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DEVELOPMENT AND PERFORMANCE OF AN IN-WHEEL SUSPENSION CONCEPT WITH AN INTEGRATED E-DRIVE

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ABSTRACT

Automobile manufacturers developing electric vehicles currently tend to convert existing conventional internal combustion engine powered vehicles into designs for electrically driven automobiles. One effect of this is that electrification’s attendant new requirements and restrictions are not met, but also that its larger degrees of freedom are not optimally exploited. To meet the revised conditions, new approaches are necessary as well as a holistic view of the vehicle and its subsystems.

In the presented paper the development of a suspension for electrically driven vehicles is shown. The suspension is developed through the application of a methodical procedure model that was previously developed at the German Aerospace Centre. The process model addresses the altered boundary conditions brought by electrification and the development of road vehicle suspensions suited to the requirements of electro mobility is enabled. One of those suspensions created with the help of the process model is the *LEICHT*, an innovative suspension for urban vehicles. *LEICHT* stands for the main characteristics of the in-wheel suspension: Lightweight, Energy-efficient, and Integrative Chassis with Hub-motor Technology.

The *LEICHT* is developed using computer aided design, simulation and multi-body dynamics software. In the paper the results of the virtual product development are shown. Those are among other things: the methodical construction process (CAD) including a databased materials selection step, the chosen simulation strategy (FEM) as well as the strength verification for different materials combinations. Following the virtual product development, the competitiveness of the proposed *LEICHT*-chassis/drive module is demonstrated by comparing it to solutions from the state of the art using quantifiable criteria such as the unsprung mass, packaging and vertical dynamics.

Finally an insight on the current state of the physical prototype is given as well as on the test bench that was designed.

INTRODUCTION

When designing electric vehicles, automobile manufacturers (OEMs) currently focus on converting combustion engine vehicles into electrically powered ones, which are developed using conventional processes and procedural models *(conversion design)*. This is further reinforced by the trend for modular construction strategies favoured by the OEMs, whereby processes and material flows are the same for a number of different models [1]. This means that electric vehicles are built on the same platform as the corresponding combustion-engine vehicles in order to guarantee flexibility and diversity and so reduce risk at market launch [2]. On the one hand, this results in a relatively fast and cost-effective development of electric vehicles, but, on the other hand, changes to the boundary conditions and requirements associated with electro mobility are not taken into consideration and degrees of freedom go unexploited. New requirements of future, electric lightweight suspensions include integrating drive units into the chassis [3], reducing unsprung mass [4], creating space through new packaging variations [5] and incorporating individual wheel drives to apply new driving strategies [6].

METHODICAL APPROACH

The modified requirements and the degrees of freedom associated with electrification also have implications for chassis/suspension design. Suspension concepts specifically for electric vehicles are already the subject of R&D in a few cases (e.g. [7], [8], [9], [10], [11]). However, the processes, methods and procedural models needed to meet the requirements involved in developing chassis for electric vehicles have not attracted the level of research interest they deserve. Only [12], [13] present a procedural model which fills this research gap. In [12], [13] a *"procedural model to meet the requirements for the design, evaluation and virtual product development of drive-integrated chassis for electric road vehicles"* is developed, applied and validated in a virtual environment. This procedural model can be seen in ***Figure 1***.

The procedural model shown is divided into three phases. In phase I, the drive design is defined and the requirements of the chassis are specified based on the full vehicle characteristics. In phase II, innovative chassis concepts are designed through the iterative application of a variety of lightweight construction strategies. The focus here is on meeting the new functional requirements of the chassis and on the possibility of integrating the drive system into the chassis. After a holistic evaluation of the drive-integrated chassis concepts produced, the *LEICHT*[1] concept, as the solution with the best rating, is validated in phase III based on the classical suspension development process consisting of construction (CAD), simulation (FEM) and multi-body simulation (MBS). The contents of phase III and the actual realization of the physical prototype are discussed in more detail in the following sections of this paper.

[1] *LEICHT* is an acronym which stands for the main characteristics of the innovative chassis/drive module developed in [6], [12], [13], [17], [15]: **L**ightweight, **E**nergy-efficient, **I**ntegrative **C**hassis with **H**ub-motor **T**echnology

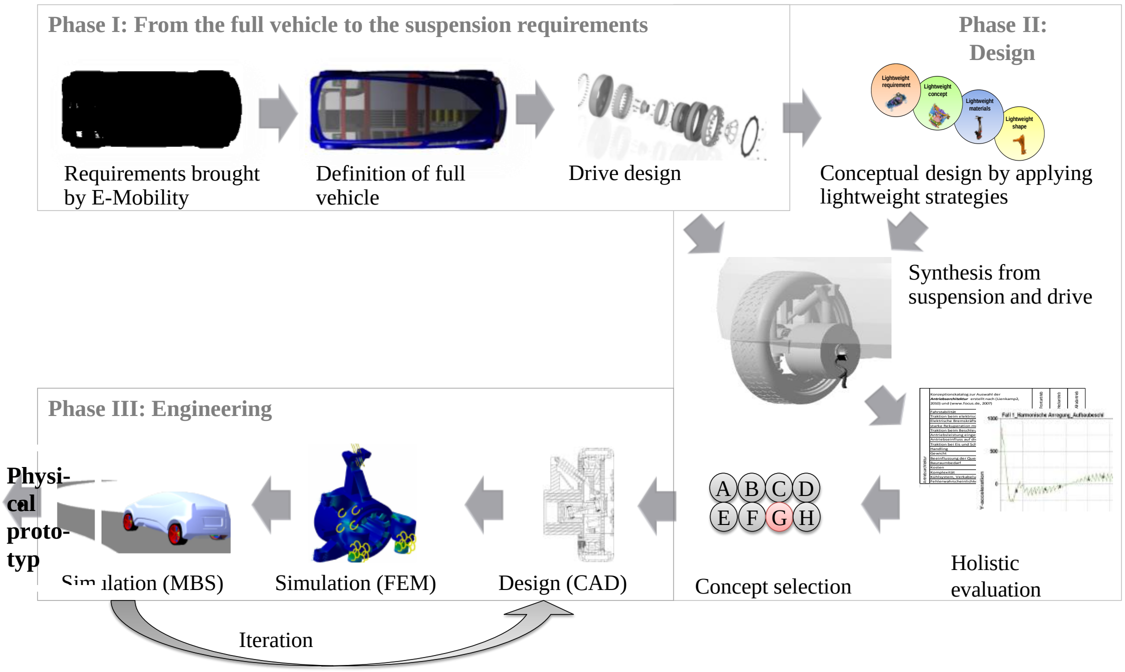

Figure 1: Illustration of the "procedural model to meet the requirements for the design, evaluation and virtual product development of drive-integrated chassis for electric road vehicles" from [12], [13]

DESIGN AND SIMULATION OF THE LEICHT-CONCEPT

The construction of the *LEICHT* concept according to phase III of the procedure model is initially described as a non-material-specific concept design (cf. ***Figure 2***, left). Seventeen different materials are then examined, with the material that best conforms to the developer's requirements being methodically selected for each component. The methodical selection of materials takes place with the aid of a variety of data, which is compiled in [12]. [12] contains data on the availability of material, density, CO_2-emissions during production and costs. The materials (including 42CrMo4, EN AW-7075, EN AW-6060, EN GJL-250) are then implemented in the FEM analysis model used (cf. ***Figure 2***, centre). With the aid of the FEM model, the strength of the individual components of the LEICHT chassis concept is verified and the geometries are optimized.

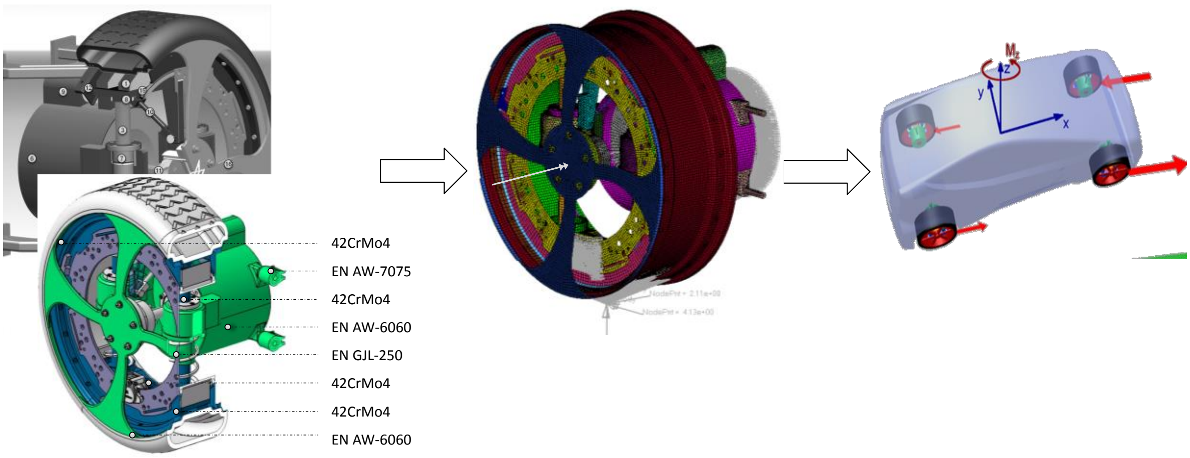

Figure 2: Design (CAD) and simulation (FEM and MBS) of the LEICHT-Concept

Figure 3 provides an insight into the spring and damper configuration during the development process (phase III). Here, the damping ratios of two concept variants are examined in detail to test whether they are roughly constant. The result of the analysis of the two variants' damping performance can be seen in ***Figure 3***. It shows clearly that damping

concept 1 displays a markedly non-linear damper stroke pattern in relation to the wheel travel. This will result in a constantly changing ratio across the overall wheel travel and is caused primarily by the poor kinematic positioning of the damper.
Concept 2, on the other hand, shows an almost constant damper stroke and damper ratio across the overall wheel travel. The ratio here can be taken as an almost constant 1,33.

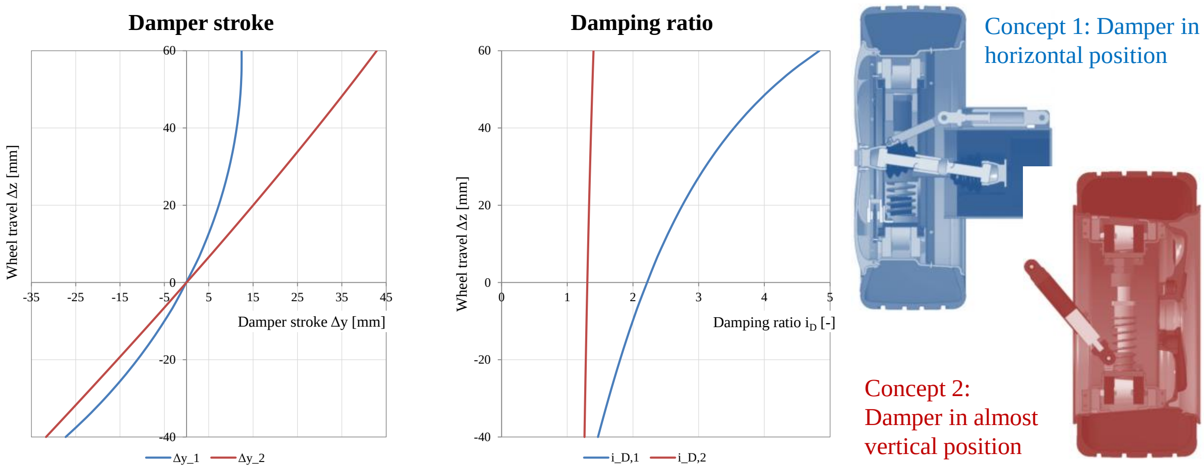

Figure 3: Damper stroke (left) and damping ratio (right) of two damping concept variants

The damper position in concept 2 is then accepted and implemented in a multi-body simulation model[2]. The multi-body simulation of the innovative chassis evaluates the LEICHT concept in terms of driving dynamics and establishes that the kinematic characteristics of the suspension are fully functional. The multi-body simulation (Figure 2, right) displays good driving dynamics and fully functional kinematic characteristics of the suspension [14]. In the driving dynamics simulation, the deflection behavior, camber angel and slip angle behavior of all four wheels are examined. For illustrative purposes, the slip angles are shown below in Figure 4.

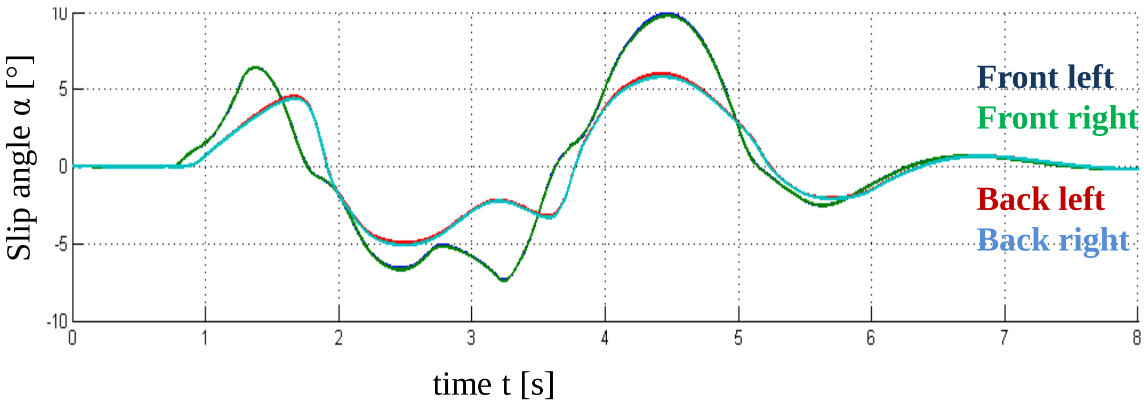

Figure 4: Slip angles α [°] as a function of the time t [s] during the simulated vehicle maneuver „double lane change“ [12], [15]

The diagram above first shows that the slip angles only occur in a range of |0°|–|10°|. These values, which occur at the innovative wheel suspension, are in a common range, as in practice slip angles |α| > |12°| rarely occur in normal driving [16]. The diagram further

[2] The MBS-model was created as part of the *DLR@Uni-Leichtbaufahrwerk für EV der nächsten Generation* (*DLR@Uni-lightweight chassis for next-generation electric vehicles*) project (cf. [18], [15]) with scientists of the University of Stuttgart Institute for Internal Combustion Engines and Automotive Engineering (IVK).

shows that the slip angles at the front axle α_F are almost consistently greater than those at the rear axle αR. This is because, in the simulation model, an anti-roll bar is fitted to the front axle. From α_F and α_R, it is possible to derive the slip angle difference (over/understeer behaviour) ($\Delta\alpha = |\alpha F| - |\alpha R| > 0$). As this is almost consistently positive, the vehicle displays understeering characteristics [16].

COMPETETIVE ADVANTAGES OF LEICHT

Following on from the virtual product development, which also contributes to the validation of the procedural model in [12], the competitive advantages of the LEICHT concept are discussed below. For this, the innovative concept is compared against state of the art benchmark suspension designs to verify the performance of the concept in specific areas. The chassis concept is evaluated in quantifiable terms with reference to the following areas: unsprung mass, package space, service life (vibration issues, electric motor mounting). Along with an improvement in unsprung mass of up to 53%, it shows that the proposed chassis concept provides an increase of up to 43% in package space and an almost 10-fold improvement in vibration characteristics. Analysis of the vibration characteristics is conducted with the aid of a ¼ -vehicle vertical dynamics model.

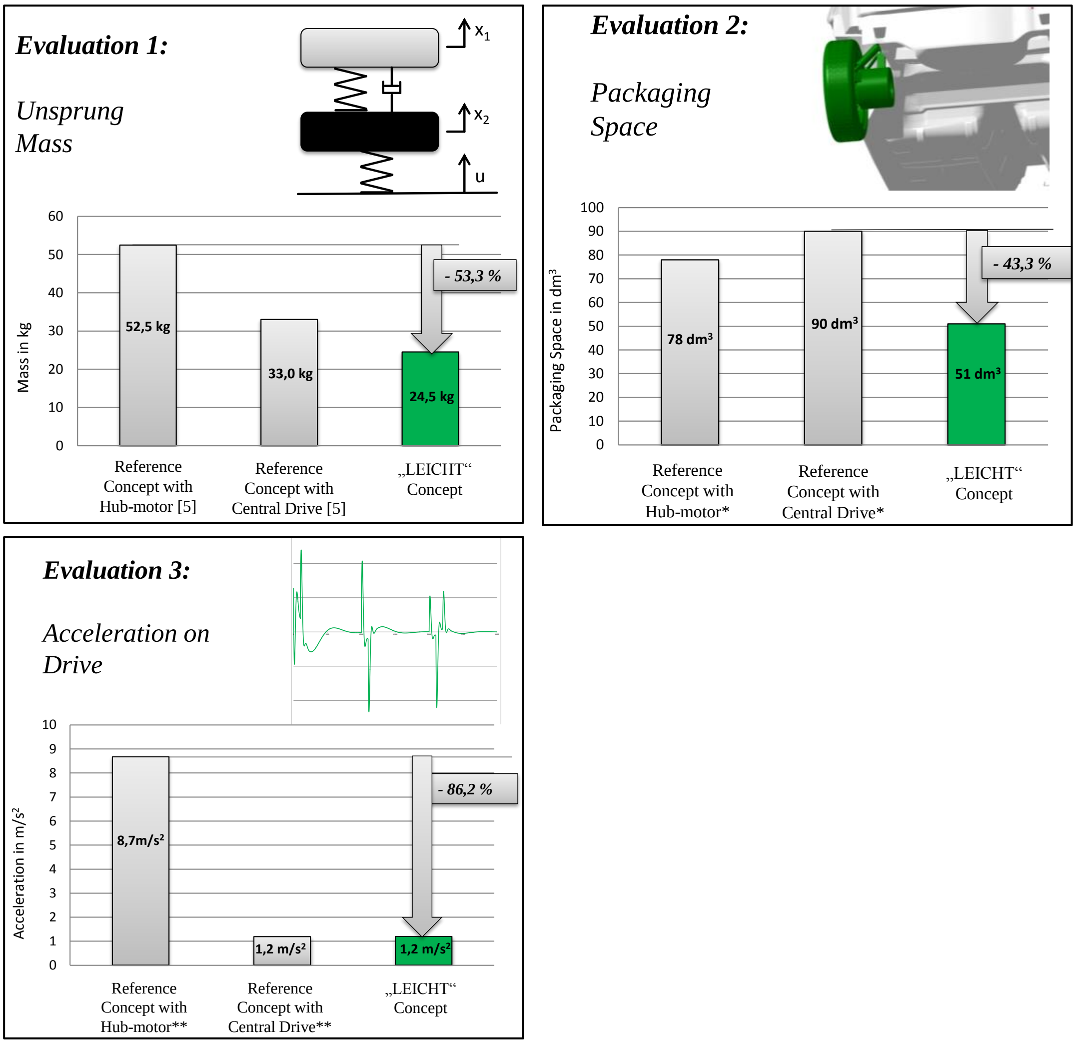

Figure 5: Competitive advantages of LEICHT
* Comparison based on the best data available
** Comparison through simulation of the vertical dynamics with the masses from [3] and [6]

VIRTUALITY BECOMES REALITY: INSIGHT ON THE PROTOTYPE

The virtual prototype has already been described in [6], [17], [15]. Figure 7 now shows the initial draft design of the physical prototype. The concept has the following characteristic features and is described in [6] as follows:
„The conventional wheel bearing in the centre of the wheel is replaced by an innovative, non-centric bearing element, (1). This connects the rotating and stationary parts of the chassis. The reason for the introduced innovation is primarily an improvement of the force flow (lightweight form), since positioning of the new wheel support near the wheel contact patch enables forces to be absorbed where they originate. This unconventional wheel support has the secondary advantage that more packaging space is available in the centre of the wheel for the placement of additional components. The wheel bearing is not implemented as a complete ring, but is located only in the upper and lower area of the rim in order to reduce mass. Each bearing element is fitted with six spherical roller bearings, (2), which execute rolling motion inside the rim. The space available within the wheel bearings is used to position two guide elements, (3). The guide elements' curved form makes it possible to specifically specify wheel travel kinematics. Vertical force absorption is implemented using two coil springs, (4), integrated into the wheel. Depending on the spring material used, it is possible to achieve a total spring travel of 160 mm and a total spring constant of 24 kN/m (within the 19" rims, (5), used here). The shock absorbers attached to the lower wheel bearing element, (6), serve as the suspension's upper impact point. A monotube shock absorber ((8), partly hidden) is used. The lateral forces induced in the wheel contact patch are passed on to the two wheel bearings via two lateral guide rails, (8). [6]*"* The bearing seal (9) is a labyrinth seal produced by additive manufacturing.

In the next phase of the prototyping the electrical drive shall be positioned on top of the coil springs. The drive shall than be guided along the two guide elements using self-sealing ball bushings. The torque shall be transferred from the electrical machine to the wheel via a cv-joint shaft and a perimeter brake's disc shall be attached to the inner lateral guide rail. The brake caliper shall be attached to the lower wheel support and can thus generate braking forces near the wheel contact point. (Components not displayed in ***Figure 1***; compare CAD-model in ***Figure 2***, left).

"Since, in contrast to conventional suspension designs, the forces are not directed over the rim star, through the wheel's centre but are introduced from the wheel contact patch over the linear guide into the structure, the rim star no longer has a load-bearing function and can be designed to be significantly lighter [6]*."*

Figure 6: First prototype of the innovative in-wheel suspension *LEICHT*: wheel guidance, springing, damping, bearings and sealing is shown

SUMMARY AND OUTLOOK

An innovative suspension concept has been developed that was designed especially for the requirements of electro mobility and that promises significant competitive advantages. An insight is given on the results of the design process (especially material selection, CAD, FEM and MBS) as well as on the physical design of a first prototype.

A test bench set-up is currently being designed and built for testing the *LEICHT* prototype at DLR (cf. Figure 7). An easy to assemble/dismantle test bench has been designed using the geometric data from the dynamometer at the Institute for Vehicle Concepts. For testing the chassis demonstrator under a variety of wheel loads, a compact linear axis is used. Together with the chassis springs, this enables various wheel loads to be applied to the LEICHT prototype on the Z axis, both continually (static) and alternately (dynamic). This way, various function tests can be carried out on the dynamometer in the areas of acoustics and kinematics.

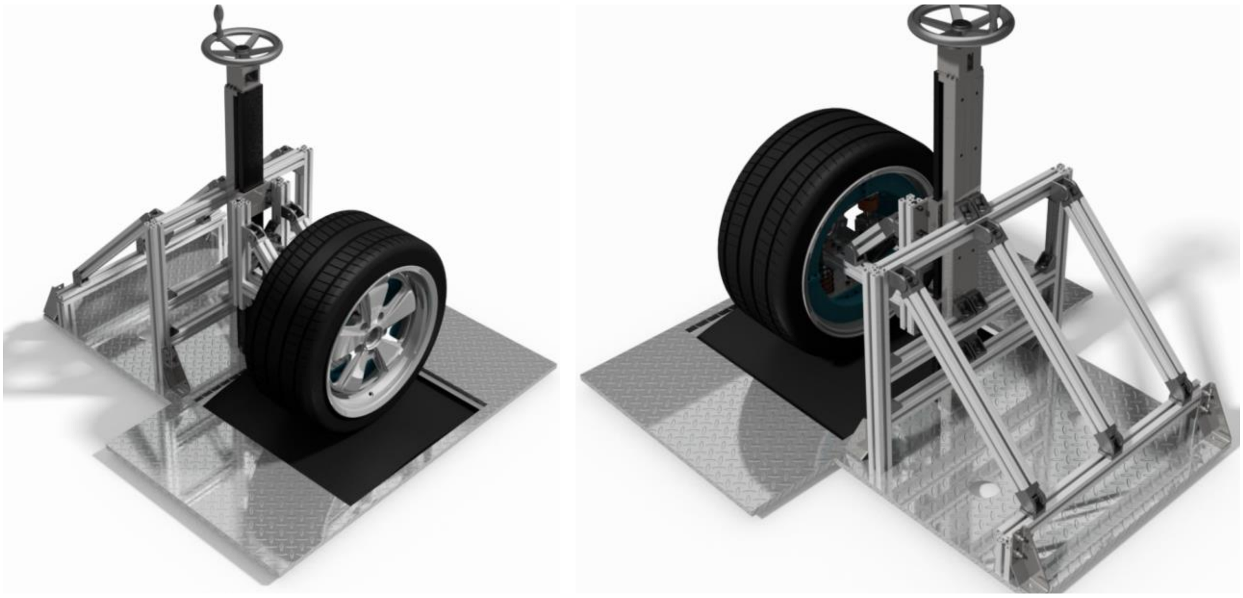

Figure 7: Model of the planned ¼- vehicle test bench

After the real validation of the innovative components of the LEICHT on different test benches (chassis dynamometer, chassis test bed) its integration in different research vehicles (DLR-Next Generation Car) is planned in 2018-2022.

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