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Possibilities for Further Development of the Airbags in the Case of Non-conventional Seating Positions

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Abstract
The first ideas and experiments aimed at protecting passengers from the vehicle's internal components with airbags date back to the 1960s. Twenty years later, the airbag appeared in series production, in December 1980, the Mercedes-Benz S-Class (W126) was the first serial production car to be equipped with a driver airbag, and since its introduction, the use of airbag technology has been uninterrupted. Airbag systems are currently regarded as almost mandatory protection systems in a vehicle. The article generally presents the development of airbags used in cars, followed by the currently used airbag folding types. After that, the article presents the simulation of the airbag deployment, its types and theoretical background, as well as the most important stages of the deployment of the airbag. In the following, the article presents the results of the research so far in the case of frontal and side crashes. The next section of the article introduces the materials capable of absorbing energy, then details the simulation model built and the airbag concept created. The last part of the article contains an evaluation of the results and the summary. The modified seat examined in the earlier phase of the research and the airbag concept that is the subject of this research also fulfill the set goals, but the latter has a great advantage.
Keywords
crash test, occupant safety, finite element method, electric vehicles, autonomous driving

1 Introduction

Seat belts and airbags are currently part of a carefully coordinated subsystem of the occupant safety protection system. In the early days of vehicle safety in the United States, some believed that airbags could replace seatbelts, but this is not the case. The seatbelt is the primary restraint system in an accident. It keeps the occupants in the correct seating position during the journey and restrains them to prevent contact with hard interior surfaces. In more severe collisions, the seatbelt reduces the impact speed, minimising the risk of injury. It is, therefore, important to emphasize that the development and use of airbags is inextricably linked to advances in safety belt technology. The fact that the airbag is a matter of course is due to the new research results and developments. The concept of airbags originated in the aviation industry in the 1920s, with early experiments using pneumatic restraint systems. On 6 October 1951, Munich engineer Walter Linderer filed a patent for a "device for protecting persons in vehicles against injury in the event of a collision", marking the beginning of the automotive airbag development. These early airbags relied on simple pneumatic systems rather than pyrotechnics. The first ideas of using a pressurized air cushion to protect passengers from the vehicle's interior components date back to the 1960s. The short inflation time required for the airbag in connection with the pressure to be applied and the large capacity of the airbag were the main problems. At the beginning of the 1970s, the positive protective effect of the air cushion was made usable through the development of solid gas generators.

In December 1980, the Mercedes-Benz S-Class (W126) was the first serial production car to be equipped with a driver airbag, and since its introduction, the use of airbag technology has been uninterrupted. In 1987, the Porsche 944 Turbo, sold on the American market, was the first car to be equipped with driver and passenger side airbags as standard. Depending on the type of impact, the risk of injury to vehicle occupants can be reduced. The relative speeds between the occupants and the vehicle interior structures that occur in an accident can be reduced within a few milliseconds with an airbag. The average airbag opening time is between 20 and 40 ms, depending

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on the type and size. The function of the airbag is linked to triggering electronics. In the event of an accident, the electronics recognize the danger and send an electronic impulse to the igniter on the airbag generator.

This mechanism leads to the ignition of a pyrotechnic propellant charge, with which a gas mixture, which usually consists of combustion gases, is introduced into the air cushion. This fully deploys the airbag. The prerequisite for triggering the generator is a negative acceleration of approx. 4 g. This corresponds to a frontal collision with a fixed obstacle at a speed of approx. 25-30 km/h. If the collision speed is less than 25 km/h, the triggering electronics will not be activated because the seat belts fitted offer sufficient protection. Also, no pyrotechnic components of the belt are ignited. The air cushions are fitted with outflow openings (vents) and contribute to reducing the occupant's kinetic energy with minimal injury. When the occupant dives into the air cushion, the gas mixture is pressed out of the air cushion through the vents, which prevents the occupant from being thrown back and leads to gentler braking. As a result, the relative speeds between the passenger compartment and the occupant that occur in the event of an accident are reduced gently. The size of the airbag has a great influence on the volume of the airbag and its protective effect. Accordingly, there are a number of different types of airbags, some of which differ significantly in size and shape. Fig. 1 shows the most common types of airbags. In the top left is the driver's airbag, which usually has a volume of between 45 and 60 liters, and the Time To Fire (TTF) is usually between 10 and 20 milliseconds. This is the moment when the airbag starts to inflate, 0 ms is the moment when the signal comes from the crash sensor. In the top right-hand corner is the front passenger airbag, which is usually between 80 and 130 liters, making it much larger than a driver's airbag, TTF is usually between 20 and 30 milliseconds, so it starts about 10 ms later than a driver's airbag. Frontal airbags have been standard in all passenger cars since the 1998 model year. Many new cars have a weight sensor for the front passenger seat, which prevents the airbag from deploying if there is a small child in the seat. In older cars without a weight sensor, the force of the airbag can cause injury to younger children, so the government recommends that children under 13 should ride in the back seat. In the bottom left cornerare the head and side airbags, which are usually between 15 and 20 liters, TTF is usually between 5 and 10 milliseconds. In the bottom right is the knee airbag, which is usually between 15 and 20 liters, TTF is usually between 10 and 20 milliseconds. The far-side airbag is an innovative addition to the car's safety features, designed for

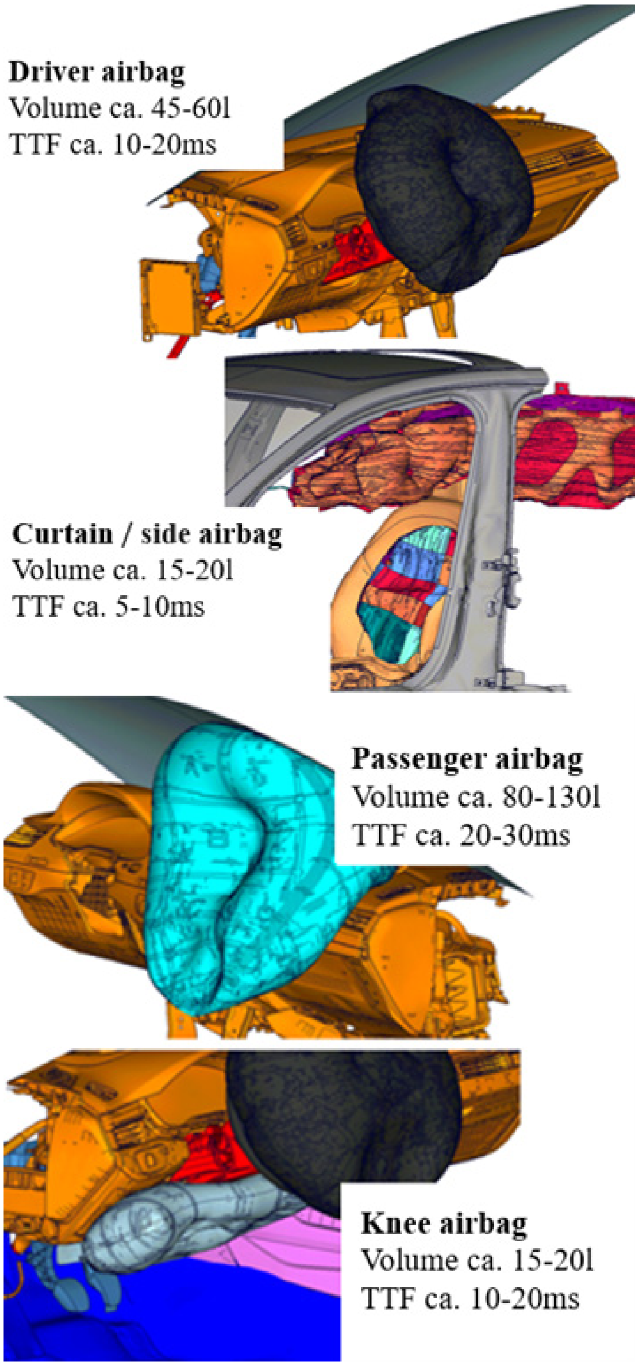

Fig. 1 Types of airbags with typical volume and average Time To Fire (TTF) value (Source: Author's plot)

side-impact collisions. With a volume and TTF similar to side airbags, it deploys from the seat and inflates towards the headliner to prevent the driver and front passenger from colliding in a side impact. This new type of airbag minimizes injuries caused by passenger interaction in the front row and can reduce serious side impact injuries by around one third. The first cars with side airbags were introduced in 2020.

A classification of airbags into mid-size airbags and full-size airbags is due to the different legal situation in Europe and the USA. In Europe, a mid-size airbag, the so-called Euro airbag (Euro-size airbag), is often used. The capacity of this airbag is only 25 to 35 liters on the driver's side and approx. 65 liters on the passenger's side. Due to the small volume, the airbag has to be inflated with high pressure. In some parts of the USA, load cases are being reviewed in which unbelted occupants must not be ejected from the vehicle interior. For this reason, driver airbags with a volume of 65 to 75 liters and front passenger airbags with a volume of 100 to 150 liters are used, which correspond to full-size airbags. This difference stems from the differing understanding of the airbag system in both regions. In the European Union, the airbag is seen as a secondary safety system in combination with the seat belt. Due to new findings, the trend is increasingly towards mid-size airbags with a volume of 45 to 60 liters on the driver's side and 80 to 120 liters on the passenger's side.

However, there are other airbag designs located at different points in the interior. The following airbag systems support the protection of the occupants in a frontal collision. The first concept is the belt airbag, since the risk of injury from a seat belt is not negligible. The belt airbag distributes the tensile force of the belt better over the chest thanks to an enlarged contact surface. The anti-sliding bag exists to reduce the submarining effect. This is located under the knee cups in the seat and prevents the occupant from slipping under the lap belt. This airbag system reduces possible serious upper body injuries. The lower extremities (feet, legs) undergo large deformations in a frontal impact. A measure to reduce the risk of injury or the severity of the injury is the knee airbag, which is intended to prevent the knee from impacting. The airbag is usually located in the lower part of the dashboard. In the side protection, side airbags serve as a safety system to reduce injuries to the chest and pelvis of the occupants.

Due to the smaller deformation area of the side structure compared to the front structure, the side airbag has the task of securing the occupant's survival space by keeping the dummy away from the impact area. Another airbag system is the head airbag. Because the side airbag does not cover the head in a side impact, this airbag is of great importance. This type of airbag prevents the head from coming into contact with the side structure of the vehicle, windows and parts penetrating from the outside. The life-saving protective function of airbags is well known. Although, this function is only effective without errors in a certain predetermined range of the seated position of the occupant. If the airbag deviates from the known area of application, the protective function of the airbag is only partially effective or no longer effective at all. This area in which the airbag no longer fulfills its function is referred to as the out-of-position. The deployment of an airbag can even have serious consequences. The out-of-position is understood to mean, for example, a lying or forward-bent sitting position, reading a book, but also transporting objects on the thighs. The out-of-position also includes above-average large and small occupants, as well as small children without appropriate booster seats, because there is a risk of injuries induced by the airbag. It is important to point out that modern passenger safety systems only ensure the proper protection of passengers through the optimally coordinated interplay of the vehicle's structure, the movement of the steering wheel, and the behavior of the seats in combination with the seat belt and the airbag that deploys at the right time.

The current phase of this research focuses on effectively protecting occupants in non-conventional seating positions. Previous phases investigated the ability of existing passive safety systems to protect occupants in arbitrary seat rotation and the effect of seat position on occupant loads in collisions, several publications have been produced on frontal and side impact. Subsequent research explored ways to improve the design of the driver's seat to improve passive vehicle safety. This phase aims to replicate the findings from seat development using airbags tailored to the new positions, sizes and shapes characteristic of fully autonomous vehicles. The rest of the paper is organized as follows: presentation of different types of airbag folding, followed by the theoretical background and implementation of the airbag deployment simulations used in the research. It then reviews the previous research stages, discusses the theory of energy absorbing elements and concludes with the presentation and summary of airbag deployment solutions and its results.

2 Airbag folding types

The folding of an airbag is crucial to minimize the risk of injury to vehicle occupants during deployment. The folding pattern of the fabric has a clear impact on the protective potential of the air cushion. The manner in which the airbag is folded allows the deployment process to be controlled in a targeted manner. Due to the special nature of the type of fold with regard to the position of the upper and lower layers and at the same time the positioning of the airbag fabric in relation to the gas generator, the fold types have different unfolding mechanisms. The driver airbag in the steering wheel is folded in a star shape (Mao and Appel, 2002).

In general, four types of folding can be distinguished, the first of these is leporello-folding shown in Fig. 2. The leporello-folding is one of the conventional folds in which the

Fig. 2 L-folding (Mao and Appel, 2002)

airbag is folded over the generator. The fold lines here run in a straight line. The increase in volume is limited by the self-blocking of the fabric layers and by fabric friction, which results in a higher opening pressure. This suddenly throws the airbag towards the occupants. With the following types of folds, the airbag spreads out without self-locking and thus pronounced laterally to the direction of the shot, resulting in less resistance.

These types of folds are able to accurately reproduce the rupture behavior of the airbag, with the S-folding in particular being used because of its very good economics. In general, when designing passive safety systems, it must be taken into account that vehicle occupants can position themselves in the deployment area of an airbag, which is why injuries can result from the deployment of an airbag in such cases. For this reason, out-of-position (OoP) load cases are tested, which are already required by law in the United States due to the large volumes of driver and passenger airbags. It is necessary to examine these cases as well, because even a small deviation can have an intensive effect on the actual kinematic reaction and the resulting injuries.

The second method is the ruffled-folding, which is shown in Fig. 3, the airbag is located on the side of the generator. The expanded air cushion is formed into a concentric, preferably cylindrical 3D wave structure around the gas generator and then radially compressed into a package in the airbag module. The main folding lines run along closed paths around an imaginary center and essentially form concentric circles.

With the Z-fold, which is shown in Fig. 4, the airbag fabric is radially ring-shaped and arranged in the vertical direction in the manner of an accordion above the gas

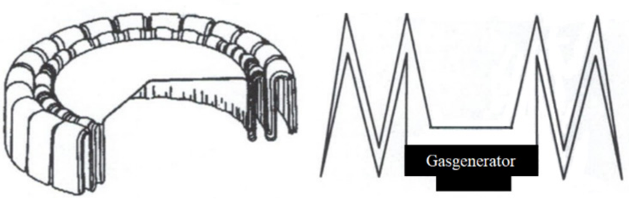

Fig. 3 R-folding (Mao and Appel, 2002)

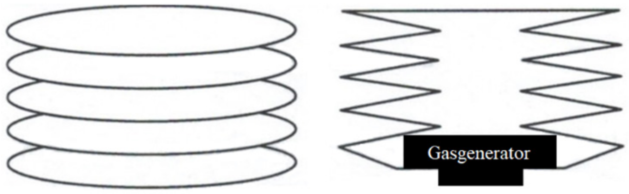

Fig. 4 Z-folding (Mao and Appel, 2002)

generator. Analogously to the ruffled fold, the main fold lines run along closed circles and radiate from the center.

Fig. 5 shows the S-folding, which describes a stochastic type of folding. The fold lines on the spread airbag are neither regular nor oriented. It thus represents a random arrangement of the fold lines. The airbags, made of thin, synthetic material, are folded into place very precisely, as lives depend on their perfect operation. If the folding is not correct, the airbag can open in an unexpected situation, which poses a great danger to the passengers. Nowadays, the airbag module can be folded into a very small space, it is expected that the folding technology will continue to develop in the future. If an airbag is deployed, the entire module must be replaced, it is not possible to repair the deployed airbag. During the research, we used the Z-folding method.

3 Airbag deployment simulation

Since a large number of airbags are installed in modern vehicles, the constantly evolving, sophisticated airbag simulation proves its worth. Above all, the deployment that follows the ignition of the gas generator is a highly complex process. The pressure conditions in the airbag depend heavily on the deployment, the temperature and the resulting gas volume. In addition, these are influenced by the incoming gas mass as well as the gas losses at the permeable airbag fabric and at the outflow openings. But not only is the simulation of the gas movement a complex process, the representation of the orthotropic, non-linear airbag material is also extremely difficult. Since many very small folds occur when folding and also during the unfolding process and, therefore, very fine networking

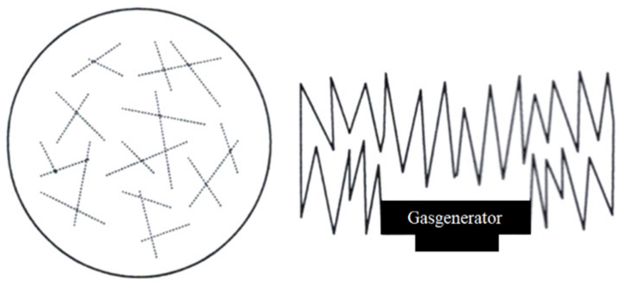

Fig. 5 S-folding (Mao and Appel, 2002)

would be unavoidable, this results in the use of simplified model assumptions. Therefore, when creating the virtual model, the airbag chamber is assumed to be a simplified gas space, which is determined based on a scalar balance of incoming and outflowing mass. In addition, the elements are allowed to deform in the compressive direction in order to obtain a model with a tolerable number of elements (Porkolab and Lakatos, 2021).

The first and simplest calculation method was the uniform pressure method (UPM), which saves computing time and is based on an even pressure distribution in the entire control volume within the airbag chambers. The deployment of the airbag can be well simulated here, with inflow and outflow processes and flow phenomena within the airbag not being taken into account, so that the pressure cannot be resolved locally. Constantly new regulations and complex airbag shapes require more and more precise simulations than the UPM allows, in order to be able to depict the real deployment behavior as precisely as possible. Over time, simple air cushions have become complex connections between several chambers and outflow openings with little space for the folded airbag. Even the gas generator has become much more complex. In order to determine the inflow, the local recording and representation of the gas movement within the simulation is required. There are different calculation approaches for this. Common methods are the Finite Point Method (FPM) and the Arbitrary Lagrangian Eulerian (ALE) coupling. Likewise, simulation models of airbags can be calculated using the Corpuscular Method (CPM) based on a particle approach, as well as coupled with Computational Fluid Dynamics (CFD) programs. These methods allow for the resolution of the gas state while still assuming simplifications for gas modelling. The research utilized Pam-Crash software to simulate airbag deployment, employing the Finite Point Method (Porkolab and Lakatos, 2021).

FPM fills the volume inside the airbag with the cloud of points, as shown in Fig. 6, and calculates a set of thermodynamic variables for them, including pressure, density, velocity, and temperature, then assigns them to neighboring points by interpolation. Finally, it calculates the momentum transfer between the FPM points and the Lagrangian mesh representing the airbag. The amount of mass injected into the airbag needs to be defined with respect to time. The gas exerts a pressure load on the airbag causing it to expand. In this study, heat conduction and heat transfer are not taken into account. In the deployment of an airbag an inflator supplies high velocity gas into an airbag causing it to expand rapidly (Kim et al., 2023).

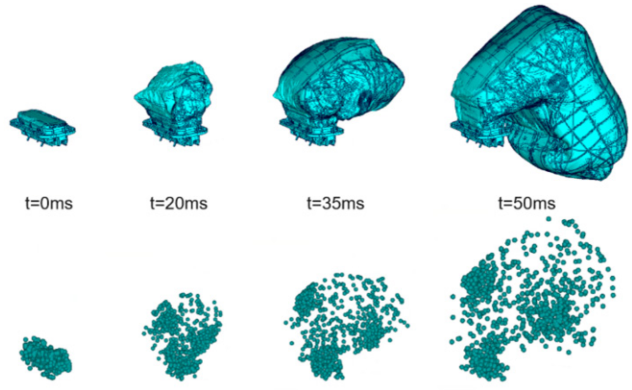

Fig. 6 Simulation airbag deployment external skin and showing FPM Points (Source: Author's plot)

Basically, three phases of the opening of the airbag can be observed (see Fig. 7). The gas inside the airbag is assumed to be ideal, to be of constant entropy. It is worth choosing these phases separately for the purpose of analysis as this helps to understand the related phenomena. At the beginning of the first stage, the gas starts to flow out of the generator into the bag, which is illustrated in Fig. 8. Due to the inflow of gas, the volume of the bag begins to increase, which also leads to an increase in pressure, since the cover of the airbag is closed currently. The continuous increase in volume and pressure at one point generates such a force that is already able to break through the seam holding the airbag cover. In the case of airbags of different sizes, designs and placements, of course they mean different force effects (Samantray and Parashar, 2023).

In the second stage, the airbag starts to leave its housing and continues to increase its volume. Due to the high pressure in the airbag in the first stage, this exit is very fast. During the process, the volume continues to increase continuously, but the pressure continuously decreases along with it. It is important to note that at the beginning of this phase, the pressure in the airbag is the highest,

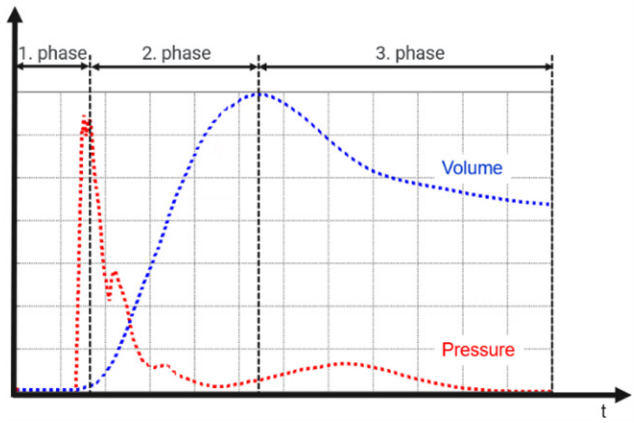

Fig. 7 Characteristic development of the pressure and volume occurring in the airbag during the phases of deployment (Source: Author's plot)

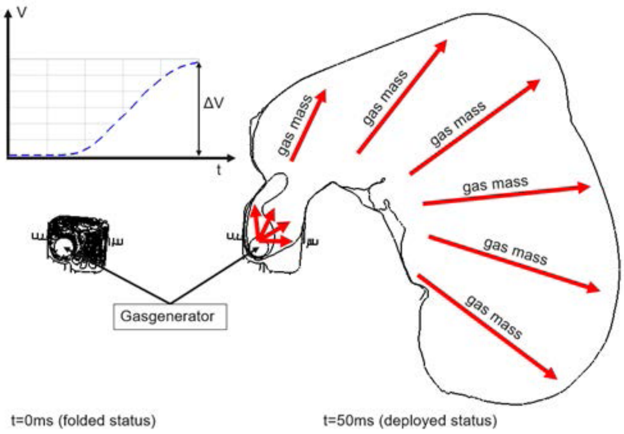

Fig. 8 Illustration of airbag deployment with physical quantities (Source: Author's plot)

which can be the most dangerous for those sitting too close to the airbag (Out of Position). This danger is known as the "Punch Out" phenomenon. In the second half of the phase, the airbag continues to open until there is no more folded part left in the housing (Nie et al., 2020).

In the third, therefore, the last stage, the entire airbag is already outside the housing, the volume can increase until all the gas is dispersed in the bag, but typically the size of the airbag does not change much. After that, a slight increase in pressure can be observed again, as the airbag is no longer able to increase, but gas is still coming from the gas generator, but this is a much milder increase than what was observed in the first stage. At the end of this stage, it can generally be said that the pressure and volume inside the airbag are uniform and the airbag is ready to receive the passenger.

4 The results of the first and second phases of the research

In the first phase of the research, in addition to the traditional sitting position, we have examined sitting positions rotated by 30°, 60°, 90°, 135°, and 180° (see Fig. 9).

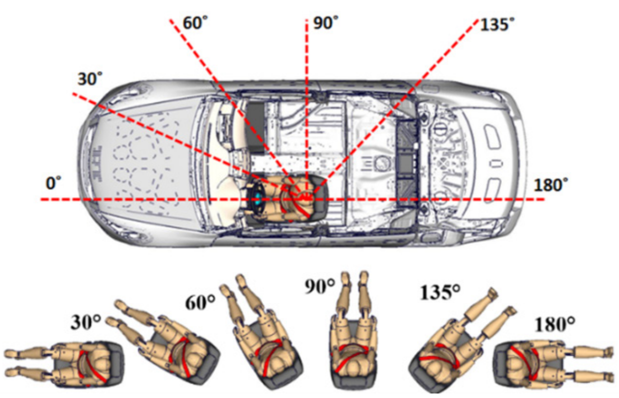

Fig. 9 Representation of the examined angles of rotation (Source: Author's plot)

The examined spectrum, therefore, extends from 0° to the 180° position, in which the driver's vision is directed backwards (Kia et al., 2021).

The first step was to validate the simulation model. We used the results of a real crash test as a basis for validation. Modifications had to be made to the vehicle model to test the rotated seating positions. These modifications were made on the already validated simulation model. During the research, we examined two types of load cases. The first among these is the frontal collision, when the vehicle collides with a rigid wall at a speed of 50 km/h with 100% overlap.

In addition to frontal collisions, we also examined side collisions during the research. The vehicle collides with a 254 mm diameter column at a speed of 32 km/h, which column makes an angle of 75° with respect to the longitudinal axis of the vehicle. Table 1 summarizes the results of the research regarding the frontal collision test.

In the case of a frontal collision, all seat positions were examined (0°/30°/60°/90°/135°/180°), the kinematics of the driver's movement fundamentally changes as an influence of the rotation of the seat. In this phase of the research, the effectiveness of traditional passive protection systems is significantly reduced, so they no longer

Table 1 Results overview frontal crash (yellow = maximum value) (Porkolab and Lakatos, 2022; 2023a)

Criteria	Limit	Unit	0°	30°	60°
Head (HIC15)	700	[-]	487	1159	964
Head (a3ms)	80	[g]	55.1	91.3	93.1
Head (BrIC)	1.05	[-]	0.57	0.93	0.95
Neck (Nij)	0.85	[-]	0.43	0.59	0.48
Chest (Compress.)	60	[mm]	41.4	50.6	54.9
Abdomen (Compress.)	88	[mm]	68.1	113.4	103.5
Femur (Force)	7.56	[kN]	6.88	4.39	6.11
Criteria	Limit	Unit	90°	135°	180°
Head (HIC15)	700	[-]	833	803	731
Head (a3ms)	80	[g]	83.3	75.3	72.9
Head (BrIC)	1.05	[-]	1.74	1.43	1.18
Neck (Nij)	0.85	[-]	0.57	0.63	0.61
Chest (Compress.)	60	[mm]	48.3	46.1	56.7
Abdomen (Compress.)	88	[mm]	91.4	78.6	71.4
Femur (Force)	7.56	[kN]	6.32	8.17	7.26

provide adequate protection. It can be stated that, along with this, the chance of fatal injuries also increases significantly (Porkolab and Lakatos, 2022; 2023a).

A large increase in the head injury value can be observed, which indicates a decrease in the protective effect of the airbag. The highest head acceleration value was observed in the case of the seat position rotated at an angle of 60°, here at the maximum forward movement the head is in direct contact with the steering wheel, therefore, this rotation angle is the most dangerous. Leaving this rotation position, a slow decrease in injury values can be observed, which is primarily due to the damping effect of the driver's seat. In the second phase of the research, we investigated this effect with an improved driver's seat. Table 2 shows the results obtained in frontal impact with the seat position rotated by 60° for the original and modified seat.

A clear reduction in head acceleration can be observed, as the test head receives less load due to the increased seat size. Head impact occurs about 20 ms earlier for the modified seat. The force generated during the collision is distributed over a larger area, which can also reduce the maximum value of chest compression. In summary, looking at the head values and the chest load, it can be said that in the case of the modified seat, the obtained values show a large improvement and meet the consumer protection regulations of Euro NCAP. Simulations of frontal impact with a 60° seat significantly improves the coordination of passenger movements throughout the duration of the collisions.

In the case of a side impact, only one angle of rotation was examined, based on what we experienced in the case of a frontal impact, this was the case of a 60° angle of rotation. Similar to the frontal collision, it can be established here that the kinematics of the driver's movement changes radically as a result of the rotated seat position. The obtained values differ to a greater extent than in the case of a frontal collision,

Table 2 Results overview frontal impact original and modified seat (yellow = maximum value) (Porkolab and Lakatos, 2023a)

Criteria	Limit	Unit	0°	60° ori. seat	60° mod. seat
Head (HIC15)	700	[-]	487	964	628
Head (a3ms)	80	[g]	55.1	93.1	71.3
Head (BrIC)	1.05	[-]	0.57	0.95	0.67
Neck (Nij)	0.85	[-]	0.43	0.48	0.73
Chest (Compress.)	60	[mm]	41.4	54.9	48.4
Abdomen (Compress.)	88	[mm]	68.1	103.5	81.9
Femur (Force)	7.56	[kN]	6.88	6.11	7.22

except for chest and abdominal injuries. Table 3 shows the results obtained in side impact with the seat position rotated by 60° for the original and modified seat.

The large improvement in the obtained results can clearly be explained by the ability of the driver's seat to absorb deformation, so in the second phase of the research, the modified seat was also examined in the event of a side impact. In the event of a side impact, with the modified seat, we get partly decreasing and partly increasing values, which, however, remain well below the desired limit values. In this load case, a different type of problem must be dealt with, namely that due to the large deformation of the seat, there is a risk of the passenger slipping out of the seat. Thanks to the geometric modifications of the modified seat, it is possible to fix this problem and stabilize the seat during the entire deceleration process.

Overall, it can be said that in the case of the modified seat, the movement of the passenger is more coordinated during the entire process. The movement of the upper and lower body acts in the same direction, in the original sitting, the upper body, especially the head, moves uncoordinatedly, independently of the lower body. It is very important to coordinate the movement of the passenger during the accident, because if the movement is not coordinated, unexpected and large-scale injuries can easily occur and the seat belt cannot work properly. Table 4 summarizes the results (Porkolab and Lakatos, 2023b).

5 Components capable of absorbing energy

Deformation elements and foams are important elements of energy absorption in motor vehicles. These are used to absorb energy in frontal, side or rear collisions and convert kinetic energy into deformation energy. They are able to deform significantly and thus dissipate energy. Knowing the contribution of individual components to energy release is, therefore, essential to reduce the stress level on the vehicle's passengers. Basically, they

Table 3 Results overview side impact (Porkolab and Lakatos, 2023b)

Criteria	Limit	Unit	0°	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 (Compress.)	60	[mm]	27.4	37.1
Abdomen (Compress.)	88	[mm]	53.7	61.2

Table 4 Results overview side impact original and modified seat (yellow = maximum value) [8]

Criteria	Limit	Unit	0°	60° ori. seat	60° mod. seat
Head (HIC15)	700	[-]	592	141	268
Head (a3ms)	80	[g]	77.6	41.7	53.9
Head (BrIC)	1.05	[-]	1.01	0.89	0.93
Neck (Nij)	0.85	[-]	0.41	0.69	0.42
Chest (Compress.)	60	[mm]	27.4	37.1	29.3
Abdomen (Compress.)	88	[mm]	53.7	61.2	57.2

use different structures made of different materials. For example, honeycomb structures or ribs are considered flexible energy absorbers. In addition to the exclusive use of honeycomb structure, a combination of deformation structure and foam is also possible. The goal is to couple most of the energy with a small deformation path, so the force-time curve should be as constant as possible. Different elements are used to control the appropriate force level depending on the deformation path. One possibility is the use of honeycomb structures, such structures are used with different materials to design energy absorption inside the vehicle. Plastics made of polypropylene or polycarbonate, which exhibit elastic-plastic behavior, are particularly suitable. Energy absorption has two shape change options. The ribs can be compressed both longitudinally and transversely. Compression of the deforming structure leads to significantly less energy absorption, as the deforming element collapses much faster in a short time than when the ribs are compressed longitudinally (Wu et al., 2020; Abdul Samad et al., 2022).

However, plastic and polymer foams are more important from the point of view of occupant safety, they are mainly used in the interior of the vehicle, for example in the glove box or the steering column cover. The foams can be produced in different densities, which in turn directly affects the stiffness of the material. These foams consist of expanded, on the whole closed-cell foam particles made of polypropylene and offer very good cushioning and flexibility properties in addition to high energy absorption. Their characteristic feature is also good heat resistance and low water absorption. It is important to note that these foams are free of propellants and other chemical foaming substances and are, therefore, considered environmentally friendly. Despite multiple impacts, they are particularly suitable for occupant safety due to their largely unchanged energy absorption (Kang et al., 2022).

In the second stage of the research, we modified the foam structure of the seat, which is subject to the elasto-visco-plastic material law. In contrast to the elasto-plastic material law, the evolution of plastic deformations over time is considered within the framework of the viscoplasticity theory. The elastic behavior of the foam material is described by the modulus of elasticity for compression (Ecomp) and for tension (Eten). The modulus of elasticity varies depending on the foam used. The foam structure shows a different structural behavior in terms of tensile stress than in the case of compressive stress. In compression the local deformation is dominated by bending, while in tension the deformation is caused by pure stretching. Therefore, two flexibility modules are considered and differentiated in the simulation (Leledakis et al., 2021; Diez-Marín et al., 2022).

6 Possibilities for the further development of the airbag in the case of rotated seat positions

In the third phase of the research, we wanted to achieve the effect of the modifications made to the driver's seat with an airbag. When modifying the seat, the goal was to expand the geometry of the backrest, thus providing wider protection in the event of an accident and creating a larger deformation zone. Due to the principles of symmetry, the backrest was only extended in one direction, however, during the airbag research, the airbag that only opens in one direction causes stability problems and is unable to coordinate the passenger's movements. In the first step, we only placed an airbag in one direction, but this proved to be insufficient, so we mirrored the completed model, which is now able to provide adequate stability in both directions. During the airbag research, we had to create a model of unique size and shape, which we placed in a new location and position. In terms of the size of the airbag used, it is approximately the same size as the driver's airbag integrated in the steering wheel, and in terms of its shape, it is most similar to a side airbag. The developed airbag was placed on the side of the seat in such a way that it can surround the passenger when it opens (Porkolab and Lakatos, 2024).

In the first phase of airbag research, we followed the concept marked in blue in Fig. 10, so we wanted to build a deformation zone for the passenger based on the model of the modified seat. However, no matter how thick we made the airbag, we had to face the problem that the airbag could not hold itself, it was not rigid enough against a load coming from any side. During a collision, the passenger slams

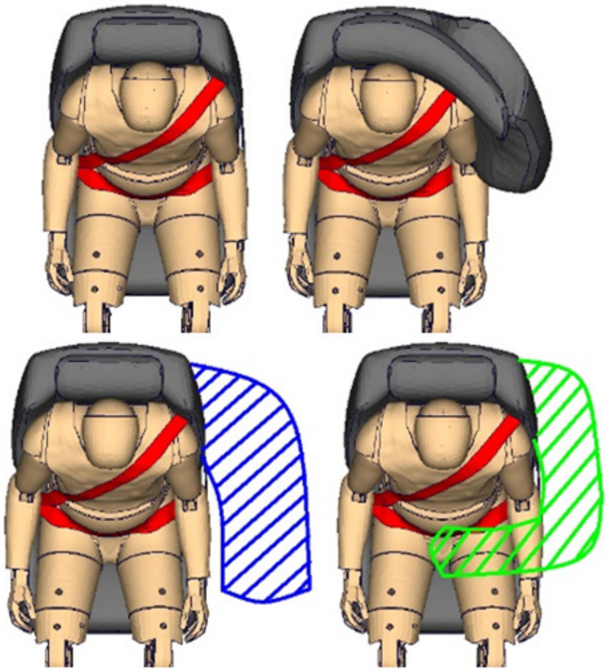

Fig. 10 Original, modified seat and the tested two airbag concepts (Source: Author's plot)

into the airbag with great force, so it must be sufficiently robust, since in this case there is no supporting surface. Such a surface is, for example, the door cover in the case of a side airbag or the steering wheel in the case of a driver airbag, a rigid surface that provides sufficient support for the airbag opening above/in front of it (Hu et al., 2023).

Recognizing the problem and analyzing it, we switched to the concept marked in green in Fig. 10, which eliminates the previously described problem and has sufficient resistance against loads coming from anywhere. The final form was naturally achieved by further development of several intermediate phases. As shown in Fig. 11, 30 ms is required for the airbag to fully open, which is an average opening time for airbags. In the initial stage, the airbag naturally grows based on what was presented in Section 3, after about 10 ms one fifth of the total gas volume reaches the bag. As the pressure continues to decrease, the volume increases, at 20 ms, the airbag reaches more than half of its final size. At this point, the most important thing happens, thanks to the folded shape, the additional inflowing gas from this point on stretches the airbag, which opens bigger and bigger, in the direction of the passenger. The quality of the folding and the shape of the deflated airbag therefore determine the shape after inflation. Fig. 12 shows the locations of the dummy, seat belt and seat, as well as the final version of the airbag.

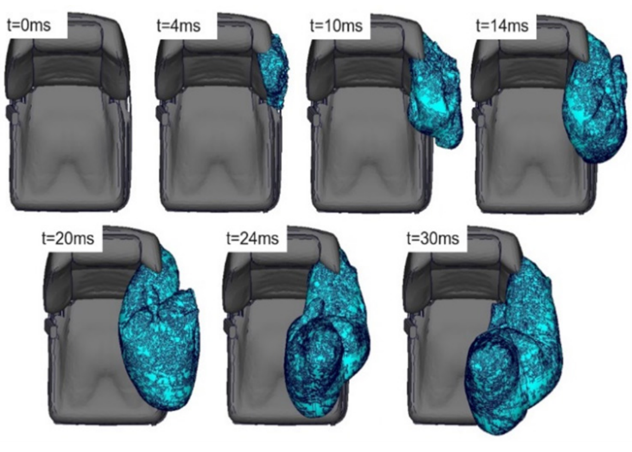

Fig. 11 The final form of the researched airbag (Source: Author's plot)

As mentioned earlier, an airbag that only opens in one direction causes stability problems and is unable to fully coordinate the passenger when under load. We have therefore mirrored the finished model, which can now provide sufficient stability. Fig. 13 shows the airbag concepts that open only in one direction and in both directions.

7 The results of the simulations with the new airbag concept

In the first part of this Section, we present the results obtained in the case of a frontal collision. As in the case of the modified seat, in the case of the airbag concept, only the seat position rotated by 60° was examined in frontal and side crashes too. Fig. 14 shows the head acceleration of the three available versions, the basic version, the modified seat model version

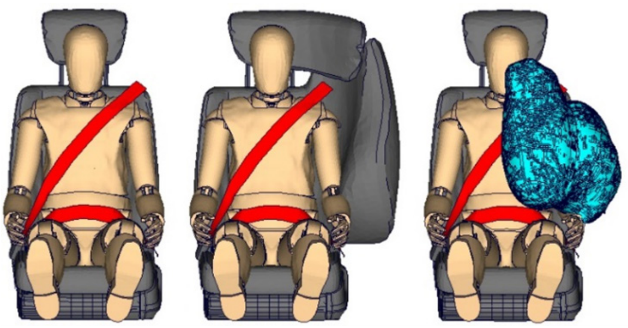

Fig. 12 Original, modified seat and the final airbag concept (Source: Author's plot)

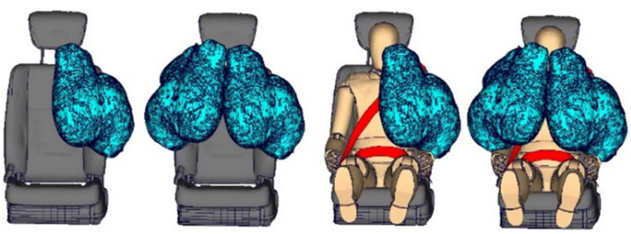

Fig. 13 The different airbag concepts, one-way open only and both-way open versions (Source: Author's plot)

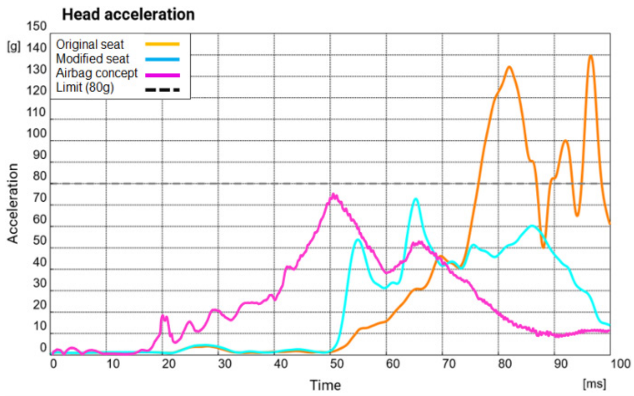

Fig. 14 Head acceleration in case of original, modified seat and airbag concept (Source: Author's plot)

and the airbag concept version. It can be clearly seen that the head acceleration shows a clear reduction, both in the case of the modified seat model version and the airbag concept version, compared to the basic version. The loads on the head are radically reduced, but a time shift can be observed, compared to the basic version where the maximums are at 80 ms and 95 ms, the maximums are at around 55 ms and 65 ms, respectively, for the modified seat model version. For the modified seat model version, the first maximum shows the initial contact of the head with the extended size headrest, and the second maximum indicates the reduction of the protective effect of the headrest. The maximum head acceleration of the airbag concept version can be made even earlier, it occurs at 50 ms, previously we saw that the airbag is already fully deployed at 30 ms and is able to receive the loads coming from the passenger side. The load builds up continuously and the airbag is able to exert the appropriate counter-effect. In general, it can be said that the earlier we can exert a strong restraining force against the passenger, the smaller the resulting injuries will be. The head acceleration curve of the airbag concept version is therefore more favorable, despite the fact that it reaches a minimally higher peak than the version with a modified seat model.

In addition to all this, it can also be observed that in the case of the airbag concept version, the acceleration builds up gradually, while that in the case of the modified seat model version is an unexpected shock-like jump, this is due to the behavior of the foam material.

In addition to the head acceleration value, from which the HIC (Head Injury Citeria), BrIC (Brain Injury Citeria) and Nij (Neck Injury Citeria) can be calculated, the other most important injury value is chest deflection (see Fig. 15).

The time shift is also excellently observable here, both in the case of the modified seat version and in the case of the airbag concept version. The time shift compared to the basic

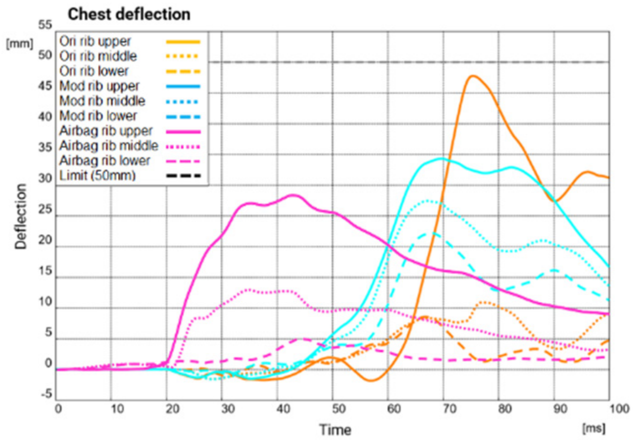

Fig. 15 Chest deflection in case of original, modified seat and airbag concept (Source: Author's plot)

version is only around 10 ms in the case of the modified seat version, but more than 30 ms in the case of the airbag concept version. In the case of the most relevant upper rib, a reduction of more than 12 mm in the case of the modified seat version and more than 20 mm in the case of the airbag concept version can be observed in terms of rib deformation compared to the basic version. In addition, however, an increase in rib deformation in the middle and lower part of the chest can be observed. The extent of this increase is more significant in the case of the modified seat version than in the case of the airbag concept version, which is also due to the properties of the foam material. The airbag concept version is, therefore, able to provide a much softer protection here as well.

Compared to the basic version, however, it is true for both additional versions that the force generated during the collision can be distributed over a larger area on the increased impact surface, which reduces the maximum value of chest compression. Summarizing the head values and the chest load, it can be stated that the airbag concept version is able to bring the values of the modified seat version in the event of a frontal collision, which thus already fulfills the consumer protection regulations of Euro NCAP. Table 5 shows the results obtained in frontal impact with the seat position rotated by 60° for the original, modified seat and airbag concept.

In the event of a side impact, a large improvement in the damage values can already be observed in the case of the modified seat version compared to the basic version, this is improved even more in the case of the airbag concept version. The problem with the basic version in the event of a side impact was primarily that the kinematics of the driver's movement changes radically, so the seat is no longer able to coordinate the passenger's movement and the passenger can easily slip out of the seat. The modified seat provided a good

Table 5 Results overview frontal impact original, modified seat and airbag concept (yellow = maximum value)

Criteria	Limit	Unit	60° ori. seat	60° mod. seat	60° airbag
Head (HIC15)	700	[-]	964	628	672
Head (a3ms)	80	[g]	93.1	71.3	75.1
Head (BrIC)	1.05	[-]	0.95	0.67	0.72
Neck (Nij)	0.85	[-]	0.48	0.73	0.77
Chest (Compress.)	60	[mm]	54.9	48.4	41.4
Abdomen (Compress.)	88	[mm]	103.5	81.9	86.5
Femur (Force)	7.56	[kN]	6.11	7.22	6.89

solution to this problem, but the airbag concept version is an even better solution, since while the modified seat only provides lateral protection, the airbag completely surrounds the passenger, thus ensuring their stability. In addition to all this, the soft protection of the airbag previously seen in frontal collisions is beneficial here as well.

In the case of a side collision, even in the case of the basic version, all values are below the limits prescribed by Euro NCAP. Stabilizing the passenger comes at a price, an increase in head acceleration must be expected both in the case of the modified seat version and the airbag concept version, which also leads to an increase in brain and neck injuries, however, these values still remain well below the desired limit values. Overall, it can be said that in the case of the modified seat version and the airbag concept version, the passenger's movement is much more coordinated and the load on the ribs and chest is reduced. The problem with the basic version, where the upper body, especially the head, moves uncoordinatedly and separately from the lower body, is solved. Table 6, which summarizes the results of the side impact, also confirms this tendency.

Table 6 Results overview side impact original, modified seat and airbag concept (yellow = maximum value)

Criteria	Limit	Unit	60° ori. seat	60° mod. seat	60° airbag
Head (HIC15)	700	[-]	141	268	344
Head (a3ms)	80	[g]	41.7	53.9	47.3
Head (BrIC)	1.05	[-]	0.89	0.93	0.87
Neck (Nij)	0.85	[-]	0.69	0.42	0.72
Chest (Compress.)	60	[mm]	37.1	29.3	31.1
Abdomen (Compress.)	88	[mm]	61.2	57.2	58.4

8 Conclusion

In this article, based on the results of our research so far, we analyzed them in detail and carried out further research with different airbag concepts. The article provides an overview of the development of airbags used in cars, airbag folding technique and the operation of airbag deployment simulations. In addition, the article reviews the results of the first and second phases of the research, discusses the most important energy absorption methods from the point of view of passenger safety, and presents the airbag concepts examined in the latest phase of the research and the obtained results. In the course of the research, we used the previously constructed and validated computer simulation model to investigate frontal and side collisions. In each case, the obtained results were compared with the results obtained in previous phases of the research. In the case of frontal and side collisions, relying on the results obtained in the first phase of the research and evaluating the experience gained from them, we examined the most critical seating position, which was the one turned by 60°. Even in the case of the modified seat and the airbag concept version, it can be said that all desired results fall below the permissible limit. In the event of a side collision, the injury values of the basic version were not high either, so the goal here was less to reduce the injury values, and more the coordination of the passenger's movement during the accident. Both the modified seat and the airbag concept version fulfill the set goal, however, the latter has a big advantage of soft restraining force. In the case of a side impact, the injury values of the different body parts show a more mixed picture than in the case of a frontal impact, the values of the upper body increase, while the values of the lower body decrease both in the case of the modified seat and in the case of the airbag concept version.

Summarizing the results of the research so far, it can be said that both the modified seat and the chosen airbag concept can meet the expectations. However, the feasibility of the modified seat used in the research may be questionable due to its size. It cannot be used with the currently known interior designs, its application would require a completely new interior design philosophy, which offers passengers more space for a reason. Full self-driving at the maximum level five is only a long-term plan for the time being, however, the results of the research clearly show that its implementation will require radical changes in the entire car design process. In addition to the reasons mentioned above, the modified seat version has an additional disadvantage, which is the restriction of the passenger's view. Although in the era of the fully self-driving car, no human intervention will be needed during the movement of the car, these devices can also fail, which means that the passenger has to become the driver again and control the vehicle in a classic way. In this case, the limited view in both directions is a real problem. However, the airbag concept version can also solve this problem. The airbag is always in a closed state and is therefore invisible, it does not disturb the passengers until the accident occurs. The research did not cover the investigation of the airbag feasibility and production possibilities of the applied concept. A future research direction is to combine the seat and airbag concepts by integrating the airbag into the seat design and developing an optimal solution that meets these challenges while maintaining adequate stability.

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