A Simulation System for Testing Side Crashes, in Non-Traditional Seating Positions, for Self-Driving Cars

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Abstract: Historically, vehicle safety reflects the current state of the art and new innovations will continue to make our cars even safer in the future. Since its invention, the car has enjoyed a unique, triumphal procession. Safety plays a central role in the development of a car model today. The number of accidents has also risen, in line with the growth in traffic. In addition to carelessness or distraction at the wheel, the most common causes of accidents are excessive speed, risky maneuvers and disregard of traffic rules. The introduction of the speed limit on rural roads and the obligation to wear seat belts, were particularly important positive milestones. Two different methods are also used to check the effect of the individual technical options and safety, in the event of accidents. First are the crash tests. Here, an accident situation is simulated in practice, under realistic conditions. The other solution is the simulation. The Finite Element Method, behind this term, lies the virtual calculation of various consequences of an accident, on the basis of mathematical differential equations. The degree of deformation of various components or the entire car, as a whole, is examined by calculation.

Keywords: crash test; occupant safety; finite element method; electric vehicles; autonomous driving

1 Introduction

Safety technology played almost no role in the first automobiles that rolled down our streets at the beginning of the 20th Century. However, the increase in the power of engines with higher speeds and the increase in traffic have gradually led to the fact that cars are becoming more and more extensively equipped in this area. From the beginning to the present day, vehicle safety also reflects the current state of the art. New innovations should continue to make our cars even safer in the future. Since its invention, the car has enjoyed a unique triumphal procession. Not only the vehicles themselves, but also the necessary infrastructure, has been consistently developed. Safety plays a central role in the development of a car model today.

Today, the number of accidents is declining in many places, despite the steadily increasing volume of traffic. In addition to restrictions due to legal regulations, the modern safety equipment of the vehicles is also responsible for this. While the vehicles did not have a proper body at the beginning, this aspect became more important from around 1920. In addition to greater comfort and a wide range of options for shaping the appearance of the car, the body was also used specifically to improve stability. Above all, the protection of the occupants was initially in the foreground. Different systems emerged. From floor plates or frames on which the body is built, to lattice frames and the "space frame", from AUDI to the self-supporting body (monocoque), these are still used today, depending on the vehicle type. In the post-war period, the bodies were increasingly produced by the car manufacturers themselves and the principle of the self-supporting body gradually prevailed in passenger cars. The chassis and body form a single unit and the overall structure offers great stability to various loads (shearing or torsional loads). A body with a crumple zone was used for the first time in 1959 on the Mercedes Benz W111. It ensured that the impact energy in the event of an accident was initially absorbed by the body, so that the forces on the occupants were less. Today, the crumple zone in a vehicle has different tasks. First of all, the bumpers, for example, ensure that the energy can be absorbed in very small collisions and other vehicle parts are spared damage. In addition, the front part of the vehicle in particular is designed in such a way that the impact energy is reduced at medium speeds and the rear of the car remains as intact as possible. The latter in particular is designed to be particularly stable in order to minimize the risk of injury.

The number of accidents has also risen for a long time in line with the growth in traffic. In addition to carelessness or distraction at the wheel, the most common causes of accidents are excessive speed, risky maneuvers and disregard of traffic rules. Technical defects are also a reason. Due to the consistent upgrading of vehicles with the appropriate safety technology, the number of accidents has been declining since around 1970, despite the further increase in traffic. In addition, new rules and regulations gradually began to have an effect. The introduction of the speed limit on rural roads and the obligation to wear seat belts were particularly important milestones.

Two different methods are also used to check the effect of the individual technical options and safety in the event of accidents. First are the crash tests. Here, an accident situation is simulated in practice under realistic conditions. The vehicles are equipped with extensive sensor technology and the crash is documented on video from a wide variety of perspectives. "Crash Dummies" are used as the vehicle occupants. They are equipped with sensors and can provide information about the degree of an injury. In 1996, the testing company Euro NCAP (European New Car Assessment Program) was founded by the British Department for Transport and other European organizations quickly followed suit. The increasing publication of results from crash tests to inform consumers has led to vehicle safety becoming a greater focus in the development of new vehicles. Every year there are innovations in the assessment, so that the results are only really comparable within a year. The other solution is simulation. Finite Element Method (FEM), behind this term, lies the virtual calculation of various consequences of an accident, on the basis of differential equations. The degree of deformation of various components or the entire car as a whole, is examined by these calculations.

The possibilities of improving safety through driver assistance systems are becoming more and more extensive. By monitoring the traffic area around the vehicle with the help of a wide variety of sensors, they can be used to prevent accidents and driving errors caused by fatigue or carelessness. The more extensive the technology becomes, the more the vehicle approaches autonomous driving. As more and more modern technology is installed in vehicles, they have become heavier in recent years. To counteract this, innovative materials are increasingly being used for construction. Aluminum, magnesium, but also fiber composite materials help to reduce the weight. Depending on the intended use and type of component, the best possible material can be selected and, in the case of hybrid construction, assembled into a body. The modular design that is predominantly common today ensures that each individual part offers maximum safety thanks to its specific design and contributes to the overall stability of the body.

The progressive developments in the field of artificial intelligence and the first practical projects are currently testing the use of self-driving vehicles in road traffic. The current state of technology already makes this possible, but completely different questions arise here. In various emergency situations, the vehicle system may have to make decisions that affect people's lives. The example here is a situation in which the vehicle is moving towards two people and only one of them could be saved, by an evasive maneuver. In order to take the various security aspects into account, there are also ethical criteria that are difficult to implement with the automatic control of artificial intelligence. The question of liability in the event of a simple accident has also not yet been clarified. Self-learning systems and increasingly sophisticated mathematical calculation models should ensure maximum security here. Before autonomous driving can be integrated into everyday life, however, a number of open questions must first be clarified. Adequate protection against unauthorized access to the systems from outside is also not yet fully developed.

2 Vehicle Occupant Safety

Vehicle occupant safety refers to the combination of active and passive vehicle safety. While active vehicle safety helps to avoid accidents, passive vehicle safety deals with measures to minimize the consequences of an accident.

Active safety systems record driving conditions using sensors and intervene to support driving operations. A distance cruise control (Adaptive Cruise Control) recognizes the vehicle in front and simultaneously determines its driving speed. This allows it to maintain a desired distance through targeted braking and engine interventions. The active safety systems also include emergency braking assistants. These detect imminent collisions via integrated cameras and environment sensors and, depending on the configuration, initiate partial or full braking. Another driver assistance system is the Electronic Stability Program (ESP), which recognizes imminently dangerous situations such as yawing of the vehicle and then brakes individual wheels in a targeted manner to counteract this rotation. Under certain circumstances, this will prevent the vehicle from swerving.

In addition to comfort and performance criteria, as well as environmental friendliness, passive safety is of great importance in the development of modern and innovative automobile concepts. In particular, crash simulations in the area of occupant protection and partner protection (pedestrians, cyclists or occupants of other vehicles) are essential in an early development phase for the design of the vehicle structure. In doing so, it is important to meet both legal requirements and country-specific consumer protection requirements. This consideration leads to a large spectrum of different calculations and tests. With the help of passive safety systems, the occupants of a vehicle in particular are to be protected from serious or even fatal injuries in the event of an accident. Intelligent systems, consisting of seat belts and airbags, are an important part of passive safety.

In principle, the seat belt is the restraint system that acts first, in the event of an accident. The belt ensures that the occupants are in the intended seating position while driving and that they are restrained in the event of an accident. This prevents vehicle occupants from coming into contact with hard interior parts of the vehicle. If an impact can no longer be avoided in a more severe accident, the seat belt system ensures that the impact speed is reduced. This principle becomes clear in *Figure 1*. It is noticeable here that when the seat belt is worn, the angle α is significantly smaller than is the case without a seat belt. This means that the occupant is braked much more gently by the seat belt and is already being adapted to the vehicle acceleration at time $t1$, at the start of the locking effect of the belt. This can possibly prevent an impact with parts of the interior and reduce the stress on the occupants. In the case of an unbelted case, the occupant continues to move due to his inertia from the point in time of the crash $t0$ at a constant speed v until he hits the steering wheel or dashboard at point in time $t2$ and is severely decelerated.

In order to brake the occupants even more gently, the seat belt must be coordinated with other systems. For example, the seat belt is often designed to be very soft in order to keep chest compression below the critical value, and contact between the body and vehicle parts is then prevented by an airbag. In addition to the seat belt, airbags thus help to avoid impacts with interior parts.

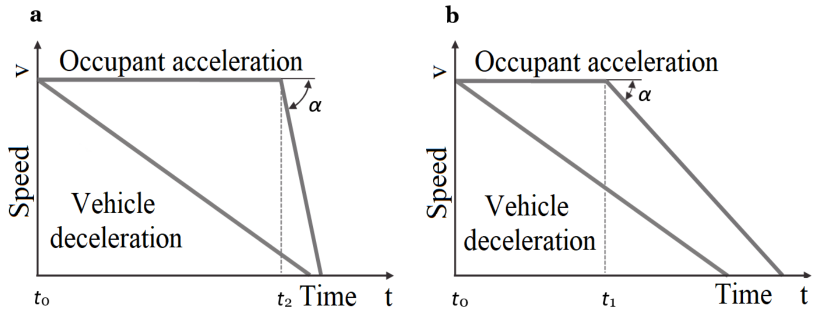


Figure 1

Comparison of the vehicle and occupant accelerations a) without seatbelt and b) with seatbelt [1]

In the event of an accident, the airbag is automatically opened and the occupant is specifically picked up. The idea of this type of restraint arose back in the 1960s. However, airbags were considered problematic and unreliable because of the short inflation time required for the air cushion, the high weight and the large construction volume due to the high-pressure gas cylinders used. The necessary filling time could only be achieved with the development of solid gas generators in the 1970s. Initially, airbags were offered at extra cost in luxury vehicles, whereas nowadays airbags are standard equipment in almost all vehicles.

A large number of sensors detect acceleration and forward these signals to the control unit for processing. When dangerous situations are detected, the gas generator is activated. The ignition pulse, which is generated by the trigger electronics, ignites a pyrotechnic propellant charge. A gas mixture is released and unfolds the airbag. The time required for this is between 30 ms and 40 ms on the driver's side and between 40 ms and 60 ms on the passenger's side. A schematic structure of an airbag system is shown in *Figure 2*. The airbag is in a folded state here.

The energy dissipation of the airbag is determined by the dimensioning of the outflow openings, so-called "vents", and the air permeability of the membrane fabric. The specially designed "vents" ensure that the gas mixture flows out precisely and regulates the pressure in the airbag. This prevents the occupant from being thrown back into the seat backrest. In addition, the pressure regulation serves to ensure that the vehicle occupant gently immerses into the airbag and thus the targeted energy absorption of the occupant kinematics. The outflow openings are always integrated on the back of the air cushion and thus face away from the vehicle occupants. When the relative speed of the vehicle occupants to the body is reduced, the air bags collapse. This happens about 120 ms after the impact.

Due to the larger installation space on the passenger side and the lack of a steering wheel, the passenger airbag has to fill a significantly larger volume than the driver's airbag.

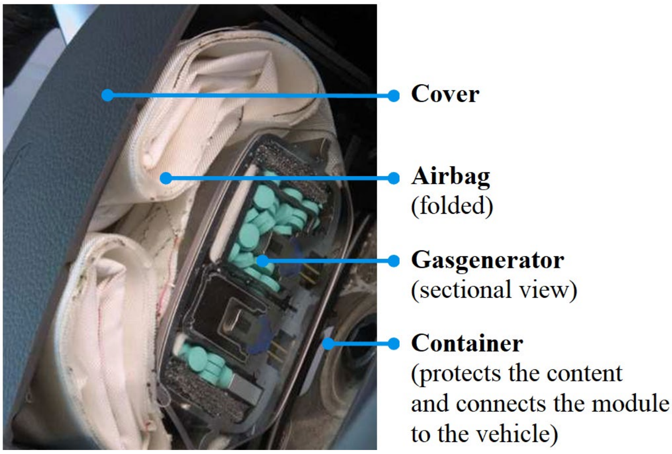


Figure 2
Structure of an airbag module [2]

In addition, the volumes differ due to the different legal situation in the European countries and the United States. Furthermore, the pressures when the occupant enters the airbag are designed differently. The immersion pressure on the driver's side is usually $p = 0.6$ bar and on the passenger side between $p = 0.1 - 0.4$ bar. A significant difference can also be observed regarding the size of the airbags, the typical size of the driver airbags is 45-60 liters, while the passenger airbags are much larger, between 80-130 liters. [3]

Not only the size of the airbag, but also the shape of the air cushion is important. The driver's airbag is rotationally symmetrical and circular. It is usually integrated in the steering wheel. This shape enables the driver airbag to behave in the same way at every possible steering angle. In contrast, prismatic, rectangular shapes are preferred for a passenger airbag. Coordination of the head is an important aspect of the design of the airbags on the passenger side. To this end, the “butterfly”, shaped passenger airbags, have appeared in recent years, which thanks to their design, are able to direct the head towards the center of the airbag and reducing the loads on the head in case of oblique collisions. Driver airbags and front passenger airbags, alongside the seat belt, are now state-of-the-art technology from restraint system. Basically, airbags can be designed as single-chamber or multi-chamber systems and also offer a great deal of leeway in the overall design of the passive safety systems.

3 Description of the EuroNCAP Side Crash Load Cases

In order to be able to evaluate the safety of the occupants equally for different scenarios, both frontal and side impacts are taken into account in the EuroNCAP crash tests. There are two frontal load cases, one with a deformable barrier and one with a rigid wall. In the side load cases, a pole and a deformable barrier are used as crash partners for the vehicle. Various loads on the structure and the dummy used are measured. The greatest challenge of all side load cases is that, compared to frontal load cases, there is almost no vehicle structure between the crash partner and the occupant that can already take a lot of energy out of the system through deformation before the impulse reaches the occupant. Consequently, severe injuries often occur in these crash situations. In order to be able to estimate the risk of injury, key figures were introduced over time. [4]

For example, a very important value for assessing the severity of a head injury is the Head Injury Criterion (HIC). The acceleration a(t) is measured here in the center of gravity of the head and is included in the criterion as a multiple of the gravitational acceleration g. The time interval considered [t1, t2] is either 15 ms or 36 ms long, which is why HIC15 and HIC36 are often also written for a more precise distinction. Furthermore, there are also several values for this, since the time intervals considered are usually longer than 15 ms or 36 ms. In this case, the maximum occurring value must be taken. The importance of this criterion can be seen in *Figure 3*, for example an HIC value of 1000 means that there is a 50% probability of irreversible injuries occurring in the occupant's head area.

The Maximum Abbreviated Injury Scale has a scale from 1 to 6, where level 1 is minor (superficial laceration), level 2 is moderate (fractured sternum), level 3 is serious (open fracture of humerus), level 4 is severe (perforated trachea), level 5 is critical (ruptured liver with tissue loss) and level 6 is maximum (total severance of aorta) injurys means.

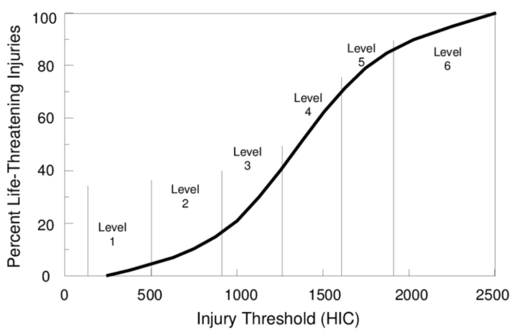


Figure 3
Maximum Abbreviated Injury Scale [5]

Other measurement points in the dummy, such as the compression of the chest or the force on the hips, are also used for the evaluation. Points are then distributed according to a prescribed point system, which then go into an evaluation scheme for the Adult Occupant Protection section of EuroNCAP. This section describes the test execution and evaluation for test cases with adult occupants. Overall, the ratings from this sub-area and other sub-areas, such as test cases for underage inmates, are combined in a star rating. These overall ratings are then published by EuroNCAP.

3.1 Pole Test

The idea behind the pole impact is to simulate a load case in which a vehicle crashes sideways into a tree at low speed. In the test setup, this is a rigid pole with a diameter of 254 mm and a height that is greater than the entire vehicle. The test vehicle is crashed onto this pole at a speed of 32 ± 0.5 km/h under 75° to the longitudinal axis of the vehicle (see *Figure 4*). The target line runs exactly through the center of gravity of the dummy head. For the crash test, the vehicle is positioned on a platform, but in the simulation, this problem can be solved simply by applying the appropriate boundary conditions.

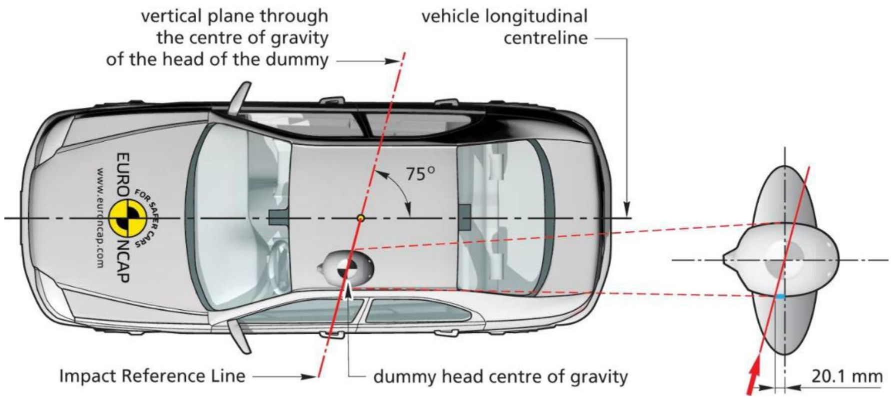


Figure 4
Point of impact of the pole test [6]

In order to be able to estimate the loads and the behavior of the system, numerous simulations are already carried out before the first tests. This is particularly useful because this test setup depicts a situation that is as critical as possible. This is because the accelerations here are lower than in the case of a barrier impact, but the deformation or intrusion is significantly higher. Since the head is close to the action here, this is always more threatening to the occupant.

3.2 Mobile Deformable Barrier Test

Most real side impacts can be classified as being either a wide or a narrow crash partner. The narrow crash partner is to be represented by the pole load case, whereas the wide crash partner is represented by the mobile deformable barrier. The Advanced European Mobile Deformable Barrier used by EuroNCAP is a further development of the original mobile deformable barrier. It consists of a car with four tires and a deformable honeycomb structure at the front. This structure shown in *Figure 5* serves to absorb energy and is intended to represent the front of a larger car. The external dimensions of this structure are around 1700 × 560 mm.

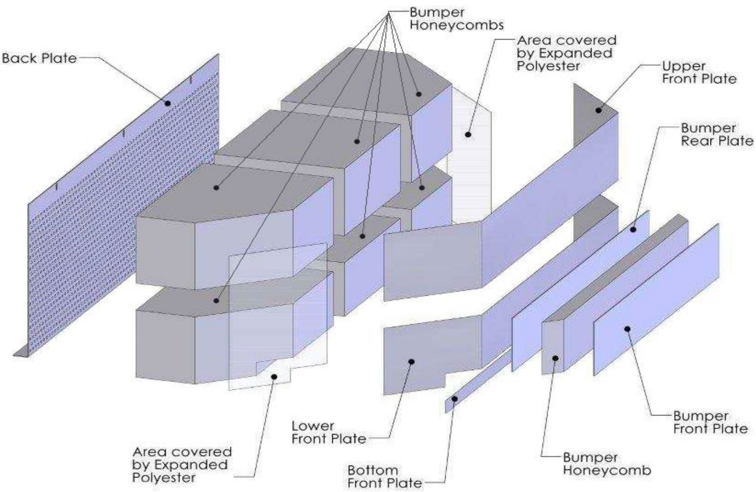


Figure 5
Exploded view of the Advanced European Mobile Deformable Barrier front honeycomb structure [7]

Overall, the barrier should have a mass of 1400 kg. The barrier then hits the vehicle in the area of the two doors at a speed of 60 ± 1 km/h after it has been accelerated to the corresponding speed. The vehicle stands still in this load case. Due to the greater width, less deformation or intrusion occurs in this load case compared to the pole load case, whereas the acceleration is greater due to the greater difference in speed.

In this research, I examined the pole test because this means more stress for the passengers. Car body protection is minimal and deformations are large. During the examination of the side crash, I used the experience and knowledge gained during the examination of the frontal crash.

4 Description of the Simulation System

4.1 Finite Element Method in General

With the help of the FEM (finite element method), complex assemblies can be examined with regard to their static and dynamic behavior. FEM is used in particular in the areas of structural mechanics, heat transfer and fluid mechanics. The basic idea is to divide the structure to be examined into finite elements, which are coupled to each other via nodes. For each of these elements, equations are defined that describe the physical problem. Taking into account the boundary and initial conditions, these can be solved with suitable algorithms. The exact procedure of such a numerical calculation is divided into the three areas of pre-processing, solving and post-processing (see *Figure 6*).

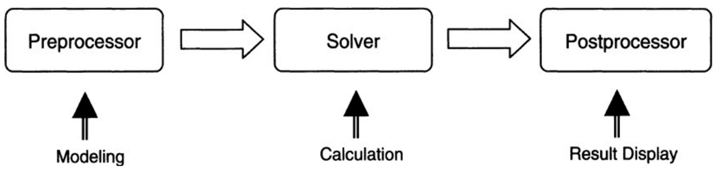


Figure 6
Simulation steps [8]

The model for the respective solver is set up in pre-processing. First, geometry data is imported or generated directly from the preprocessor. Furthermore, components with a finite number of finite elements and their nodes are discretized. The material properties are also defined in this process step and assigned to the respective components. In addition, contacts, boundary conditions and initial conditions must be defined in order to be able to subsequently carry out a model check and transfer the model to the solver. The solver serves as an equation solver and, taking the boundary conditions into account, determines the displacements of the individual nodes, whereupon other variables such as stresses and strains can be calculated for each element with this information. During post-processing, the focus is on evaluating the respective finite element calculation. Here the results are checked with the previously defined evaluation criteria using suitable post-processing tools and presented visually. The results are then documented and the model improved if necessary.

In order to carry out this activity and to model the necessary adjustments, the ANSA preprocessor from BETA CAE Systems used in this work. After the boundary conditions and the model have been transferred, the solver is able to determine and solve the differential equations and save them in an output file for each time step. The LS-Dyna solver from Livermore Software Technology Corporation is used for the simulations set up to calculate the FE model. By using the postprocessor Animator 4 from GNS mbH and in combination with ANSA META, the results in this work are evaluated and made available graphically. ANSA META is a postprocessor developed explicitly for ANSA. Analysis results include deformations and movements over time, as well as stresses and natural frequencies can be displayed. [9]

4.2 Basics of Occupant Protection Simulation

In principle, solvers can solve systems of equations implicitly or explicitly. With the implicit time integration, the following equation of motion becomes

$$\underline{\underline{M}}^{t+\Delta t} \cdot \ddot{\underline{u}} + \underline{\underline{C}}^{t+\Delta t} \cdot \dot{\underline{u}} + \underline{\underline{K}}^{t+\Delta t} \cdot \underline{u} = \underline{F}_{ext}^{t+\Delta t}$$

evaluated at the unknown point in time $t+\Delta t$. $\underline{\underline{M}}$ represents the mass matrix, $\underline{\underline{C}}$ the damping matrix, $\underline{\underline{K}}$ the stiffness matrix, $\ddot{u}$ the acceleration vector, $\dot{u}$ the velocity vector, u the displacement vector and $\underline{F}_{ext}$ the acting external forces. With linear relationships of the gradient matrices $(\underline{\underline{M}}, \underline{\underline{C}}, \underline{\underline{K}})$, a solution can be determined by solving the differential equation system once. The calculation of non-linear systems, on the other hand, is carried out incrementally with successive equilibrium iterations. Strongly non-linear structures can lead to convergence problems with implicit time integration, which is why no solution can be found. Therefore, the method of implicit time integration is suitable for linear dynamic or static tasks. [10]

In the case of explicit time integration, on the other hand, the equation of motion is evaluated at the known point in time t:

$$\underline{\underline{M}}^{t} \cdot \ddot{\underline{u}} + \underline{\underline{C}}^{t} \cdot \dot{\underline{u}} + \underline{\underline{K}}^{t} \cdot \underline{u} = \underline{F}_{ext}^{t}$$

Assuming a diagonalized mass matrix and thus the simplification that the masses at the nodes are understood as point masses, the system of equations can be converted into Newton's second axiom and decoupled:

$$\underline{F}_{\mathrm{int}}(\underline{u}, \dot{\underline{u}}, \ddot{\underline{u}}) - \underline{F}_{ext} = 0$$

$$\text{with } \underline{F}_{\mathrm{int}}(\underline{u}, \dot{\underline{u}}, \ddot{\underline{u}}) = \underline{\underline{M}} \cdot \ddot{\underline{u}} + \underline{\underline{C}} \cdot \dot{\underline{u}} + \underline{\underline{K}} \cdot \underline{u}$$

$$\ddot{\underline{u}} = (\underline{F}_{ext} - \underline{F}_{\mathrm{int}}(\underline{u}, \dot{\underline{u}})) \cdot \underline{\underline{M}}^{-1}$$

This means that each equation can be evaluated independently, which is why an overall faster solution is found compared to the implicit method. Since stresses are generated as pressure waves (sound waves) in the material at the speed of sound c:

$$c \approx \sqrt{\frac{E}{\rho}}$$

propagate, it is essential to select the calculation time step in such a way that it is always smaller than the greatest possible information propagation (sound propagation in the component) over the smallest element length. If this stability criterion is met, each discretization point can be calculated separately. Otherwise, there is a loss of information, which means that the solver cannot find a suitable solution using the explicit method.

The critical time step Δt can then be:

$$\Delta t < 1_{\min} \sqrt{\frac{\rho}{E}}$$

to calculate. As a result of plastic deformation, it is possible for some elements to become very small. As a result, these very small elements are used to determine the critical time step. This would increase the computing time extremely and lead to calculations that could not be carried out. Therefore, during the explicit calculation, these elements are deleted or the density of these small elements is increased. This artificial scaling of the mass is called "mass scaling" and allows the time step to be increased. [11]

Compared to the implicit calculation, non-linear influences mean only a small additional effort. However, a dynamic calculation must be carried out for static problems. The explicit calculation method is therefore suitable for very short-lasting dynamic processes such as crash, explosion, impact and puncture simulations. Furthermore, explicit solvers can be used for contact problems as well as for calculations of highly discontinuous structures in which no corresponding result can be found with implicit methods.

4.3 Seat Position Definition

In the earlier stage of my research, we examined injuries that occur in frontal crashes. In the event of a frontal crash, we examined a total of five rotated positions, these were 30°, 60°, 90°, 135°, 180° and, of course, the normal non-rotated state. It is absolutely necessary to narrow down the seating positions to be analyzed when examining the effect of swivel seats on passive safety systems. The process of rotating the seat is completely identical to the method used in frontal crashes. Rotating the driver's seat is impossible without modifying the interior of the vehicle, so I took all previous modifications from the frontal crash.

In the case of a frontal crash, it was observed that the maximum value of HIC15 is reached in the simulation model already at a rotation angle of 30°. There was a risk of serious head injuries due to the changed impact point of the head, which is no longer in the center of the airbag, the protective effect of the airbag is significantly reduced. The test head does not optimally reach the center of the airbag for all angle variations. In the 60° version, the steering wheel is hit directly. The seat with an angle of 60° is the worst for the airbag and the highest damage values occur here, so we will examine this case in the case of a side impact.

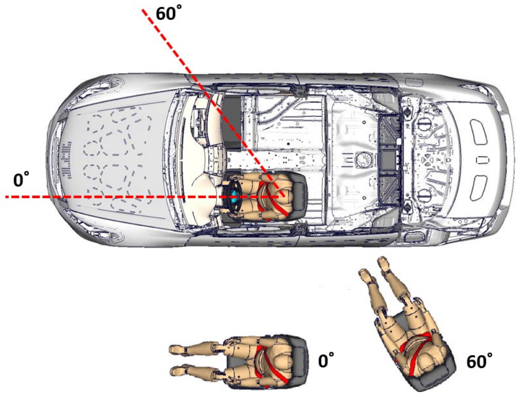


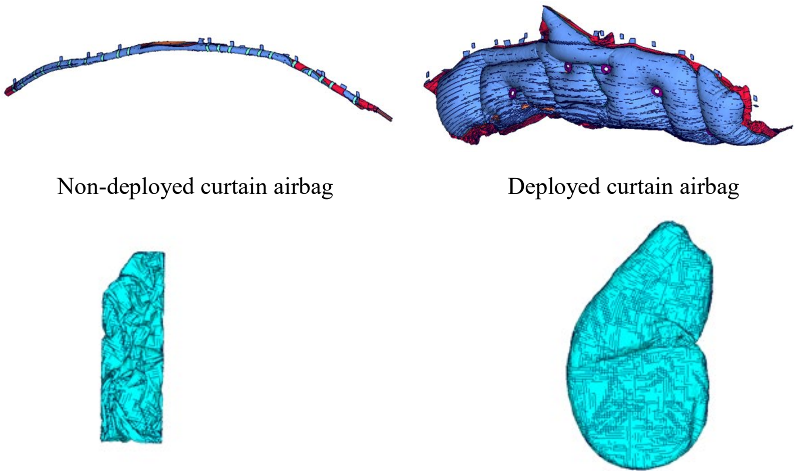
Figure 7
Representation of the examined angles of rotation (Source: Author's plot)

The frontal crash investigation showed that, as a result of the modified seating positions, the driver's movement kinematics changes radically in the event of an accident. We found that the effectiveness of the passive protection systems is greatly reduced and the risk of fatal injuries is greatly increased in the case of inverted seating positions. This is especially true for head and neck injuries, but the value of chest compression and the extent of leg injuries also become more severe. In this research, we examine the effect of this on side crashes.

5 Results of the Simulations

In the following chapter, an overview of the results of all examined angles of rotation during a side pole crash test is presented. Only the driver side position was examined during the simulations. On the basis of this preliminary investigation, certain trends can be established for certain properties of the angle of rotation.

In general, all necessary side crash restraint systems are deployed for the 0° variants. This includes the side airbag and the head airbag. The airbags used here are head or curtain airbags, which are primarily intended to protect the head area of the occupants of the first and second row of seats. It is installed under the interior from the A-pillar to behind the second row of seats along the entire side and, when it is triggered, unfolds like a protective curtain between the heads of the occupants and the vehicle structure. The side airbag is also intended to prevent the occupant from coming into direct contact with the vehicle structure, but in its position it prevents contact between the trunk area and the door panel or the paneling of the B-pillar. Due to its location in the first row of seats, this airbag is often referred to as a front-side airbag (see *Figure 8*).



Non-deployed curtain airbag

Deployed curtain airbag

Non-deployed side airbag

Deployed side airbag

Figure 8

Relevant airbags in side impact (Source: Author's plot)

A conflict between the created headrest and the head airbag arises from a rotation angle of 60° or greater, since the effective range of these two restraint system overlaps. From a rotation angle of 60°, the head airbag can no longer unfold correctly and completely and thus loses its protective effect. By rotating the seat, the proportion of the side crash changes with increasing angle in the direction of a rear-end crash during the impact. Since the most important restraint system for a rear-end collision is the headrest, the head airbag is not used for the 60° rotation angle. Therefore, for good comparability, not used the head airbag in the 0° version either. *Table 1* shows the values determined for the angles of rotation 0° and 60°.

It should be noted that there is no center console due to the geometric adjustments to the vehicle model. In a conventional vehicle, the seat is supported by the center console, among other things, in the event of a side impact. This restraint does not exist in the fitted simulation model. The trend of falling head values can be clearly explained with the impact point of the pole in the side structure of the vehicle.

Table 1
Results overview

Criteria	Limit value	Unit	Simulation 0°	Simulation 60°
Head (HIC15)	700	[-]	592	141
Head (a3ms)	80	[g]	77.6	41.7
Head (BrIC)	1.05	[-]	1.01	0.89
Neck (Nij)	0.85	[-]	0.41	0.69
Chest (Compression)	60	[mm]	27.4	37.1
Abdomen (Compression)	88	[mm]	53.7	61.2

The orientation of the pole is adjusted to the 0° seating position and no realignment takes place for the selected seating position for the purpose of comparability. According to this, the point of impact changes from the head with increasing angle degrees. For the THOR dummy in the side crash, the head values in the 60° position are significantly reduced compared to the upright and straight-ahead sitting position. In particular, the HIC values are reduced by almost 80% to 141. In addition to the changed point of impact, the seat has a damping effect. It should also be added that the position of the seat has been pushed further into the interior with a translation. As a result, the distance between the head and the post is too great, so that no serious consequences can be seen.

The turning angle of 60° changes the character of the side crash to a rear crash. This can be seen from the slight hyperextension of the neck, which is evidenced by the increase in the Nij value. There is also an increase in chest indentations with decreasing HIC values, because the protective effect of the seat back does not provide sufficient stability to respond to the intrusions from the pole. It should be added that due to the rotation of the seat, the side airbag integrated into it does not provide sufficient protection for the selected rotating seat scenarios due to the lack of support. For illustration, the maximum intrusions of the pile at the rotation angles of 0° and 60° for the THOR dummy are shown in *Figure 9*.

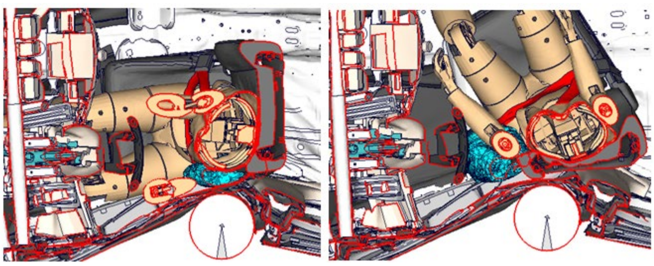
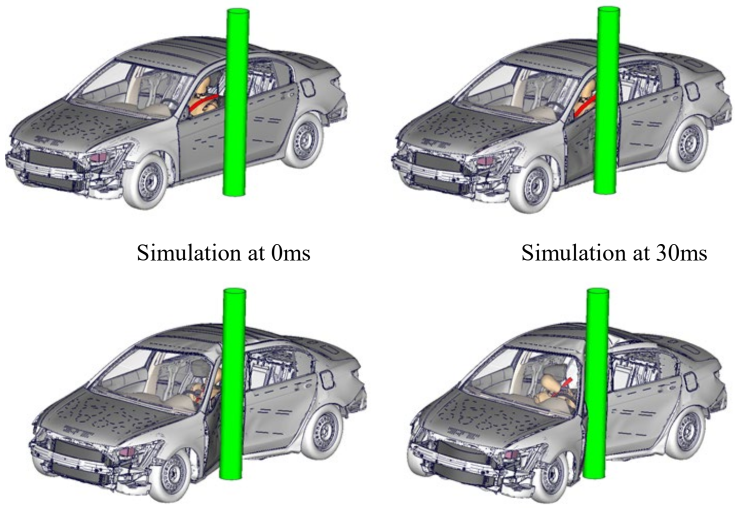


Figure 9
Pole impact on the THOR dummy 0°(left) and 60°(right) (Source: Author's plot)

6 Validation of the Simulations

It is absolutely necessary to use a real test to validate the simulations. The simulations were based on the 2008 model of Honda Accord, therefore requisite to use the real test of this model as a basis for validation. However, before validation a first way of checking the plausibility of the calculations is to look at the crash simulation visually. This can be found for the pole side crash for selected points in time in *Figure 10*. This visual inspection should be done together with an inspection of the energy flows.



Simulation at 0ms   Simulation at 30ms

Simulation at 60ms   Simulation at 110ms

Figure 10
Selected points in time during a side pole crash (Source: Author's plot)

During an inspection of the energy flows a distinction is made between three different types of energy. The kinetic energy of the system, the internal energy and third the hourglass energy. One can see very well that at the beginning the total energy consists purely of the kinetic energy. After that, the kinetic energy drops to a plateau and the internal energy also increases to an almost constant value up to about 10 ms. This is the case because the engine block is very heavy and deflects laterally, which is also the reason for the fluctuations in the total energy at the beginning. The initial contact with the stake happens just before 10 ms. From this point on, the kinetic energy of the vehicle is gradually converted into internal energy through plastic deformation until the vehicle is almost stationary after around 110 ms. Since under-integrated elements are used here, the hourglass energy with which the elements are provided increases over time in order to prevent the hourglassing effect (see *Figure 11*).

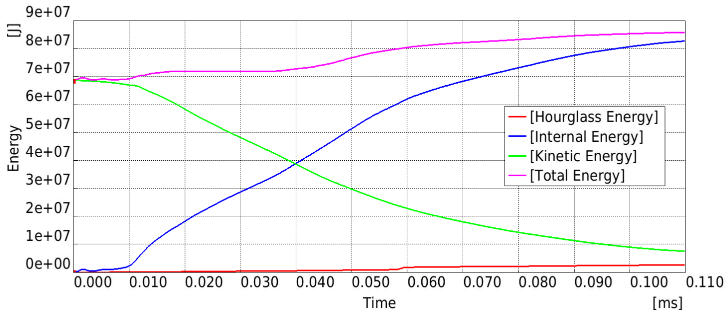


Figure 11

Course of the energy at the pole side crash (Source: Author's plot)

The tested model of the Honda Accord introduced in 2008 was released in Australia. It also included dual front airbags, side airbags and head protection airbags as part of the standard equipment. In terms of active safety, anti-lock brakes system (ABS), electronic brake distribution (EBD) and electronic stability control (ESC) were also standard equipment. In addition to all of this, an intelligent seat belt reminder is installed on every seat. In the front row, the seat belt buckles are mounted on the seats and the upper anchorage points are adjustable. These features greatly improve the effectiveness of the seat belt, thereby increasing safety. Belt tensioners were installed on the seat belts in the first row of seats, so that in the event of a collision, they are able to reduce the slack in the belt. The middle rear seat is equipped with a three-point seat belt. This can provide better protection than a conventional two-point seat belt. [12]

The Accord scored the maximum 8 out of 8 in the side pole crash test (5 Stars). The passenger compartment held its shape well. Airbags and seatbelts tailor the timing and the degree of restraint to suit the size of the occupant and the severity of the impact. In this case, both the driver and passenger were well protected. The Honda Accord scored maximum points in the car side impact test. In the pole side impact, the chest was adequately protected and there was good protection of all other body regions. The head restraint provided good protection against whiplash injuries.

The car includes a passenger airbag deactivation function so that the rear-facing child seat can be used safely in this position. However, the driver does not have enough information about the current state of the airbag. In any case, a warning label clearly warns of the danger of using a rear-facing child seat in the passenger seat without first deactivating the airbag. Unfortunately, this information is not available in all European languages. The existence and exact location of the ISOFIX points on the rear outer seats is not clearly marked, which can also cause confusion.

Figure 12
Honda accord 2008 EUNCAP side pole crash test [12]

Table 2
Results of the base model and the modified model in comparison with the crash test

Criteria	Unit	Limit value	Crash test	Simulation 0° Base model without any modifications	Simulation 0° Fitted model with all modifications
Head (HIC15)	[-]	700	541	575 (+6%)	592 (+9%)
Head (a3ms)	[g]	80	71.4	72.9 (+2%)	77.6 (+8%)
Head (BrIC)	[-]	1.05	0.86	0.93 (+8%)	1.01 (+17%)
Neck (Nij)	[-]	0.85	0.62	0.44 (-29%)	0.41 (-34%)
Chest (Compression)	[mm]	60	25.8	27.0(+5%)	27.4 (+6%)
Abdomen (Compression)	[mm]	88	58.9	55.2 (-6%)	53.7 (-9%)

Table 2 shows the results of the basic model, the version without modifications, and the modified model compared to the results of the crash test. The basic model is validated, it can be seen that all deviations in the simulation results remain within the appropriate limits. The situation is similar with the modified model, because the modifications mainly affect the frontal collision only. The only major difference is in the values of the neck, the main reason for this being the replacement of the seat belt attachment point. The modified model must be used for comparison with the rotated seat versions, as these modifications allow the driver's seat to be rotated. [13]

Conclusions

The aim of this research was to investigate a pole side crash, in the case of a fully self-driving vehicle. In order to do this, we used as a basis the computer simulation model used in the frontal collision investigation. We have created the necessary definitions of side impact from the point of view of passive passenger safety. We validated the completed computer model with a real crash test and then transformed it so that it is suitable for testing the rotated seating positions. In the case of a side impact, We examined the most critical rotation angle in the case of a frontal impact. We examined to what extent the seating position of the passengers affects their injuries in the event of a side pole collision. During the simulations and the evaluation, we compared the results of the injuries that occurred in the case of seat positions turned by 60° with the case of the driver's seat in the normal basic position. As a result, we received that although the kinematics of the driver's movement changes radically during an accident due to the modified seating positions, the degree of injuries is still greatly reduced. Exceptions to this are injuries to the chest and abdomen area. This decrease in injuries can be explained primarily by the damping effect of the driver's seat, because in the case of the driver's seat turned by 60°, the driver's seat protects the passenger from the direct load and deformation coming from that side. Based on the results, although the damage values only partially increase in the case of side crash, it is still necessary to expand the passive safety system. Next goal of the research is the creation of a protection system capable of providing protection even in a seat position rotated at any angle. This system must be able to provide sufficient protection in both frontal and side collisions. In order to achieve this goal, the possibilities of further developments for the driver's seat need examination. The seat must be able to coordinate the movement of passengers in the event of any accident and must participate in the prevention of serious injuries and the absorption of large deformations a model to test and verify this will be built. In addition to the possibilities for further development of the driver's seat, examination is needed for future new possibilities of the use of airbags, in self-driving vehicles. The future development of the airbags as known today, will be inevitable, in a vehicle without a steering wheel. The aim of the research will be to define the challenges that affect airbags and to define any possible solutions. It will certainly be necessary to examine the new position, shape and size of the airbags known today, in order to achieve the desired goal.

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