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High potential: lightweight optimised structural design of car bodies for railway vehicles with alternative drive systems

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Abstract

Climate change and related goals and measures require a shift away from fossil fuels as an energy source. One solution for non-electrified lines for rail transport is the use of alternative drive technologies such as battery or hydrogen drive instead of diesel units. In order to use these efficiently in rail vehicles, it is imperative to make adjustments to the body structure. Existing car body structures must be adapted to integrate the space-intensive and heavy additional equipment components. Within the framework of the project AnoWaAS those with the highest lightweight construction potential are methodically identified from a large number of different derivatives of car body designs. The high influence of a force flow-compliant design on the lightweight potential is analysed in depth. Possible adapted construction methods for further exploitation of the lightweight potential are shown and analysed with regard to their potential. With the help of trapezoidal windows and the structural integration of equipment enclosures, it is possible to reduce the structural mass of a car body by more than 20%.

Abbreviations

AnoWaAS	Project acronym for Adapted and optimized car body concept for alternative drive systems in rail vehicles
BMWK	Federal Ministry of Economics and Climate Action of the Federal Republic of Germany
CAD	Computer-aided design
DLR	German Aerospace Center
FE	Finite-element
FEM	Finite-elemente-method
MBS	Multi-body simulation
MMD	Multi material design
TRL	Technology readiness level

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1 Introduction

The accelerated climate change and the associated targets and measures also have an impact on the railway vehicle industry. As one of the largest global emitters of CO_2 and greenhouse gases, the transport sector, which includes rail-based transport, must also make a significant contribution to their reduction [1]. In the White Paper on the Future of Europe [2], the European Commission defined that in 2050 more than 50% of road freight over a distance of 300 km shall be transported by rail or waterways and that the majority of people shall use the rail system for medium-distance journeys. To ensure that these requirements can be met and that the rail system remains attractive in terms of sustainability, safety and availability, future railway vehicles must be as light, safe and energy-efficient as possible [3]. In Germany, 61% of the federally owned rail network is electrified, slightly more than the EU average of 54% [4]. Although the share in Germany is expected to increase to 70% by 2030, secondary lines will in perspective continue to be operated with vehicles that are independent of catenaries, so far mainly diesel multiple units. In order to reduce greenhouse gas emissions on these non-electrified routes, vehicles with battery, fuel cell and bimodal drives have been developed in recent years and are increasingly available on the market [5, 6]. A more sustainable use of the resources is inevitable to decrease the emissions caused by operations on these non-electrified lines. A turn to alternative drive technologies offer the opportunity to significantly increase the energy efficiency and thus to reduce the energy consumption. At around 40% to 50%, the efficiency of a fuel cell drive system is more than twice as high as that of a conventional combustion engine, and that of a battery vehicle is significantly higher at 60% [7]. However, alternative drive systems based on batteries and/or fuel cells (bimodal) have a much more space-intensive design. This leads to higher mass and thus a greater load on the car body. Furthermore, the first generation of these railway vehicles with alternative powertrains are based on a conversion design approach primarily adaptations of vehicles originally developed for diesel drive. The existing mechanical vehicle architecture and basic car body structure is largely adopted and is therefore not optimised for the changed boundary conditions caused by the alternative drive [8]. For example, Alstom's Coradia iLint, the first hydrogen-powered passenger train, is based on a conversion of the Lint54 diesel vehicle. Here, the diesel engines were replaced by asynchronous engines and the roof structure was reinforced to accommodate the hydrogen tanks and the fuel cell [9]. Like the other Flirt models from Stadler, the hydrogen powered Flirt H2, which is due to start passenger service in the USA from 2024, has a centre carriage in which the traction components are housed. There is no explicit adaptation of the supporting structure of the car body to the changed boundary conditions caused by alternative drive systems [10]. Safety aspects and increased loads from the components are absorbed by local adaptations to the body structure, but at the same time require an increase in mass, additional raw material consumption and increased manufacturing costs for the overall system.

Furthermore, the current production technology is already highly optimised and with all its support processes well-established. This makes it challenging to introduce lightweight construction innovations on an industrial scale. The integral construction method, which is preferably used in regional trains, is based on aluminium extrusion profiles. For these profiles, aluminium blocks are pressed through dies that represent the cross-section of a car body tube segment. These segments are extruded over the entire length of the vehicle, which is why the cross-section must always be adapted to the highest load that occurs. Local adjustments of the cross-section geometry over the running length of the individual extruded profiles cannot be made [11]. However, this economical production leads to the fact that the car body is globally overdimensioned and the ratio of energy consumption per payload kilogram is considerably lower than possible. Subsequently energy consumption and operating costs are higher than necessary. There are approaches to solving this problem in a number of research projects. Within the EU Roll2Rail project, car bodies have been optimised in terms of their lightweight construction using topology optimisation. Conventional car bodies are modified and adapted through local design measures in connection with material substitution. For this purpose, the positions and dimensions of the windows and doors were varied and it was shown that these cut-out geometries have a significant influence on the propagation of the force flows and thus the lightweight construction potential [12]. Winkler-Höhn et al. [13] have developed a fibre composite-intensive roof structure for a steel differential construction of a railway vehicle. Positions for the appropriate use of reinforcement profiles are determined on the basis of topology optimisations. Partial segments of this optimised roof structure were manufactured and tested on a test rig. A mass reduction of 18% was achieved, whereby the authors assume a possible mass reduction of up to 25% through further optimisations. The influence of topology optimisation on the possible mass reduction is also demonstrated by a topology-optimised freight wagon for goods trains [14]. The structural mass of the prototype in relation to the length can be reduced by a further 19.6% compared to comparable wagon bodies without impairing its dynamic running characteristics. What all current and past approaches have in common is that they have a low technology readiness level (TRL) or only partially pursue a comprehensive lightweight construction approach. In addition, in many cases there is no comprehensive consideration of the relevant system (integration of the drive components in the vehicle body, vehicle dynamic behaviour, etc.). These challenges are being addressed within the framework of the project AnoWaAS (Adapted and Optimised Car Body Concept for Alternative Drive Systems in Railway Vehicles), which is funded by the Federal Ministry of Economics and Climate Action of the Federal Republic of Germany (BMWK). By following a purpose design approach, the goal of this project is to develop a lightweight optimised car body structure adapted to alternative drive technologies. This has the largest possible installation space in order to be able to achieve the required range and comfort despite the space-intensive alternative drive components. The use of lightweight construction methods and materials and their interaction with the extruded aluminium profile construction is being investigated in this project.

2 Methodology

For the development of a corresponding car body structure, a methodology developed at the German Aerospace Center (DLR) [15] is applied and further developed with regard to the interconnection between multi-body simulation (MBS) and topology optimisation (Fig. 1). Here, a parameter-controlled shell model of a car body is built in computer-aided design (CAD), with which various derivatives of car body geometries are created. Through parameterisation, geometries and positions, such as window cut-outs or length of the low-floor area, can be varied quickly and efficiently. Subsequently, Finite-Element (FE) models are derived from the different derivatives of the car body geometry. The derivatives differ in terms of window geometry, sidewall extensions in the area of the underframe equipment, enclosures of the roof-mounted H_2 tanks, different door positions and transitions between the high-floor and low-floor areas. The loads applied correspond to the loads and load cases to be verified according to the standard EN 12663-1, whereby the relevant operating and exceptional masses are also implemented according to both the relevant standards and the real equipment components.

A mass analysis of all body structures is carried out in the subsequent step "Assessment", to achieve a body geometry that is optimised in terms of installation space and lightweight construction. In order to ensure comparability of the more than 120 variants examined and to determine the configuration with the highest lightweight potential, topology optimisations are first implemented with the aim of qualitative mass estimation. For this purpose, the stiffness required

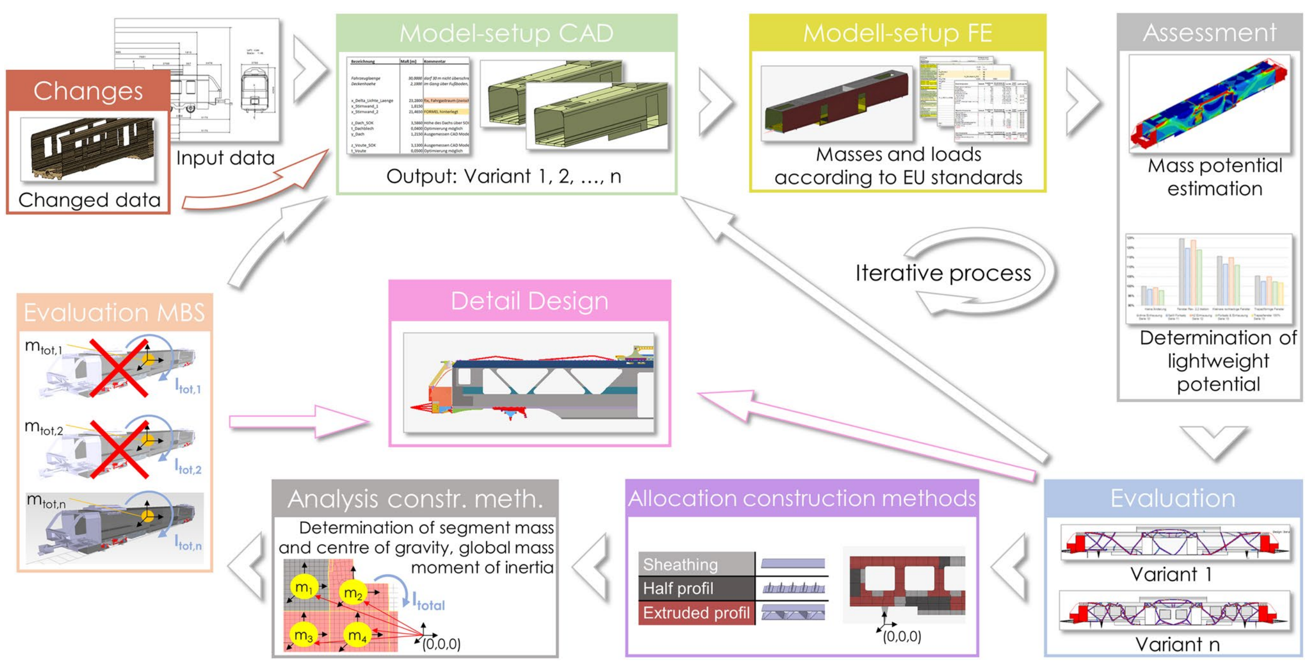

Fig. 1 Methodology of the design process for the evaluation of a lightweight railway car body

to fulfil the set boundary conditions is calculated for each element. The fictitious material density required for this is calculated via a linear relationship. Through the resulting theoretical mass distribution, a meaningful comparability with regard to the lightweight construction potential is possible despite different configurations. Constraints imposed by an algorithm or complexities due to forced force flows would distort ideal comparability. At the same time, the influence of the respective configuration on the total as well as component mass is evaluated. Conclusions can be drawn about the extent to which a change in geometry affects the individual areas, such as the sidewall, roof or floor. Due to its theoretical approach and rapid feasibility, this procedure is well suited for investigating a large number of variants and identifying the most promising ones in terms of low mass. Subsequently, the variants with the highest lightweight potential and the most optimal packaging of the components are analysed in more detail with regard to their structural characteristics. In this way, areas subject to lower loads can be specifically identified. In these areas, the structural properties of the conventional extruded profile design with constant wall thicknesses over the entire length of the car body are not necessary. At these points, it is possible to deviate from the structural point of view with regard to the construction method. Furthermore, the force flow through a car body can be directed in such a way that the potential of less stressed areas can be utilised in the best possible way. In this work, Chapter 3.1 looks at the results of the steps "Model setup in FE" and "Assessment". The following chapters 3.2 and 3.3 analyse the results of the "Detail Design" in more detail. The step "Evaluation" forms the bridge between the two chapters and the results are therefore included in both chapters. The results of the ideal but theoretical topology optimisation could further transferred into real, feasible structures or construction methods by means of a segmented evaluation of the car body. This segmentation methodology and the associated MBS are not considered further in this work, but the individual steps are nevertheless mentioned here. In this way, real masses, centres of gravity and mass moments of inertia are assigned to the hitherto exclusively theoretical findings. An early integration of vehicle dynamic investigations by MBS in the conceptual phase is made possible and unfavourable vehicle dynamic behaviour can be counteracted from the beginning in the body shell [16]. A car body geometry that meets both the dynamic and (quasi-) static loads and at the same time has the highest possible lightweight potential is essential, especially due to the heavy and space-intensive equipment components in alternative drive systems for railway vehicles. After selecting the configuration with the highest lightweight potential under the given boundary conditions, the shell model is transferred to a detailed design and analysed. Causes for occurring problem areas can be identified on the basis of many theoretical preliminary investigations and can be eliminated with the knowledge of these.

3 Results of the systematic studies

3.1 Theoretical lightweight potential of structural changes

Dimensions and masses of a railway vehicle on the market, which was scaled to 30 m, serve as a reference vehicle for the investigations of the influence of various adaptations. The detailed vehicle provided was abstracted and features interfering with the force flow (window and door cut-outs, etc.) were removed. The results of a qualitative topology optimisation of the reference vehicle serve as a basis on which the further adjustments are based and thus the influence of each individual measure is quantified. The (quasi-) static load cases were applied to the vehicle in accordance with EN 12663-1 [17], whereby the masses were taken into account in accordance with EN 15663 [18]. These include static

Table 1 Possible average reduction of the theoretically required ideal structural mass

Structural change	Mass reduction (%)
One door shifted towards the centre	– 1.8
Both doors shifted towards the centre	– 2.1
Rounded sidewall to roof transition	– 4.7
Round sidewall to roof transition	– 7.0
Sloping transition	– 1.4
Sidewall extension	– 1.9
Roof housing	– 0.5
Sidewall extension and roof housing	– 2.4

longitudinal loads, quasi-static acceleration loads and various lifting loads that lead to torsion of the vehicle body. Table 1 summarises the findings and averaged mass saving potentials from the (quasi-) static investigations compared to the reference vehicle. The tilting, the derailment safety and the superstructure load of the railway vehicles must be considered from the beginning and unfavourable behaviour must be eliminated by adjustments. A close link with the vehicle dynamic design is therefore necessary for lightweight optimised vehicles. Various vehicle variants were analysed with the aid of the MBS and on the basis of EN 14363 [19]. The comfort assessment was carried out in accordance with EN 12299 [20]. These results were in turn fed back to the theoretical considerations in order to rule out unfavourable behaviour of the rail vehicle due to an unfavourable arrangement of the components and the structural centre of gravity at an early stage. A detailed analysis of the results within the project can be found in [21] and will not be explained further here. Furthermore, it should be noted that the changes shown and their mass-saving potential cannot be directly superimposed. Careless superimpositions can lead to an increase in mass. Due to the idealised car body without constraints and the consideration of the body-in-white mass incl. the non-optimised head structure, the relative figures are only low. A modification with a possible mass reduction of more than 1% can therefore be considered a significant influencing factor.

Due to the given load introduction and boundary conditions, like maximum deformation of relevant nodes, a bridge-like structure is formed in the middle of the vehicle. If the door cut-outs are pushed into this low load area, the force flow can be almost ideal compared to the original position. Moving one or both door cut-outs towards the centre reduces the mass of the necessary load-bearing structure by more than 2% in some cases and is considered a significant influencing factor. However, due to the given boundary conditions (toilet for persons with reduced mobility and space for a wheelchair user), these modifications could not be implemented. A rounded or completely round transition between the roof and the sidewall instead of a flat transition allows the force flow to be guided without interruption and saves 5–7% mass compared to a square transition. It must be considered that a round transition provides more space in the interior, but conflicts with the loading gauge are possible with a corresponding roof height. By chamfering the previously right-angled transition between the high-floor and low-floor areas, the force flow is improved, thus reducing stresses and, considering the boundary conditions set here, a mass saving of up to 2% of the car body is possible.

Structurally supporting extensions, which serve as connecting elements of the equipment, have a high potential for lightweight construction and functional integration. Both a structurally supporting sidewall extension in the area of the transition between the high-floor and low-floor area laterally over the underfloor components and a structurally supporting enclosure in the roof area above the H_2 tanks were qualitatively and quantitatively investigated and evaluated (Fig. 2). The results show that a sidewall extension allows a more undisturbed and thus more homogeneous force flow from the sidewall into the underfloor structure (Fig. 2, variant 2 and 4). Main load paths must be strongly dimensioned due to their load-bearing function. Therefore, it makes sense to direct the mass of the underfloor equipment into a strongly dimensioned structure such as the sidewall extension. In this way, an additional structure in the floor can be avoided and

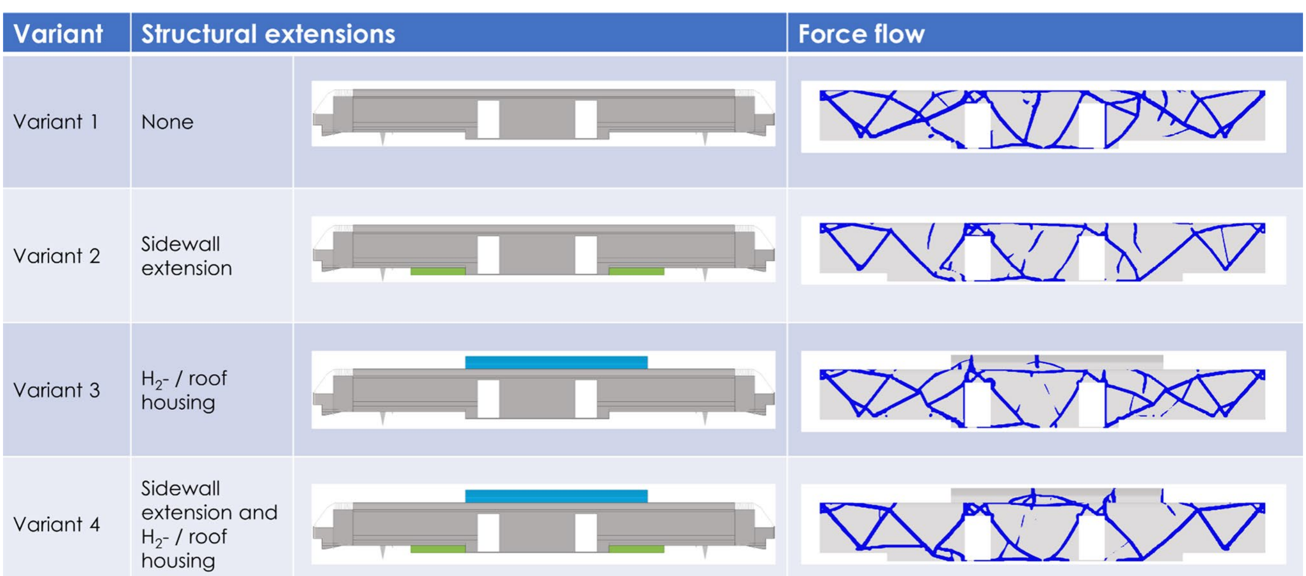

Fig. 2 Overview of different variants with structurally supporting extensions and their influence on the force flow

further mass savings in the floor area are possible. Furthermore, the sidewall extension can absorb the inhomogeneity and disruptive effect of window cut-outs on the force flow and reduce the ideal mass by up to 4%.

For a fuel cell multiple unit, more space-intensive powertrain components (H_2 tanks, fuel cell) are required than for a conventional one. In order to achieve the required ranges, the roof must be modified. On the one hand, the roof must be lowered in the low-floor area, at the location of the H_2 tanks, in order to comply with the loading gauge, and on the other hand it requires a functional connection to the tanks. The investigations show that an integration of the H_2 tanks into the supporting structure of the car body is advantageous. A bridge structure with up to three transverse frames is formed by a co-supporting enclosure during the topology optimisation, which leads to a relief of the highly stressed areas around the doors (Fig. 2, variant 3 and 4). Through the targeted use of ring-span-like structures around the entire body and stringers in the area of the H_2 tank enclosure, a hull skeleton is formed and the body is sufficiently stiffened despite the weakened area. Although the direct mass saving potential of 0.5% is comparatively low, the roof structure allows the low-floor area to be kept almost force-free, creating a large low-load area which leads to secondary mass savings, since other materials can be used. The two additional load-bearing structural elements ensure a more undisturbed force flow and a focusing of the load paths, creating larger low-load areas where the structure can be slimmed down without disadvantages. Large lightly loaded areas are important for the transformation of theoretical results into real manufacturable structures. In the theoretical mass estimation by means of topology optimisation, these areas have no structures and thus no mass. In real structures, however, they must be realised in a construction method just like the rest of the car body. If the areas are too small, the Multi Material Design (MMD) approach may not be feasible. MMD means that the car body is made from an intelligent combination of different materials. Depending on the task and the requirements of the structure, a material is used that fulfils both and at the same time builds the lightest.

3.2 Force flow optimised design

In order to validate the design in line with the load flow, a detailed car body based on an existing train of the consortium partner Alstom with the required equipment was constructed in CAD as part of the project on the basis of the conventional configuration and calculated in HyperWorks using the finite element method (FEM). This car body serves as a reference car body. Based on this, the structural modifications listed in the following section were then carried out. This allows a direct comparison of a conventional car body with the potential of the various structural modifications. All the numerical results of the stresses listed are calculated and presented within the project on the basis of the "von Mises" – equivalent stress.

The changed mass distribution and necessary modifications in the area of the roof structure due to the alternative powertrain as well as the set boundary conditions lead to two challenges with an unchanged model. On the one hand, the lower door corners of the passenger compartment are very close to the transition from low-floor to high-floor area. This area is heavily stressed due to the force flow deflection and is further weakened by the large door cut-out. On the other hand, the areas around the window corners in the analysed model of the project are more than twice as stressed at 359 MPa compared to the tolerable stress of 173 MPa. Adjusting the cover plate thickness within the framework of the project from the standard 2.5 mm to up to 6.0 mm of the extruded profile cross-section at corresponding points reduced the stresses to 222 MPa (Fig. 3). Due to the locally necessary adjustment, the mass is increased globally by 5%. Nevertheless, the local stresses were not completely shifted into the subcritical range.

The above theoretical findings were implemented in the detailed design, which was improved to a force-flow-optimised design. In addition to accommodating the underfloor mounted equipment, the sidewall extension also allows for a significant reduction of stresses in the area of the critical corners at the passenger compartment doors.

Conceptual investigations showed a significant influence of large-area cut-outs on the force flow and thus the lightweight potential. The previous rectangular window cut-outs increase the mass by 20–25% compared to the windowless reference car body depending on the variant investigated. The structurally necessary mass can be further reduced by larger free spaces for the force flow. In this study, a 15% reduction in window area reduced the structural mass by 7%, although this is at the expense of passenger comfort. This is contrasted by force-flow-adapted geometries of the windows. In an undisturbed sidewall and considering the structural attachments, the topology optimisation results in a cross-shaped force flow with a slope of the load paths of about 45°. Boundary conditions, such as the length of the car body and the position of the bogies, have an influence on the force flow and thus on the slope of the crossing diagonal elements (Fig. 4a). Uniform window cut-outs in the form of trapezoids adapted to the force flow enable a reduction in mass of 15% compared to the original rectangular windows with the same window area. In relation to the windowless reference car body with ideal mass distribution, the necessary structural mass is increased by only 1.8% despite strong

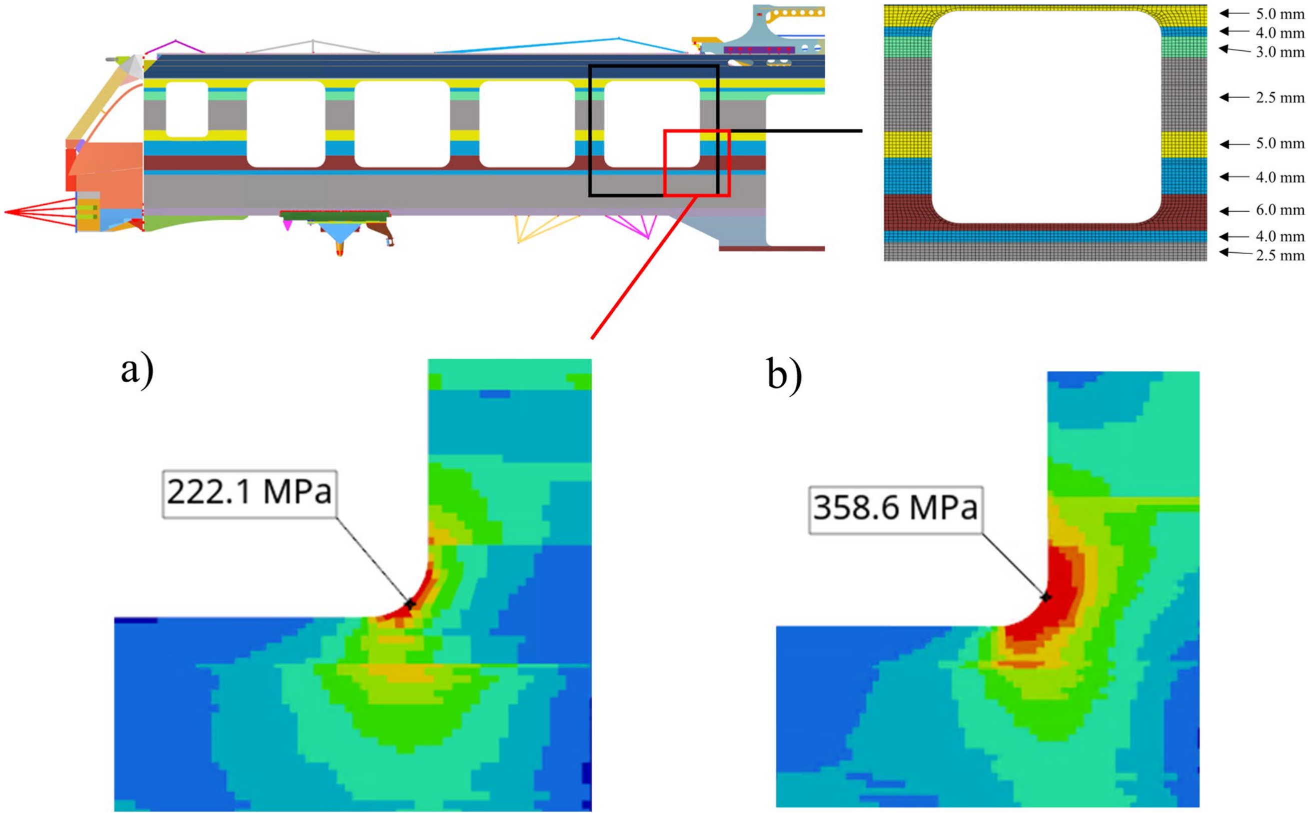

Fig. 3 Stresses of the investigated critical window corner. **a** With adjusted cover plate thickness, **b** with a cover plate thickness of 2.5 mm of the extruded aluminium profile

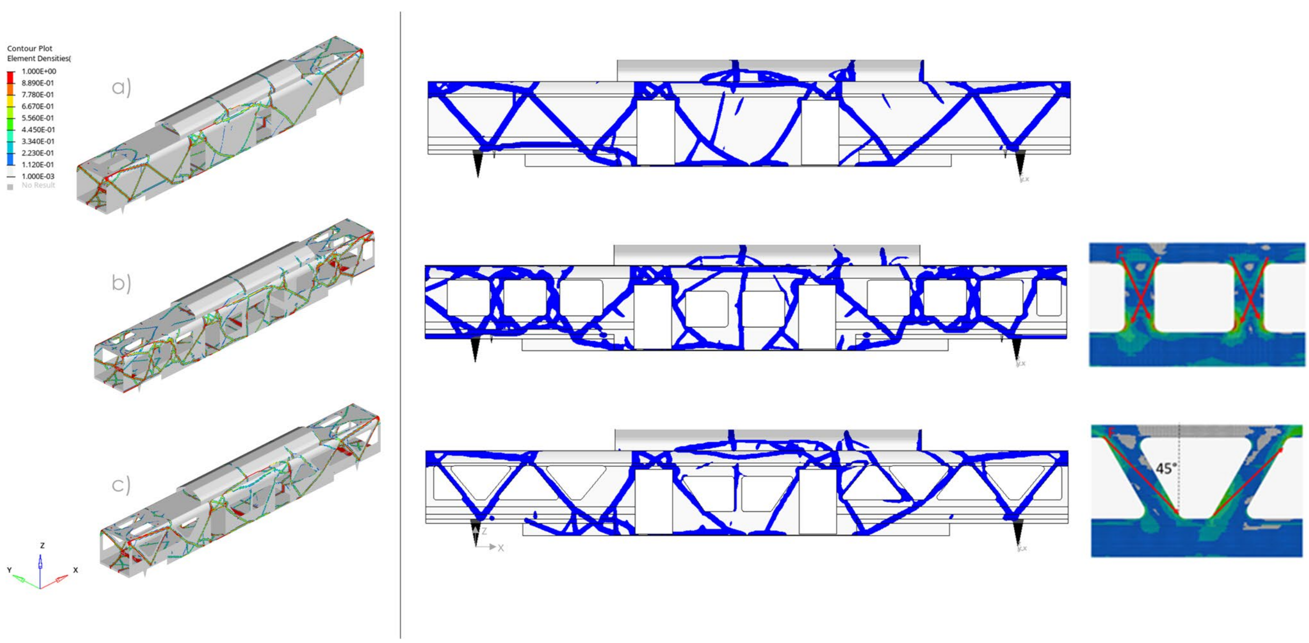

Fig. 4 Force flow through a car body (**a**) without window cut-outs, (**b**) rectangular window cut-outs, (**c**) force flow adapted window cut-outs with a slope of 30°

intervention in the possibility of structural formation. This high effect of the window geometry correlates with literature values, which show a theoretical mass saving of 10.3% with trapezoidal windows for the body of a metro [12].

The findings from the investigations on the window geometry in this work also explain the high stress peaks at the window corners and contribute to their solution. The conceptual investigations showed that the force flow runs at a 45° angle regardless of the extrusion direction of the profile. When the window strut is oriented vertically, the force flow is redirected and tries to regain its natural 45° inclination within the strut (Fig. 4b). This creates the characteristic cross structure of the force flow in the window strut. This ensures that the force flow is forced to exit again at the opposite window corner, which is why the stresses are concentrated there. The natural orientation in the 45° angle can also be seen in adapted window geometries, which are only inclined by 30° (Fig. 4c).

The investigations in this work show on the basis of the above-mentioned virtual reference car body that a force flow adapted window geometry significantly reduces the stress peaks at the window corners and thus enables a high lightweight construction potential. In Fig. 5 the two window geometries are compared. The basic geometry of the car body remains the same for all variants.

The reference car body (Fig. 5a) has been slightly revised to meet the requirements but still has rectangular window cut-outs (Fig. 5b). These two variants only differ in the thickness of the cover plates, which were adjusted in accordance with Fig. 3, and the driver's door, which was converted into a window due to changed boundary conditions. For the car bodies with trapezoidal window cut-outs, only the cut-out geometry and the driver's window were changed. Due to the design adapted to the force flow, the width of the window struts for the trapezoidal windows can be reduced by 70% from 450 to 132 mm without critical stress peaks occurring at the window corners or struts. Two local adjustments were made to the side wall geometry in order to eliminate the last minimal localised excess stresses in the area of the second strut from the left. The cover plate thickness of the extruded profile was increased from 2.5 mm to 3.0 mm in the specified area for Fig. 5c. In Fig. 5d, the cover plate thickness of the extruded profile remains at 2.5 mm over the entire side wall and only the critically loaded window strut was increased by 50 mm in the x-direction to 182 mm. The window struts with force-flow adapted cut-outs are more homogeneously loaded and local stress concentrations occur only to a small extent compared to the conventional rectangular cut-outs. Increasing the cover plate thickness in corresponding areas from 2.5 mm to 3.0 mm eliminates the critical stresses (Fig. 5c). At the same time, the mass of the sidewall increases by 0.5%. This corresponds to one tenth of the mass required for rectangular cut-outs. Whereas, as explained above, even then supercritical stresses continue to occur with rectangular window cut-outs. Another measure that influences the

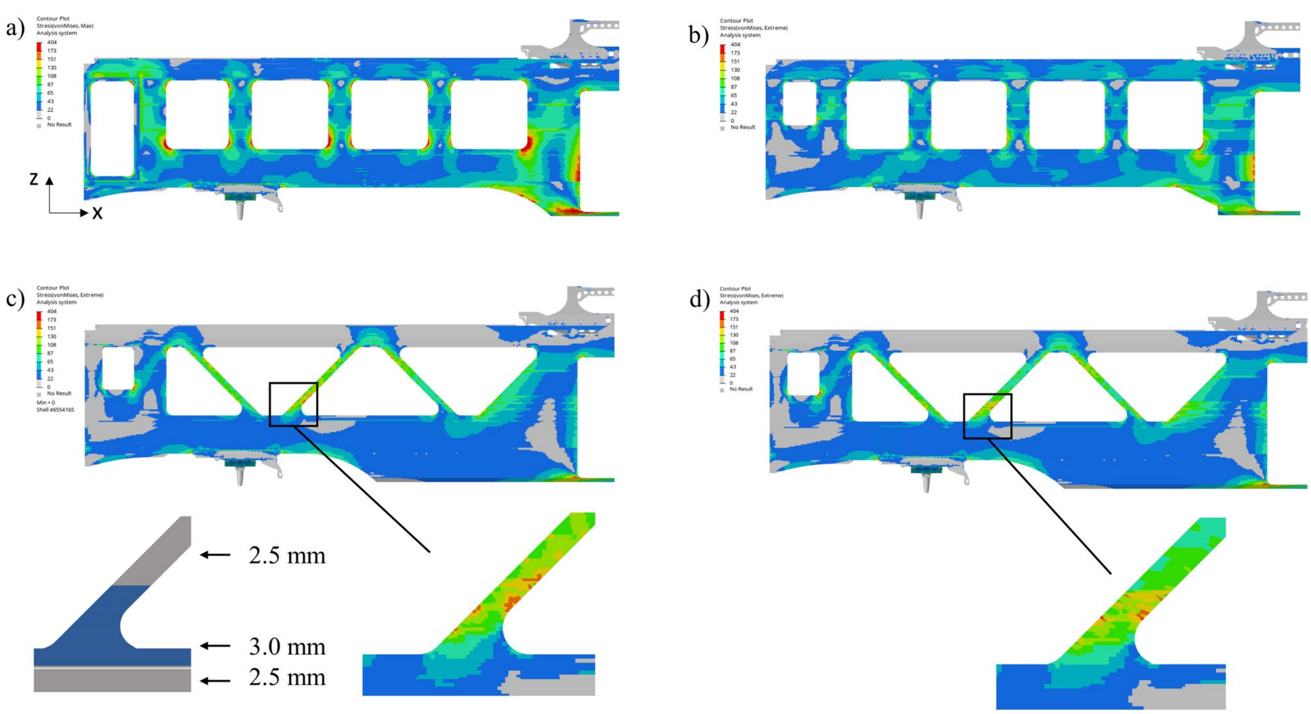

Fig. 5 Comparison of the influence of the window geometry on the stresses. Rectangular window with (**a**) 2.5 mm (**b**) up to 6.0 mm outer sheet. Trapezoidal window with (**c**) a partially outer sheet of 3.0 mm and (**d**) a 50 mm wider strut

mass to an even lesser extent would be to widen the critically loaded struts by 50 mm in the x-direction (Fig. 5d). This would increase the mass of the entire sidewall by only 3.3 kg (0.1%). On the other hand, the outer appearance of the car body would be less uniform.

As mentioned above, a sidewall extension according to the theoretical findings in Chapter 3.1 reduces the stresses in the critical areas (e.g. the corners at the passenger compartment doors). Furthermore, this sidewall extension reduces the maximum deflection, as it stiffens the car body structure as a whole (Fig. 6). In addition to this, the cut-out geometry reduces the deflection of the entire system, including the sidewall extension, by a further 12.5% (Fig. 6). This is due to the fact that the inclined struts provide stiffening in the z-direction of the car body and thus counteract the deflection. Due to the possibility of slimming the window struts and at the same time alleviating the local critical stress in the area of the window corners, the window area can be increased by 11% under the given boundary conditions. Further sensible and economical adjustments to the window geometry and the maximisation of the window area are currently being investigated. By adapting the window geometry, the mass is reduced by 8.4% compared to rectangular window geometry due to the unnecessary reinforcement of the cover plate. Moreover, the comfort for the individual passenger is increased due to the increased window area.

3.3 Targeted construction methods modifications

As shown above, a force flow optimised car body design enables for a high lightweight potential with the same construction. However, it is shown that the car body is still globally overdimensioned. Based on the design optimisations, the potential of construction modifications and the use of MMD structures was systematically investigated. Initial assessments were made qualitatively at the conceptual level. Targeted modifications were then analysed for a robust quantitative comparison in the detailed design.

The results of the conceptual topology optimisation showed a roof structure that was characterised by structures running in the y-direction, between which less loaded areas were formed. By shifting the connection of the equipment

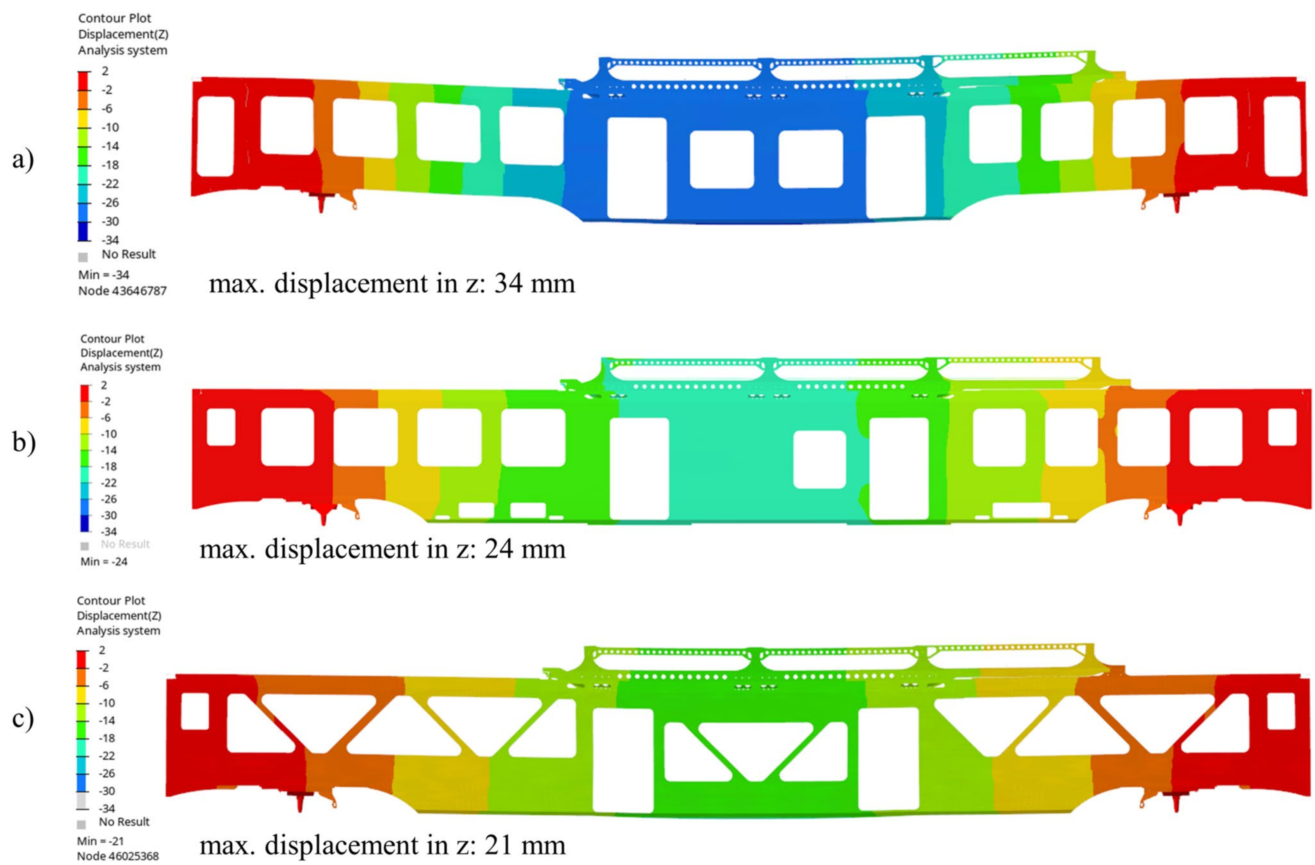

Fig. 6 Displacement of the car body for exceptional payload in z, (**a**) without any changes, (**b**) with sidewall extension, (**c**) with force flow optimised windows and sidewall extension

units to the outside of the roof area, the load flow can be concentrated on a few cross struts. The intermediate areas are thereby kept largely free of force flow and thus less loaded. Thus, the use of lightweight construction methods is made possible. Sandwich materials with a 1 mm thick aluminium top layer and a PET foam proved to be effective. Due to the adapted construction method in the MMD, the mass of the roof structure could be reduced by 28.5% compared to the conventional aluminium extruded profile construction method. The insulation function is integrated into the load-bearing sandwich structure, which saves a further 2% of the mass compared to the reference vehicle.

In contrast, a sandwich construction in the underfloor area proved to be unsuitable. High through loads, which are introduced into the floor by the coupling connection, the connection of the bogies and the loads from dead weight and payload lead to a high load on the floor segments. Due to the breaking up of the continuous structure and the necessary welding seams for the integration of the sandwich structure, the floor structure is additionally reduced in its load capacity. Critical local stress concentrations occur due to the force redirection from extruded profile to sandwich structure. The sandwich structures investigated could not withstand these loads.

The investigations also showed that a use of sandwich in the sidewall of the high-floor area would not be effective. Due to the window cut-outs and the introduction of forces through the bogies, load-bearing structures with high load-bearing capacity are indispensable. Although there are a number of areas subject to lower loads, these are only of small dimensions. Many welds would be required and would further reduce the load-bearing capacity of the structure. A sandwich structure also requires a bonded aluminium frame profile due to the sealing against environmental influences and the weldability to the adjacent structure. The added value in terms of mass savings is too low compared to the high costs and manufacturing effort. In order to exploit the lightweight construction potential of these areas, a targeted weakening of less stressed areas was therefore investigated by means of removal processes (milling out). Milling out low-stress areas does not require any weakening welding and can be controlled with millimetre precision in any spatial direction with the aid of CNC milling machines. In this way, it is possible to mill out inner cover plates of the extruded profiles as well as parts of the ribs with millimetre precision. These milling operations can be carried out according to the results of the topology optimisations. On a conceptual level, a possible mass reduction of the sidewall in the high-floor area without loss of the load-bearing properties of 9.4% was determined. In the detailed design, the low-floor area is also milled out over a large area. Compared to the concept phase, however, due to the above-mentioned modifications in the roof, the sidewall is much more heavily loaded and is the main load-bearing unit of the car body. Overall, the mass of the sidewall is nevertheless reduced by 8.1% with over 300 kg. Figure 7 shows the milled-out areas of the detail design for a car body with conventional rectangular window cut-outs. The associated calculation based on the FE-method of the model confirms the basic feasibility of this design modification of a load-bearing structure. In addition, two points should be mentioned. Firstly, despite significant weakening, the sidewall structure in the low-floor area is only slightly loaded. The load on the roof-frame construction in the low-floor area, however, is higher compared to the rest of the frame construction. This reflects the results of the previous topology optimisations. A frame structure for enclosing the H_2 tanks enables a bridge structure to be formed which at the same time relieves the low-floor area. Larger window cut-outs and thus more comfort for the passenger could thus be realised. Secondly, a higher but still subcritical load can be seen in the milled-out areas

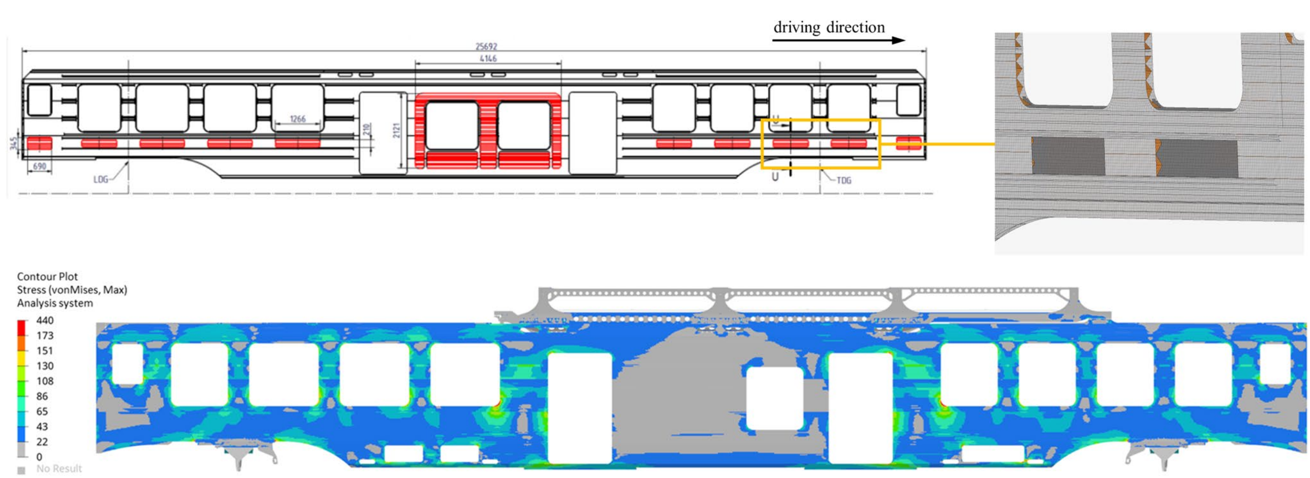

Fig. 7 Targeted milling of the extruded profiles. Top in red: areas to be milled out incl. detailed view; bottom: results of the calculation

of the high-floor area compared to the non-milled-out structure. The load propagation shows diagonally running structures correlating with the findings from force-flow-adapted windows and thus underlines the advantage of force-flow-adapted cut-out geometries in railway car bodies.

If the optimisations and modifications are considered with regard to the variants with the rectangular windows and compared with the reference model, the lightweight construction potential of railway vehicle car bodies becomes apparent. In relation to the mass per metre, the car body mass could be reduced by 15.8%. The use of trapezoidal windows without further adaptations reduces the structural mass per metre to 18.2%. If the potentials of the force flow-adapted window geometries are also considered and implemented, a mass reduction of more than 20% can be assumed due to unnecessary reinforcing elements and a homogeneously utilised structure and thus a higher potential for milling out.

4 Conclusion

As part of the research project AnoWaAS (Adapted and Optimised Car Body Concept for Alternative Drive Systems in Railway Vehicles), a car body was developed that considers the requirements of alternative drive systems and at the same time is up to 20% lighter than conventional car bodies. Structural changes were qualitatively investigated in a first step and target-oriented solutions were implemented directly in the detail design. In a second step, the detail design was modified with further findings from the concept phase and a quantitative comparison of the various modifications was made.

Large cut-outs have a decisive influence on the mass of the car body. Compared to conventional rectangular window cut-outs, fewer and smaller critical local stress concentrations occur. In order to eliminate these, very limited local measures are required and the mass is increased only by 0.1%. Rectangular windows, on the other hand, require a structural reinforcement that requires a 5% higher mass. Critical areas are nevertheless not completely eliminated and further modifications (e.g. additionally welded-in milled parts) are necessary. Overall, an increase of 11% in the window area of force-flow-adapted windows with a simultaneous reduction of 8.4% in the mass and a reduction of 22% in the deflection compared to rectangular windows is possible. Structural attachments can reduce the mass of the overall system as they give more freedom to the force flow and thus relieve critical areas and counteract deflection. Furthermore, large areas of less stress are generated in which the conventional oversized construction can be replaced by MMD or adapted construction methods. However, the use of sandwich materials or MMD is only partially effective in this work. While the mass of the roof can be reduced by 28.5% by replacing the conventional extruded aluminium profile construction with a sandwich construction in the roof area, the use in the side wall is not expedient. Particularly in the case of rectangular windows, but also in the case of trapezoidal windows, the possible areas for the economical use of sandwich components are too small in this particular case, which is why other adaptations in terms of mass reduction (such as milling) are preferable here. The mass of the sidewall could thus be reduced by 8.1%. Overall, the research project showed that a reduction in structural mass per metre of up to 18.2% is possible with an adapted car body design compared to the reference vehicle, with further potential currently being investigated.

It is recommended that future developments of railway car bodies and their construction methods be even more strongly oriented towards the theoretical force flows in order to exploit the lightweight construction potential and the associated energy and resource efficiency.

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Data availability The data sets created as part of the work are available on reasoned request from the corresponding author. The data sets of the topology optimisations are available from DLR, the detailed calculations from Hörmann Vehicle Engineering GmbH. However, the availability of this data, which was used for the current work, is subject to restrictions and is therefore not publicly accessible.

Code availability Not applicable.

Declarations

Competing interests Not applicable.

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