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An innovative and safe active light weight design chassis suspension system - An enhanced development methodology

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Abstract
Lightweight design is still very important for an all-electric vehicle especially when used in an urban area. Simple chassis systems for small urban vehicles covering the weight limitations often lack an acceptable drive comfort and driving stability in extreme situations. A new active chassis suspension designed for such an urban car is in development at the DLR Institute for Vehicle Concepts in the founded project Next Generation Car (NGC) Urban Modular Vehicle (UMV). This concept even provides active safety measurements regarding small overlap crash scenarios. Main components are a composite traverse leaf spring, an orbital wheel bearing optional with an integrated electrical drive and an innovative wheel independent two axis steering actuator changing the toe and camber angle. For the creation of this concept an existing development methodology is used, which is extended by a (partly) automated design and dimensioning process.

Keywords: road safety; occupant safety; active chassis system; lightweight design; automated design methodology

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Nomenclature

CAD	Computer Aided Design
CFRP	Carbon Fibre Reinforced Plastic
DLR	Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Center)
ECU	Electronic Control Unit
FE	Finite Element
GFRP	Glass Fibre Reinforced Plastic
IIHS	American Insurance Institute for Highway Safety
IUV	Inter Urban Vehicle
NGC	Next Generation Car
SLRV	Safe Light Regional Vehicle
UMV	Urban Modular Vehicle

1. The need for a new chassis systems for full electric vehicles

1.1. Motivation

Full electric vehicles have always a problem with their driving ranges. Either the vehicles 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 100km. 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 increased by 21%, if the total mass of the vehicle is reduced by 20%. Deißer et al. (2012).

According to a study done by Lotus Engineering published in 2010, the chassis with brakes, wheels and tires has nearly the same part of the total mass of a conventionally driven vehicle as the body-in-white. Lotus (2010). Although the reference car of the study was equipped with a combustion engine, the weight of the complete powertrain plus the energy storage with fuel is comparable to an electric drivetrain with a small battery used in an urban car. Also as the body in white gets more and more advanced in material, such as carbon fibre reinforced plastics e.g. the BMW i3, the chassis systems have still very conservative concepts and materials. Simple but lightweight design chassis often lack of good driving performance or comfort. New intelligent active systems are capable to close the gap between those simple chassis and highly sophisticated ones like multi-link-chassis. But these systems are often complex and expensive and therefore mostly used in upper class cars.

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

To fulfil the crash standards and to get a good rating of the official crash scenarios is one of the hardest issues regarding 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-I). 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.

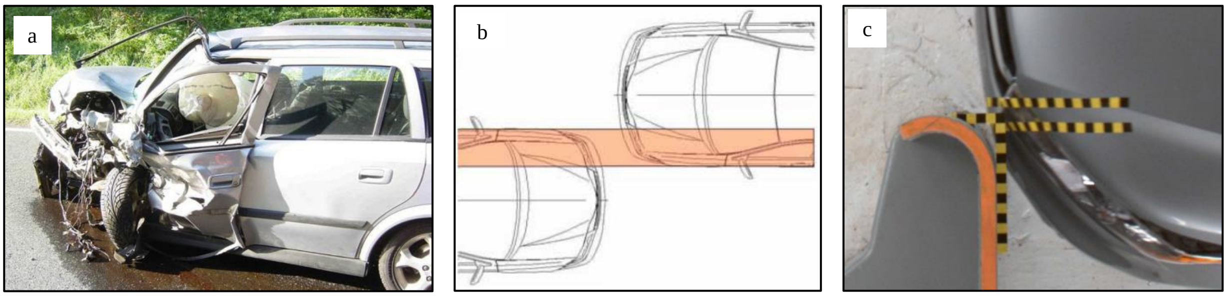

Fig. 1: (a) real crash on the street. ADAC (2000); (b) schematic hitting area. ADAC (2000); (c) Test barrier and impact area. IIHS (2017-I).

To solve the problem of failing this crash test and to enhance the occupants' safety more than 100 patents and inventions have been registered since the implementation of this test. Some of these use additional structure to absorb the resulting energy at a crash. These energy absorbing structures are very mass intensive, as the energy to be absorbed is very high and the available design space in conventional cars is very limited. A second possibility and a more effective one for the enhancement of the crash safety is to deflect the energy. So only little energy has to be absorbed by the structure within its limited space and time, but the kinetic energy of the car can be reduced in the greater space available post-crash.

Deflection of the crashing partner is a well-known method for improving the general crash behaviour. 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. In Fig. 2 (a) two cars equipped with such a big bumper are drawn at a crash with a small hitting area. 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 Fig. 2 (b), where a mechanical extendable deflector is used. This deflector is designed to turn the wheel 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.

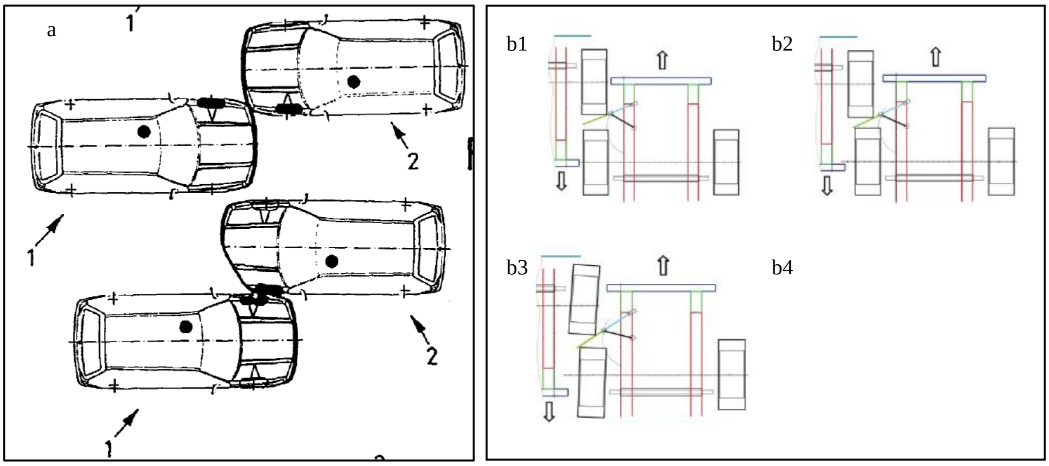

Fig. 2: principle of deflection using (a) the bumper. Schimmelpfennig (1996); (b) the "Flexible Collision Deflector". Schimpl (2005).

Today no car uses these techniques 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. An example for a high rating at this test is the all-electric vehicle BMW i3. It has a very stiff structure with the CPRF "Life-Module". For preventing the wheel to be driven into the cabin, it is sheared off instead. In the crash video provided by IIHS this can be clearly seen as shown in the frame captures in Fig. 3.

Fig. 3: Deflection of a BMW i3 at IIHS small overlap crash test. IIHS (2017-II)

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

2.1. The Urban Modular Vehicle

In the Next Generation Car (NGC) research project at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR), within the program topic of terrestrial vehicles, different institutes are working on issues for the cars of the future. In this context three different vehicle concepts are being developed according to the technical requirements and capabilities within the next ten years: Urban Modular Vehicle (UMV), Interurban Vehicle (IUV) and Safe Light Regional Vehicle (SLRV) (see Fig. 4). The aim of NGC is to consolidate the technologies, methods and tools for the various vehicle concepts researched at the DLR in the field of transport, to generate synergies and to demonstrate research results. The NGC project is systematically divided into the following areas: Vehicle Concepts, Vehicle Structure, Energy Management, Drivetrain, Chassis and Vehicle Intelligence.

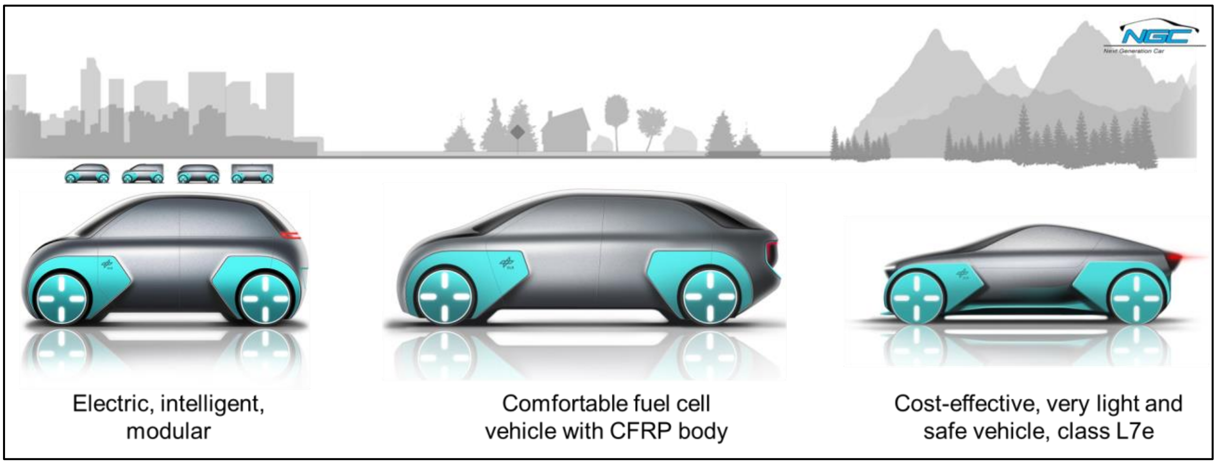

Fig. 4:NGC Vehicle Concepts: Urban Modular Vehicle (UMV), Interurban Vehicle (IUV) and Safe Light Regional Vehicle (SLRV). Deisser et al. (2018).

For the urban use vehicle a new active chassis suspension system is in development. Basis of this concept is the patent pending idea described in the document DE102017204698A1. This system contains three major modules: the orbital wheel bearing, the two axis steering system and a traverse GFRP leaf spring. The combination of these modules allows especially small cars to benefit from a lightweight design active chassis for an enhanced passive and active safety.

2.2. 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 lately a formula student racing team used it on their car in combination with an innovative wire ball bearing for weight benefit. Jankowski (2014).

But the orbital wheel concept has other benefits in addition to the aesthetical as illustrated in Fig. 5. 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 centre into the wheel bearing. From there the forces are split into the primarily vertical forces (Fig. 5a, F_v) and into the primarily horizontal forces (Fig. 5a, 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. 5a). 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. 5b). Due to direct force routing, which leads to reduced mass and reduced parts, a lightweight potential is obvious.

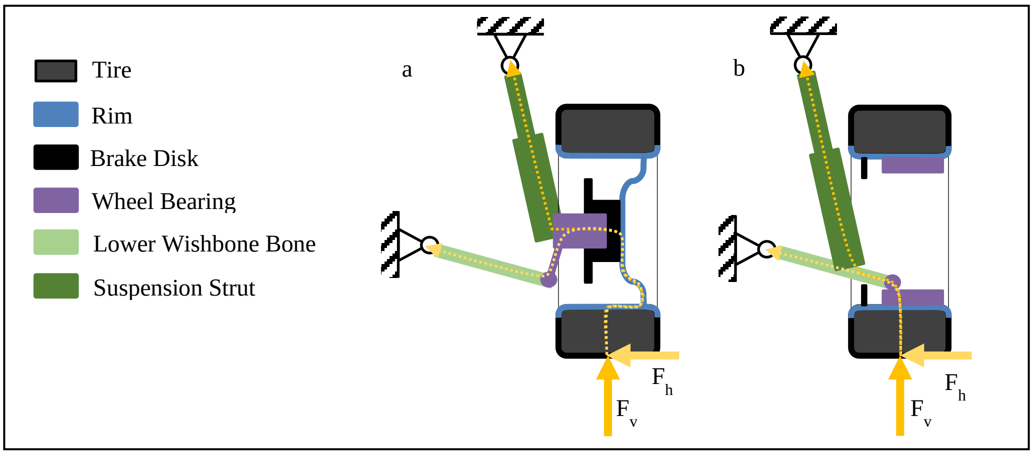

Fig. 5: (a) conventional MacPherson suspension; (b) orbital wheel with MacPherson

Beside the more expensive bearings 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. So the rim with the tire can be detached and attached to the lilac part of Fig. 5b. 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.

2.3. 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. Two different articles concerning the independent steering remark upon the positive effects of reduced energy consumption, better driving dynamics and a high active safety potential. Bünte et al. (2014), Klein et al. (2013). As the desired steering ratio of 1000 degrees per second is commonly known as ideal for active steering systems, the initial desired speed for the steering system of the NGC-UMV should be likewise. Tests with the DLR Robomobil from the Institute of Robotics and Mechatronics in Oberpfaffenhofen showed that even 700 degrees per second are still sufficient to cope with all driving situations at speeds of up to 100 km/h. This steering ratio of the Robomobil should be sufficient for the UMV, as it is an urban vehicle mainly used below that speed. Simulations are going to be made to prove, that even higher driving speeds are uncritical.

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 dynamics 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 degrees 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 ~17rpm.
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 degrees. 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 is still very massive and complex due t 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 gearboxes are not designed to take heavy axial and radial forces, new bearing housings had to be developed. The massiveness of the needed bearings is visualized in the fully dimensioned conceptual design in Fig. 6.

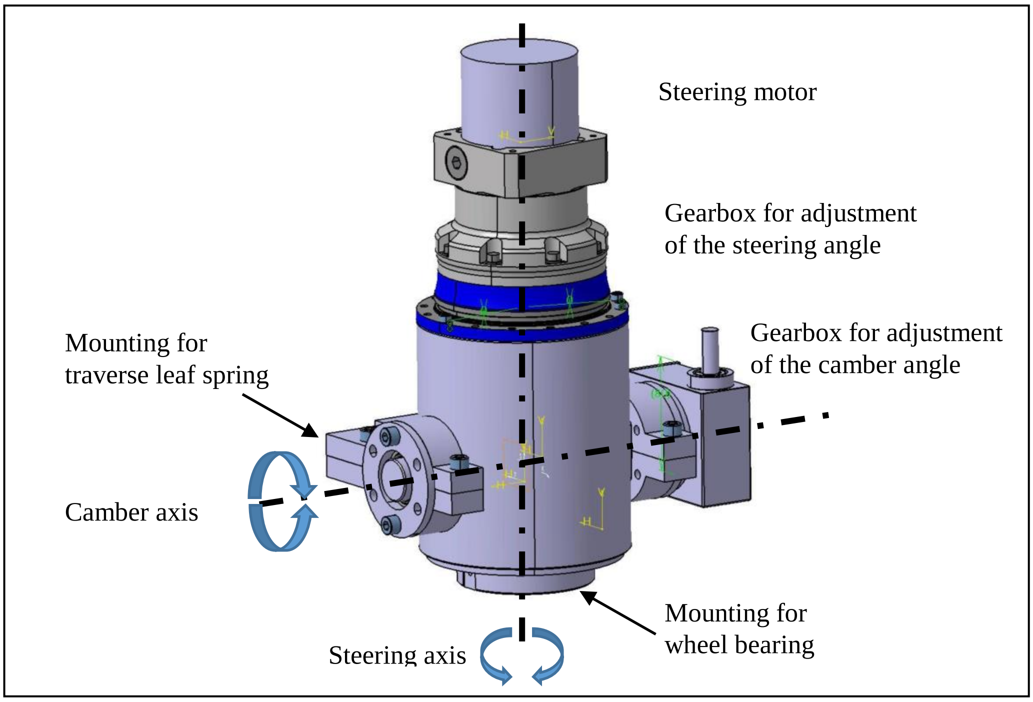

Fig. 6: Two axis steering system. Strübel (2019).

2.4. GFRP transverse leaf spring

The third important part of the new suspension concept of the NGC-UMV is the glass fibre reinforced plastic (GFRP) transverse leaf spring. In 1986 the first patent for plastic leaf springs can be found from the French company Bertin & Cie, with several more patents in the following years. Wheel guiding leaf springs were used in carriage building from the beginning of the use of springs for more comfort. With the upcoming of wheel independent suspension for higher driving dynamics only rigid axles for heavy duty vehicles still used leaf springs. By the use of the fibre reinforced material as well as the required new kinds of attachment and the connection joints, traverse leaf springs gave a new impulse to wheel independent suspension. Plastic leaf springs are more durable than the metal coil springs, as they have higher fatigue strength and docile failure behaviour. Due to the fibres within the composite the growth of cracks is minimized and there is no sudden failure as can occur with their metal counterpart. Another benefit of fibre reinforced composites is the possibility to change the changing the fibre layup. This leads to a different spring ratio and local stiffness within the part, which can even influence the bending kinematics. Under most conditions this means different sets of moulds.

The full capability of the material is still not in series production, although different companies explored and evaluated wheel guiding leaf springs. The first car manufacturer who tried to implement this concept was Renault in the 1990's. Their patent EP0436407 from 1990 displays their idea of using a GFRP leaf spring as a single part with integrated lower wishbones, spring and antiroll bar function in combination with a MacPherson damper strut. In the following years they optimized the fibre layup up to readiness of series production. Others followed but no car was ever produced for sale; only studies and concept cars were shown.

The use of plastic leaf springs in series production cars was first seen in the first smart city coupe in the year 1998 with their suspension developed by Porsche, as can be seen in the corresponding patent DE19721878A1. The main reason for their cancellation in the next year's model was the lack of adjustability to different vehicle weights, due to extras and motor configuration, as well as the hard suspension tuning. Today GFRP leaf spring technology is still mainly used in the commercial vehicle sector as in the Daimler Sprinter or VW Crafter. Only as a leaf spring without wheel guiding function the sports car Corvette sticks to the leaf spring in its third generation and the actual Volvo XC90 also integrated one.

For the NGC-UMV a highly integrated suspension concept is in development. As explained in the previous section, all the wheel forces flow through the two axis steering system and from there into the mounting seat of the GFRP leaf spring. The linear damper is attached there only by a ball joint to the leaf spring. Therefore all the reaction forces of the wheel are guided through the leaf spring during the driving, in order to enable the camber angle adjustment by simple ways. First simulations of the preliminarily dimensioned leaf spring show evidence of the potential of the concept.

During the development of the wheel guiding traverse leaf spring different steps are made to evaluate and test a new design method for the purpose design of the chassis. Regarding the front and rear axle system the focus lies on both: vehicle dynamic control concepts and the structure of the chassis components. In order to remain economical and therefore competitive, certain steps of development have to be in a virtual environment. Especially in evaluating driving dynamics at a very early stage, the overall chassis system performance is measured by multi-body simulation models and driving simulators. This means particularly the evaluation of the handling depends massively on the knowledge of attachment points, masses, spring ratios et cetera. Furthermore these simulations are used for specifying and testing vehicle dynamic control concepts. Automation of the different development steps to enhance efficiency is essential, even if this automation process is only partially or based on sub-models. This could be for example the development of optimal structural designs and their characteristics. Combining intelligent control concepts and reasonable structural development can result to simpler axle geometries.

The development of the fibre-reinforced plastic transversal leaf spring for the UMV, is done primarily and entirely structural in the first steps. Amongst others the required kinematics of the wheel carriers are considered as well as various load cases and boundary conditions. These kinematics for example describe the motion during spring extension and compression. The considered systematically approach respectively process for developing and dimensioning the leaf spring is shown in Fig. 7. It shows in the clockwise direction from a given design space to a parametric CAD model, fibre layup or laminate optimisation to finally the exemplarily front suspension with the transversal leaf spring.

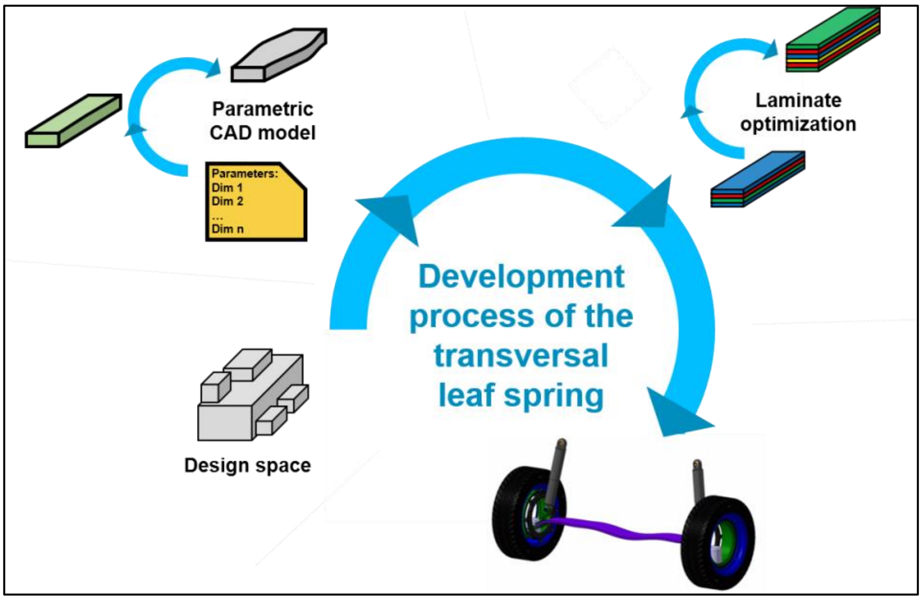

Fig. 7: Development process of the transverse leaf spring

In a first step, the derivation of the available design space for the front axle is transferred to the CAD level. Sub sequentially, a fully parametrized CAD model of the transversal leaf spring is created. For the generation of geometry variations, selected parameters can be controlled on script basis. These geometry variations are related to the front axle design space. In each step during the optimization a valid geometry generation is guaranteed for the following process. In the next step the corresponding finite element model is generated automatically. The optimization of the layer structure and corresponding layer thicknesses is followed sub sequentially. The basic prerequisites needed are appropriate load cases and restrictions regarding mass, displacements and stresses. Furthermore, the test and verification of the front axle kinematics as well as elasto-kinematics are performed by using multi-body simulations. After a successful verification, the movements of the virtually wheelmount caused by kinematics and elasto-kinematics are written into characteristic maps. Based on these maps, the vehicle dynamic control concept can be reconciled and verified. In order to generate adequate axle system concepts at an early stage, the whole development process of the transversal leaf spring can be performed iteratively and for various geometry variations.

2.5. 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 700 degrees per second, only need to be activated, when the opponent is less than 0.5 meter away. This means, that the wheels are turned by the steering motors or the steer-by-wire-system only milliseconds 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.

For verification of this idea to use the wheel of a common passengers' car as a shield, a vehicle finite element (FE) crash model of the Toyota Yaris from the National Crash Analysis Center library was used. The FE model is based on the structural definitions of a real vehicle and contains 1.5 million elements. It was verified and validated by comparing crash test and simulation results for the acceleration and energy absorption of the vehicle

(NCAC2012). At first the standardized crash test setup with a zero degree steering angle was simulated to hit the non-deformable barrier for the IIHS small overlap crash test scenario. Several measurement points (Fig. 8) were defined to detect the maximum intrusion into the cabin for a later comparison. Secondly a model with an additional 30 degree clock wise toe-in angle of the corresponding wheel was used for the simulation. Nothing else was changed in this reference model. This setup was chosen to prove, that this turning of the wheel is enough to use it as a deflection shield and to improve the crashworthiness.

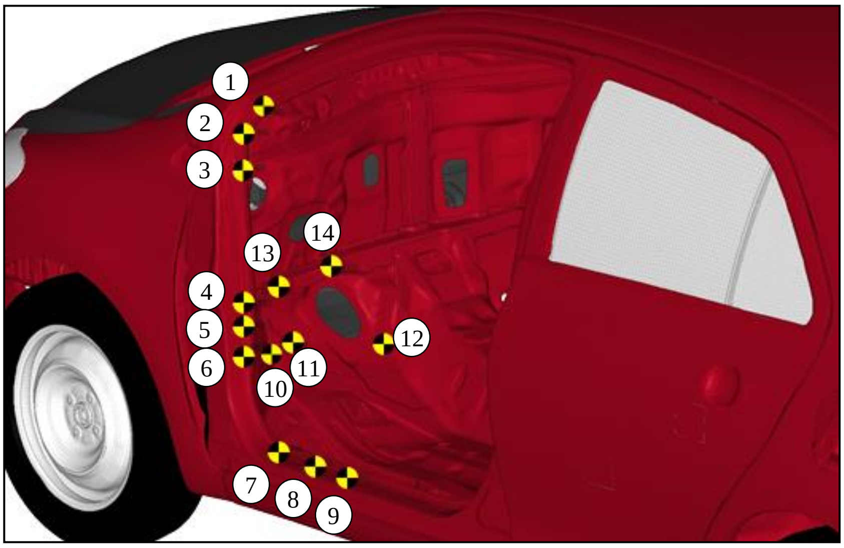

Fig. 8: measurement points to compare the two crash concepts

The comparison between the two simulations shows, that the concept with the 30 degree steering angle has a positive effect on the intrusion into the cabin (Table 1). The intrusion can be reduced by up to 32 % in the area of the rocker panel and the hinge pillar. This results in a better accessibility for rescue measurements, as the door is less likely to be jammed after the crash. Due to the new kinematics of the wheel during the crash, the intrusion into the footrest can be also reduced. At a steering angle of 0 degrees, the wheel completely intrudes into the rocker panel and the firewall. In the case of a crash with the imposed steering angle of 30 degree, the front wheel no longer intrudes into the rocker panel, instead the wheel slides past it, which leads to this reduced intrusion. This results in an enhanced crash performance during the small overlap crash test according to IIHS

Table 1: intrusion values with zero degrees steering angle and with 30° steering angle:

Point # (Fig. 8)	Node ID (FE model)	intrusion 0° [mm]	intrusion 30° [mm]	percentage change [%]
1	2007878 Upper hinge pillar	256.91	177.36	-31.0
2	2007848 Upper hinge pillar	294.36	210.31	-28.6
3	2007420 Upper hinge pillar	330.18	248.76	-24.7
4	2007051 Lower hinge pillar	456.36	365.01	-20.0
5	2096876 Lower hinge pillar	473.33	375.88	-20.6
6	2096928 Lower hinge pillar	492.79	390.40	-20.8
7	2004495 Rocker panel	415.50	281.56	-32.2
8	2004955 Rocker panel	364.47	256.87	-29.5
9	2005127 Rocker panel	328.43	252.34	-23.2
10	2109759 Footrest	455.88	395.08	-13.3
11	2110680 Left toepan	424.27	403.78	-4.8
12	2114869 Throttle pedal	385.67	361.09	-6.4
13	2198647 Left firewall	462.04	436.35	-5.6
14	2199020 Right firewall	453.52	443.30	-2.3

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 traverse leaf spring. It is furthermore combining these concepts with the new and innovative two axis steering system. These 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 to absorb the crash energy. This applies in such cases, if the crash is inevitable, but there is no save place to steer. 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 fibre layup, the kind of fibres and the matrix system. Also the dimensioning and the calculation of the needed torsion moments of the two axis steering system will be done this year. The build-up of a non-functional demonstrator is planned for the beginning of the next year. The final 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 functional demonstrator is build.

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