Crash Simulation for Biomechanical Research

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Abstract

Since a number of human models have been developed it appears sensible to use these models also in the accident analysis. Especially the understanding of injury mechanisms and probably even injury risk curves can be significantly improved when interesting accidents are reconstructed using human body models. However, an important limitation for utilising human models for accident reconstruction is the effort needed to develop detailed FE models of the accident partners or to prepare the human model reconstruction by running physical accident reconstructions.

The proposed approach for using human models for accident reconstruction is to use simplified and parametric car models. These models can be adapted to the crash opponents in a fast and cost effective way. Although, accuracy is less compared to detailed FE models, the relevant change in velocity can be simulated well, indicating that the computation of a detailed crash pulse is not needed.

Two frontal impact test accidents that were reconstructed experimentally and using the parametric car models are indicating sufficient correlation of the adapted parametric car models with the full scale crash reconstructions. However, further developments of the parametric models to be capable for the use in lateral impacts and rear impacts are needed. For the PC Crash simulation runs the output sampling rate is too large to allow sufficient analysis. In addition the performance appears to be too general.

INTRODUCTION

Accident research allows to statistically analyse a set of accidents for example to review accident causation, injury pattern and effectiveness of safety devices. However, for more detailed investigation often single case studies are used to better understand injury causation, injury criteria etc.

Adolph et al. [1] for example studied lower spine injuries and concluded that frontal accidents not involving the standard crash structures and frontal accidents involving an important lateral component are prone for low severity accidents with lower spine injuries. However, they were unable to explain how these accident mechanisms cause these injuries.

In a sequence of child safety projects single accident cases were experimentally reconstructed to pair the injury severity with the dummy readings [2]. This approach allows more insight into the accident but the physical testing approach allows only to test with dummies that are not a perfect surrogate for humans. Human body models would probably offer a better opportunity but a full numerical accident reconstruction involving complete FE models of the involved opponents are too costly. Another issue is the lack of availability of the FEM vehicle models due to confidentiality and the usage of different types of crash solvers at different OEMs.

Technische Universität Berlin developed simplified Parametric Car Models for the analysis of car crash compatibility issues [3]. These models in principle would offer to adapt the vehicle models to the cars that were involved in the crash in an easy and cost effective way and to run an FE reconstruction of the accident in order to acquire the pulse and vehicle movement during the crash and to transfer this knowledge to interior models. This approach would help to gain additional knowledge from single accident cases at a relative low cost level.

In this study the approach is tested using accident cases that were already experimentally reconstructed in order to compare the simulation results with the testing results. In addition to the FE models the PC-Crash models will be used to compare an even less complicated approach. Here only the pulses are evaluated; in a next step dummy readings need to be gathered.

DESCRIPTION OF THE METHODOLOGY

A general overview of the proposed methodology is shown in Figure 1.

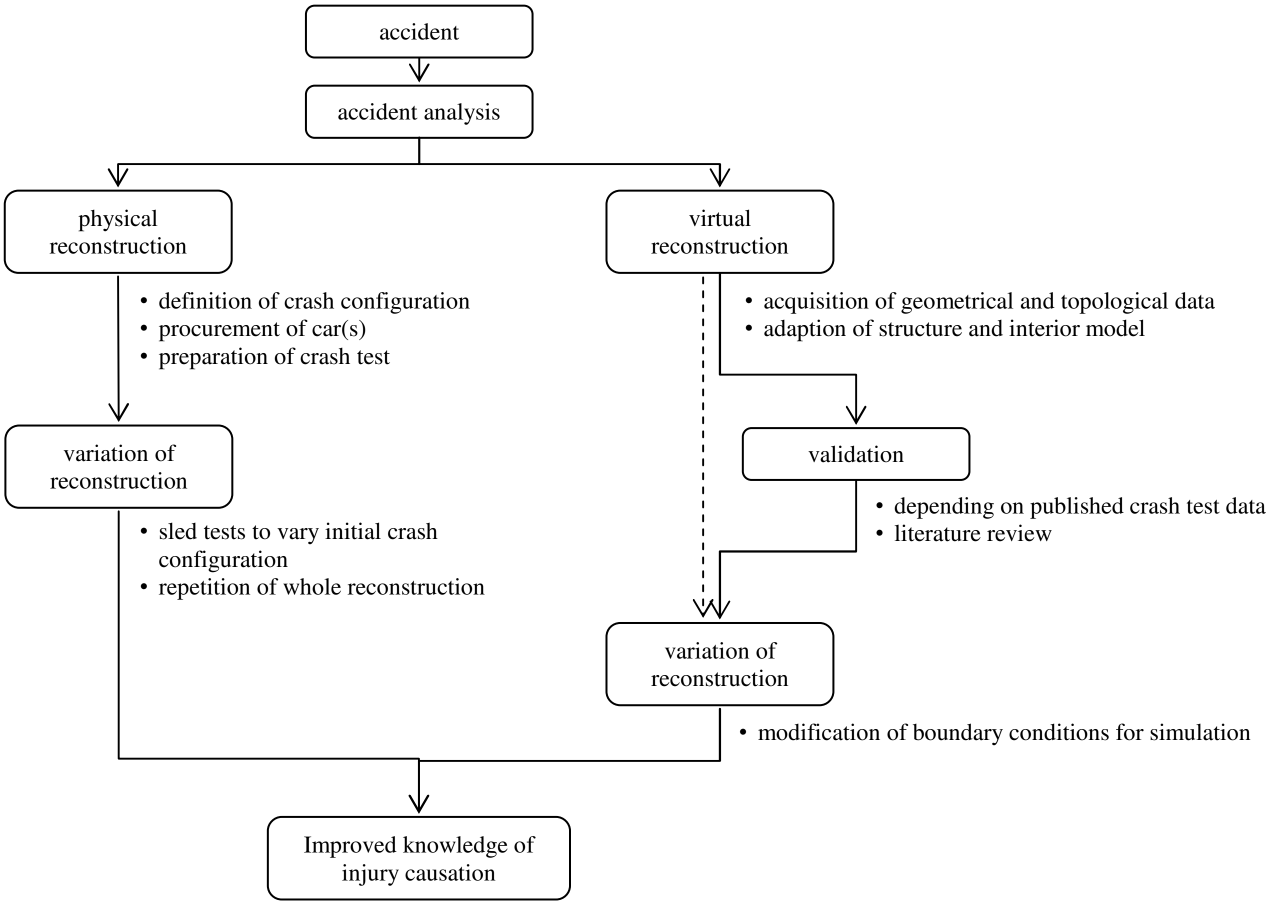


Figure 1: Comparison of physical and virtual reconstruction

Today accident reconstruction for biomechanical research often is done by physical crashes. This offers the advantage to replicate the real accident in detail, but requires a detailed accident analysis to minimise the number of unknown variables. To limit the costs only one full-scale crash can be conducted. Depending on the correlation of real accident and reconstruction sled tests are used to vary parameters of the crash condition. But here only minor changes can be realised because initial velocity and crash pulse as well as impact location and impact angle are fixed due to the conducted full-scale crash. However, variation of seat and seating position or different kinds of misuses with regards to the usage of CRS are possible. The most important limitation is that only ATDs can be used in physical reconstruction to investigate injury mechanisms. Thereby requirements like robust design, repeatability and reproducibility restrict the significance of the measurements and the correlation to real human beings.

The availability of human body models (HBMs) offers the possibility to use virtual surrogates for accident reconstruction providing detailed information about injury causation. However, the usage of those HBMs only makes sense if there is an appropriate virtual environment to simulate the accident. In order to ensure an appropriate virtual environment it would be best to use detailed FEM models of the accident partners. This would guarantee validated models and therefore the best correlation to the crash performance. But typically the OEM FEM models are validated only for the specific load cases as required in compulsory and consumer crash tests. Furthermore the FEM models are not available due to confidentiality reasons and they are modelled in different crash codes depending on the manufacturer; making it difficult to use them in one common simulation. Alternatively generic models are available representing typical characteristics of crash performance of a vehicle or an occupant protection system [3]. But due to the generic design their validity is limited to general evidence. Their usage for specific analysis as needed for accident reconstruction is not sensible.

The development of parametric models closes this gap. As explained in detail in the following section the parametric design allows the adaption of a baseline model to represent the specific characteristics of the accident partners in terms of mechanical behaviour of the crash structures. Thereby the validity of the numerical models can be confirmed with publicly available crash test data. Amongst the usage of HBMs one further advantage is the limited effort needed to vary the boundary conditions for the simulations. Thus a better adaption of the crash configuration to the real accident is possible which lead to a better understanding of injury causation.

Parametric Car Models – PCMs

The basic idea of the PCMs was to develop a tool to investigate structural interaction in frontal car-to-car crashes. Thereby the FEM models should have the capability to represent typical structural concepts of the crash relevant structures that can be found in different vehicle classes. To fulfil this requirement a full implicit parametric CAD model of a vehicle was developed [3]. This offered the possibility to modify geometry and topology of the crash relevant structures in a time efficient manner. In addition the specific CAD software can automatically create a computable FEM model without further pre-processing. To allow a larger degree of freedom for the geometrical and topological modifications (e.g. changing the distance between the longitudinal members or changing the height of the sub frame) all front end structures were modelled in a simplified manner, see Figure 2. That means all components of the power train were combined into one rigid structure and the wheel suspension was simplified to represent the wheel kinematics. However, the primary energy absorbing structures and the secondary energy absorbing structures as well, were modelled to represent their typical mechanical behaviour during the crash like folding, bending and Euler buckling.

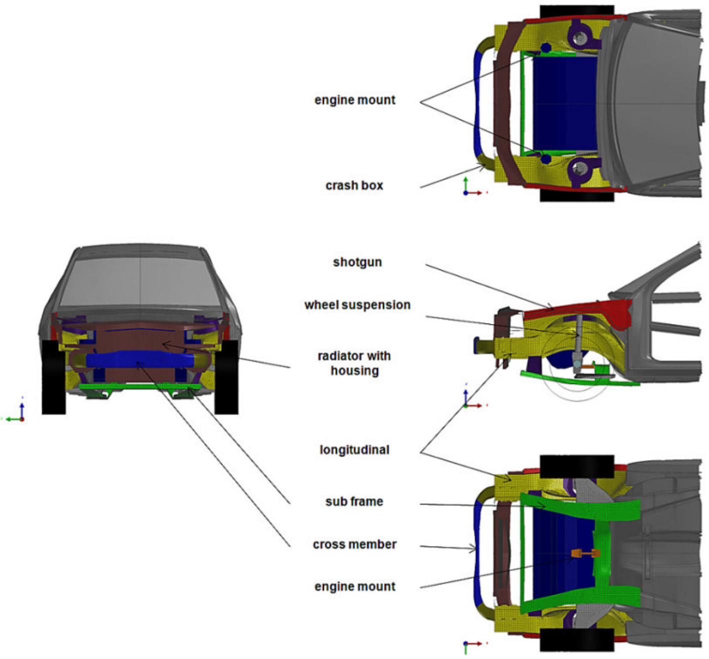


Figure 2: Front end structures of the PCMs [3]

Because the combination of the power train components into one common part lead to untypical deformation pattern in the PDB test procedure [4] the approach of the PCMs was reviewed and a second generation was modelled, based on the same modelling approach. The main improvements are the generic design of the front end structures derived from a geometrical database [5], more realistic design of power train components (e.g. separated engine and gear box, longitudinal or lateral engines, cooler and cooler housing) and wheel suspension. Furthermore a fourth vehicle class representing off-road vehicles was added to the existing super mini, family and executive car classes see Figure 3.

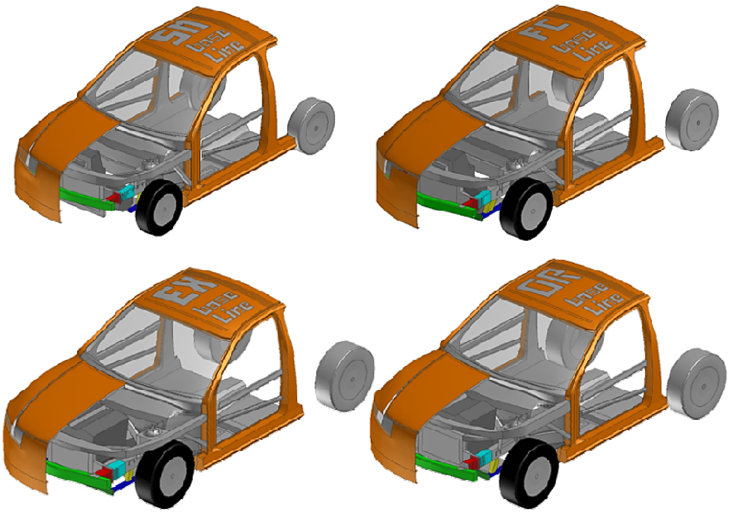


Figure 3: Vehicle fleet of 2nd generation of PCMs (top left: Supermini; top right: Family car; bottom left: Executive; bottom right: Off-roader)

To ensure model quality and transferability of the results efforts were spent to verify the modelling approach and to validate the crash performance of the improved PCMs. Crash test data of FWRB 56 (Full Width Rigid Barrier, 56 km/h closing speed, as used e.g., for US NCAP) and ODB 64 (Offset Deformable Barrier, 40% overlap, 64 km/h closing speed, as used e.g., for IIHS) crashes, in combination with low speed crashes (repair crashes defined by RCAR) were used to derive a generic crash performance for each vehicle class. Exemplarily the crash performance of the Super Mini model (SM) in comparison to reference cars is shown in Figure 4.

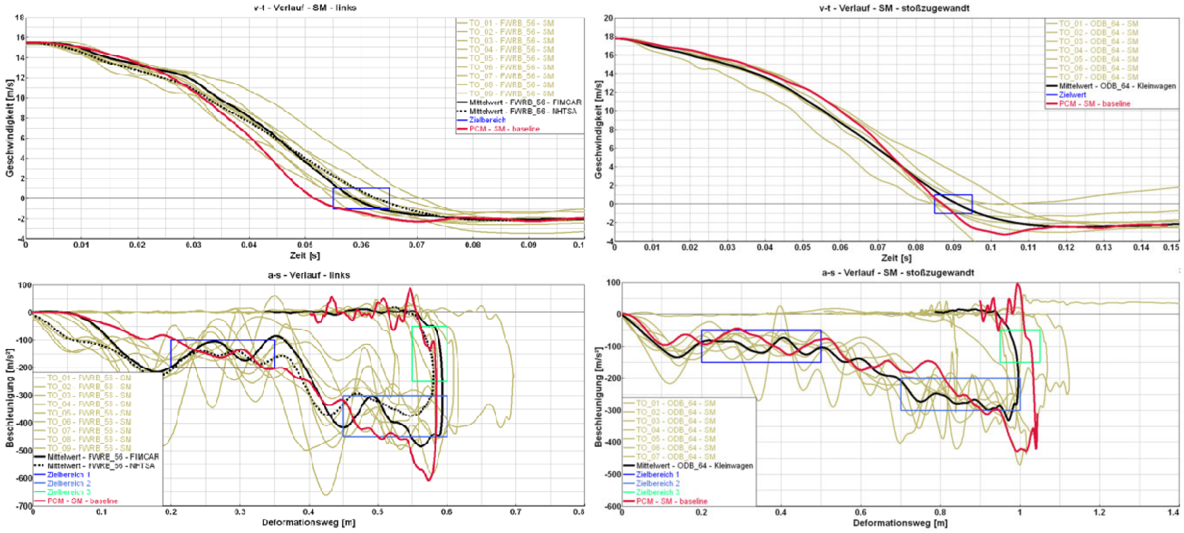


Figure 4: Crash performance of Super Mini model (left – FWRB 56; right – ODB 64)

The generic design and crash performance of the 2nd generation PCMs with regards to the corresponding vehicle class is a good starting point to adapt the models to specific cars. Because the crash performance mainly is controlled by the crash relevant structures the implicit parametric CAD models allows fast and robust modification of the baseline structures. Once the geometry and topology of the case car is modelled only slight adjustments of the stiffness of the structures will be necessary.

To adjust the crash performance public available crash test data can be used as well as published data of used materials.

DESCRIPTION OF THE SAMPLE ACCIDENTS

The following selection criteria were used for the definition of the cases to be checked from the experimentally reconstructed accidents from the CHILD and the CASPER project:

- frontal impact (the PCMs were developed for frontal impact)
- impact against rigid object (in order to reduce the modelling effort and variability for the initial investigations by using one car only)

Furthermore it was important that accident data as well as reconstruction data was made available by the owner of the data for this study. Finally after selecting the first accident it appeared sensible to use as the second accident one with a similar case car. This approach allows to check the robustness of the model for different impact situations which was ranked higher than to show for two different cars that the models can be created.

Accident 1

The driver of a VW Polo 6N (model introduction 1994) went out her line, in the following the car touched a tunnel wall and impacted with the right side (off-centred by approx. 250 – 300 mm) a pole including a concrete block below the pole (actually the base of the pole). The impact speed was estimated to be between 50 and 55 km/h.

The female driver of the car sustained MAIS 2 injuries (injuries at head, chest and abdomen). The 3 years old boy sitting behind the driver using a backless booster sustained AIS 3 chest injuries, AIS 5 abdomen injuries and AIS 5 spinal injuries.

For the experimental reconstruction the set-up was simplified using a rigid off-set barrier with a rounded edge representing the combination of pole and concrete base of the pole.

The deformation pattern of the accident car and the reconstruction car is shown in Figure 5. In the accident car the right shotgun is less deformed than the rest of the right car front, which is not the case in the reconstruction. However, the reconstruction was considered to be valid considering that the majority of energy was expected to be absorbed by the longitudinals and the engine block.

accident car reconstruction car

Figure 5: Comparison of vehicle damage between accident and accident reconstruction Accident 1

For the numerical reconstruction using PC Crash both configurations, the one corresponding to the accident and the one corresponding to the experimental reconstruction are analysed. For the FE model only the configuration according to the reconstruction is considered. The crash pulses are shown below in the Results section and the Discussion section together with the simulation results.

It is important to mention that it appeared to be difficult to reproduce the occupant kinematics causing the observed injuries with the Q3 dummy. In the end three sled tests using an approximation of the crash pulse were conducted with different initial dummy postures. Finally a posture with the feet at the seat cushion and a sloughed posture was judged to reproduce the expected occupant kinematics best. However, it can be expected that using a human model would allow much better insight.

Accident 2

As mentioned before the main reason for selecting this accident was to use the same vehicle model to check model robustness. Although both accidents were pole impacts the first experimental reconstruction was conducted against an off-set rigid barrier. The experimental reconstruction of Accident 2 represented an almost centred impact against a pole. In addition to the differences in the impact opponent the impact speed was different too.

The driver of a VW Polo 6N (model introduction 1994) left the road to her left side and collided purely frontally with an off-set of approx. 60 mm to the centre line against a pole with a diameter of 330 mm. The impact speed was calculated to approx. 35 km/h.

The female driver sustained MAIS 1 injuries while the 7 years old boy using the front passenger seat suffered from an AIS 2 abdominal injuries, an AIS 1 neck distorsion and an AIS 1 thorax contusion. The child was using a backless booster. The front passenger seat airbag deployed during the accident (however, the reconstruction video did not show important interaction between dummy and airbag, except some minor contacts between extremities and airbag).

The deformation pattern between accident and experimental reconstruction are similar, see Figure 6. As for Accident 1 crash pulses are shown below together with the simulation results.

accident car reconstruction car

Figure 6: Comparison of vehicle damage between accident and accident reconstruction Accident 2

PREPARATION OF THE ADAPTED PARAMETRIC MODEL

The following section describes the adaption of the parametric structure model to the VW Polo 6N (model introduction 1994) which is further referred to as case car. In the first part the geometrical adaption of the 2nd generation PCMs (Supermini), further referred to as baseline PCM, is explained briefly. Here, the fitting of the generic structures of the baseline PCM to the case car is described. In the second part the validation of the model is described.

Geometrical adaptation

The geometrical database [5] used to create geometry and topology of the PCMs provides information of approx. 50 pre-defined measurement points for the front structures. Most of the measurement points describe the distance to fix references like the ground or centre of the front axle. However, several points are in relation to other structures and create variable measurement chains which can differ depending on absence or presence of components like the compressor of the air conditioner or different packages influencing the position of e.g. radiator or alternator.

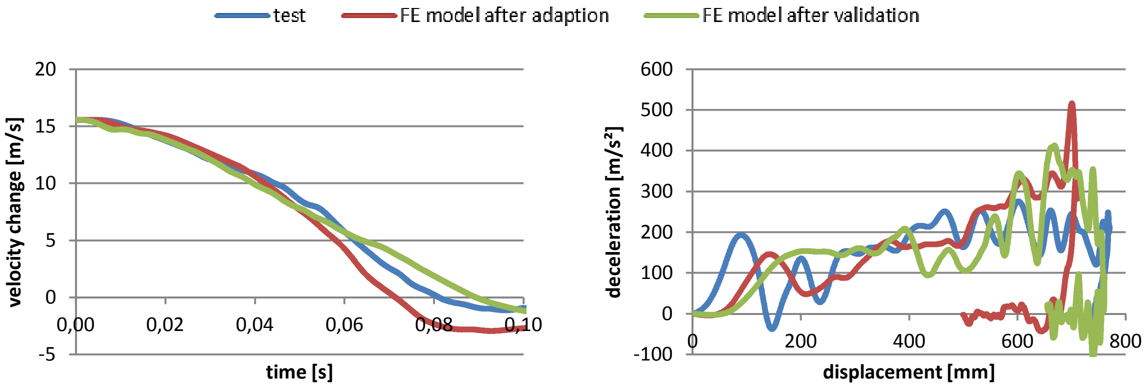
To adapt the baseline PCM to the case car the measurement points according to the geometrical database were measured and transferred to the implicit parametric CAD model. In addition to the pre-defined points new components were added to the engine compartment: starter battery and air filter. Because the position and the mounting of these components differ depending on the package, they are not included in the baseline PCMs. The data acquisition was done without disassembling the front end structures of the case car, except the front bumper. Thus, only little effort was needed to collect all relevant data. For trained staff it can be expected that one person day would be sufficient to acquire the data. General material data was acquired from literature [6].

Validation test

A large number of cars is already crash tested and the results are published in more or less detail. In order to validate the adapted model public available crash test results of the accident car were reviewed. For the case car of this study the following crash test results were published:

- Euro NCAP (40% overlap off-set deformable barrier, 64 km/h)
- auto motor und sport (50% overlap off-set rigid barrier with 30°, 55 km/h)
- FWDB test at NHTSA crash test data base (full-width deformable element, 56 km/h)

The Euro NCAP raw data appeared to not be available for this study. The auto motor and sport test was judged to be too similar with the experimental reconstruction of Accident 1 to proof the concept. Basically it is an advantage to correlate the response of the FEM model with the real car in a test that is close to the accident to be considered. However, the idea of the proposed methodology is to use only geometrical data of the crash relevant structures to adapt the generic FEM models to the specific car. Depending on the availability of crash test data the crash performance of the FEM model can be validated within this intermediate step. But due to the diverse number of real crash configurations these crash test data normally do not represent the real accident. Therefore the validation of the adapted FEM model is just a possibility to ensure the model quality but is not needed in principle. Following that the FWDB test was used to optimise the model.



velocity change characteristics

deceleration-displacement plots

Figure 7: Crash performance of adapted and validated PCM

Figure 7 exemplarily shows the crash performance of the PCM after only geometrical and topological adaption and after the validation process. The PCM after adaption (red line) showed relative stiff deformation behaviour, resulting in an early time to zero for the velocity at approx. 70 ms and a too short deformation length, approx. 700 mm. By stepwise decreasing the wall thickness of the rear parts of the longitudinal members and the shotgun the deceleration peak at the end of the crash could be decreased. Thus a good correlation to the maximum deformation could be achieved. The lower deceleration level had a positive influence on the velocity, in particular after 50 ms of the crash. In total the validation process took two person days which is comparable to the time needed to prepare a crash test.

COMPARISON OF ACCIDENT RECONSTRUCTION APPROACHES

Accident 1

For Accident 1 the pulse of the FE simulation approximates the pulse of the test quite well during the first 50 ms, see Figure 8. The PC Crash simulations show a low time resolution and following that serrated curves. The output time step was set to the minimum that is allowed by PC-Crash. However, the large distance between the data points creates uncertainties as the frequency of the measurement signal is much smaller than the sampling rate. The differences between the pole configuration and the configuration with the off-set rigid impactor are small in the PC Crash simulations. As mentioned before in the FE simulation only the chosen approach for the experimental accident reconstruction was simulated.

It needs to be acknowledged that the stiffnesses in the PC Crash simulation of the collision partners were considerably increased compared to the standard stiffness in order to avoid that the car passes through the object.

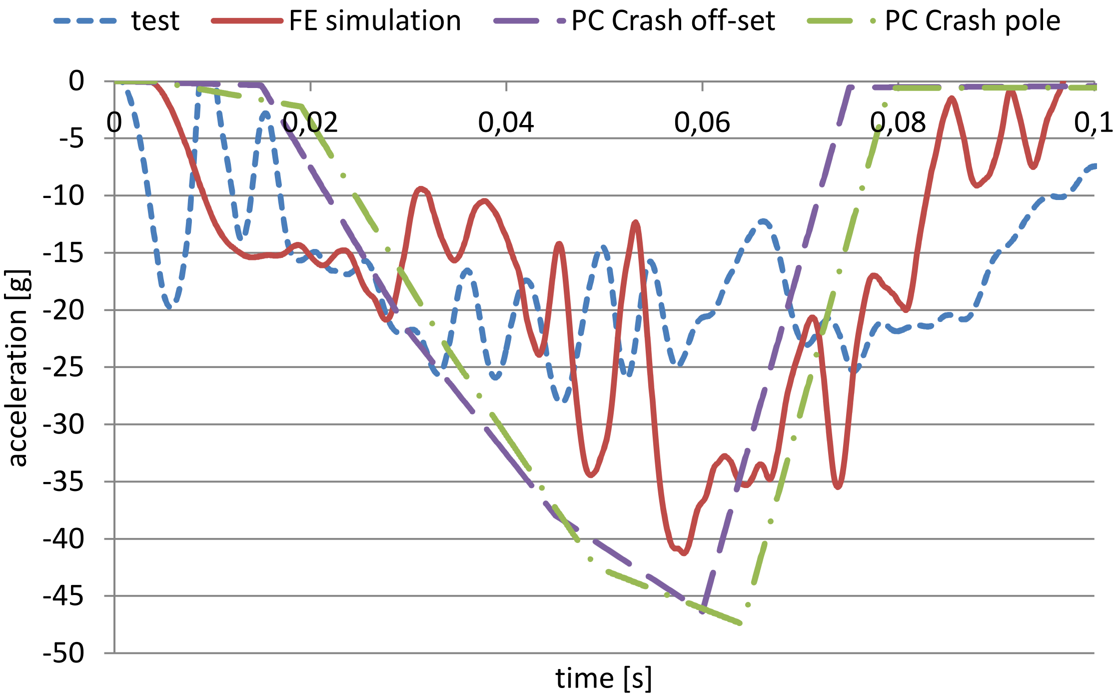


Figure 8: Pulse comparison Accident 1

Accident 2

The pulse comparison between experimental accident reconstruction and the numerical simulation approaches in Accident 2 appears to be much better than for Accident 1. Similarly to Accident 1 the PC Crash plot shows a low sampling rate. The FE model approximates the test result sufficiently for the whole duration of the impact, see Figure 9.

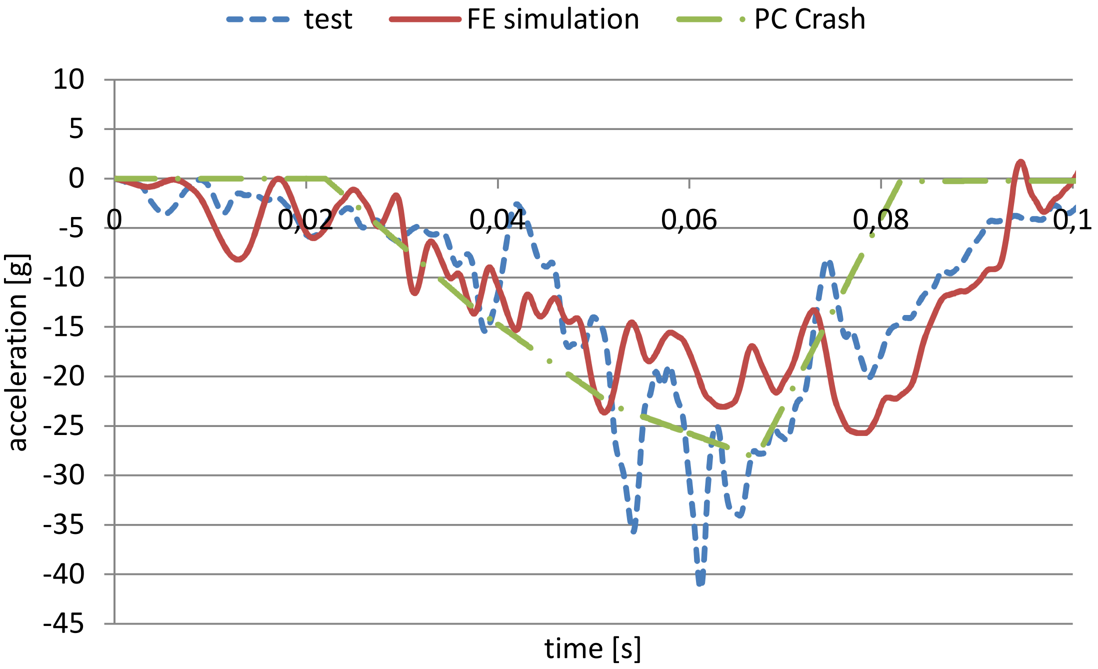


Figure 9: Pulse comparison Accident 2

DISCUSSION

Pulse Criteria

Before starting to discuss the simulation results it is important to start with a general discussion on pulse criteria. Pulse criteria are normally used to judge the quality of sled tests w.r.t. the car test they should represent. There are mandatory pulse requirements, e.g., as defined by UNECE Regulation 94 for sled tests and by Euro NCAP for the knee mapping protocol [7]. Furthermore there are internal pulse requirements defined by car manufacturers for their suppliers or defined by the owner of the sled facility. Finally there are fixed corridors defined for acceleration curves to be met, e.g., for sled tests according to UNECE Regulation 16 and 44.

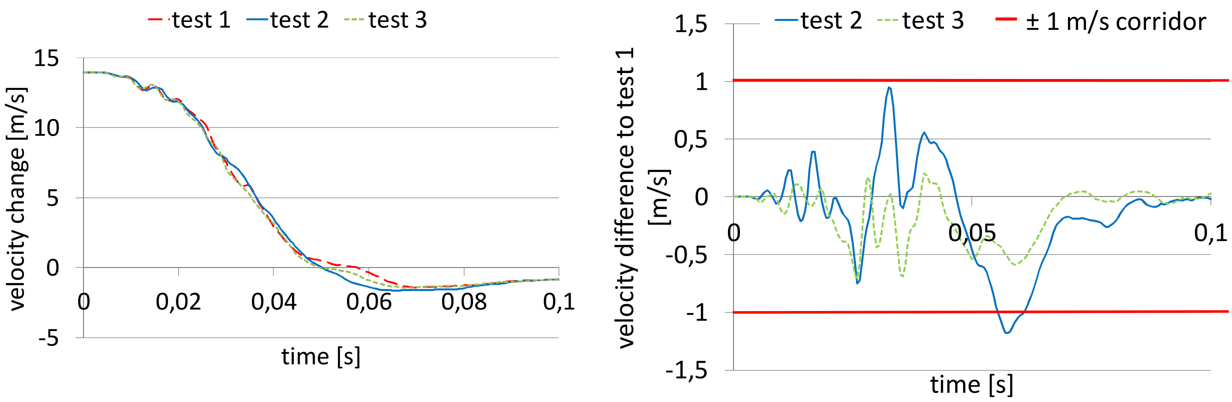
There is a general trend not to assess the acceleration itself but the velocity change curves. This account for the fact that the acceleration signal is often spiky and difficult to match while it is assumed that individual spikes do not influence the occupant loading in a significant way. In order to account for the spikes an acceleration corridor is often quite wide (e.g., UNECE Regulation 44 corridor). When computing the velocity change curve form the acceleration curve the signal is somehow filtered resulting in a smoother curve. This allows a narrower corridor.

For UNECE Regulation 94 a tolerance of +/- 1 m/s is allowed. The same requirement is often used in internal specifications according to interviews with OEM and users of sled test facilities. However, there are also more stringent requirements. For example the delta-v corridor for the new side impact test procedure for CRS according to UNECE Regulation 129 defines a maximum tolerance between lower band and upper band of approx. 1.2 m/s. Similarly Euro NCAP requires a tolerance of +/- 0.6 m/s while after 50 ms the sled may be faster than that [7].

Following the pulse criteria described above it appears sensible to follow the velocity change approach.

In order to fix a reasonable threshold a number of repeated car tests are analysed below. The selected tests are always tests against rigid objects in order to rate only the repeatability of the car and not the repeatability of a deformable element. In most of the cases old and used cars were utilised.

In test series A three full width rigid barrier tests using a city car that was sold between 1996 and 2008 are analysed. All tests were conducted using used cars with introduction year in 1996. Test 3 exceeds the 0.6 m/s tolerance band as defined by Euro NCAP, see Figure 10. Test 2 touches the 1 m/s limit before 50 ms and exceeds it after 50 ms.

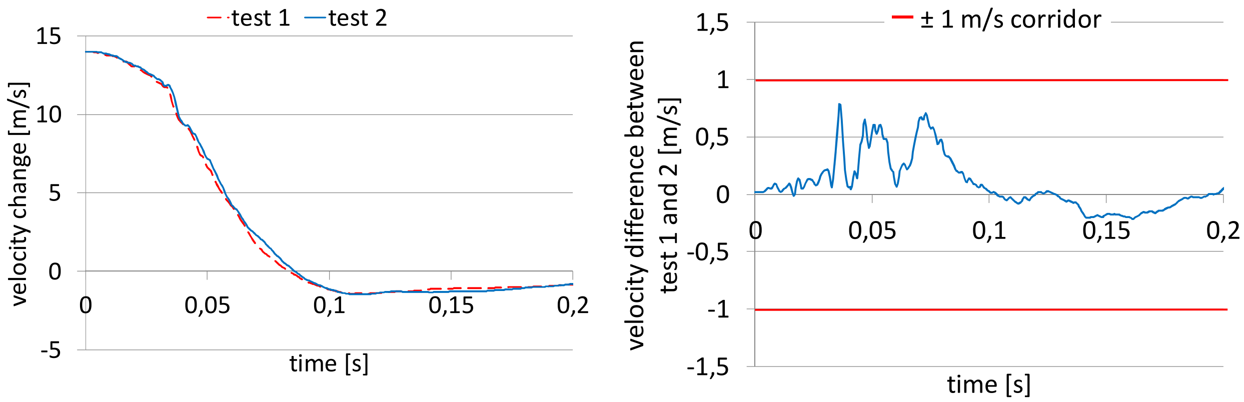


velocity change characteristics of test 1, 2 and 3

velocity deviation between test 1 compared to tests 2 and 3

Figure 10: Velocity change comparison in test series A

In test series B and C a Super Mini with first introduction of the used facelift model in 1997 was crashed against a rigid off-set barrier with a horizontal off-set of 40% and a ground clearance of the barrier forcing an underride behaviour of the car. The situation was meant to represent an actual frontal collision accident of the respective car against the rear end of a truck. The tests were conducted 4 times but using two different impact velocities in each case for two tests. Furthermore for each speed different dummies were used (5th percentile or 50th percentile). Following that the complete test series was split into test series B and C to better account for the different impact speed and the different test weight; it is important to note, that the different test mass resulted in a slightly different ride height causing different underride behaviour. In test series B the velocity change deviation between the two tests exceeds 0.6 m/s but stays within the 1 m/s criterion, see Figure 11.

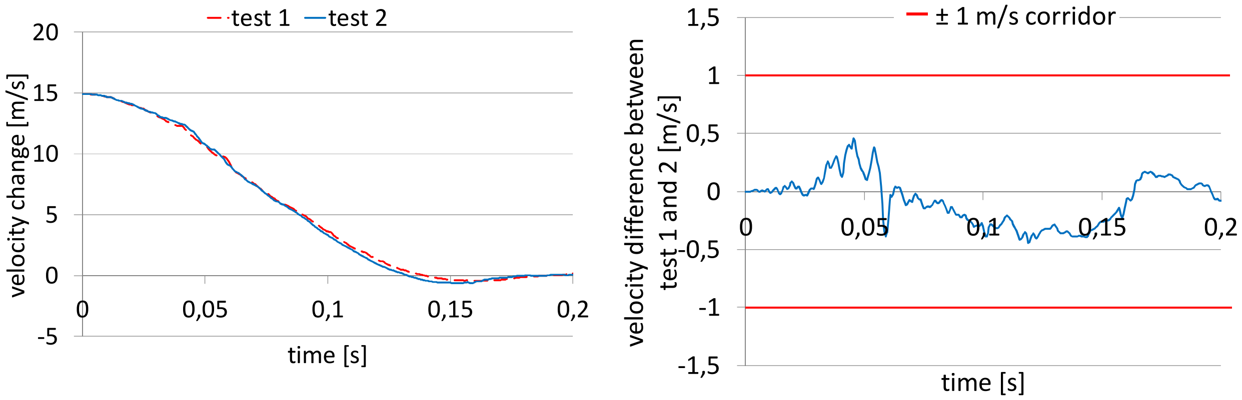


velocity change characteristics of test 1 and2

velocity deviation between test 1 and 2

Figure 11: Velocity change comparison in test series B

In test series C the deviation in velocity change never exceeds the 0.6 m/s criterion, see Figure 12.

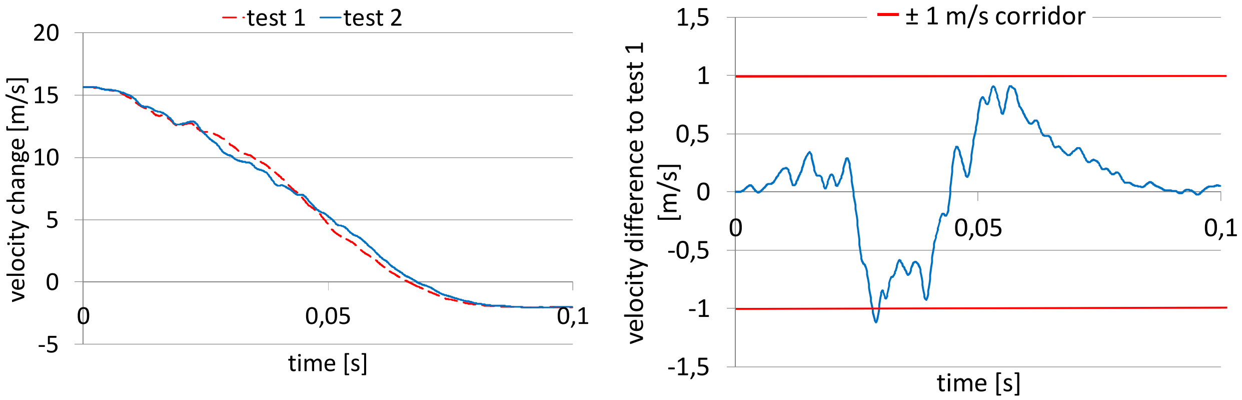


velocity change characteristics of test 1 and 2 velocity deviation between test 1 and 2

Figure 12: Velocity change comparison in test series C

While test series A, B and C were conducted at TU Berlin test series D is acquired from the NHTSA crash test data base [8]. The rational behind looking for another test series is to check another test lab on the one hand and to include a newer car in the study on the other hand. By random choice a large family car (Model Year 2011) that was tested twice according to the US NCAP full frontal test protocol was selected.

In the two tests the velocity difference exceeded the 1 m/s criterion for a short peak and the 0.6 m/s criterion several times, see Figure 13.



velocity change characteristics of test 1 and 2 velocity deviation between test 1 and 2

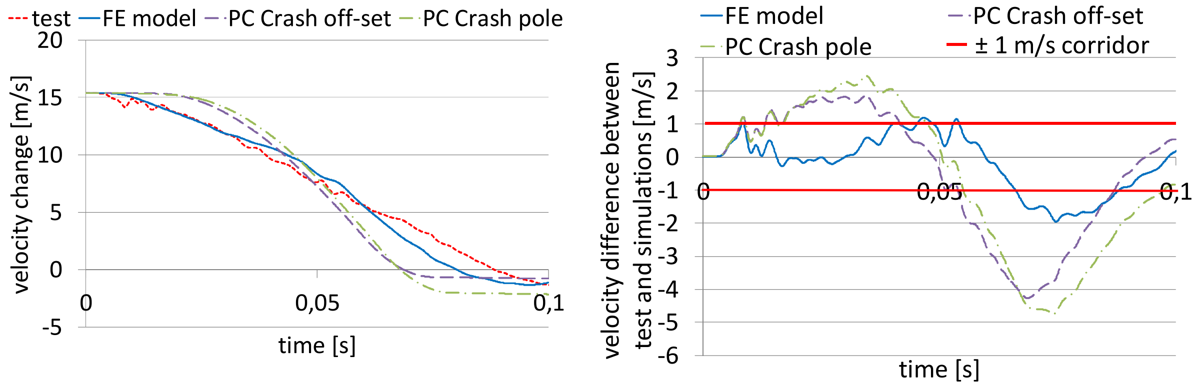
Figure 13: Velocity change comparison in test series D

To conclude the section on pulse criteria it appears to rate the quality of correlation between test and simulation for the accident reconstruction approach by the difference in velocity change. Repeated tests of old and modern cars show that the difference in the change of velocity between identical cars often exceeds 1 m/s in impact conditions against rigid stationary objects. For the assessment of quality of the accident reconstruction a deviation below 1 m/s can be considered as good and below 1.5 m/s as acceptable.

Accident 1

The structural loading in Accident 1 exceeds the loading from the model validation test FWDB. While the test speed is almost identical the validation test loaded both longitudinals while the accident involved only one. Following that the capability to predict loadings beyond the FWDB test could not be assessed beforehand. When analysing the deformation characteristics the longitudinals in the

FWDB test were approx. 400 mm deformed. This deformation length was exceeded in the accident simulation after 32 ms. Up to that time and even approx. 20 ms later the velocity difference between the FE simulation and the actual test mainly stayed below +/- 1 m/s, see Figure 14. After this time the model became too stiff resulting in exceeding 2 m/s. The PC Crash simulations exceeded 2 m/s in the beginning and 4 m/s in the later part of the simulation. In general the PC Crash models are too stiff. However, the stiffness is needed for an appropriate accident kinematics. Furthermore the low sampling rate for the PC Crash simulations contribute to large deviation between test and simulation results.



velocity change characteristics

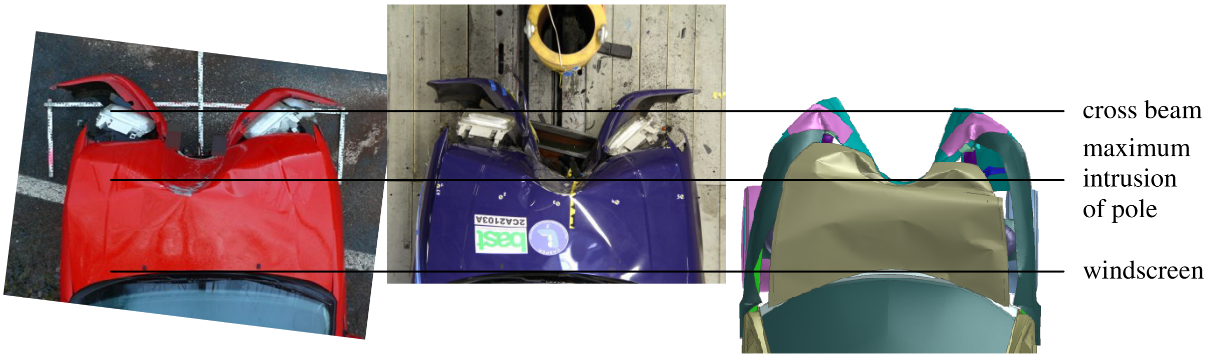
velocity deviation between test and simulations

Figure 14: Velocity change comparison in Accident 1

Accident 2

In contrast to Accident 1 the structural loading in Accident 2 stayed within the validation range of the FWDB test. However, it was questionable whether or not the crossbeam stiffness, that largely contribute to the crash performance in the centre pole impact while the influence is less in the FWDB test, was modelled adequately. The comparison of the deformation pattern as well as the pulse and velocity change indicates good correlation also for the crossbeam, see Figure 15. Even though it sounds sensible that the cross beam is an important factor in the investigated pole impact it has to be mentioned, that the typically cross beam is not designed to withstand heavy bending loads. Due to the centred impact Euler buckling occurred and the resistance of the cross beam decreased to a low level that did not affected the crash pulse. Therefore the good correlation could be a result of the geometrical fitting of the structures because the block building mechanism and the inboard bending of the longitudinals seems to be the most important factor in this accident. The simulation velocity change did deviate from the test velocity change less than 1 m/s.

For the PC-Crash simulation there seems to be an issue of the stiffness of the model. In order to avoid that the model runs through the pole the stiffness characteristics needed to be modified in a way that no rebound was observed.



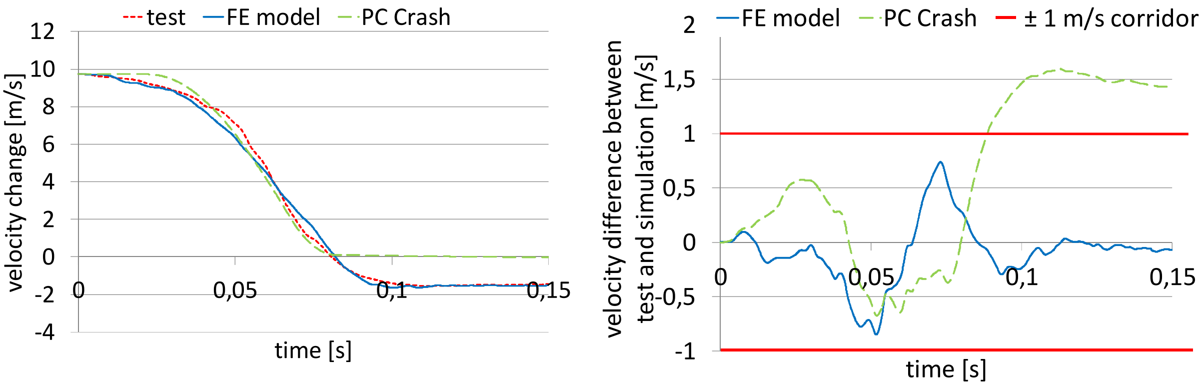
accident car

reconstruction car

numerical model

Figure 15: Comparison of deformation pattern of accident 2

For both simulations the time axis was shifted by 7 ms in order to obtain a better fit with the experimental reconstruction. This shift appears to be eligible as the first milliseconds of the crash are mainly defined by bumper and soft padding for pedestrian protection that is not represented in the FE model, Furthermore t0 seems not to be important for the injury causation. The shift was conducted visually by making the parts above and below the test curve virtually of the same size.



velocity change characteristics

velocity deviation between test and simulations

Figure 16: Velocity change comparison in Accident 2

CONCLUSION AND NEXT STEPS

In order to improve the insight into single accidents numerical accident reconstructions using Human Body Models would be beneficial. However, using OEM full FE models is normally not an option because these models are not available and are often incompatible between different brands because car manufacturers are using different tools. A solution could be the use of FE Parametric Car Models that are adopted to represent as good as possible the crash opponents.

As a first step one Parametric Car Model was adopted to an actual car that was used in two different experimental frontal impact accident reconstructions. For the adaptation geometrical information and the result from one published crash test was used. The two accident reconstructions were numerically repeated using the adopted parametric car model. However, only structural models without occupants were used.

In general the two numerical simulations indicate sufficient replication of the crash pulse between experimental and numerical accident reconstruction, i.e., deviation of the velocity change curve was for most of the time within general accepted limits. However, it is unclear how the observed deviations will influence the occupant output.

In parallel to the Parametric Car Model approach PC Crash simulations using the stiffness approach were conducted. They were proven to deviate from the experimental crash pulse too much and to deliver the output with a too low sampling rate.

In the next steps occupant models will be added in order to investigate the influence of deviations on the occupant outputs and to compare dummy readings between experimental and numerical accident reconstruction. Furthermore the Parametric Car Models need to be developed further to be suitable for other impact configurations than frontal impact.

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