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Innovative design steps towards a safe active lightweight chassis for an electric vehicle

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Abstract

Lightweight design is still very important for an all-electric vehicle especially when used in urban areas. A new active chassis suspension designed for such an urban car is in development at the DLR. The first main component is a composite transverse leaf spring, where a new (partly) automated design and dimensioning process is in development. The second component is an orbital wheel bearing with an optional integrated electrical drive. The third component is an innovative wheel independent two axis steering actuator changing the toe and camber angle. This enables an increase of the active and passive safety of the occupants. First simulations proved the benefits of the concept regarding enhanced crashworthiness. The modular concept of the system allows to use the same wheel at each corner of the vehicle without changing a single part, thus reducing vehicle part variants and costs.

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Keywords: active and passive saefty; automated design process

1. Reasons for the need of a new chassis systems for full electric vehicles

1.1. Motivation

Driving ranges have always been an issue for full electric vehicles. Either they have big batteries in order to get an accepted range, which makes them heavy and expensive, or the batteries are small and the electric range especially at winter conditions is not above 100 km. Simple parametric simulations of the effect of mass reduction to electric range showed, that at urban usage the range of such a vehicle can be in-creased by 21 %, if the total mass of the vehicle is reduced by 20 %. [Deisser et al., 2012]. The lack of the combustion engine and its components including the gearbox

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give the vehicle layout and the crash management whole new possibilities but also risks. New ways have to be found to enhance safety and comfort with an additional reduction of mass for an enhanced electric range.

1.2. Current regulations, the lack of crash compatibility in reality and a possible solution

To get a good rating of the official crash scenarios by fulfilling the crash standards is one of the hardest issues within the homologation process. But to get a high occupant safety at nonstandard crashes is even harder to achieve. The crash scenarios get more and more realistic as it can be seen at the so-called small overlap crash test protocol from the American Insurance Institute for Highway Safety (IIHS). With this synthetic test results due to a crash with a small hitting area can be evaluated. The car hits a small non-deformable (massive) barrier with only 25 % overlap of the vehicle's width. The shape of this test barrier is a flat wall with a 150mm radius cylindrical edge. [IIHS, 2017]. The result on the road of a real crash with only a small overlap can be seen in Fig. 1 (a). In (b) the schematic hitting area and in (c) the official test barrier and the hitting area at a car is shown.

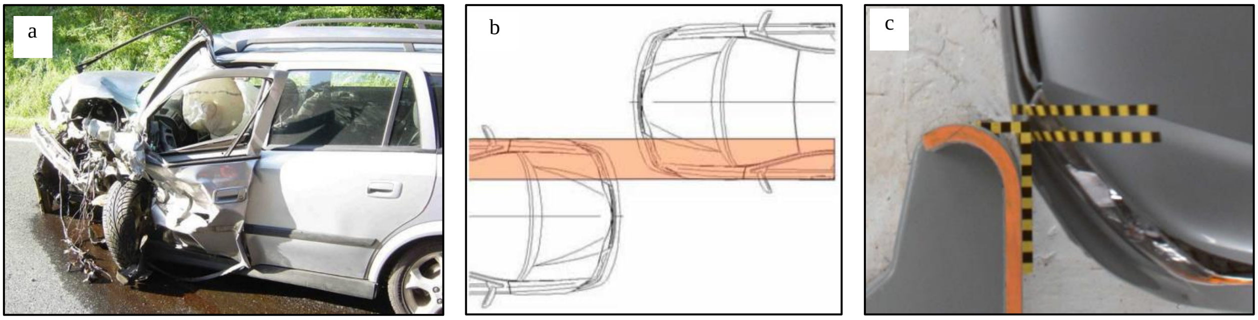

Fig. 1: (a) real crash on the street [ADAC]; (b) schematic hitting area [ADAC]; (c) Test barrier and impact area [IIHS 2017].

Deflection of the crashing partner is a well-known method for improving the general crash behavior. This can clearly be seen at the safety fences on motorways. With this principle only a very limited risk of intrusion of the wheel or another part into the passengers' cell is left. The first documented invention regarding deflection for use within the car structure came from Prof. Schimmelpfennig in the 1990´s. At the beginning he concentrated his efforts on trucks and trailers, for the accidents with those vehicles are often severe for cars and their occupants. In 1996 he submitted a patent application called "safety bumper for motor cars" (Sicherheitsstossstange für Personenkraftwagen, European patent EP0758597 B1), where a practical solution of deflection for passenger cars is described.

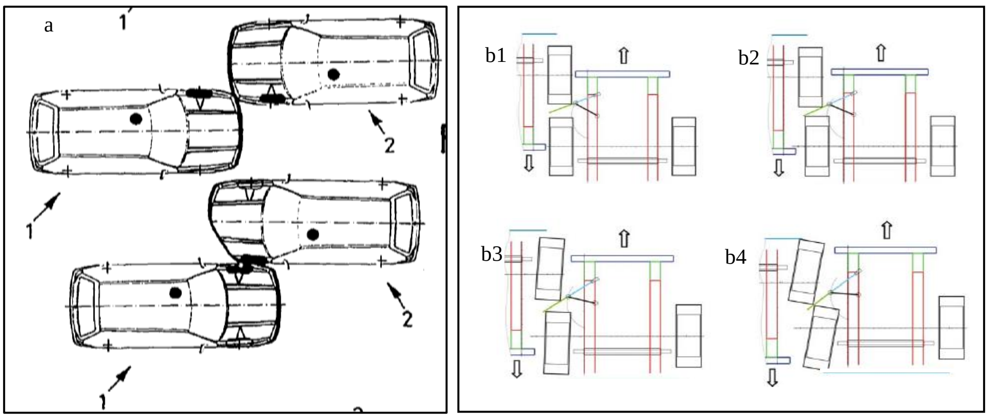

Fig. 2: principle of deflection using (a) the bumper [Schimmelpfennig, 1996]; (b) the "Flexible Collision Deflector" [Schimpl, 2005]

In Fig. 2a two cars equipped with such a big bumper are drawn at a crash with a small hitting area. Top picture shows two cars hitting each other; bottom picture milliseconds after the first contact. [Schimmelpfennig, 1996]. Due to current design restrictions demanding short front overhangs and especially for small urban vehicles, these long bumpers are currently not very realistic for series production cars. Another promising concept is also shown in schematic sketches of the main car structures Fig. 2b, where a mechanical extendable deflector attached to the longitudinal rail is used. This deflector is designed to turn the wheel (black rectangle) in order to use it as the shield. (b1) shows the impact on the deflector and (b2) to (b4) illustrates the sliding mechanism of the blue part for the turning of the wheel inward. [Schimpl, 2005]. Today no car uses these ideas to get a good rating at the small overlap crash test, but the manufacturers mostly try to slide at first a bit to the side and then to absorb the crash energy within the body structure.

2. The chassis system of the Next Generation Car – Urban Modular Vehicle (NGC-UMV)

2.1. The orbital wheel concept

The idea of the orbital wheel is not new. The Italian designer Franco Sbarro invented it and holds several patents on it. His first European patent (FR000002633877B1) is from 1988 and was republished as world patent two years later with the number WO90/00477. The main idea is, to put the wheel bearing into the rim base without any visible hub and give the wheel and vehicle new design possibilities, to reduce the rotating mass and friction. Several mostly custom-made motorbikes and show cars later, not only from Mr. Sbarro, there is still no series production for this wheel bearing concept. Only some motorbike customizers still use this concept for show and a formula student racing team used it on their car in combination with an innovative wire ball bearing for weight benefit. But the orbital wheel concept has other benefits in addition to the aesthetical as illustrated in Fig. 3. In conventional suspensions for the front axle, like the MacPherson concept, the road forces are distributed from the tire to the rim base and over the rim center into the wheel bearing. From there the forces are split into the primarily vertical forces (Fig. 3a, F_v) and into the primarily horizontal forces (Fig. 3a, F_h). The vertical forces are carried by the suspension strut and the horizontal forces are borne by the lower wishbone. So, the forces take long and indirect ways into the body of the car (Fig. 3a). The orbital wheel concept simplifies the path of the forces and leads them nearly direct into the wheel guiding parts: lower wish bone and the suspension strut (Fig. 3b). Due to direct force routing, which leads to reduced mass and reduced parts, a light-weight potential is obvious.

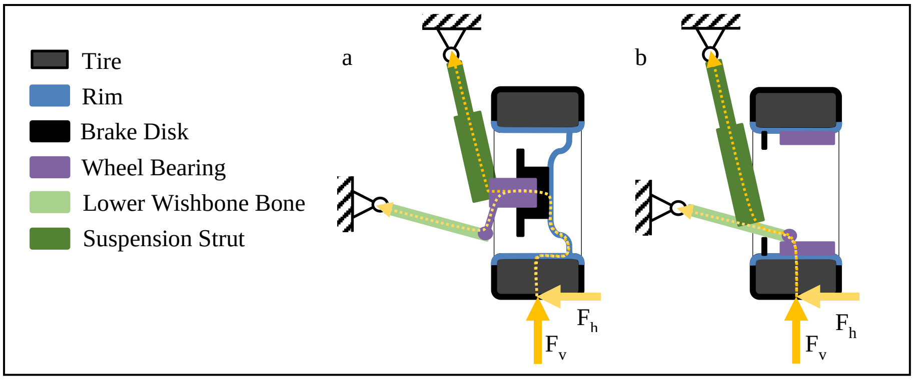

Fig. 3: (a) conventional MacPherson suspension; (b) orbital wheel with MacPherson

Beside the more complex/expensive bearings and sealings other challenges also occur according to this bearing concept. The most demanding question is the mounting and balancing of the tire. If the bearings are directly fixed to the base of the rim, they have to be dismantled for mounting the tire. This leads to complex procedures, where cleanness and precision is very important not to worsen the wear or even damage the bearing or the bearing seats. One solution to this problem is an additional housing for the bearing, even as there is an extra weight. The rim with the tire can be detached and attached to the lilac part of Fig. 3b. Then only an additional adaptor, like a wheel star of a three parted rim, has to be used, when balancing the wheel. Also, within this housing an electric drive can be integrated as an in-wheel motor.

In order to gain as much space as possible within the wheel center and at the same time reduce unneeded mass, the outer shell of housing of the bearing, as well as the base of the rim, are designed as thin walled cones. The finally used cone angle of 2° was chosen in order to provide a strong enough interference fit assembly to bear all forces and torsions. Without consideration of cases of misuse analytics proved, that the angle of 4° is enough, when applying a tightening torque of less than 1000 Nm. A splined hub in the rim is used to reduce the stress within the thin walled rim and bear the loads of misuse. For first functional demonstrator conventional bearings with a big inner diameter of approx. 400 mm would have been too expensive and heavy, even when using existing thin ring ball bearings. Therefore, the flexible and known wire bearings from the company Franke were chosen. They can be adapted very easily regarding diameter and loads. The only disadvantages within this concept are the reduced endurance due to the use of existing wire and ball diameters and the closing joint of the "open" wire ring for its manufacturing/assembly. This joint affects the quietness of the bearing, especially when running under load. In the sectional view of Fig. 4 the detailed design done with Catia V5 without breaking disc and brake caliper can be seen.

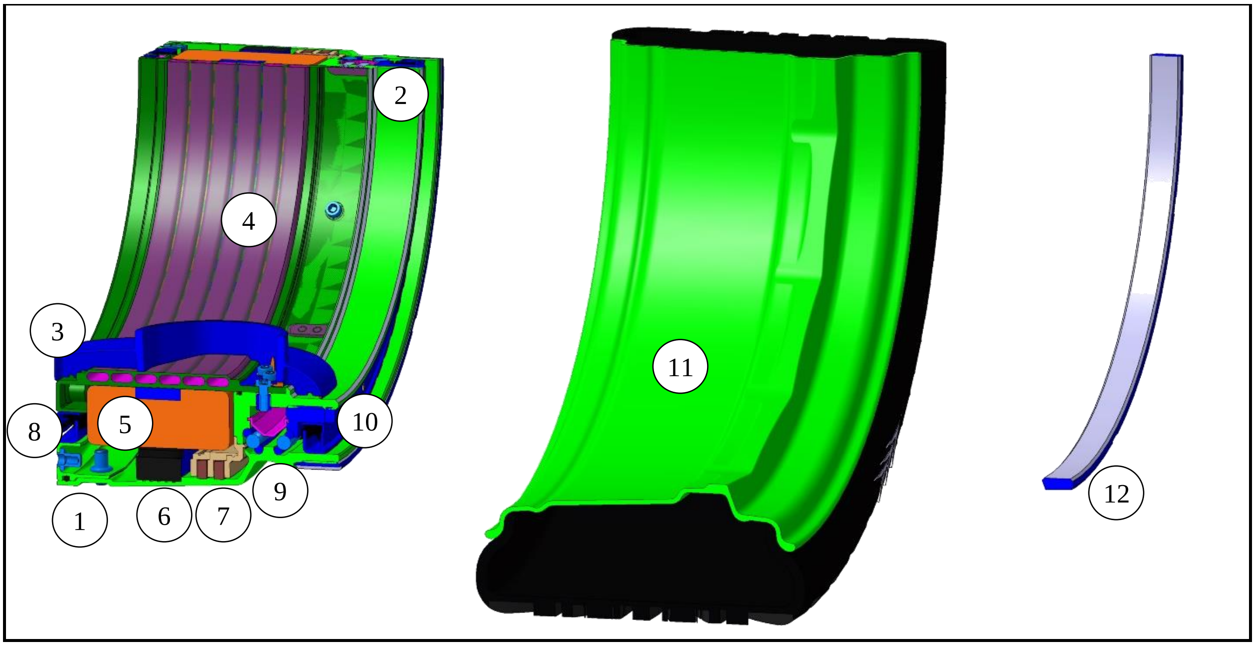

Fig. 4: Sectional view of the wheel assembly

1. Outer housing for bearing
2. Inner housing for bearing
3. Link to wheel guidance comp.
4. Cooling jacket
5. Electric stator
6. Permanent magnetic rotor
7. Labyrinth sealing rings
8. Radial shaft sealing rings
9. Wire bearings
10. Adjusting ring
11. 7x20 rim with tire
12. Central locking nut

2.2. The two-axis independent steering system

If the connection point of the chassis control arm is chosen correct, it is possible to use it as a steering axis. This means that there is the possibility to implement an independent electric power steering attached to the rim bearing. In this way both wheels can be steered independently of one another. As the desired steering ratio of 1000 degrees per second at the steering wheel is commonly known as ideal for active steering systems [Klein et al., 2013], the initial desired speed for the steering system of the NGC-UMV should be likewise. The Next Generation Car – Urban Modular

Vehicle (NGC-UMV) is a small all electric driven car in development at the DLR. Tests with the DLR Robomobil from the Institute of Robotics and Mechatronics in Oberpfaffenhofen showed that 240 degrees per second at the wheel is more than sufficient to cope with all driving situations at speeds of up to 100 km/h. The Robomobil is a research demonstrator using wheel independent full electric steering and drives. [Bünte et al., 2014]. The steering ratio of the Robomobil should be sufficient for the UMV, as it is an urban vehicle mainly used below that speed. When there is just one single point, where the wheel is connected to the chassis control arm, a cardan like joint can even be used to influence the camber angle as well as the toe angle for steering. There is now the chance to integrate a simple camber angle actuator. No complicated hydraulics or expensive linear actuators are needed to change the length of one control arm for the same effect. Then even a small car like the NGC-UMV can be equipped with an independent two axis steering system to gain a better driving dynamic and a better active safety. As a negative camber angle is positive for a better grip of the tire at cornering, this can be adjusted and optimized by the active system individually for each wheel. Though there is only a small angle range of +/- 10° needed to improve the driving stability effectively, small high-revving motors with a high gear transmission ratio can be chosen to cope with the requirements of a high torque at estimated 100°/s or ~17 rpm. The research engineers of Daimler showed in their concept car “F400 Carving”, that the maximum effect of driving stability and agility would be by an angular range of +/- 20°. They realized an increase of 30 % cornering force compared to a conventional car’s suspension and a lateral acceleration improvement of up to 28 % compared to sports car with a passive suspension. [Daimler, 2001] As safety is within the chassis at highest priority, all electronic systems should be deployed redundantly. This can be achieved by electric motors using double rotor windings and doubled circuit points. The gears are unlikely to fail, if dimensioned with a safety factor high enough. The first concept of a two-axis steering system able to bear all loads is still very massive and complex due to the desire to use as much components already available on the market. All the gearboxes and motors were taken from re-known partners. As the standard gearboxes are not designed to take heavy axial and radial forces, a new bearing housing had to be developed. The massiveness of the needed bearings is visualized in the fully dimensioned conceptual design in Fig. 5, which has to be redesigned to fit into the previously presented wheel.

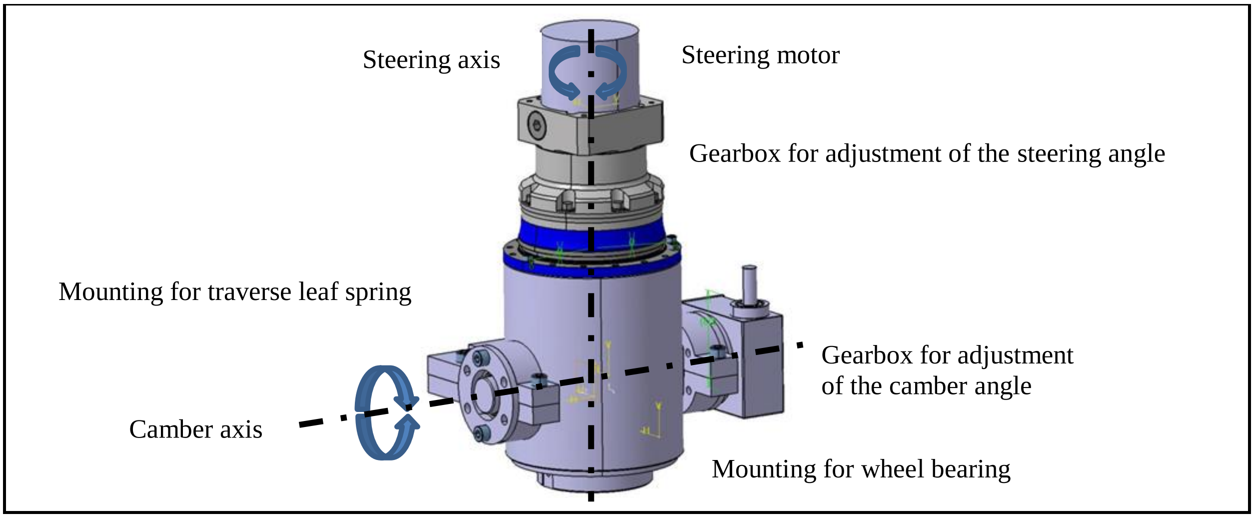

Fig. 5: Two axis steering system [Strübel. 2019]

2.3. Virtual dimensioning process for the GFRP transverse leaf spring

The efficient dimensioning of a fully or partially wheel-guiding transverse composite leaf spring is a technical challenge. On the one hand, the kinematics of the wheel must be ensured under typical loads, such as compression and rebound or cornering. On the other hand, overloads caused by pothole driving, for example, must be endured. The efficient and economical finding of at least one geometric design including layer structure points to the necessity of using automated virtual process chains. The goal of these process chains is to propose at least one concept for a leaf spring design. Additionally, this concept can be subjected to a virtual verification by subsequent simulations, such as multi-body simulations (MBS). Optimization algorithms are used to determine the concept from the large number of design variables, such as geometry parameters, number of layers or fiber angles. In particular, this process involves the combination of shape and size optimization. Besides the handling of the large solution space, the increased computation time due to necessary non-linear simulations compared to linear simulations can be challenging. The search for suitable concepts is further complicated by mandatory multi-objectives due to different load cases. The mesh quality of the generated models must be consistent so that the simulation results of different models are comparable. Depending on the fiber angles and ply thicknesses, the laminate plies influence objective functions such as kinematics. The drapability of different ply semi-finished products such as unidirectional or bidirectional plies and the projection of the fiber angles in the FE model must be taken into account. In finding solutions, it is important to maintain (economic) manufacturability.

Process chains of this type are being developed in the GEM-EF research project and the DLR Next Generation Car project. The focus is, among other things, on the coupling of CAD, FE and, for example, MBS tools, as well as the use of evaluation, analysis and assessment routines. For the implementation it is necessary that the corresponding tools have a script language to pass parameters via ASCII files and to generate and simulate models. With a programmed software-architecture it is possible to couple and control these tools. Furthermore, implicit or explicit FE tools like Optistruct, Radioss, LS-Dyna or Pam-Crash can be exchanged or inserted into the process chain. Essential are programmed evaluation, analysis and assessment routines. Thus, errors can be detected quickly and raw calculation results can be processed and visualized efficiently. Fig. 6 shows an exemplary process chain for generating leaf spring concepts.

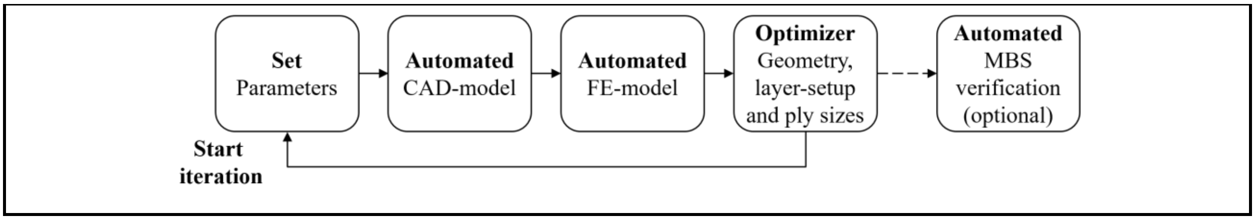

Fig. 6: Exemplary process chain with optional subsequent MBS verification.

The first step is the definition of the design space, which is used to define the maximum dimensions of a fully parameterized CAD model of the leaf spring. Further-more, the type of laminate structure, such as fabric and/or unidirectional layers, must be selected, as well as possible numbers of layers. After that, connection elements and the load cases have to be defined. With this set of parameters, the CAD and the FE model are automatically created in a second and third step. The layer-setup and plies are then optimized. If the optimization results in leaf spring designs whose current kinematics are similar to desired kinematics, for example, this model is saved. After completion of the laminate optimization, a new parameter set and thus a new iteration is started. In parallel, the verification process for multi-body simulations in the complete vehicle or the chassis suspension can be started automatically. If the models meet the evaluation criteria (i.e. strength criteria, deviations in kinematics), they are declared as leaf spring concepts and can be reviewed by the engineer.

2.4. The wheel as deflection shield is enough for an improvement in passive safety

The possibility to combine wheel individual steering and pre-crash sensors offer new ways to enhance occupants' safety. As shown at the beginning, deflection is a very effective way to reduce the effects of impact at a small overlap crash. If the wheel as a massive structural part can be used as a deflection shield, no additional heavy structure or complex body stiffeners are needed for this purpose. The steering components, with their high turning speed of at least 240 degrees per second, only need to be activated, when the opponent is less than 1.5 meter away. This means, that the wheels are turned by the steering motors or the steer-by-wire-system only an eighth of a second before the crash occurs. Both wheels turn to a toe-in in order like a plough to stabilize the car and give it the right direction. As there are many sensors built in the car today, e.g. for parking, future vehicles with autonomous driving systems will provide even more possibilities to trigger the steering mechanism in a crash scenario. These sensors will be connected to the cars' safety systems and will detect, when a crash is inevitable. The sensors in today's cars are ultrasonic for parking assistance or even radar for automatic distance control and can give the exact timing for the actuation even now. The electronic control units (ECUs) just have to be enabled to act in a proper way. In Fig. 7 are displayed the measurement points of the a-pillar and the foot rest at the inner firewall of the FEM model of the NGC-UMV. These points are relevant for the evaluation of the crashworthiness at the IIHS small overlap crash test scenario.

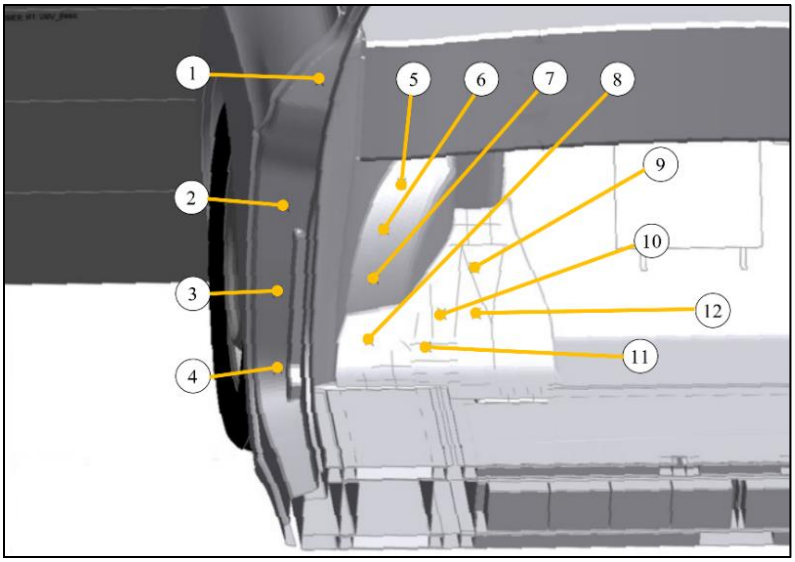

Fig. 7: Measurement points for the evaluation of the intrusions

In the Table 1 are the simulation results of the small overlap crash according to the IIHS standard. Listed are the results of a normal oriented wheel (at 0°) and the intrusion values with a wheel turned in at 30°. There is a big improvement of the intrusions within the structure (less intrusion is better). The displacement of the a-pillar is significantly lower by an overall reduction of more than 25 %, which results in less risk of the jamming of the door after a crash. Also, the overall reduction of the intrusion in the foot area is approx. 25 %.

Table 1: Evaluation of intrusion values at the NGC-UMV

Point	Intrusion at 0° [mm]	Intrusion at 30° [mm]	Difference (abs.) [mm]	Difference (rel.)
1	104,8	85,1	19,8	19%
2	116,6	85,9	30,7	26%
3	124,1	86,1	38,0	31%
4	129,2	93,4	35,8	28%
5	133,2	145,3	-12,0	-9%
6	138,8	134,3	4,5	3%
7	132,9	124,0	8,9	7%
8	90,0	64,7	25,2	28%
9	65,2	49,6	15,6	24%
10	75,4	33,0	42,4	56%
11	48,1	30,9	17,2	36%
12	59,2	31,2	28,0	47%
				~25%

The little or negative effect on the intrusions of the upper footrest left (points 5-7) are due to the massive structures of the NGC-UMV, which result in block building when crashed. Due to geometric restrictions of the body structure, the wheel is not possible to act as a deflection shield for this car with the current design. The barrier hits the edge of the rim, which is pushed into the safety cell. There is no space for the wheel to turn in by more than 30° because of the position of the longitudinal rail. There are two possible ways to enable the wheel as a deflection shield, which can only be applied by a re-design of the vehicles body structure. Firstly, by the shifting of the longitudinal rails to the middle of the car in order to give the wheels more space to turn in more. Secondly, by the re-design of the bumper. When adapted correctly, it can act as a prolonged rim flange and thus initiating the deflection.

3. Conclusion and outlook

New crash test scenarios like the IIHS small overlap crash test and new all electric vehicle concepts demand new safety solutions. The new NGC-UMV suspension concept is bringing together the individual existing concepts orbital wheel bearing and transverse leaf spring. It is furthermore combining these concepts with the new and innovative two axis steering system. The modular concept of the systems allows to use the same wheel at each corner of the vehicle without changing a single part, thus reducing vehicle part variants and costs. This new chassis concept is giving a promising answer to the demands of new electric vehicles. With such active steering systems and even partly automated driving including intelligent trajectory planning it is also possible to enhance the crash safety. These systems can also be used to steer the vehicle more into the opponent vehicle in order to use more crash structure of both cars to absorb the crash energybetter. This applies in such cases, if the crash is inevitable, but there is no save place to steer. Although there is no actual deflection by the aid of the wheel alone possible in the case of the NGC-UMV, the crash behavior is improved significantly. The DLR proved the feasibility by first static and dynamic simulations and is now investigating further to develop the concept in more detail. A methodical design and dimensioning of the transverse leaf spring is actually a work in progress. This includes the geometric dimensions as well, as all parameters of fiber layup, the kind of fibers and the matrix system. Also, the dimensioning and the calculation of the needed torsion moments and the energy demand of the two-axis steering system will be done during this project. The build-up of a functional demonstrator for the bearing is planned within this year. The final virtual integration of the suspension system into the NGC-UMV CAD model with all joints and at least the dynamic crash simulation of the whole concept within the car is the last step before a full functional demonstrator is build.

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