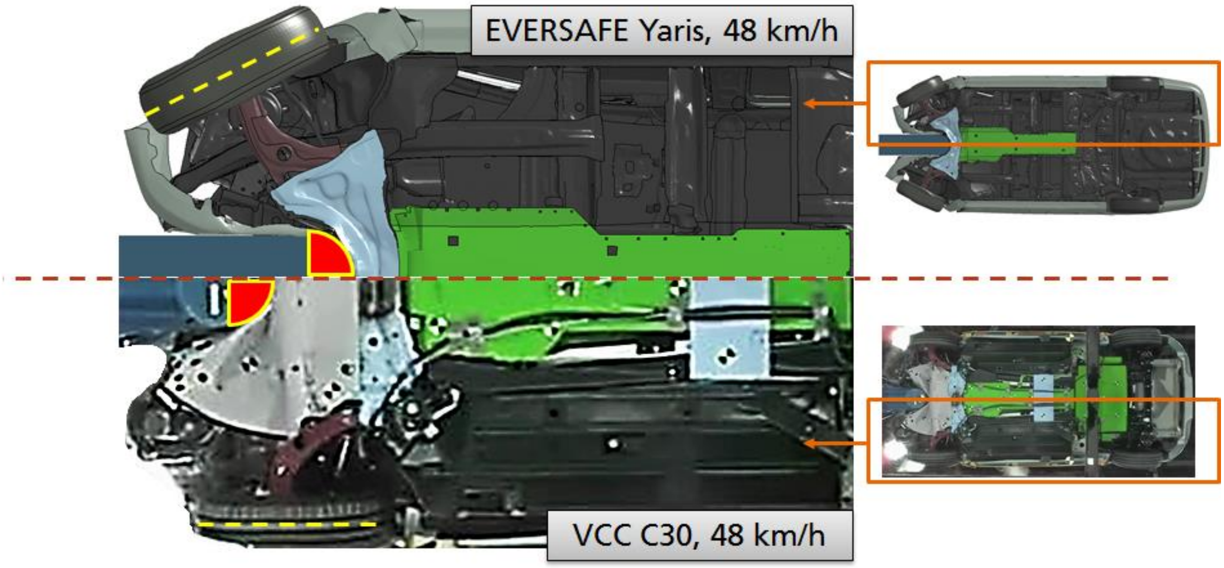

Fig.20: Comparison in front pole impact between VCC C30 at 48 km/h (bottom) and Toyota Yaris 1GEV at the same velocity (top).

Substantially less intrusion is to be seen on the C30 (bottom half of image). The steering components are not even impacted, in contrary to the Toyota Yaris (see front wheels orientation). The Yaris model could be considered as a worst case in comparison with optimized 1GEVs models.

6 Literature

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