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Integration of an Active Suspension System for Better Driving Dynamics and Enhanced Small Overlap Crash Performance

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Abstract

Deflection of the crash opponent is a well-known method to improve general crash behavior, as seen with safety fences on motorways. Within the DLR's Next Generation Car (NGC) project this behavior was applied to the suspension functions of the Urban Modular Vehicle (UMV), a small, fully battery-electric car for four passengers to cover the needs of the inner city inhabitants. To achieve this, a patent pending concept was developed, in which independent wheel actuators turn the car's front wheels to act as a deflection shield. In addition to the steering actuator, the safety of the UMV is also increased through a second actuator for each wheel controlling the camber angle. Because of the holistic approach of the suspension concept, it weighs less than the suspension of a reference car, but with enhanced driving dynamics through wheel independent toe-in and camber actuators.

Keywords: crash safety; small overlap; lightweight design; full electric vehicle

Nomenclature

CAD	Computer Aided Design
CFRP	Carbon Fiber Reinforced Plastic
DLR	Deutsches Zentrum für Luft und Raumfahrt (German Aerospace Center)
GFRP	Glass Fiber 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 difficulties of a sustainable body design for a full electric vehicle

1.1. Motivation

Vehicle mass is a key resistance factor at constant speed or on gradients, even if the acceleration energy inevitably lost when braking can in part be recuperated by hybridization of the powertrain. A simple parametric calculation model was constructed to illustrate this. The basic parameters of the vehicle were selected as follows:

Table 1: Vehicle parameters:

Parameter	Value
Vehicle mass	1000 kg
Rolling resistance coefficient	0.01
Drag coefficient	0.32
Front Face	2.2 m²
Usable battery capacity	28.2 kWh[1]
Efficiency of powertrain	70%

Simple calculations on a hypothetical representative small electric car with the specifications from Table 1 show that in urban traffic a 23% range increase (without recuperation) is possible by reducing the weight by 20%. If the recuperation of brake energy is included, which is state of the art for electrified urban vehicles, an increase in range of 21% can still be expected. In the following diagram the dependence of range increase on mass reduction in different driving cycles is shown. From this it can be seen that the range of electric vehicles is heavily dependent on the field of use, but that in any case mass reduction always pays. Deißer et al. (2012)

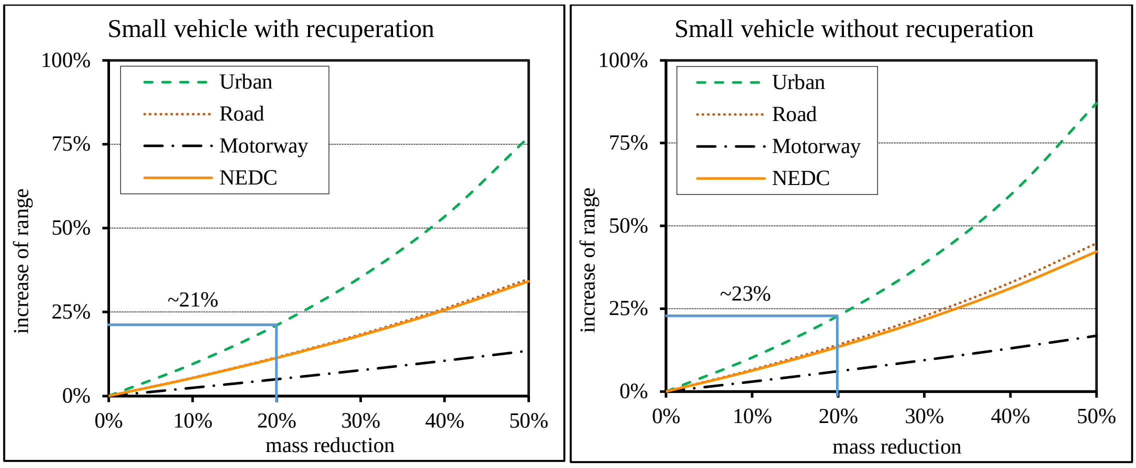

Fig. 1: Range increase by mass reduction. Deißer et al. (2012)

[1] The 200km range in the NEDC corresponds to a total battery capacity of ~35kWh (at 80% usable capacity)

1.2. New mass distribution and package situation for electric vehicles

Most of the current cars with a combustion engine based powertrain have the problem of an unequal axle load distribution due to the heavy motor block in the front. When looking at electric vehicles this is usually not the case anymore. Many purpose design full electric vehicles have the battery located in the floor of the car, where the high mass of several hundred kilograms, as the biggest standalone component, is placed best. The reason is to give the car a low center of gravity and moment of inertia, as well as protecting the battery. The lack of the combustion engine and its components including the gearbox give the vehicle layout and the crash management whole new possibilities but also risks. There is no engine block stabilizing the front structure in case of a frontal or front-side crash of the electric vehicle and new designs for the crash energy absorption and protecting the occupants have to be found. The BMW i3 and i8 are examples of a differential approach of heavy structure in the chassis including the whole drivetrain and batteries, named the “Drive-Module” by BMW, and the cell for the occupants giving their protection, named the “Life-Module”. All the energy absorption in case of a crash is handled by the aluminum “Drive-Module”, whereas the “Life-Module”, built mainly from CFRP, has the function of crash load distribution and providing a stiff frame.

1.3. Current (international) regulations and lack of crash compatibility in reality

One of the main challenges in the development of a vehicle is to fulfil the crash requirements. A frontal vehicle crash is often fatal if the crash partners only partially hit another. The crash structures of the participating vehicles seldom take up the crash energy, as the longitudinal rails of the body structure are not involved and miss one another. The wheels often get hooked and each wheel gets pushed into the vehicle’s passenger cell. The hooking results in undefinable rotation of the cars and the intrusion in severe injures of the occupants, especially the driver. To evaluate cars in a synthetic test, the American Insurance Institute for Highway Safety (IIHS) defined a new crash test scenario, where the car hits a small non-deformable (massive) barrier with only 25% overlap of the vehicle’s width. This test is called “small overlap crash test protocol”. The shape of this test barrier is a flat wall with a 150mm radius cylindrical edge. IIHS (2017-I). Fig. 2 shows on the left the result of a real crash with small overlap on the road, in the middle the realistic crash scenario with two cars hitting one another with a small overlap and on the right the barrier and the hitting area in the test scenario.

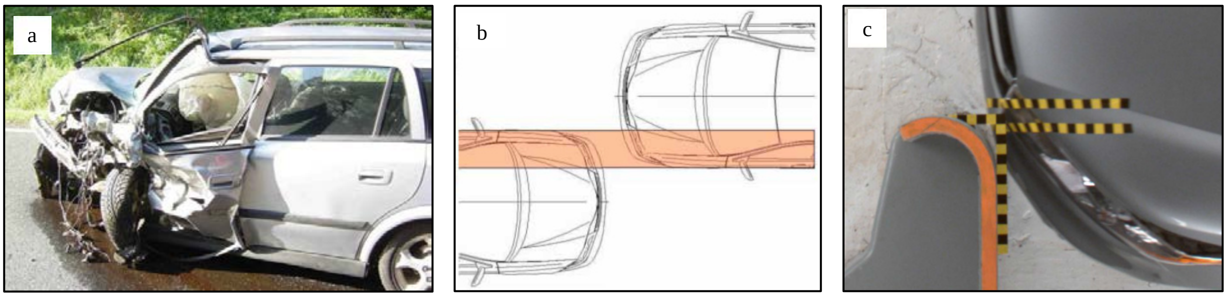

Fig. 2: (a) real crash on the street. ADAC (2000); (b) schematic hitting area. ADAC (2000); (c) Test barrier and impact area. IIHS (2017-I)

To cover these new crash requirements more than 100 patents and inventions have been made to improve the situation within the last few years. Some of the inventions found in pending patent applications and granted patents bring in new and additional structure for absorbing energy. These energy absorbing structures are very mass intensive. The energy to be absorbed is very high and the available design space in conventional cars is very limited. Therefore the second possibility for enhancement of the overall crash performance covers the field of deflection. With deflection 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.

1.4. Principle of deflection and existing solutions

Deflection of the crash opponent is a well-known method to improve the general crash behavior, as seen with the safety fences on motorways. With deflection there is a limited risk of intrusion of the wheel or any other massive component into the passenger cell. The first known invention regarding deflection using the vehicle’s own structure was made by Prof. Schimmelpfennig in the 1990’s. In his patents mostly trucks and trailers where described, but within the patent “safety bumper for motor cars” (Sicherheitsstossstange für Personenkraftwagen, European patent EP0758597 B1) a practical solution for deflection in small overlap crash scenarios involving cars was published. The principle of this deflection mechanism is shown in Fig. 3a, where the two cars have the same protection mechanism. Here the bumper should be made long enough to cover the wheel in case of contact to provide a gliding surface for the crash participants. Due to current design restrictions demanding short front overhangs, these long bumpers are currently not very realistic for aesthetically pleasing series production cars. In Fig. 3b anther promising concept is shown, where there is an extra extendable deflector. This deflector has to turn the vehicle's own wheel in such way as to use it as an additional shield. Fig. 3b1 shows the first impact, b2 to b4 illustrates the sliding mechanism of the blue part out of the green part in order to turn the own wheel inward and use it as a deflector.

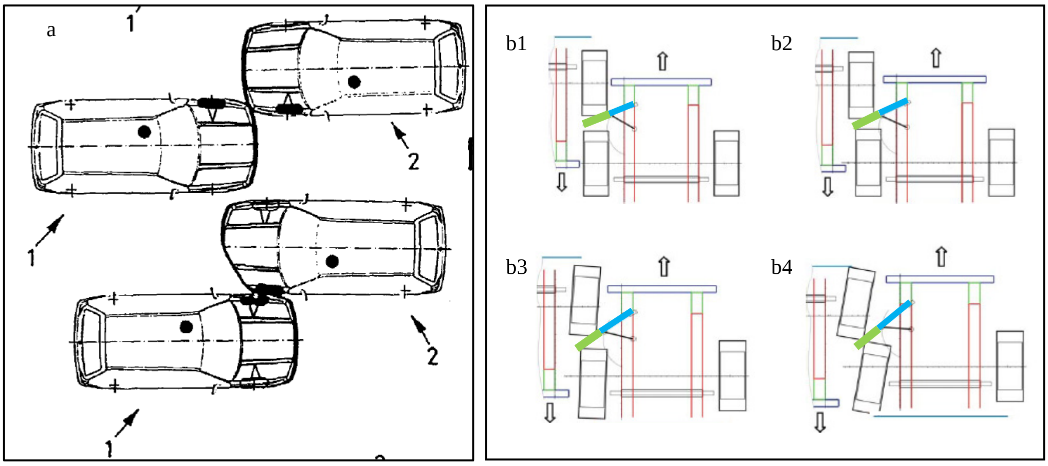

Fig. 3: principle of deflection using (a) the bumper. Schimmelpfennig (1996); (b) the "Flexible Collision Deflector". Schimpl (2005)

In present cars on the road there are no such mechanisms, but the car manufacturers try mostly to slide from the massive barrier, then to absorb the crash energy. A good example for an electric vehicle which has a good crash performance according to this IIHS test by sliding past the barrier is the BMW i3. This car has a stiff structure with its CFRP "Life-Module" and BMW accepts the fact, that, in order to prevent the wheel getting pushed into the passengers' cabin, the wheel gets sheared off the vehicle. The screen captures of the i3 crash video provided by IIHS are shown in Fig. 4.

Fig. 4: Deflection of a BMW i3 at IIHS small overlap crash test. IIHS (2017-II)

2. The new suspension concept of the NGC-UMV

2.1. Next Generation Car - Urban Modular Vehicle

In the Next Generation Car (NGC) research project at the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt, DLR), in the program topic of terrestrial vehicles, different institutes are working on topics for the cars of the future. In this context three different vehicle concepts are being developed according to the technical requirements and capabilities of 2030: Urban Modular Vehicle (UMV), Safe Light Regional Vehicle (SLRV) and Interurban Vehicle (IUV) (see Fig. 5). 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 divided into the following areas: Vehicle Concepts, Vehicle Structure, Energy Management, Drivetrain, Chassis and Vehicle Intelligence.

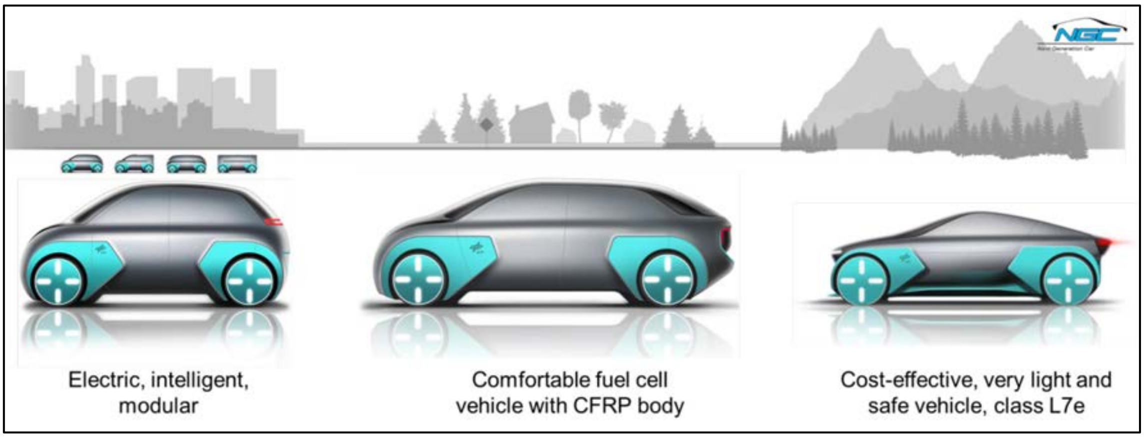

Fig. 5: NGC Vehicle Concepts: Urban Modular Vehicle (UMV), Interurban Vehicle (IUV) and Safe Light Regional Vehicle (SLRV)

In this article all DLR contents are taken from the NGC-UMV, where the main focus lies in the development of a design method for a modular multi material body concept. The vehicle body structure development phase starts with the selection of the basic vehicle shape and the vehicle floor concept. Two configurations are examined in this respect (see Fig. 6a):

- V1: Five-door with tunnel, double bottom with seat cross members. This vehicle floor concept offers the maximum available space for the installation space model and uses the classic arrangement, as in a combustion engine vehicle. (Fig. 6a-c upper row)
- V2: Five-door with double bottom. This vehicle concept offers a new sense of space as well as improved space. (Fig. 6a-c lower row)

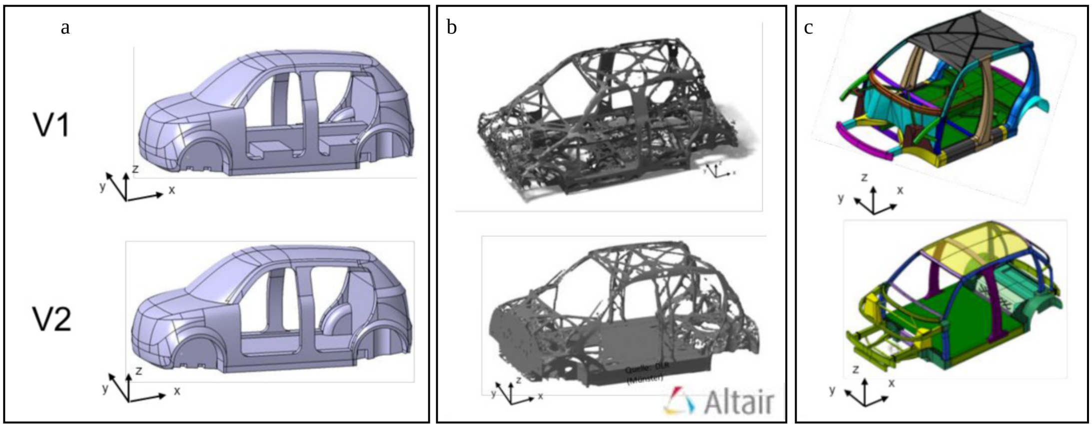

Fig. 6: (a) Space model, V1 Five-door with tunnels, double bottom with seat cross members, V2 Five-door with a double bottom; (b) Topology optimization for global load path finding of V1 and V2; (c) Body in white V1 and V2

At first a package is assumed for Phase 1 (Fig. 6a), where a maximum available design space for a static topology optimization is defined: energy storage in the double floor/tunnel, electric motor near the wheels on the rear axle and cooling module in the front. The space models V1 and V2 are examined in the next step of Phase 2 (Fig. 6b) using the topology optimization tool Optistruct from Altair on global load paths. During topology optimization the available design space is put under stress according to predefined load cases and according to their predefined weight. After the calculation of the result, the design space is reduced by elimination the least needed material. Then the calculation starts again with the reduced model of the design space. The iterations come to an end, if either a maximum volume reduction of for example 30% from the original design space or the predefined maximum stress values of the material are reached. Many iterations on the model result in an optimized design space, where material is only left were needed. The aim is to analyze the global load paths that arise on account of the new package boundary conditions for electric vehicles. The requirements for the topology optimization were defined as follows:

- Nine crash load cases (100%, 40% 25% overlap front crash, pole crash side, IIHS side crash, 100% rear crash, 100% front crash rigid wall, Bumper test front, Bumper test rear)
- Three static load cases (Torsion, bending and roof impression test).

Based on the results of the topology optimization with the target of maximum stiffness (Fig. 6b) at a volume fraction of 30% from the original design space, a body structure concept is developed for V1 and V2 respectively (Fig. 6c). The design of state-of-the-art vehicle bodies is taken into account for the design of the car body. The result is in both cases an aluminum-intensive space frame body with castings for the complex nodes in the floor or the roof frame.

For this NGC-UMV a basic suspension was defined, which represents the state of the art used by urban vehicles today. A classic MacPherson suspension strut is used in the front and an electrically powered twist-beam rear axle is chosen for the rear (similar to the ZF electric twist beam) (Buchmeier, 2014). The applied load cases are introduced as static elements in the optimization model. The masses of the packages are integrated through mass points; the structure, as well as the exterior and interior masses, is distributed on the installation space model.

In the following chapters a new chassis concept for this NGC-UMV is described, which is based on the geometric boundary conditions of the MacPherson suspension being used.

2.2. The orbital wheel concept

The idea of the orbital wheel is not a new one. An Italian designer named Franco Sbarro invented it and has several patents on it. His first European patent (FR000002633877B1) is from 1988 and was republished as world patent 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 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 as illustrated in Fig. 7. In conventional suspensions the road forces are distributed from the tire to the rim base over the rim center into the wheel bearing. From there the forces are split into the primarily vertical forces (Fig. 7, F_v) carried by the suspension strut and into the primarily horizontal forces (Fig. 7, F_h), borne by the lower wishbone in the common MacPherson suspension. So the forces take long and indirect ways into the body of the car (Fig. 7a). 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. 7b). Therefore a lightweight potential is obvious due to direct force routing and reduced parts.

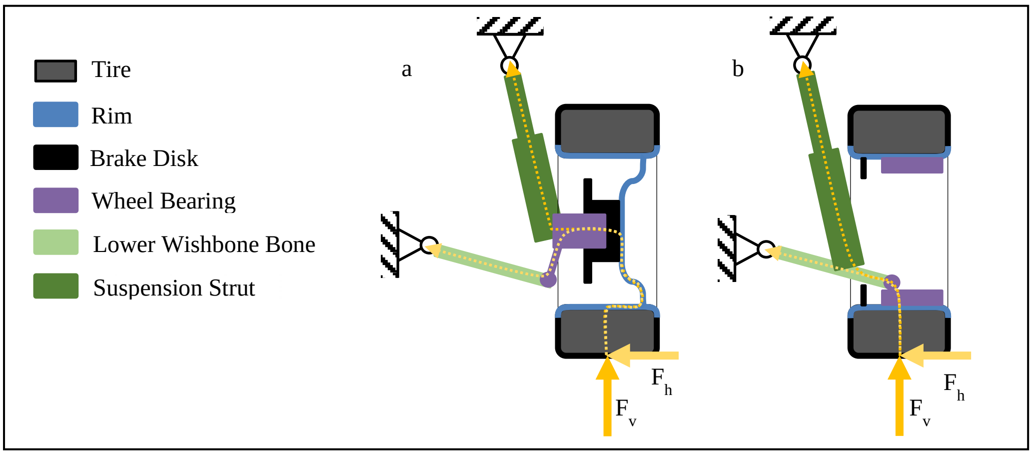

Fig. 7: (a) conventional MacPherson suspension; (b) orbital wheel with MacPherson

There are some challenges involved with this type of wheel bearing. The first challenge is the mounting of the tire because of the flat rim base. This is solved by using a two parted rim base, where the tire can be mounted without any machine just by screwing the two halves together (Fig. 8a-c). In the concept developed for the NGC-UMV the two part rim base is made of a thin high grade roll-formed steel sheet metal for a better damage tolerance compared to aluminum rims. The final assembly of the wheel to the bearing can be seen in Fig. 8d. The second problem solved is the balancing of the wheel, when there is no center mounting of the wheel center. This issue can be avoided by the use of a balancing adaptor, which is solely used for the balancing of the wheel. The wheel bearing is assembled with a rotational-friction-welded outer bearing seat (Fig. 8e), two tapered roller bearings and two radial sealing rings (Fig. 8f), an inner bearing seat and an adjusting ring (Fig. 8g). The brake disk is mounted to the outer bearing seat (Fig. 8h).

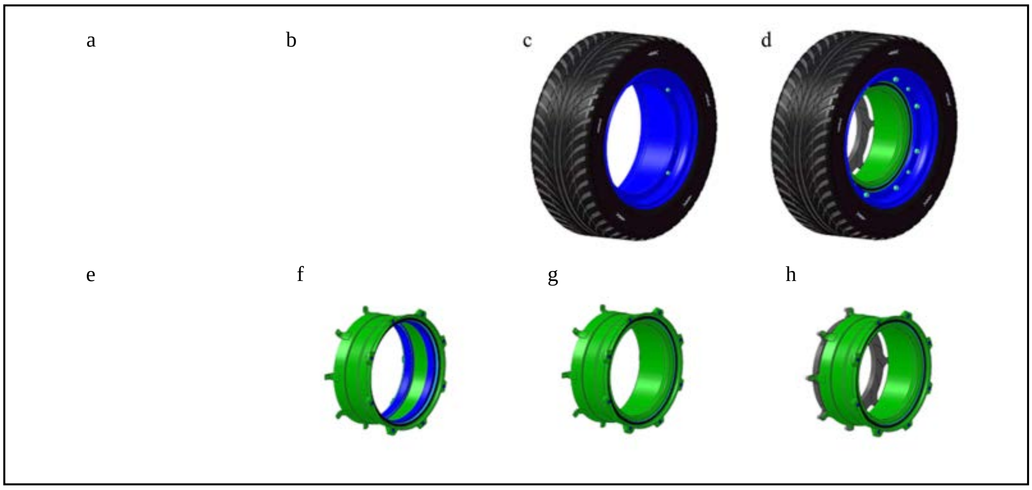

Fig. 8: Assembly sequence of the first orbital wheel concept for the NGC-UMV; (a) inner rim base; (b) with mounted tire; (c) and mounted outer rim base; (d) final assembly of wheel and bearing; (e) outer bearing seat; (f) with two tapered roller bearings and radial sealing rings; (g) with inner bearing seat and adjusting ring; (h) assembled with brake disk

2.3. Active two axis independent steering system

The center wheel guiding joint attached to the inner bearing seat can be actuated around a vertical axis to provide the steering system. This means that there is the possibility to implement a independent electric power steering into the rim bearing, in which both wheels can be steered independently of one another. Two 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). A steering ratio of 1000 degrees per second is the desired specification for the steering system of the electric steering of the NGC-UMV. 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.

When there is just one single point where the wheel is connected to the wheel guiding system, there is also the chance to integrate a simple camber angle actuator without complicated hydraulics or expensive linear actuators. So a small car like the NGC-UMV can be equipped with a 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 maximum effect of driving stability and agility would be by an angular range of +/- 20 degrees as is shown by the Mercedes-Benz F400 Carving. They realized a 30% increase of 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 have to 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 which is high enough.

2.4. GFRP transverse leaf spring

The third important part of the new suspension concept of the NGC-UMV is the glass fiber reinforced plastic (GFRP) transverse leaf spring. The first patent for plastic leaf springs to be found is from the French company Bertin & Cie from year 1986, 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, but the use of the fiber reinforced material as well as the required new kinds of attachment and the connection joints were new. Plastic leaf springs are more durable than the metal coil springs, as they have a higher fatigue strength. Another benefit of fiber reinforced composites is the possibility to change the spring ratio and local stiffness within the part by changing the fiber layup, which then means different sets of molds. Due to the fibers within the composite the growth of cracks is minimized and there is no sudden failure as can occur with their metal counterpart. Although fiber leaf springs have many advantages, their use in series production was canceled and they were replaced by conventional metal coil springs. 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 used in the commercial vehicle sector as in the Daimler Sprinter or VW Crafter.

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 fiber layup up to readiness of series production. Others followed but no car was ever produced for sale; only studies and concept cars were shown.

For the NGC-UMV a highly integrated suspension concept is in development. As explained in the previous section 2.3, 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 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.

The current suspension concept is illustrated in Fig. 9 with its modular components:

- tire on rim
- orbital wheel bearing and brake disk
- two axis independent steering system
- leaf spring and linear damper

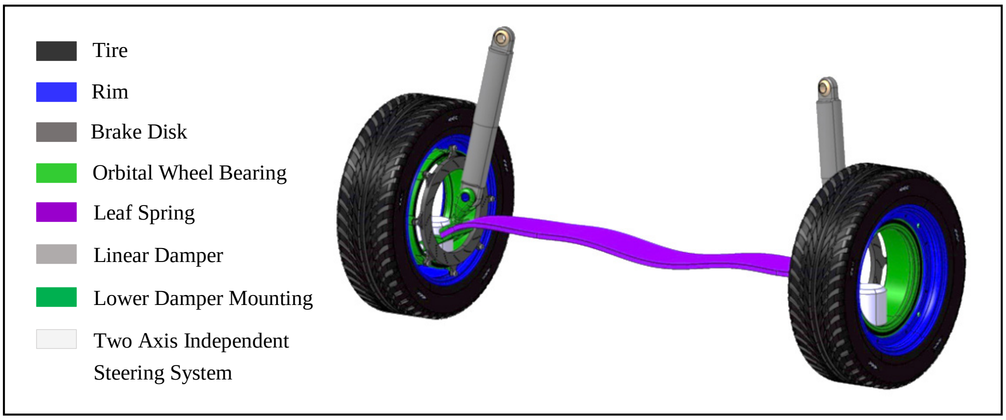

Fig. 9: NGC-UMV front suspension concept

2.5. Activation of the system for enhanced crash performance

In order to provide substantial benefits in the case of a small overlap crash, 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 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.

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

For verification that the wheel with a toe-in angle of 30 degrees is enough as a deflection 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). Two different setups were simulated. First the standardized crash test setup with a zero degree steering angle and the setup of the new concept with a 30 degree steering angle clock wise of the wheel. For the comparison of the two models several measurement points (Fig. 10) were defined to detect the maximum intrusion into the cabin.

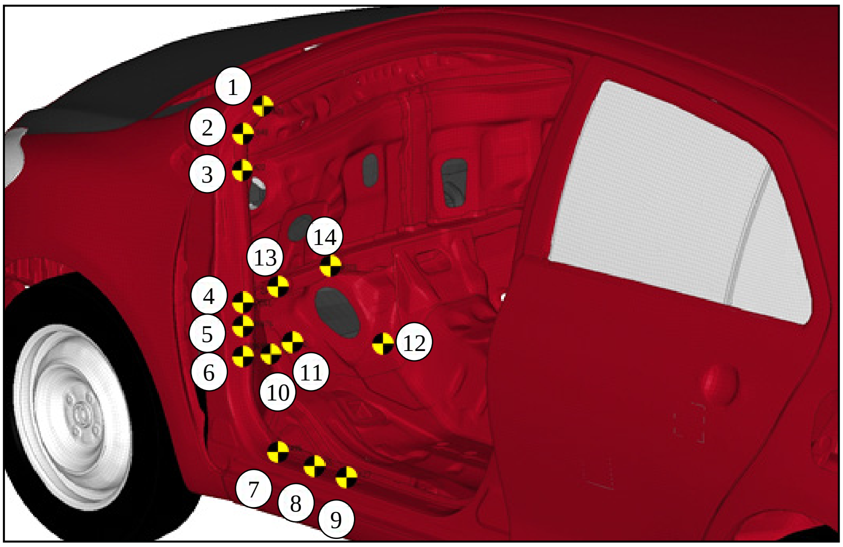

Fig. 10: measurement points to compare the two crash concepts

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 2). The intrusion can be reduced by up to 32 % in the area of the rocker panel and the hinge pillar. 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, the front wheel no longer intrudes into the rocker panel, instead the wheel slides past it, which leads to this reduced intrusion.

Table 2: intrusion values with zero degrees steering angle and with 30° steering angle:

Point # (Fig. 10)	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 NGC-UMV suspension concept with its two axis steering system is a promising answer to these demands. The DLR proved the feasibility by first static and dynamic simulations and is now ready for further investigation to develop the concept in more detail. The next steps are to dimension the needed torsion moments of the two axis steering system, to detail the concept and to design the transverse leaf spring. This includes all parameters of fiber layup and kind of fibers as well as the matrix system. The final integration of the suspension system into the NGC-UMV CAD model with all joints and the dynamic crash simulation of the whole concept within the car is the last step before the buildup of a demonstrator.

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