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Integral consideration of the lightweight design for railway vehicles

1 INTRODUCTION

Optimizing the efficiency of all transport vehicles requires comprehensive and systematic solutions, particularly when the objective is to reduce energy consumption connected with CO_2-emission. Driving resistance and reducing mass play key roles in this effort.
The lightweight design of railway vehicles leads to numerous primary as well as secondary advantages. The primary effects are e.g. energy reduction and adherence of the maximum load per wheel set. Secondary effects include reduction of wheel sets itself what leads to a weight reduction of the trains and the aerodynamic resistance.
A comparison of road and rail vehicles reveals that rail vehicles must move more mass per passenger than road vehicles. Reasons for this include high requirements on static and dynamic loads (DIN EN 12663, DIN EN 15227) and a configuration of the vehicles for greater mileage. Car body weight and the required drive power are mutually influencing. If operational requirements (train schedule) demand a specific acceleration capability, then the required drive power will increase proportionally to vehicle mass. This implies that a secondary effect of a lower vehicle weight is a reduction of the installed drive power, resulting in additional energy savings.
The first section of this paper discusses opportunities for reducing the mass of rail vehicles. We also uncover additional benefits and additional effects (besides reducing energy consumption) of lightweight construction. Using this as a foundation, we introduce in the second section a methodology which describes how the car body of railway vehicles can be optimized in terms of mass. This methodology is developed by DLR within the framework of the "Next Generation Train" project (Figure 1).
How showed in (Winter and Granzeier, 2011) in the context of the project “Next Generation Train” (NGT) different scientific issues are considered. The areas are aerodynamics, structural dynamics, dynamic performance, propulsion technology, material sciences and lightweight construction. The maximal operating speed is 400 km/h with the same safety standards at least. Another aspect is the reduction of the specific energy (energy per seat) at of 50 percent.

Figure 1: Design image of next generation train

In the last section the concept of a novel load bearing car body structure is defined. The structure bases on the result of the topology optimization and promises a significant weight reduction potential.

2 OPPORTUNITIES OF MASS REDUCTION

The weight reduction of railway vehicles has different impacts. One result is the energy saving. Simulations have shown that the potential for savings through reduction of vehicle mass is dominated by the characteristics of the service profile. There is a particularly high potential for savings with service profiles that have short distances between the stations and low maximum speeds. As the maximum speed increases, the proportion of energy needed to overcome aerodynamic resistance increases and the potential for savings goes down. The potential for savings with Diesel powered railway vehicles (Diesel Multiple Units (DMU)) is up to four times greater than with electrically-powered vehicles because electrically-powered vehicles can recover a portion of the kinetic energy during braking. However, if the electric braking power is not adequate to achieve the required deceleration, then the potential for savings increases with the electrically-powered vehicles as well (cf. Dittus et al., 2011).

Beside the energy saving because of a reduced vehicle mass the maximal axle loads are defined (cf. EBO § 10 (N.N. 1967)). The reason for this is to limit the maximal static and dynamic forces on the rail tracks. The axle loads are a result of the relation of the vehicle total weight to the number of wheel sets. Regarding the static loads the limits depend on the operation purpose and the maximal speed. According to TSI rolling stock, trans-European high-speed rail system (N.N. 2008b) the static axle load is between 22.5 tons for normal speeds and 17 tons for speeds above 250 km/h. The compliance with these requirements is often a challenge. During the run of a train there are also dynamic loads which have an effect on the rail position error and the position of the wheels relative to the rails.

Weight optimised vehicles with unchanged vehicle properties, like the vehicle dynamics, leads to a reduction of the rail damage because of fewer impacts. Lighter axle loads also leads to a reduction of the abrasion regarding wheels and rail heads. Altogether this is a positive aspect on the Life Cycle Costs of the Infrastructure (Rochard and Schmid, 2004).

All over the world railway lines are built for high and very high speed trains only. Sometimes for locomotive-hauled trains it is not possible to run there, that is why on these lines operate only train sets. If it would be possible to reduce the weight of all the trains running on these lines, the superstructure and e.g. bridges could be adapted on the lighter axle loads what leads to an economical benefit.

Because of the individual originated railway lines in the urban traffic (e.g. metros) the axle loads are often fewer than for standard railway lines. A large part of the ground area of the vehicles is purposed for standing passengers. According to DIN EN 12663 (N.N. 2000) a load of 5-10 passengers/m² is expected. This leads to a challenge in respect to the axle load limit and a light weight construction becomes very important.

Lighter car bodies, and consequently lighter vehicles, permit the use of less powerful and lighter drive and braking equipment. In turn, this leads to the use of lighter rotating masses, such as the rotor in the drive motor or the braking discs. The braking discs, which on high-speed trains can weigh more than 100 kg each, are arranged in multiple assemblies directly and unsprung on the wheelset shaft. Furthermore, the force of the car body is absorbed by the running gear and directed through the wheelsets and wheels into the rails. Therefore, when the car body mass is reduced, the running gear can be adapted to the car body load and made lighter. This leads to a favourable condition for the dynamic behaviour of the vehicle. So it is possible to reduce the impacts on the track and the costs of maintenance can be reduced.

Despite the active safety measures common to railways, the possibility of collisions between railway vehicles or with obstacles cannot be completely excluded. The resulting energy must be absorbed by crash elements in the vehicles according to DIN EN 15227 (N.N. 2008a). Therefore, in the event of a collision, the mass of the colliding vehicles plays a crucial role in addition to the speed of those vehicles. How showed in (Rochard and Schmid, 2004) this means that the energy that must be absorbed will be lower with lighter vehicles, so the crash energy absorbers can be designed lighter.

Beside the described advantages the train concept can be modified because of the weight reduction. This gives the chance to reduce energy. A main target for a complete regarded light weight train is the reduction of the number of running gears and axles as far as possible. If the axle load and the number of axles are invariant, the length of the cars and the area for the passengers can be raised with light weight carriages in relation to heavier carriages. It is to consider that the length and the corresponding width of the car body are bordered because of the structure gauge. The possible increase of the car body length can lead to the saving of one car at least regarding the whole train with an unchanging length. This has the impact that running gears and connections between carriages can be reduced. The result is a weight reduction of the train, the optimised area utilisation and reduction of the aerodynamic resistance corresponding with energy saving. The aerodynamic resistance is the main factor for the energy consumption of high speed and very high speed trains (Table 1). Another fraction of the driving resistances is the resistance to rolling. It can be divided in a resistance which depends on mass (e.g. friction of the bearings) and one which depends on mass and velocity (e.g. dynamic resistance because of vehicle oscillations).

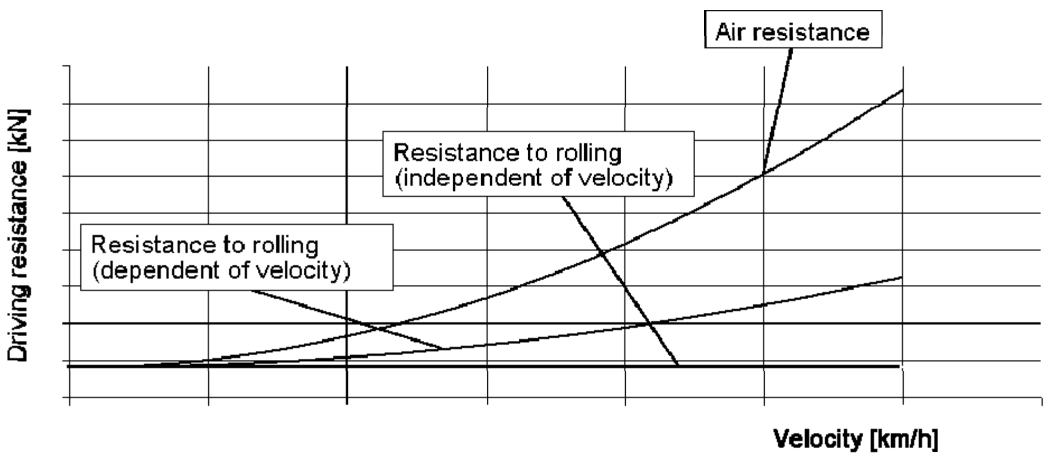

Table 1: Driving resistance related to velocity

The demand of the passengers for comfort and design increases permanently. The costumer request must be responded for attractive railway transportation. Concrete this may be the interior, thermal and noise insulation, air conditioning, comfort and width of the seats infotainment, etc.. With the pretended requirements a weight increase accompanies and a consequently light weight car body structure is absolutely necessary because of the fixed axle load.

Hence the manifold and extensive effect resulting of the weight reduction of railway vehicles, light weight constructions are a main topic for future trains.

3 Correlations Of Light Weight Railway Vehicles

3.1 Mass Distribution of a Railway Carriage

A railway carriage can be divided into three main assemblies (Figure 2): the running gears, car body structure and equipment (like propulsion, interior, car body completion, etc.).

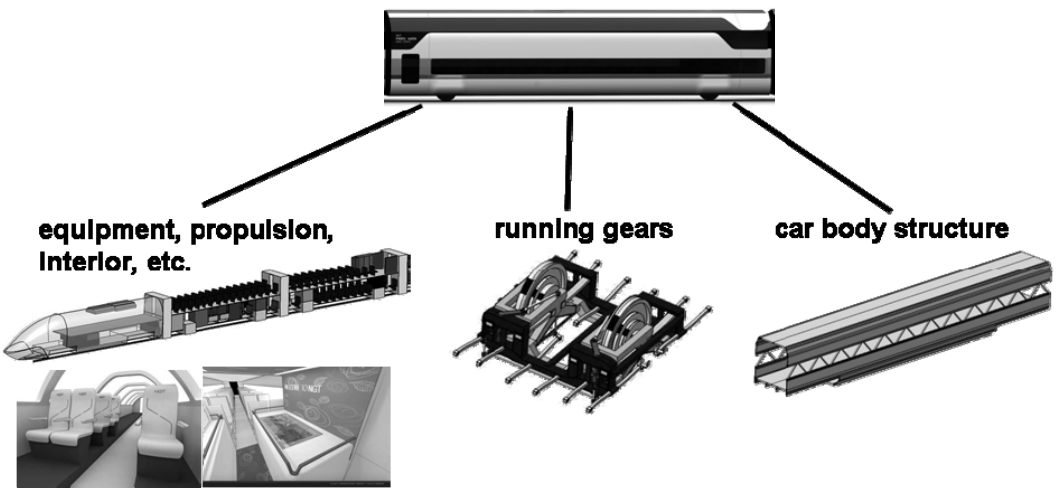

Figure 2: Main assemblies of a railway carriage

The equipment and car body completion is a main cause of the carriage weight (Figure 3). It is composed of a large number of diverse subassemblies. These subassemblies are predominantly independent from each other, so they have to be regarded separately. Based on that, the global weight saving potential resulting of the several equipments is limited.

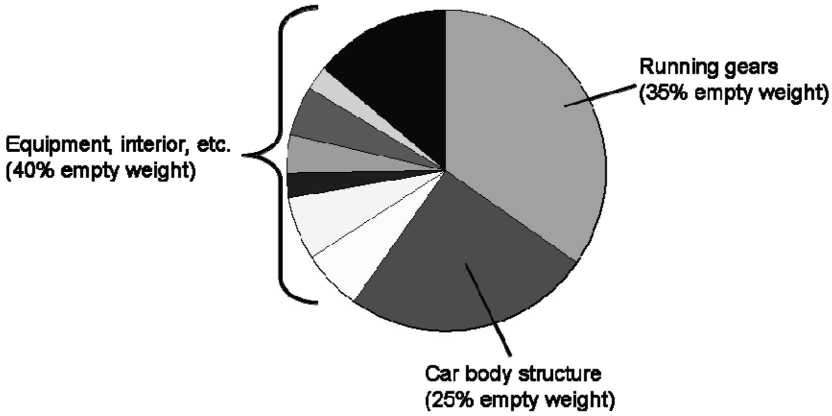

Figure 3: Exemplary percentage distribution of the main assemblies of the NGT carriage

Running gears must perform diverse requirements, e.g. stability of the run, fatigue strength, low wear in the wheel/rail contact and moveable parts. So weight saving of running gears is difficult because of the manifold and security relevant requirements. Currently there are several ongoing research activities, e.g. by the DLR (Kurzeck and Valente, 2011), to improve run stability, wear and minimize weight of the running gears. It is to note that beside the maximal velocity the car body weight, equipment weight and payload are significant influence parameters on the running gears. For this reason the weight optimisation of the car body is an important criterion for a light weight carriage.

3.2 Influence Parameters on Car Body Structure

Analyses showed that the mass of the rough car body normally accounts for 15% to 30% of the vehicle's empty weight. Nonetheless the car body structure is in an interaction with different parameters (Figure 4). This means the car body structure has a direct influence on the weight saving potential of these parameters.

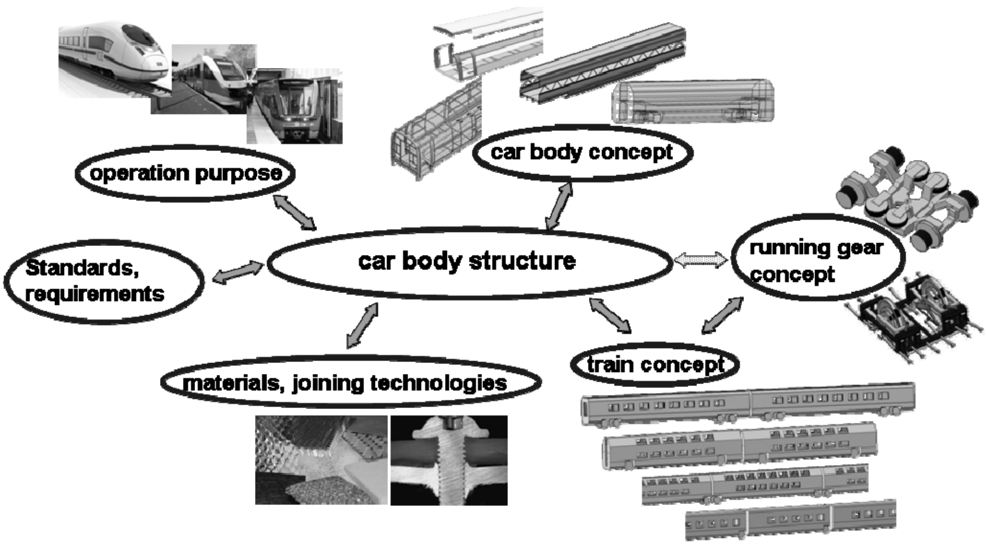

Figure 4: Influences on car body structure

The operation purpose defines the payload (because of the requested passenger capacity), the number of doors, the axle loads, the velocity connected with the air pressure during train encounters which the car body has to resist, etc.
The car body structure is also influenced by the car body concepts which can constrain the conception of the structure design. For example conventional car body structures constrain the scope of design. On the other hand a novel car body concept gives the possibility to create an ideal structure for the respective requirements. Another influence factor is the train concept which defines the geometry of the car body in principle, the position and distances between supports, etc.. Furthermore the train concept is in an interaction with the running gears. As noted above the running gear concepts define the maximal weight of the completed car body and so its length. Also the running gear concept has an influence on the design of the connection to the car body structure.
The joining technology goes together with the materials. The utilized materials have to correspond with the joining technology. The light weight approach of the multi material design (adapted material in adapted positions) brings a large number of challenges regarding the connection of materials with different characters. Materials and joining technologies have an extensive impact on the costs, design, concept and weight of the car body structure.
It is obviously that the car body structure is in interplay with different influence parameters. Therefore, optimizing the mass of the car body is particularly important.

3.3 Light Weight Principles

Currently there are different car body concepts in use. These are car bodies in the differential style, integral style and rarely in the hybrid style (Figure 5). The differential style is a metallic framework planked with blank sheets in principle. The integral style uses aluminium extruded profiles which are welded together in longitudinal direction and possibly local reinforced. The hybrid style is a mix of different materials which uses the potential of every material.

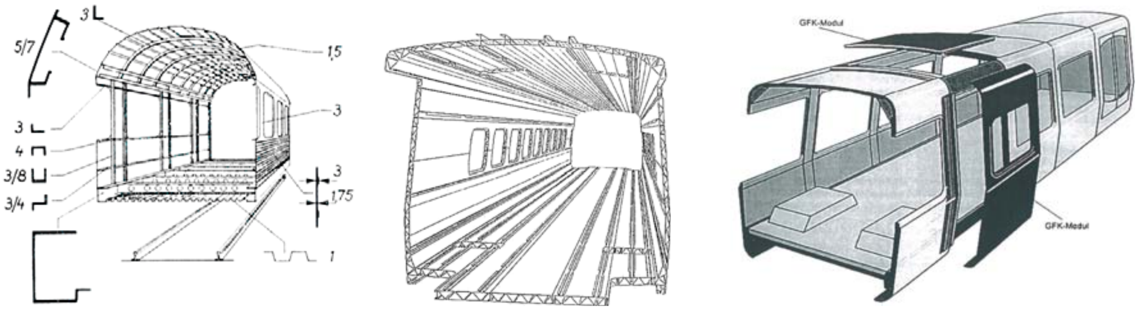

Figure 5: Car body concepts (from left to right): differential style (Bönisch et al., 1995), integral style (Elsner and Schnaas, 1993), hybrid style (Müller, 1999)

It is to note, that for actual current car body styles (integral style, differential style) a lot of expert knowledge exists. Therefore further weight reductions are limited regarding conventional constructions. A global use of light weight principles is indispensable. The light weight principles can be divided in:

- material light weight construction,
- function and system light weight construction,
- shape and form light weight constructions.

The notice of these principles gives the possibilities of a significant weight reduction. The highest potential for extensive light weight constructions promises shape and form light weight constructions. In this case the load bearing car body structure is adapted regarding the main load paths. So unnecessary material can be saved and the load bearing structure adapted to the inertial forces in the car body. A methodology created by the DLR is predestined for the design of load adapted light weight car body conceptions.

4 Methodology For Load Adapted Ligth Weight Car Body Structures

Car body designs must take into consideration a variety of static loads as well as crash loads. These are defined in standards and directives such as DIN EN 12663 (N.N. 2000), EN 15227 (N.N. 2008a), and UIC 566 (N.N. 1990). The car body is thereby divided into two zones with differing tasks and requirements. As defined in EN 15227 the end zones are designed as crash zones to absorb energy. In crash scenarios specified in the standard, the structure in the middle zone (between the crash segments) will not endure plastic deformation (Figure 6). As a result, an adequate level of protection can be provided for people in the vehicle and damage to the car body localized. However, crash elements must be designed so that the maximum forces occurring between the middle segment and the crash zones during a collision do not exceed the assumed static forces for the middle zone. Because of this requirement, only the static loads are relevant for the design of the middle zone's bearing structure. As a result, this entire zone is suitable for the principle of topology optimization. This provides the opportunity to use software to adapt the bearing structure's geometry to the flow of forces. The resulting structure reveals the main load paths that will ideally form under the specified conditions (material dimensions, etc.) and target parameters (stiffness, stress, etc.).

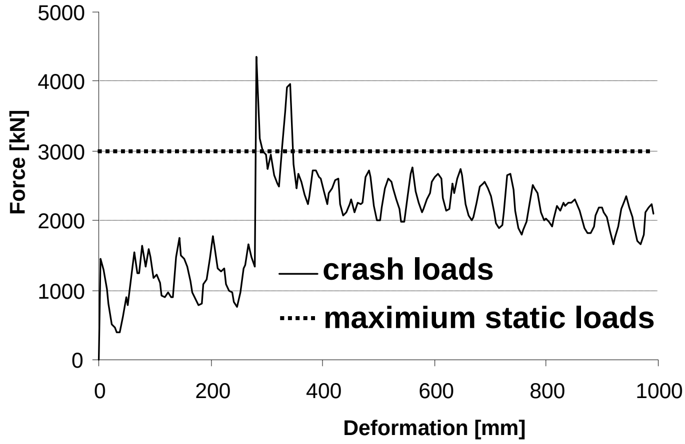

Figure 6: Gradient of crash loads and maximum static loads (according to (N.N. 2001))

The topology optimization program is based on FEM with a special algorithm. In principle, topology optimization requires definition of the design space available for optimization. This is derived from the selected external dimensions as well as the geometries of the car body, external design, and necessary internal space. The designer can also define in advance the positions where cut-outs will be required for windows, for example, as well as positions were no material may be removed during the optimization process (*Figure 7*).

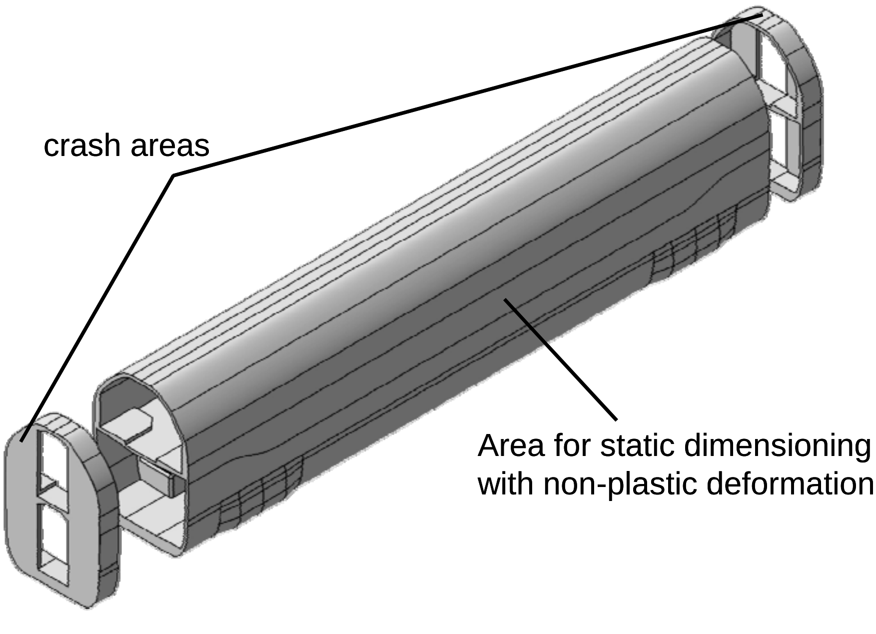

Figure 7: Contour for topology optimization

In order to give the topology optimization process adequate leeway for optimization, it is advisable to make the walls of the car body as thick as possible. For the calculation process, defined static forces according to (N.N. 2000), for instance are applied to the car body's basic body and, where appropriate, overlayed. During the process, areas of the car body's enclosure that are subject to no or little stress are weakened during iteration steps by way of localized material thickness reductions. The process continues until the previously defined termination criteria are achieved. This could be, for example, the maximum permissible stress or deflection. When the optimization is depicted, only those car body zones above a certain material thickness concentration will be displayed (Figure 8). The result is a seemingly bionic framework whose structure is pronounced only in the zones that are needed for fulfillment of the requirements.

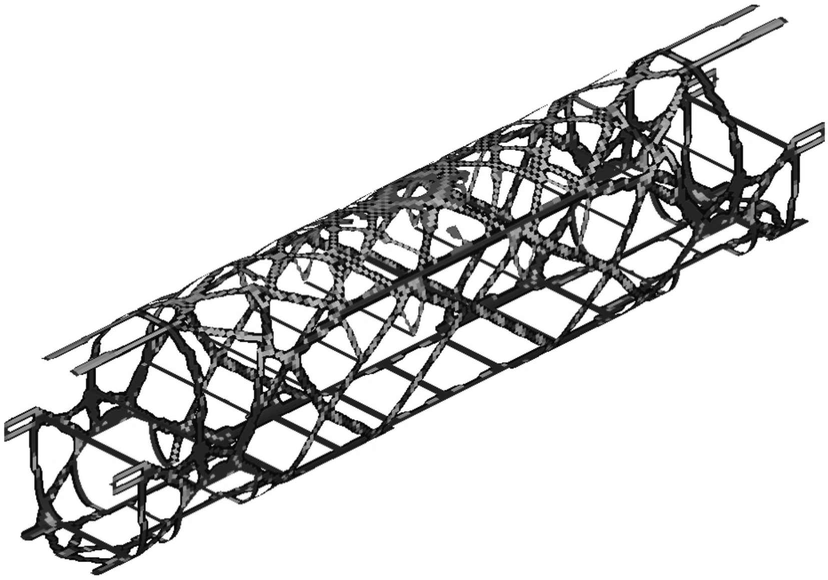

Figure 8: Topology-optimized car body

The resulting framework structure is then subjected to a FEM analysis in order to validate the optimization results. This proves that the structure satisfies the static strength and stiffness requirements. An interpretation based on the resulting stress distribution examines the relevance of the sub-zones of the created framework. From this is inferred which of the zones play a role in the overall context and which can be eliminated.

The resulting framework provides information on how an ideal structure should appear under the set conditions and target parameters. From this, we can draw conclusions for the design of the car body concept regarding where bearing structures, surface elements, or joints should be included. Nevertheless, the actual design implementation must reflect the practicality of things like suitable structural components, manufacturing capabilities, cost-effectiveness, and joining technologies.

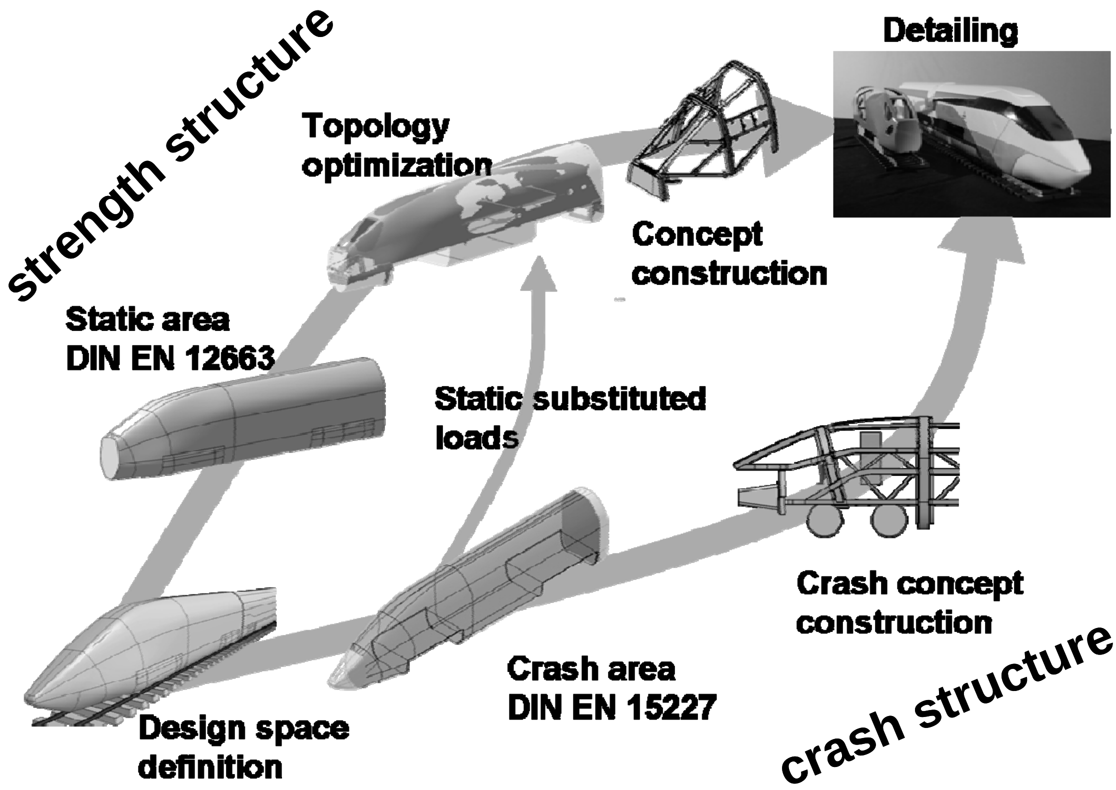

Figure 9: Methodical procedure in principle

5 NOVEL LOAD BEARING CAR BODY STRUCTURES

Based on the solutions of the topology optimization as well as basic conditions and requirements the Institute of Vehicle Concepts develops novel lightweight structures and car body concepts. It was financially supported by Bombardier Transportation, Division Passenger. The car body must resist different load cases in vertical and longitudinal direction as well as forces resulting of torsion and bending loads. Considering the topology optimization a car body structure was created. It is a self supporting bending and torsion proofed comb tube (Figure 10). The car body structure is made of 3-D cranked bulkheads and sole bars which are trough going. The cranked bulkheads consist of vertical and horizontal beams as well as diagonal beams. The sole bars are proper to mount the longitudinal forces. The vertical and horizontal beams bear the vertical forces. They and the sole bars are connected with diagonal beams. These beams carry the loads and split them in the adjoining beams and sole bars. The diagonal beams are positioned in the window areas of the two carriage levels. Therefore they are predestinated to transmit shear stress and the longitudinal and vertical forces. Against the requirements the beams and sole bars can be made of aluminum, steel or pultruded fiber reinforced plastics. The connection of steel and aluminum beams and sole bars can be made by welding. Another possibility is the use of separate designed node connections. The respective beams can be suited regarding their stiffness, wall thickness and geometry. According to the result of the topology-optimization the performances of the beams of the bulkheads can be adapted regarding the local internal loads. The principal outline is identical of the beams and the bulkheads along the car body. Therefore a scalable car body in longitudinal direction can be realized.

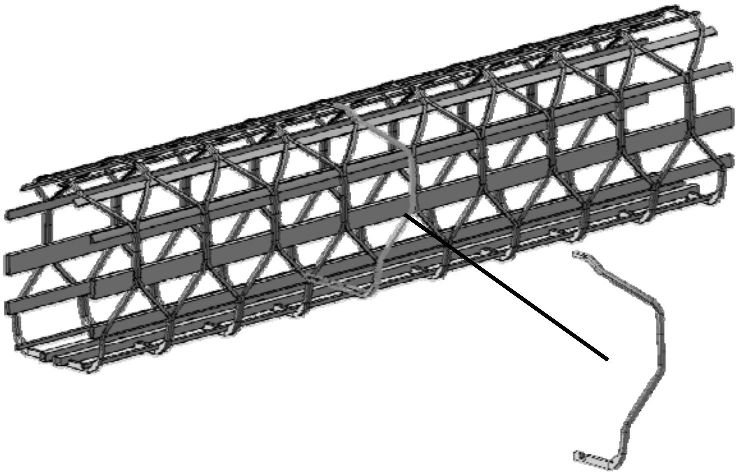

Figure 10: Weight optimized and self supporting bending and torsion proofed car body structure

6 SUMMARY

The reduction of vehicle mass has primary effects on energy saving and reduced axle loads. In addition there are secondary effects like the reduction of the rail damage or an adaption of the superstructure according to the axle loads. Furthermore the train concept can be modified and proved regarding the requirements as a result of weight saving.

The carriage can be divided in main assemblies in which the car body structure takes a key role. It influences manifold parameters and subassemblies. Based on these, lightweight construction of the car body is particularly important. One method of reducing the weight of car bodies (through the use of topology optimization) was described, whereby the main load paths for the static-designed car body zone were determined. The resulting framework structure points towards an economical and weight-saving design while reflecting an optimized flow of forces.

Considering the results of the topology-optimisation a novel car body structure was conceived. It is a self supporting bending and torsion proofed comb tube with significant improvement of the performance.

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