Methodology for force flow optimised car body structures and implementation

Dipl.-Ing. Jens **König,**

Dipl.-Ing. Gerhard **Kopp,**

Dr.-Ing. Joachim **Winter**

Prof. Dr.-Ing. Horst E. **Friedrich,**

German Aerospace Center - Institute of Vehicle Concepts, Stuttgart

Dr.-Ing. Martin **Schön**

Bombardier Transportation, Hennigsdorf

Introduction

DLR has been researching the most varied subjects in the field of rail vehicles in its field of research for land-based transport. This is carried out across the Federal Republic in various institutes and departments. The acquired skills, supported by expertise from aviation and aerospace, became focused at DLR in the Next Generation Train (NGT) Project (cf. [1]). The basis for the mutually extension of skills in research and development of trains and in rail management systems occurred in 2009 when the framework agreement was signed between Bombardier Transportation and DLR. Based on this an integral methodology for mass optimised car body structures was developed at the Institute of Vehicle Concepts of DLR in Stuttgart.

The mass reduction and the associated lightweight structures are gaining in importance in rail vehicles. The reasons for this are diverse and depend on the requirements which are demanded of the vehicle. For example, the forces exerted by the train on the track in a vertical direction are limited. This is the main reason for lightweight construction of high speed trains. Limiting the maximum axle loads often presents a challenge and demands rigorous lightweight construction. Further benefits of vehicles with reduced mass include, for example, reduced driving resistance and, as a result, significant energy saving. In addition to reducing energy as a result of the reduction in vehicle mass other primary and secondary effects justify lightweight construction of rail vehicles. (cf. [2])

The mass of a rail vehicle can be divided into subgroups. These include the running gears, the car body, the equipment, the power train, the interior etc... The car body plays a key role because of its mass (15–30% of the unladen vehicle mass) and the diversity of interactions, such as with the running gears or trainset concept. For these reasons a methodology was developed which enables weight optimised car bodies to be designed. The methodology which is applicable to the most diverse general conditions serves to create car body structures which take the holistic lightweight construction approach into account. The first step covers a methodical procedure for developing load adapted lightweight structures for car bodies. In the second step the design of the load adapted car body structure is further modified via a methodical procedure. Finally the construction of the car body is performed. In this article the principles will, in particular, be demonstrated though the running gear segment of the car body.

Initial conditions for current car body construction

Current car body structures are mainly produced in differential styles, mostly in steel and in part in aluminium, or using integral construction methods e.g. extruded aluminium profiles.

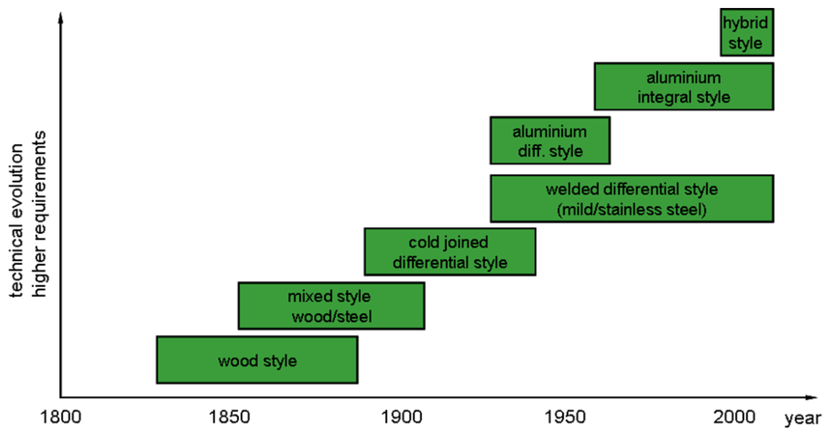

Figure 1: Chronology of the development of car bodies [6]

Differential construction uses various profiles, semi-finished products and thin walled sheets. The profiles and semi-finished products are usually connected together by welded joints to form a framework structure and planked with sheets. The materials used are primarily structural steels, high strength or stainless steels but also, in some cases, aluminium alloys. [3, 4, 5, 6]

In integral construction generally extruded aluminium profiles are used from which the car body is built up. The profiles running along the length of the car body are welded along the longitudinal vehicle axis or also sometimes bolted. The profiles can be either open profiles or hollow chamber profiles. A distinct benefit of this style of construction is the fast and part automated production of the car bodies. [3, 4, 5, 6, 7, 8].

In addition to these two styles of construction in recent years a hybrid construction style has developed which can be subdivided into framework and shell styles. The car body is produced directly from individual components or built up from segments which are connected to each other. Various materials in various combinations are used. The overall objective is to use the properties of each material to its best advantage in the part as well as the assembly. The consequent use of the most suitable material for the most appropriate application opens up a large potential for hybrid designs in lightweight construction. Plastics and fibre reinforced plastics are frequently used in combination with metal materials. Because of their wide range of advantages sandwich elements are increasingly being used. As a result of the combination of different materials special attention must be paid to the joining technology. Depending on the material combinations cold joining such as gluing or bolting is used predominantly. [6, 7, 10]

Development of force flow optimised car body structures

A comprehensive, far reaching and ongoing reduction in weight demands a holistic lightweight construction approach. For this reason it makes sense to use lightweight construction principles as far as possible. Lightweight construction principles include use of lightweight materials, function and system for lightweight construction, as well as lightweight design of structures and form. Lightweight design and shape offer the greatest mass saving potential. This is due to the fact that the design and shape of lightweight construction initially demands a force flow optimised, and therefore lightweight, structure. This can be a good basis for creating lightweight constructions and systems. This makes possible the optimum use of these lightweight construction principles. For this reason the main focus of the methodology developed is on the lightweight design of structures and form.

Methodology for creating force flow optimised car body structures

Creation of a force flow optimised car body structure is offered by topology optimisation methods. In topology optimisation the relevant main load paths are identified using numerical calculations. The programmes for topology optimisation currently available on the open market only take account of static loads. This means that the car bodies have to be divided into areas which predominantly satisfy either static or dynamic crash loads. According to the methodology used here the car body is divided into three segments. The two outer crash segments absorb the crash energies, which arise from EN 15227. The crash segments further limit the maximum loads on the link points with the middle segment. This means that the middle section must be designed expressly to correspond to the static loads. Based on the results of the topology optimisation, conclusions can be drawn on a favourable car body structure from a lightweight construction point of view. (Figure 2), (cf. [1, 2])

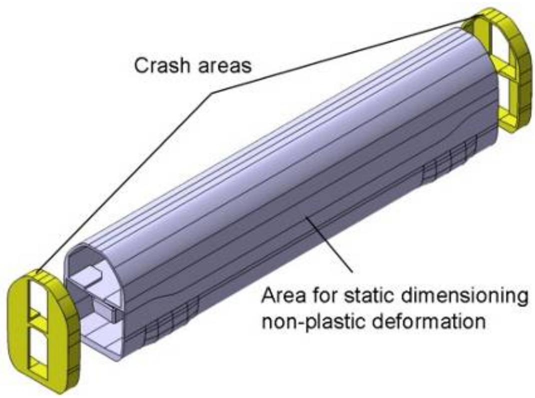

Figure 2: Subdivision of the car body into crash and middle segments [1]

To obtain generally valid findings relating to lightweight car body structure, it is desirable to use this methodical procedure for different car body dimensions and train concepts. Furthermore it makes sense to examine the effects and the relevance of the individual and combined load cases relating to the car body structure. In line with the NGT project (cf. [1]) the investigations are carried out as examples using a double-deck single car with two single single-wheel running gears. Each has a single pair of wheels (no wheelset axles) so that there can be a throughway on two levels between the cars.

Taking into consideration the limiting factors and conceptual requirements (car body length and width, double-decked, axle load, optimum space utilisation etc.) the optimum dimensions are defined for the inside and outside car body structure. The resulting car body shells are put under static loads, as defined in EN 12663, for the simulation. The non-load bearing components of the operating mass (e.g. interior, inner lining, equipment) as well as the payload are applied to the appropriate areas of the car body shell. These loads depend on, among other things, the vehicle dimensions and are individually determined for each car body model. The mass of the structure resulting from the topology optimisation is also taken into consideration at each iteration step. Sufficently realistic basic conditions for the topology optimisation can be created. It should be noted that initially no window or door openings are taken into consideration as these influence and limit the configuration possibilities of the topology optimisation. Suitable door locations can be derived from the skeleton resulting from the topology optimisation and taken into consideration in the design implementation of the car body structure.

Principle findings regarding force flow optimised car body structures

Significanty relevant for the concept is the load which results from the compressive force at buffer height combined with payload. The impact of the payload at a maximum permissible deflection of 1‰ of the distance between supports is within considered lengths for the NGT (max. 20 m) less relevant for dimensioning. Despite the relatively low compressive force (300 kN) at the height of the cant rail, this load case noticeably affects the skeleton resulting from the topology optimisation. Separate load paths are formed because of the position of the force application at the height of the cant rail. From this it follows that connection paths are necessary of these load paths to the rest of the skeleton. Also the main load paths are influenced. (Figure 3)

A comparison of the skeleton of the car bodies of different lengths shows a largely similar structure. This makes a force flow optimised style design possible, which can then be applied to various other car body dimensions. As the length of the car body increases a requirement for additional stiffening elements is identified, but the main load paths principally remain the same. This means that when the design is being implemented for various car body lengths, the same structural elements can be included. Only in localised areas additional supports are needed to match the results of the topology optimisation. As a result of the high number of common parts and segments of the car body structure both the engineering and the production costs can be minimised. (Figure 3, Figure 4).

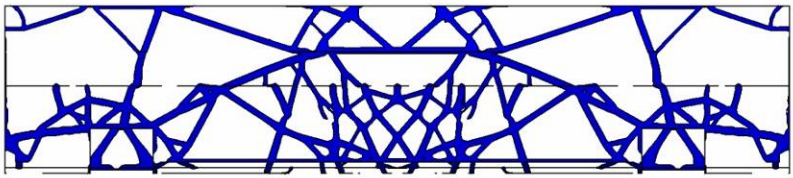

Figure 3: Topology optimisation of double-deck car body of 20m length

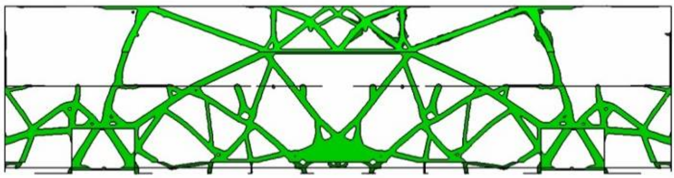

Figure 4: Topology optimisation of double-deck car body of 17m length

Concept of force flow optimised car bodies

The concept of a force flow optimised car body structure includes the support structure. Also a suitable process for optimum selection of the panelling elements according to set basic conditions is necessary.

Concept for force flow optimised support structure

Based on the findings of the topology optimisation, a structure concept for a car body can be derived. This can be adapted to various car body lengths with only minor changes. Specific segments which only show minor differences between the individual optimisation results (e.g. segment over the running gears), can be used in an identical manner for the structures of car bodies of different lengths.

Taking into consideration the load path and force directions which result from the topology optimised models, three dimensional shaped bulkheads can be used for the car body structure. The specific sequence of the individual bulkheads produces ideal a bend and torsion stiff honeycomb tube. In principle the individual bulkheads consist of beams which support each other. The beams are made to meet the local principle load path directions. Their combination and interconnection means that they prevent the local introduction of bending moments. The individual beams run along the car body structure in a vertical, longitudinal and diagonal direction. Their orientation is thus adapted to the corresponding global load directions (vertical, longitudinal, diagonal). The vertically arranged beams carry the forces which result from the net mass. To be able to bear the global tension and compressive loads (e.g. according to EN 12633), longitudinally continuous sole bars are realised. Torsion loads occur resulting from, for example, lifting the car body on one side. Furthermore the forces affecting the car body structure resulting from payload, equipment, interior etc. require a sufficiently high bending stiffness. To meet the lightweight construction concept it therefore makes sense to have a high geometrical moment of inertia of the complete car body around the lateral axis. In accordance with the topology optimisation, the greatest possible distance between the top chord member and the bottom chord member is taken. The shear connection of the chords necessary for the bending stiffness is achieved with diagonal beams and is, in addition, supported by panelling. The diagonal beams thus partially take on the function of shear areas, which is why windows can be conveniently positioned in these areas. (Figure 5)

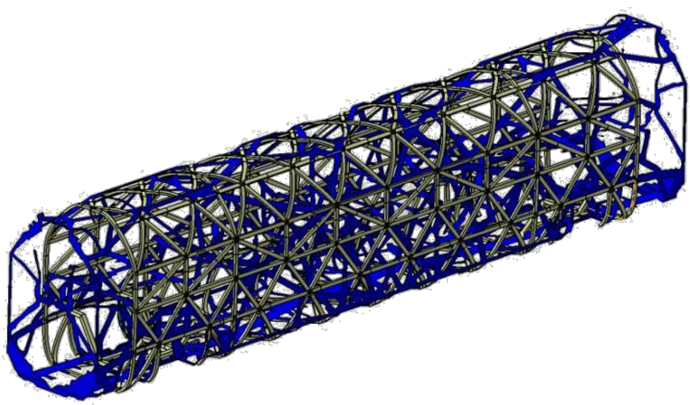

Figure 5: Force flow optimised concept of a honeycomb support structure for car bodies

A large number of common parts are achieved in construction by the wide use of repeating beams in the longitudinal direction, just as the length of the car body can relatively easily be varied by suitable arrangement and combination of the members. This leads to a reduction in engineering and production costs. From the topology optimisation the places can be defined where no strut structure is necessary. The structure is therefore developed in such a way that, within local areas, beams can be dispensed with, without causing unfavourable loads on the remaining beams. This therefore achieves an additional reduction in mass.

Systematic process for construction of panelling elements

Consistent lightweight construction is contingent on structural support of as many parts as possible. Depending on the intended panelling, construction using independent beams can be dispensed within local areas. Needed stiffness can be integrated in the panelling. Given sufficiently high stiffness and panel strength, stiffeners can possibly be completely dispensed with at appropriate locations. This can, for example, be achieved with sandwich structures, which have a high bending stiffness, by increasing the area moment of inertia. The principle of sandwich construction here corresponds to the behaviour of an I-beam. Under a bending load the sandwich core is stressed on shear and the cover layers absorb the tensile and compressive forces, like the I-beam chords. Thus the area moment of inertia and the bending stiffness of the whole structure can be greatly increased. (Figure 6). By this analysis it can be shown that, even with a total thickness of 10mm, the specific bending stiffness in comparison to solid steel sheet or aluminium sheet can be increased by over 50 %. [11]

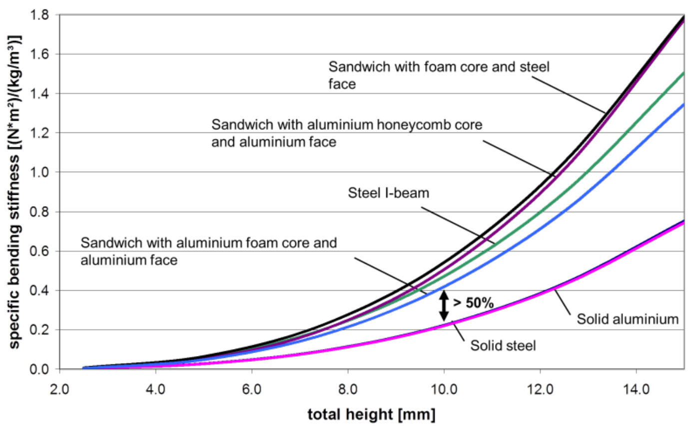

Figure 6: Comparison of specific bending stiffness of 100mm wide bending beam [11]

A systematic process must be used for optimum selection of possible panelling for structure designs which are easy to bend (Figure 7). The large number of different material and production combinations of core and cover layers mean that the space, the loading and any other requirements first have to be defined. Here, in addition to the mechanical loads, other selection criteria such as thermal properties, chemical resistance, fire protection, acoustic properties or possible functional integrations have to be taken into consideration. Based on these specified requirements, with the aid of an analytical preliminary layout and a database of sandwich materials the combinations are selected which can be used for the specific application. The analytical preliminary layout involves only a small amount of work, in comparison for example to an FEM analysis, since most requirements can, at this early stage, be simplified or abstracted.

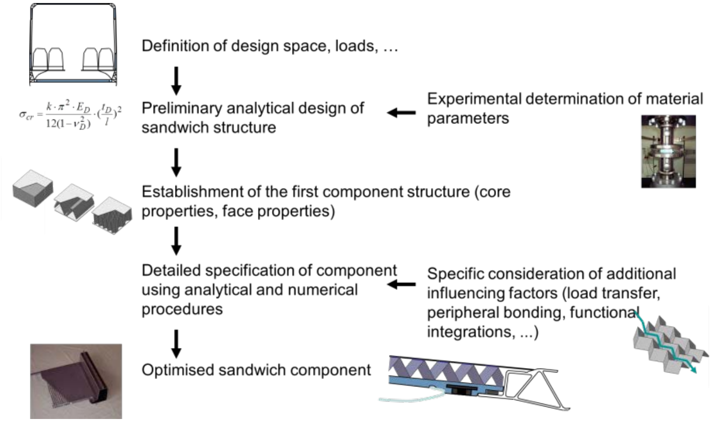

Figure 7: Procedure in selecting sandwich components for panelling (based on [11])

The detailing and the optimisation of the component then follows where other influences from the production process to the transfer of forces and installation concepts with the honeycomb support structure have to be taken into consideration. A possible concept for connecting the floor plates to the honeycomb structure is shown in Figure 8. A combination of gluing and the local introduction of force by an insert or by bolting ensures symmetrical force transmission, the necessary seal, quick installation and compensation for possible production tolerances.

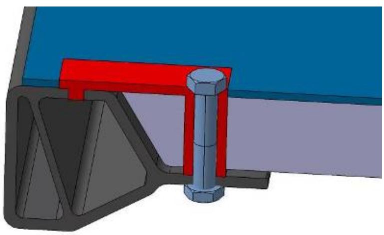

Figure 8: Cross-section of a possible connection of the sandwich with the honeycomb structure profiles in the floor area.[12]

Furthermore, with such a structure and the necessary joining technology, additional functional integrations such as acoustic properties, heat insulation using foam cores, integration of heating/air conditioning with appropriate material combinations can be achieved.

Conceptual construction of running gear segment

Based on the concept of a force flow optimised car body structure developed in the framework of the chosen innovative methodical approach, the construction of a car body structure is performed. Due to the high complexity of the car body segment over the running gears, the potential of the methodology can be well demonstrated. The loads and forces acting on the running gears result primarily from the running gear mountings, the coupling forces, the static loads according to static layout load cases in EN 12663, the mass of the rest of the car body and the payload.

All vertically directed forces are absorbed by the car body through the secondary suspension of the running gears. For this reason brackets are included within the aluminium structure for suspension support. Multiple supports assure a minimum of bending moments. The supports are integrated into the load bearing structure and designed to be continuous as well as force flow optimised. The transmission of the traction forces of the running gears is realised through the tension and compression rods, which engage through eye connections and further distribute the loads into the floor area. The connection of the running gear with the two lateral dampers is provided at the inner cross beams. A force flow optimised design is realised between the spring brackets and the load bearing floor structure. The connection points for the coupler being part of the running gear segments is dimensioned in line with EN 12663 and optimised with regards in force flow and stiffness. The forces acting in a longitudinal direction according to EN 12663 distribute themselves over the structure in the subfloor. Similarly these are introduced into the diagonal running members in the honeycomb structure, which thus form a link to the spring connection. (Figure 9)

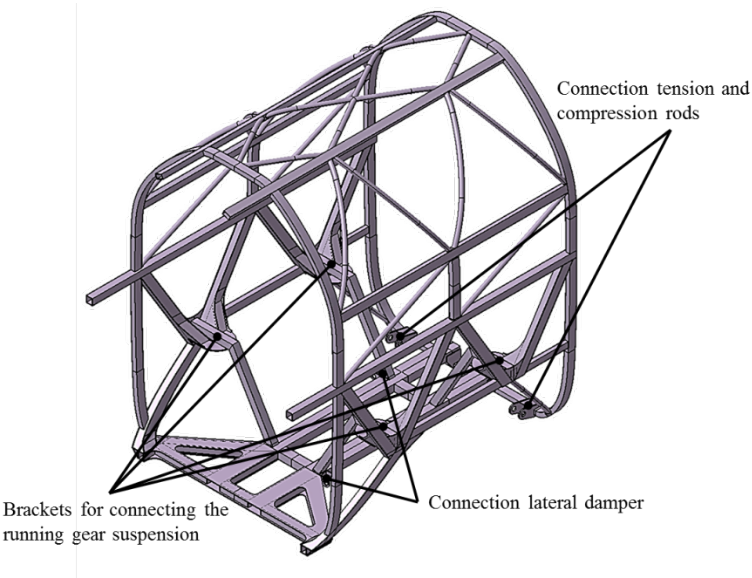

Figure 9: Construction design of a running gear segment based on a methodical approach

As a result of aerodynamic optimisation, a complex external contour of the car is predefined. This requires the diagonally running beams with a square cross-section to follow a three dimensional curve, and in addition, they must be twisted. This can be avoided by using circular cross-section beams in moderately loaded areas, which then only have to be curved in one direction. In heavily loaded areas suitable beams are welded together from individually shaped or from one-dimensionally curved sheets.

Using the described consequent lightweight design and the methodical approach can, according to present estimates, achieve a mass reduction of approximately 30% compared to a comparable aluminium, integral structure, high-speed double-deck car body.

Summary

The developed holistic methodical approach has high lightweight construction potential with regard to a rail car body. The developed procedure is carried out on a high speed car body. At first the principal force paths are calculated from which force flow

optimised structures can be derived. Within this process results of the topology optimisation are used to conclude favourable lightweight solutions. Novel basic design principles for car body structures are demonstrated. Based on general findings the application to a car body of a high-speed double-deck car body is performed. For the panelling of the car body a systematic process is described on the basis of the benefits of sandwich elements. This allows more favourable selection and construction of the sandwich elements adapted to the requirements. In a further step the car body segment in the area of the running gears is selected as an example of further construction advantages. As a result the varied and extensive requirements of the conceptual design of this segment present a special challenge. The design of the running gear segment consists of a bending and torsion restistant structure. Based on the specific findings of the topology opimisation the main load paths have been defined. Due to the methodical approach to determine the load paths and the derivation of an appropriate structure, a closed chain of development can be demonstrated. It is concluded that a weight reduction of up to 30% compared with comparable car bodies is feasible.

Bibliography

[1] Winter, J.; et al.: NGT – Next Generation Train. Published by: Rail Technology Review Special. TZ-Verlag & Print GmbH.

[2] Dittus, H. and J. Koenig (2011). Energy Reduction of Railway Vehicles by Lightweight Design. Published by: ATZlive, 11th Stuttgart International Symposium, Vol.2: pgs. 501 – 517.

[3] Böhnisch, M.; Drechsler, F.: Leichtbau von Schienenfahrzeugen - eine Rückschau (Teil 1). Published by. ZEV + DET Glas. Ann. 119, Nr. 4 April, Georg Siemens Verlagsbuchhandlung, 1995.

[4] Böhnisch, M.; Drechsler, F.: Leichtbau von Schienenfahrzeugen - eine Rückschau (Teil 2). Published by: ZEV + DET Glas. Ann. 119, Nr. 5 May, Georg Siemens Verlagsbuchhandlung, 1995.

[5] Böhnisch, M.; Drechsler, F.: Leichtbau von Schienenfahrzeugen - eine Rückschau (Teil 3). Published by: ZEV + DET Glas. Ann. 119, Nr. 6 June, Georg Siemens Verlagsbuchhandlung, 1995.

[6] Gerhard, T.; Meyer, G.; Altenburg, K.: Revolution oder Evolution? - Betrachtung zu Werkstoff- und Bauweisenentwicklung für Schienenfahrzeug. Published by: Eisenbahntechnische Rundschau ETR 51, 1-2/2002.

[7] Cabos, H.-P.: Werkstoffe für Schienenfahrzeuge. Published by: Eisenbahntechnische Rundschau ETR 41, 1-1992.

[8] Koewius, A.; et al.: Aluminium-Schienenfahrzeuge, Aluminium-Zentrale e.V., Düsseldorf. Published by: Hestra Verlag, 1992.

[9] Kim, J.-S.; Jeong, J.-C.: Natural frequency evaluation of a composite train carbody with length of 23 m. Published by: Composite Structures, Elsevier, 2006.

[10] N.N.: Schindler is on track with FRP trains. Published by: Reinforced Plastics, vol. 39, November, 1995.

[11] Kopp, Ge.; Kuppinger, J.; Friedrich, H.; Henning, F.: Innovative Sandwichstrukturen für den funktionsintegrierten Leichtbau, Published by: Automobiltechnische Zeitschrift ATZ 4/2009, vol. 111, S. 298 – 305.

[12] DE 10 2010 028 129 A1, 27.10.2011, Offenlegungsschrift, Wagenkasten für Schienenfahrzeuge.