# NEW WHEELS MADE OF STEEL – LIGHT AND STYLISH

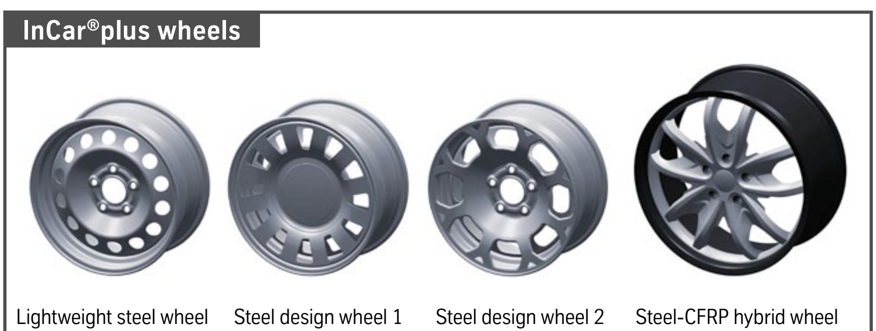
Thanks to the combination of high-performance steels and innovative manufacturing technologies, ThyssenKrupp is developing lightweight wheels which are up to 20 % lighter than current production steel wheels. In parallel, this is leading to a modular design engineering principle for an attractive visual appearance and high design flexibility. The steel wheels which have been developed are lighter and less expensive than modern aluminum wheels as well as being more ecological over the life cycle as a whole. One further highlight is the 20-inch hybrid wheel manufactured from steel and carbon fiber reinforced plastic (CFRP), which sets new standards in terms of its concept, lightweight engineering and design.

A wheel serves to connect and to transfer power between the tire and axle and has to meet the highest standards of safety. During vehicle operation, it is subject to changing dynamic and abrupt stresses, which it has to permanently withstand throughout the life of the vehicle. The wheel must additionally guarantee appealing handling and be compatible with all add-on parts in the tightly delimited wheel area. Particular attention must be given to the weight of the wheel, as the negative effects of weight are threefold. For instance, the four wheels make a significant contribution firstly to the gross vehicle weight and secondly to the moved rotational masses, impacting unfavorably on fuel economy and $CO_2$ emissions. Thirdly, the wheels form part of the unsprung masses, which have to be minimized due to reasons of driving safety and ride comfort.

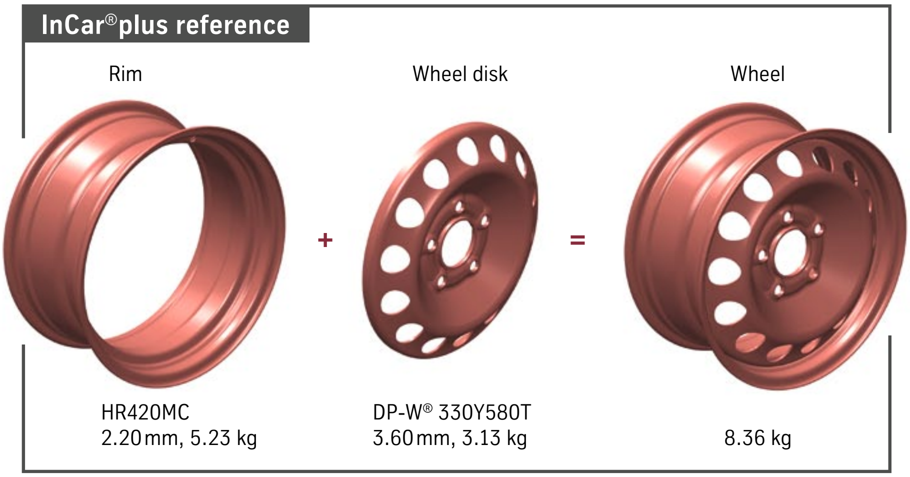
By no means least, the wheel is a prominent design feature on the vehicle. The appealing visual appearance of the wheel individualizes the vehicle and is often a relevant purchasing incentive for the customer. The wheel design additionally enables the OEM's models to stand out from the competition, ❶.

## EXTENSIVE BENCHMARK AS THE BASIS FOR SUCCESS

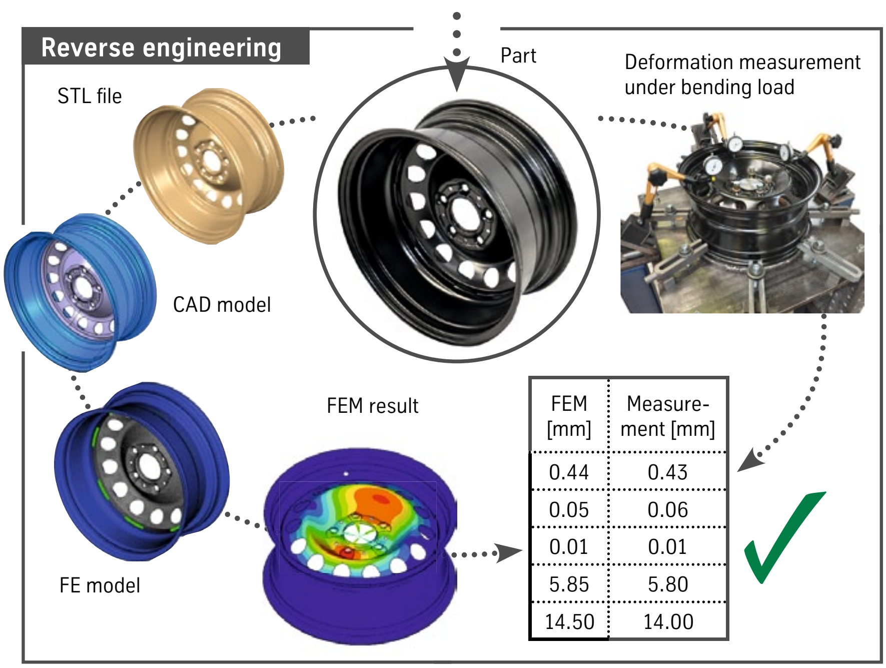
At the start of the development phase, the passenger car wheel market as well as the state of the art for passenger wheels were intensively analyzed. A market study revealed that the typical steel disc wheel is installed primarily on cars up to the mid-size class and on vans. Aluminum wheels predominate as of the mid-size class and in wheel sizes of 17 inches and over. For a number of years, their market share has also been increasing amongst mid-size class and compact vehicles. It is noticeable that, in addition to numerous aluminum wheels, only one single classically designed steel wheel is frequently offered as part of a vehicle's original equipment, despite the fact that steel wheels are significantly less expensive than aluminum wheels, whose prices rise progressively as the wheel size increases.


❶ Overview of the steel wheels developed in the InCar plus project




❷ Initial basis for the InCar plus wheel innovations




| FEM [mm] | Measurement [mm] |
|---|---|
| 0.44 | 0.43 |
| 0.05 | 0.06 |
| 0.01 | 0.01 |
| 5.85 | 5.80 |
| 14.50 | 14.00 |

❸ Validation of the reference structure

The weight of 20 representative 16-inch wheels was analyzed in a benchmark. Astonishingly, it was discovered that cast aluminum wheels are often heavier than conventional steel wheels of the same size and load bearing capability. This is firstly attributable to the fact that a wheel manufactured from sheet metal represents the optimum design in terms of performance and weight. Secondly, focus on an attractive design often leads to additional weight.

The reference wheel for developing innovative wheels is also defined from the benchmark. This involves the lightest and highest load bearing 16-inch steel production wheel with a width of 7 inches and an extremely low weight of just 8.36 kg, ❷. It is therefore lighter than the comparable aluminum benchmark wheels of the same size and load bearing capability, which weigh up to 10.0 kg.

The performance of the selected reference wheel is experimentally determined in quasi-static and cyclical stress tests. The tests are oriented towards the legally specified test procedures and the tire manufacturer's quality tests. The fatigue test under rotary bending loads simulates wheel stress on cornering at increased loads and focuses primarily on the wheel disc. The stiffness of the rim in the area of the rim flange is additionally measured to simulate the running test and deformation during tire fitting or curb impact in simplified form. The determined parameters form the target values for the new steel concepts. The reference wheel is measured digitally and was transferred to CAD. Thanks to this, the simulation tool results can be compared against the real reference wheel tests and therefore verified for the development phase, ❸.

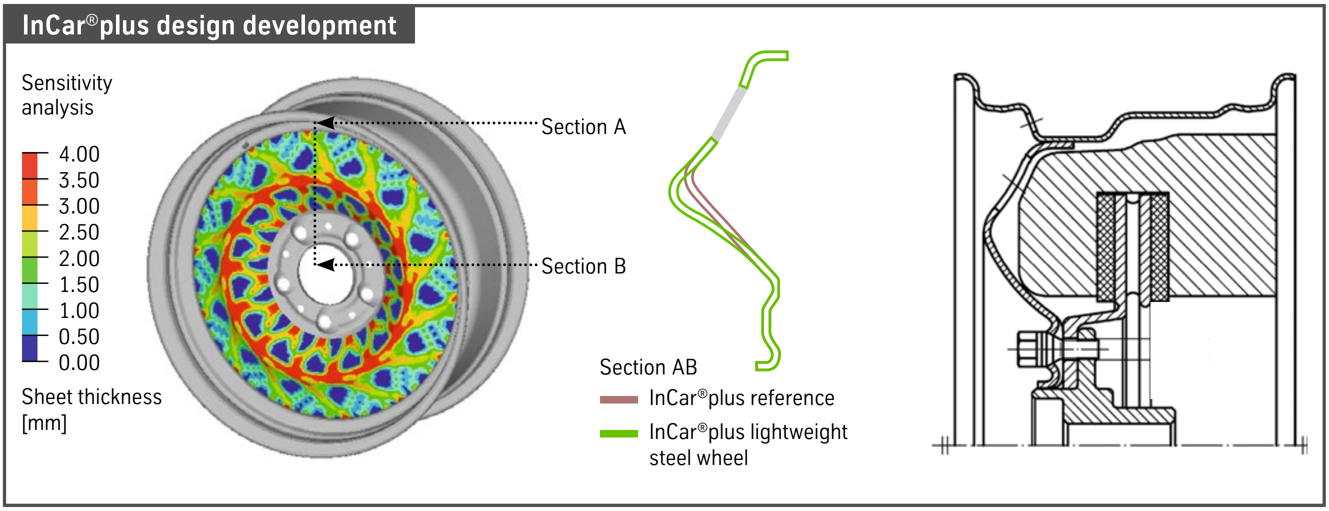
The requirement spectrum outlined so far makes high demands on the development of new steel wheels. InCar plus wheel development is therefore not only focused on the essential reduction of weight but also on the creation of design options for styling individual steel wheel looks.

## LIGHTWEIGHT STANDARD STEEL WHEEL

Do these boundary conditions still offer scope for a new standard steel wheel? Resoundingly yes, because the weight of the wheel is reduced by up to 20 % thanks to the use of new materials and manufacturing technologies for the wheel discs as well as the flow-forming method for a stress-optimized rim. Initial component tests under cyclical stress show that hot-forming will be a suitable process for manufacturing the wheel discs in the future.

The potential weight saving has been analyzed separately for the wheel disc and rim. The wheel disc is subject to particularly high mechanical stresses. In this case, a lower sheet metal thickness acts directly on global component stiffness and thus vehicle handling. A reduction in sheet metal thickness therefore has to be compensated with geometrical adaptation. However, the very tightly packed installation space in the wheel area places tight constraints on such a new geometry, ❹.

Numerical wheel disc sensitivity analyses show that the stiffening shaft exerts a significant influence on component stiffness. In the new lightweight wheel with cold-formed wheel disc, a "sharper-edged" stiffening shaft contour




❹ Sheet thickness optimization (left), stiffness optimization through beading (center) and package restriction (right)

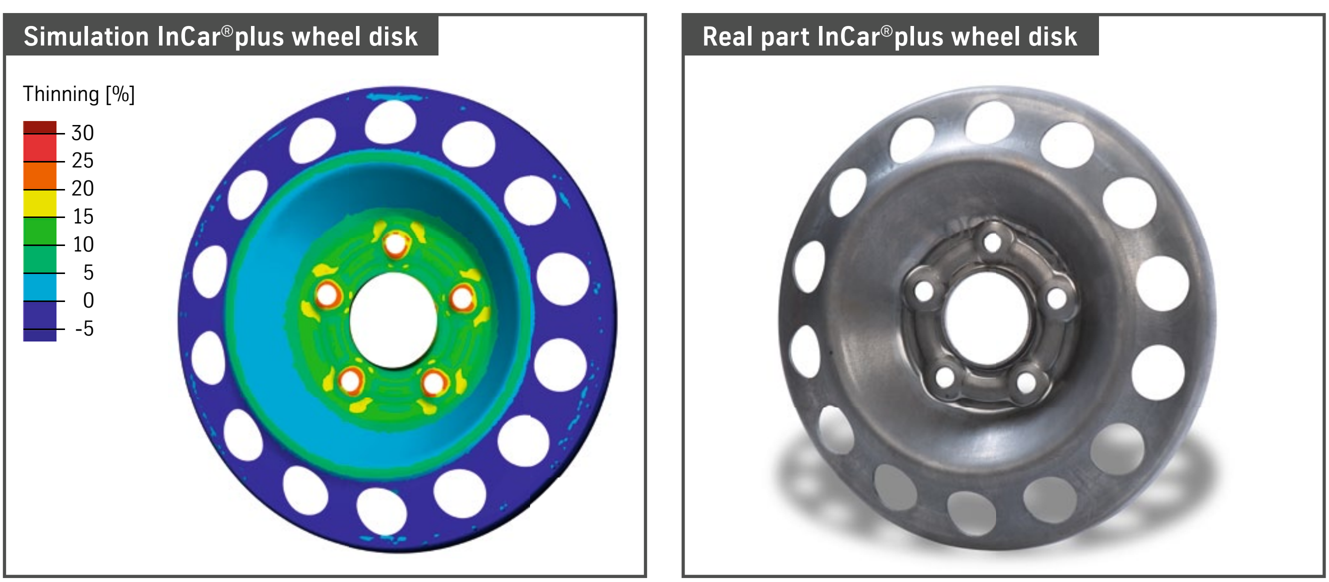
compensates the global loss of stiffening resulting from the reduction in sheet metal thickness. This design measure enables the sheet metal thickness to be reduced from 3.6 mm to 3.3 mm, leading to a weight advantage of 5 % for the wheel disc.

In addition, the reduction in sheet metal thickness is only possible using a material with a higher offset yield stress and fatigue strength under vibratory stresses, since the wheels' required fatigue strength still has to be guaranteed. However, the cyclical material strength from flat specimen tests can only be transferred to the wheel's complex component behavior to a limited extent. As a result of this, the properties were investigated experimentally on the finished wheel under cyclical stress.

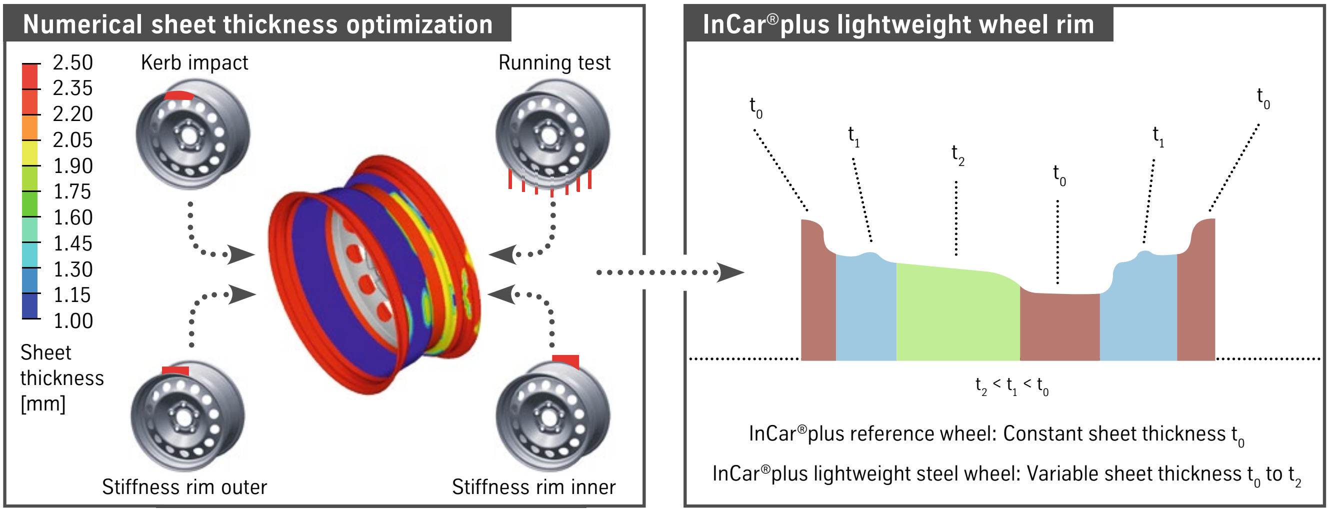
In parallel with the standard, cold-formed DP-W 330Y580T material, ThyssenKrupp is also investigating the suitability of further single and multi-phase steels in the 600-800 MPa strength class as well as an innovative composite material for the wheel discs. Promising steel materials for implementing a wheel disc which is both light and high-strength have been identified, enabling further conclusions to be drawn as regards significant material properties.

Even during the production of prototype wheels, the engineers ensure that the production processes are as close to the standard processes as possible to give consideration to certain effects on the component properties, e.g. the steels' edge cracking sensitivity or bake hardening effects. The various materials' pressings are accompanied by dimensional change analyses and are validated using the simulations performed in advance to design the process, ❺. This enables the virtual assessment of possible usage beforehand.

An increase in offset yield stress and strength generally reduces the ductility




❺ Validation of the forming simulation




❻ Sheet metal thickness optimization on the rim and its results

of steel materials. To obtain a wheel disc which is light and can be freely designed, however, attaining a very high level of both ductility and strength is desirable. Hot-forming is a suitable process for accomplishing this. In this process, the initial mill bar is heated to an austenitizing temperature of around 900 °C and is then further processed in the hot-forming or hardening tool. This improved ductility at high temperatures enables complex components with high strengths. If partial press hardening is additionally applied, local differences in strength and ductility properties can be achieved.

## INNOVATIVE WHEEL DISCS THROUGH HOT-FORMING

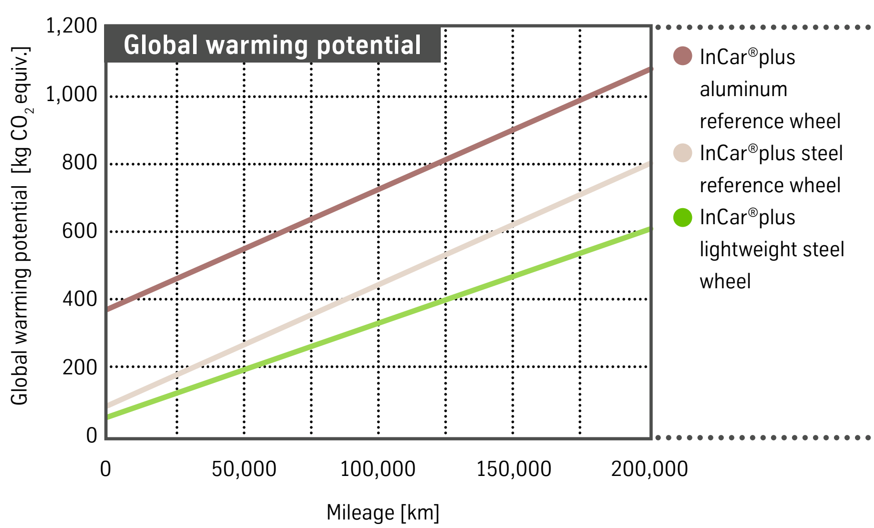
So far, no steel wheels are manufactured as standard using hot-forming. ThyssenKrupp is studying this promising process for the wheel discs and is evaluating it by means of cyclical stress tests on wheels. In comparison with the conventional cold-formed component geometry, the sheet metal thickness of hot-formed wheel discs can be reduced to 3.0 mm, as simulation calculations demonstrate. This leads to a weight saving of around 17 % in comparison with the cold-formed reference wheel disc.

To attain an efficient hot-forming process without costly rework on the hardened component, all processing steps are integrated into one forming tool wherever possible. Particular attention must be paid to the wheel fastening in this case. This is due firstly to the fact that the wheel bolt hole geometry is created using massive forming in volume production. Secondly, the wheel flange must reveal sufficient ductility, as high mechanical and thermal stresses occur here due to contact with the wheel bolts and the wheel hub. With its vast hot-forming know-how, ThyssenKrupp has succeeded in developing a prototype tool. This prototype tool can be used to manufacture hot-formed wheel discs in the direct process with local strength differences. Changed tool kinematics also enable complete press hardening of the wheel discs produced using innovative hot-forming steels and thus a reduction in cycle times.

## RIM WITH DIFFERENT SHEET METAL THICKNESSES

The rim is the heaviest part of the wheel. In the reference wheel, it amounts to 62 % of the total weight. Added to this is the fact that weight which is located far away from the wheel's axis of rotation exerts a disproportionately high influence on fuel economy due to mass inertia. Consequently, reducing the weight of the rim is particularly effective.

The ideal material distribution over the width of the rim can be determined using optimization calculations. These show that a reduced sheet metal thickness in the area of the rim flanges and in the drop center impacts negatively on




❼ With the same weight, there is no break-even between steel wheels and aluminum wheels local stiffnesses and stress conditions. A reduction in sheet metal thickness is possible in the rim shoulder area and between the rim shoulder and drop center, ❻. A maximum weight reduction of 27 % was determined based on the simulation results.

The rim's calculated sheet metal thickness distribution can be implemented using two different technologies: either with Tailored Strips or Tailor Rolled Blanks or with the flow-forming method. In this method, pressure rollers specifically and continuously adapt the rim blank's different areas of thickness. This form of mechanical processing additionally strain hardens the initial material, thus increasing its resulting strength. Flow-forming is already an established process for manufacturing wheels, particularly for truck wheel discs, and is therefore also the method of choice for realizing stress-optimized passenger car rims.

The virtual design and experimental testing of the lightweight wheel were undertaken jointly by ThyssenKrupp and wheel manufacturer Magnetto Wheels. In particular, production of the weight-optimized rim is carried out on the wheel manufacturer's production lines. The prototype wheel disc variants and the rims are joined together using conventional production methods. Fatigue tests under rotary bending loads of 75 % round off development.

## LIGHTWEIGHT WHEEL COST AND ENVIRONMENTAL PERFORMANCE

The cost assessment of the developed lightweight wheel is positive. The material savings on the rim fully compensate the additional expense of the flow-forming process. Conversely, the reduced sheet metal thickness of the cold-formed wheel disc is unable to fully compensate the higher material price. The weight saving of up to 1.3 kg is faced with maximum lightweight design costs of € 1.10/kg depending on material.

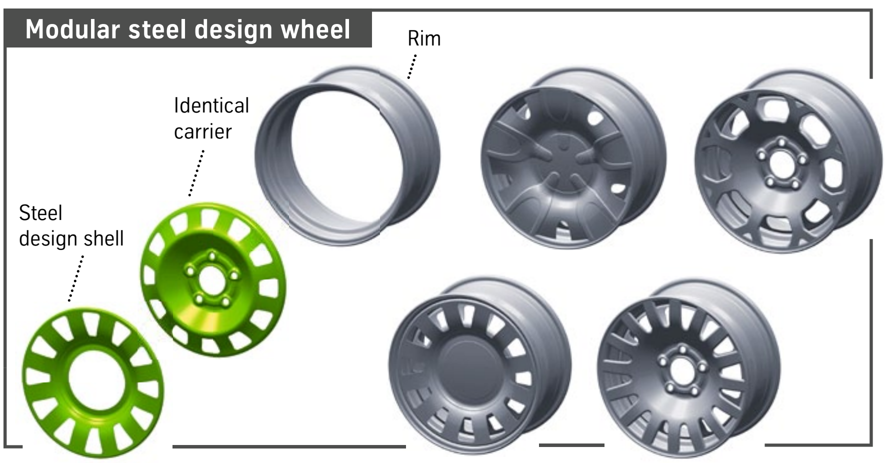
The hot-formed wheel disc also demonstrates that it is sensible and possible to relocate all hot-forming operations to one tool. The technology-related additional costs of hot-forming can therefore be approximately canceled out by material savings and fewer production steps.

Comparing the environmental performance of the reference wheel and lightweight steel wheel with representative aluminum wheels reveals particularly interesting results, ❼. The global warming potential of the different wheel variants is shown over their total useful lives. Due to the high primary energy consumption required to obtain aluminum, more $CO_2$ is created during the production of aluminum wheels than steel wheels. In addition, the aluminum wheels in the benchmark are considerably heavier than the outlined steel solutions, preventing them from achieving any advantage even during their useful lives. Steel wheels are therefore considerably more eco-friendly and are clearly the better choice, especially for the OEMs' fuel efficiency models. More detailed life cycle analyses for the wheels can be found in the article entitled "Environmental Performance as an Important Criterion" (see from page 130).

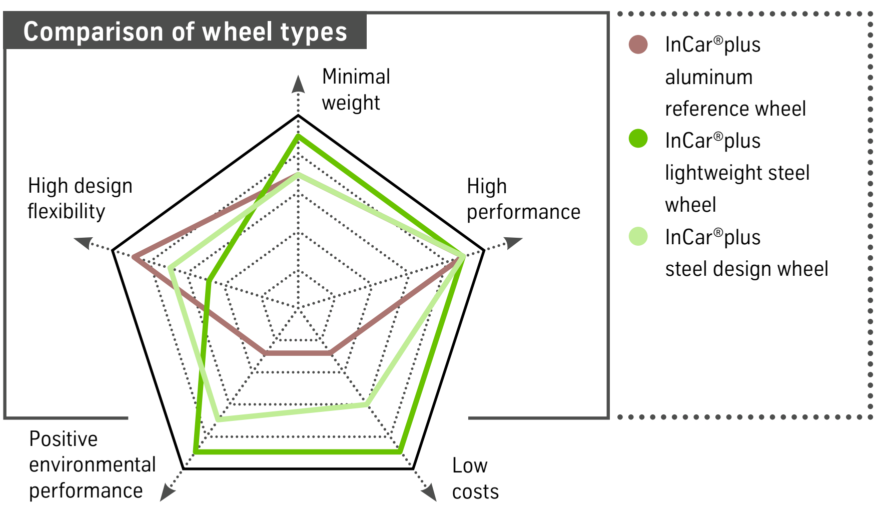
## STEEL DESIGN WHEEL CONCEPT DEVELOPMENT

Aluminum wheels are manufactured using the casting method and therefore enable highly diverse designs for comparatively low investment costs. In contrast, the classic steel wheel is characterized by performance, low weight and cost-effectiveness with high unit numbers. ThyssenKrupp combines the advantages of both methods of production in its new steel design wheel, ❽.

In this modular wheel concept, a basic element bears the majority of the




❽ Concept for the new steel design wheel




❾ Comparison of steel wheel innovations and the cast aluminum wheel in the spider diagram mechanical stress. The wheel obtains its attractive visual appearance from a modular steel design shell, which is connected to and borne by the basic element. This two-part concept offers high design diversity with moderate additional costs with the same weight level as the reference wheel. The modular steel design wheel is actually significantly less expensive than aluminum wheels and its environmental performance is better, ❾.

Fiber reinforced plastic covers are usually employed to visually enhance steel wheels. However, these covers cause up to 10 % of the wheel's weight and do not contribute to its structure. The ecological life cycle also deteriorates dramatically due to the plastic cover. Conversely, the reinforcing design shell avoids these disadvantages and offers extensive design scope.

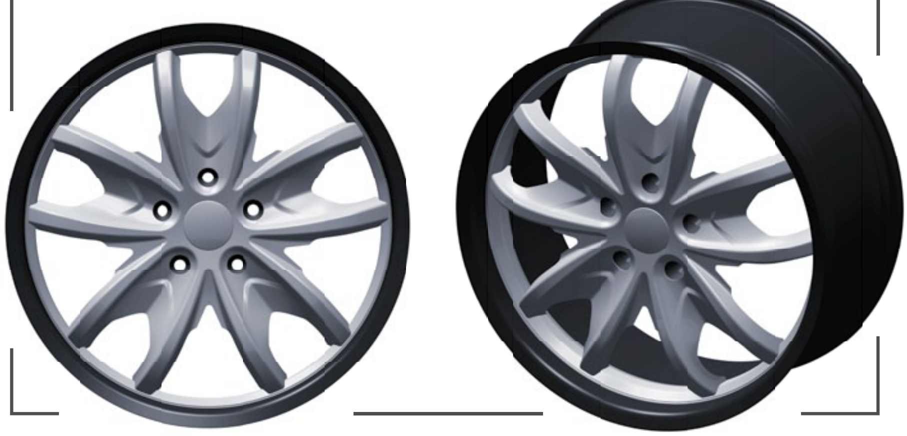
Together with Magnetto Wheels, ThyssenKrupp has verified general manufacturing feasibility and function on two prototype design variants. The prototypes use the lightweight wheel as the basic element and enhance it with two different design shells. The design shell is joined to both the wheel disc and the rim, thus improving stiffness and the flow of force in the wheel. Joining processes include laser beam brazing and classic laser beam welding. Adhesive bonding is also conceivable in the future.

Connecting the design shells in the rim shoulder area causes the wheel to appear significantly larger than a conventional steel wheel joined in the drop center, thus leading to the effect of a semi-full face disc wheel. The concept additionally enables the current trend towards more closed wheel surfaces to be embraced; this is being sped along by the $CO_2$ debate (improved aerodynamics) and current electric vehicles.

## UNUSUAL STEEL-CFRP HYBRID WHEEL

The steel-CFRP hybrid wheel is a high-quality 20-inch wheel for sports cars and the luxury vehicle class; it is competing against forged aluminum wheels in terms of design and weight. The material mix and the innovative joining methods ideally exploit the advantages of the individual materials and lead to the achievement of a visually attractive wheel weighing of just 10.5 kg.

Steel-CFRP hybrid wheel



❿ Attractive 20-inch lightweight wheel in multi-material design

The basic idea behind the hybrid wheel is "the ideal material in the right place". The majority of the wheel's weight is concentrated in the rim with maximum distance away from the rotational axis. A weight reduction is particularly effective here, which is why the new hybrid wheel's rim consists of the lightweight CFRP material. The package in the area of the rim spider is very constricted, whereas the mechanical and thermal stresses and demands on the visual appearance are extremely exacting. Due to these reasons, the ideal material used here must be highly deformable, very stiff, able to withstand high thermal loads and very strong – steel.

To meet the exclusive design requirements of luxury vehicle and sports car buyers, the hybrid wheel is styled very attractively. From numerous drafts, a fine double-spoke design was selected for implementation, ❿.

One particular challenge involved in manufacturing metal-CFRP hybrid components is the different thermal expansion coefficients of the individual materials. This challenge is met with special, detailed manufacturing and material technology solutions for the individual components of the steel-CFRP hybrid wheel. This has enabled minimization of the inherent stresses caused in the component due to temperature fluctuations during manufacturing and operation.

The structurally separate shell design used for the rim spider additionally leads to high component stiffness with low weight. For the first time, the outlined concept enabled the achievement of a 20-inch steel-CFRP hybrid wheel with correspondingly high potential savings. Initial trials with the manufactured prototypes are extremely promising. Integration of the assembled steel rim spider or the CFRP rim into further concepts is conceivable.

As part of InCar plus, ThyssenKrupp has virtually reinvented the wheel – and not just one. Optimization of the materials, manufacturing processes and geometries of the steel wheels takes their competitiveness to a whole new level. The new design concepts, in particular, open up wider application areas to the steel wheel thanks to diverse individualization options. The steel-CFRP hybrid wheel's multi-material approach even gives steel access to the segment of high-quality performance wheels with high design standards.