Impact of normative loads and conventions on car body weight and structure for a rural rail vehicle

Christian Gomes Alves[1,*], Thomas Müller[1] and Dr. Jens König[1]

[1] *German Aerospace Center, Institute of Vehicle Concepts, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany*
[*]*Corresponding author. christian.gomesalves@dlr.de*

ABSTRACT

Lightweight design in rail vehicles is crucial for enhancing energy efficiency, reducing operational costs, and lowering greenhouse gas emissions. This paper presents an overview of the key structural considerations and design principles involved in the early mechanical design of the car body of a small regional vehicle developed as part of the Horizon Europe Project "FutuRe". The project aims to create a lightweight, two-axle rail vehicle for rural Europe, with a maximum weight of 32 tons. The design process employs a comprehensive methodical lightweight design approach, including topology optimizations to estimate and minimize the structural mass of the car body and gain insights into its optimal structural design. The results indicate that longitudinal loads for different load categories from EN 12663-1 have minimal impact on the car body's structural weight. Furthermore, the location of heavy equipment like batteries has a negligible impact on the structural car body mass as well, featuring similar structural results. The findings suggest that normative boards should revaluate the necessity of distinct longitudinal loads for car body development.

1. INTRODUCTION

Lightweight design in rail vehicles is essential for enhancing energy efficiency, reducing operational costs, and lowering greenhouse gas emissions. It improves performance in terms of acceleration and braking while maintaining safety. Additionally, lighter vehicles can carry more passengers or cargo, increasing the overall capacity and efficiency of the rail network, which is

crucial for sustainable urban mobility. The mechanical design of a train car body plays a crucial role in ensuring the safety, efficiency, and sustainability of rail transportation systems. As one of the most visible and essential components of a train, the car body must withstand various environmental conditions, including high and low temperatures, vibrations, impacts, and provide structural integrity for operational loads, exceptional loads as well as crash while also providing a comfortable and secure ride for passengers. Bringing together these manifold topics is possible with an insight-driven lightweight design approach.

This paper presents an overview of the key structural considerations and design principles involved in the early mechanical design of the car body of a small regional vehicle which is developed as part of the Horizon Europe Project "FutuRe" and has the target of a lightweight optimised vehicle. In this project, a small, lightweight two-axle rail vehicle is developed for rail traffic in rural Europe. The maximum vehicle weight, fully loaded, is limited to 32 tons to reduce strain on the superstructure of the lines (Persson et al., 2024).

A comprehensive methodical lightweight design approach is used to develop and evaluate different arrangements and geometries for the car body. As part of the process, normative conventions for the car body design approach will be challenged. This paper will detail the approach taken to generate car body topology optimizations and interpret the results to generate a structural car body proposal.

2. METHODOLOGY

The design process for the car body entails comprehensive use of topology optimizations (TO) with two objectives: 1) estimate (and minimize) the minimal structural mass of the raw car body; 2) Gain insights into how to best structurally design the car body (conceptual lightweight design approach).

2.1 TOPOLOGY OPTIMIZATIONS FOR CAR BODY DEVELOPMENT

The mechanical architecture of the car body is analysed using topology optimizations. TO is a mathematical and computational method used to determine the optimal material distribution within a given design domain, subject to constraints like structural performance, weight, and functional requirements. The goal is to achieve the best possible design by maximizing desired

properties - such as stiffness and/or strength - while minimizing material usage. The process relies on advanced numerical methods (FEA) to iteratively refine the material layout based on specific optimization criteria.

The key principle behind TO is the reduction of non-load bearing material while maintaining or enhancing the structural performance of a system. For every finite element, it defines the optimal stiffness/strength properties by considering the overall model requirements like defined stiffness and minimal mass of the complete structure.

2.2. RESEARCH OBJECTIVE AND APPROACH

As part of the early development process for the small regional vehicle, two main simulation types will be used to identify properties of the small regional vehicle:

- Structural mass analyses (result = virtual structural mass of car body)

    o Influence of battery configurations on minimum structural mass: Determine a virtual, theoretically achievable minimal structural mass

    o Parameter sensitivity: influence of constraints and loads on structural mass: Determine the influence of important forces and constraints on the mass

- Structural TO analyses (result = material distribution in car body)

    o Influence of load category on structure: Analyse the effect of different load categories from EN 12663-1 on the structure

    o Influence of battery configurations on structure: Analyse the effect of battery mount locations on the optimal material distributions and load paths in the car body structure.

By performing these analyses, it is possible to gain a fundamental understanding of how the normative and assumed loads and boundary conditions influence the car body structure. As an additional secondary objective, the effect of different normative load categories on car body mass will be identified.

2.3 NORMATIVE LOADS ON CAR BODIES

The European normative system provides several norms defining load scenarios and boundary conditions on a car body. Some of these loads were defined in the mid-early 1900s and their origins cannot be verified any more (Malzacher & Mohr, 2019). Studies performed by Schmauder et al. (2022) have also shown that some of the normative longitudinal loads seem to not have a significant impact on the estimated car body mass for a typical main-line rail vehicle, instead identifying the weight force as the major factor to increase stresses (and consequentially the structural weight during a TO). They conclude that EN 12663-1 dictates considering redundant load cases which make the design of railway car bodies inefficient. As part of the car body development in this paper, the effect of normative longitudinal loads on a small rail vehicle will also be researched. The relevant norms used in the topological analyses are listed in Table 1.

While EN 13749 defines loads on bogie frames, some of these loads are introduced to the car body as well and need to be considered in the TOs. For crashworthiness, EN 15227 is not specifically considered as only static loads can be applied in TOs. Furthermore, the longitudinal loads from EN 12663-1 already apply static loads to the crash absorbers.

Table 1 mentions that several norms use vehicle/load categories (use cases) for characterizing the assumed loads on a rail car. These load categories play a major role for the car body development. They are defined as P-I through P-V, starting with the highest loads for coaches (P-I) and continually decreasing the requirements for fixed units and coaches (P-II), underground/rapid transit and light rail (P-III), light duty metro and heavy-duty trams (P-IV) and ending with tram vehicles (P-V).

It is important to note that the nomenclatures overlap for neighbouring categories, meaning that the category used during development is somewhat up to the developer. The small regional rail vehicle which is to be developed in this project is planned to travel autonomously on branch lines throughout Europe. For this application, lower load categories like P-IV could be assumed. However, branch lines could also be connected to main lines or main-line vehicles may also travel on branch lines. This mixed use leads to the fact that the small vehicle might come into contact with larger and stiffer vehicles as well, meaning it would have to withstand the larger forces of higher categories like P-II. For this reason, the mass analyses and structural TOs will be performed for load categories P-II, P-III and P-IV and their impact compared with each other.

Table 1: European norms for mechanical car body design.

Norm	Content
EN 12663-1	"Structural requirements of railway vehicle bodies" Definition of loads and load scenarios for different vehicle categories (use cases). Static load cases that simulate the maximum loads the car body will encounter, such as: • Vertical loads due to passenger weight, cargo, or equipment. • Longitudinal loads due to braking, acceleration, or train (de)coupling. • Lateral loads caused by wind pressure, centrifugal forces during curve navigation, or uneven track conditions. • Dynamic loads: equipment accelerations mounted to the car body frame.
EN 13749	"Method of specifying the structural requirements of bogie frames" Definition of loads resulting from the interaction between the bogie and car body
EN 15663	"Vehicle reference masses" Definition of reference masses for passengers/luggage for vehicle categories
EN 16404	"Re-railing and recovery requirements for railway vehicles" Definition of lifting scenarios

2.4 FURTHER MODEL SETUP

The car body is 17 200 mm long with a wheelbase of 12 700 mm, its height is 2 600 mm and its width 2 895 mm. The design space for the TOs is sectioned into modules, indicated by the coloured parts of the car body in Figure 1. The car body is symmetrical along the y-axis and partly symmetrical along the x-axis. There is one door on each side approximately in the centre of the vehicle.
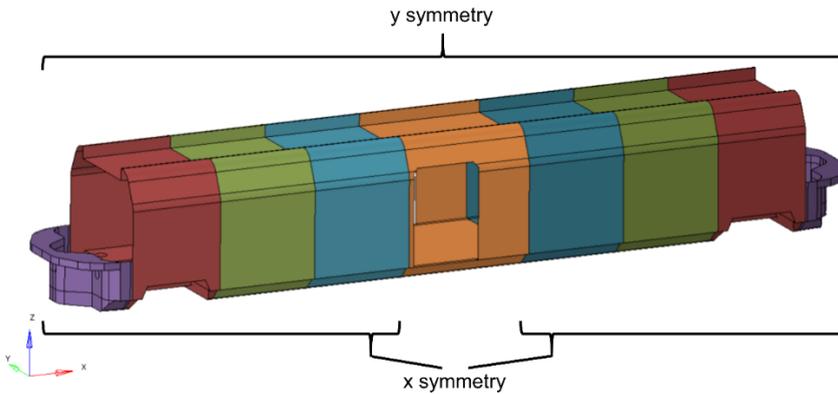
Figure 1: Car body design space with modular sections and symmetries.

The equipment setup can be seen in Figure 2. The configurations will be discussed in more detail in later chapters. The batteries are always attached on their corners to the structural design space with one battery weighing 250 kg. The material for the car body design space is steel.
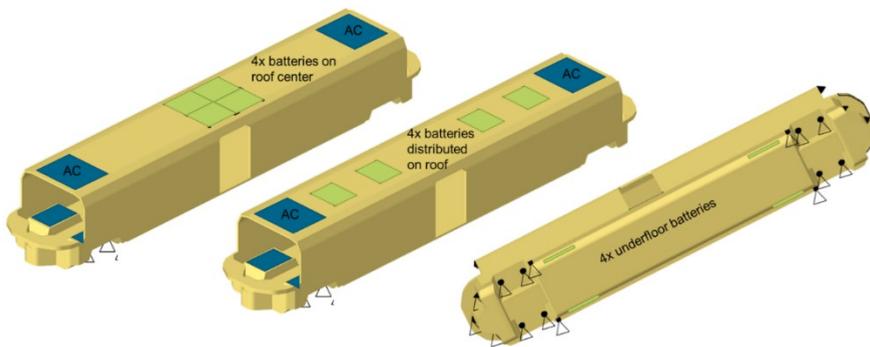

Figure 2: Car body design space with equipment and different battery configurations.

169

LOADS

The car body is subject to various loads, including passenger weight, track irregularities, and dynamic loads during operation. As mentioned in previous chapters, considered load categories are P-II (fixed units and coaches), P-III (underground/rapid transit and light rail) and P-IV (light duty metro and heavy-duty trams). All applied loads can be seen in Table 2.

OPTIMIZATION CONSTRAINTS / SENSITIVITY ANALYSIS

Topology optimizations need boundary conditions to ensure that the result performs according to the specifications. The boundary conditions used here are of a structural nature, see Table 3. They define maximum deformations on selected key points in the model. Some of these constraints are normatively mandatory, others are chosen based on common engineering experience. During the sensitivity analyses, these constraints will be varied to determine their influence on the car body mass.

Table 2: Loads and load cases of the topology optimizations.

Load / load case	Norm	EN 12663-1 load category		
		P-II	P-III	P-IV
Exceptional load (350kg/m² standing passengers + seated passengers)	EN 12663-1 EN 15663	11130 kg		
Equipment (batteries, AC, electricals, …)	-	3233 kg		
Distributed masses (cladding, HVAC, seats, …)	-	7483 kg		
Lift 1 side at 2 points	EN 12663-1 EN 15663	-	-	-
Lift at all four points		-	-	-

Lift 3 points, 4th free		-	-	-
Lift 4 points, 1 point offset by -10 mm vertical		-	-	-
Lift 4 points with lateral forces		-	-	-
P-category force on window sill	EN 12663-1	300 kN	150 kN	-
P-category force on upper corners	EN 12663-1	300 kN	300 kN	-
P-category force on buffers push/pull	EN 12663-1	1500/ 1000 kN	800/ 600 kN	400/ 300 kN
Lateral accelerations equipment	EN 12663-1	1*g		
Running gear longitudinal/lateral acceleration + max. extraordinary load	EN 12663-1 EN 13749	3*g	3*g	2*g
Emergency towing	-	196 kN		

Table 3: Constraints for the topology optimizations.

Constrained area	Max value [mm]	Axis
Undercarriage deflection	-13 (1‰)	vertical
Lifting point	-100	vertical
Roof deflection	-30	vertical

Interior floor deflection	+/- 20	vertical
Buffer deflection	+/- 50	longitudinal

3. RESULTS

The result presentation is divided into structural mass results and structural topology results.

3.1 STRUCTURAL MASS ANALYSES

The objective of mass analyses is to determine how light the car body structure can become under the specified load conditions. All loads from Table 2 are applied. The objective of the TOs is to find the mass minimum of the design space. For these analyses, all symmetry constraints are removed. The result for each analysis is a mass value in tons. This value represents the virtually possible structural mass (i.e. the net mass of the vehicle structure without any additions, cladding, equipment, seats, etc.). It can be used to compare different configurations with each other, e.g. car body geometries or component arrangements.

INFLUENCE OF BATTERY CONFIGURATIONS ON MINIMUM STRUCTURAL MASS

As shown in Figure 2, three battery locations are considered: underfloor (two batteries in slots in the undercarriage on each side), above door (four batteries on the roof above the doors), and distributed on roof (four batteries distributed over the entire roof). The objective of the analysis is to determine how much the location of heavy equipment like batteries influences the car body structure. Table 4contains the virtual mass results. They show that the location of the batteries does have an influence on the virtual mass, however, it is not significant.

Table4: Virtual mass results for different battery locations and materials.

Battery location	Load category	Virtual Mass
Underfloor		2.16 t
Above door	P-III	2.19 t
Distributed on roof		2.18 t

PARAMETER SENSITIVITY: INFLUENCE OF CONSTRAINTS AND LOADS ON STRUCTURAL MASS

The parameter sensitivity analyses were performed on the exemplary configuration "batteries distributed on roof" which serves as a baseline for comparison. All constraint values presented in Table 3were tested for their influence on the car body minimum structural mass. The results and influence can be seen in Table 5.

Table 5: Results of parameter sensitivity analysis for topology optimization constraints.

Constraint	Base value	Modified value	Cat. EN 12663	Virtual mass	Notes/conclusion
-	-	-	P-III	2.18 t	batteries distributed on roof / baseline
undercarriage z	-13mm (1‰)	-26mm (2‰)	P-II	1.79 t	undercarriage deflection has drastic influence on mass
			P-III	1.75 t	
			P-IV	1.74 t	

			P-II	2.23 t	no observable influence of dcon on mass in given setup
roof z	-30mm	-50mm	P-III	2.18 t	
			P-IV	2.17 t	
interior floor z	-20mm	-40mm	P-II	2.23 t	no observable influence of dcon on mass in given setup
			P-III	2.18 t	
			P-IV	2.17 t	
buffer x	+/-50mm	+/-100mm	P-II	2.23 t	no observable influence of dcon on mass in given setup
			P-III	2.18 t	
			P-IV	2.17 t	

It can be noted that, within each variation, the load categories again have a minimal impact on the virtual mass. Further analyses were performed on the impact of the longitudinal forces, see Table 6. Completely removing the buffer force leads to the unexpected result that the mass does not decrease much compared to the baseline model with the usual EN 12663-1 longitudinal loads. Performing another calculation with EN 12663-1 P-category loads but omitting all vertical loads (no passengers or equipment) leads to a decrease in the virtual mass. It can be concluded that the P-category longitudinal loads have minimal impact on the car body structural mass for the considered vehicle.

Table 6: Results of force sensitivity analysis for topology optimization loads.

Force	Base value	Modified value	Cat.	Virtual mass	Notes/conclusion
-	-	-	P-III	2.18 t	batteries distributed on roof / baseline
buffer push force	400 kN	4000 kN	-	3.85 t	drastic force increase has influence -> force application functional
no longitudinal forces	varying	0 kN	-	2.16 t	load categories from EN 12663 contribute little to mass
no vertical loads except structural mass	+/- 50mm	+/-100mm	P-II	1.77 t	no equipment (AC, batteries, seats) or passengers -> vertical loads contribute most to mass
			P-III	1.71 t	
			P-IV	1.67 t	

3.2 STRUCTURAL ANALYSES

Following the minimal structural mass analyses, this chapter will present the approach and results for the structural analyses. Their goal is to get proposals for the optimal material distribution for a structural design of the car body with regard to different load configurations and to provide a baseline for the following mechanical design process.

INFLUENCE OF LOAD CATEGORY ON STRUCTURE

The purpose of these analyses is to study the effect of different load categories from EN 12663-1 on the structure itself. As with the minimum structural mass

analyses, an exemplary battery configuration was chosen (distributed over entire roof). Figure 3 shows the topology results. Blue elements received a low material density during the optimization, meaning they are less important for the structure, whereas red elements received a high material density, meaning they are very important for the structure. It can be noted that all P-categories seem to not necessitate a continuous longitudinal beam along the car body. This further underlines the findings of the previous chapters that the longitudinal loads do not have a significant impact on the car body structure.
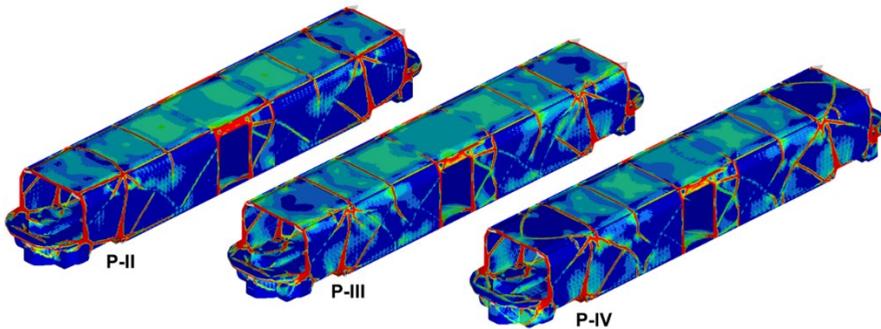
Figure 3: Car body structure for different load categories.

INFLUENCE OF BATTERY CONFIGURATIONS ON STRUCTURE

Concerning the impact of equipment location on the structure, Figure 4 shows a striking similarity between the three configurations. They all feature the same load cases (P-III). Only the battery location was changed. Most noteworthy, the configuration with underfloor batteries does not feature a distinct roof structure. In a failed attempt to prompt a roof structure, the roof deflection constraint was lowered. The air conditioning mounted above the running gears is not enough to prompt the formation of a structure in the roof. Instead, the roof mainly has to withstand torsional loads from the lifting load cases, meaning a semi-stiff shear plane is enough to distribute these loads into the surrounding structure. The other two battery configurations with the batteries mounted on the roof, however, feature a very distinct roof structure with clear X-beams leading through the battery fixation locations. Due to the absence of

continuous longitudinal beams, all models formed pronounced arches above the running gears with vertical spans to the running gear load introduction points.
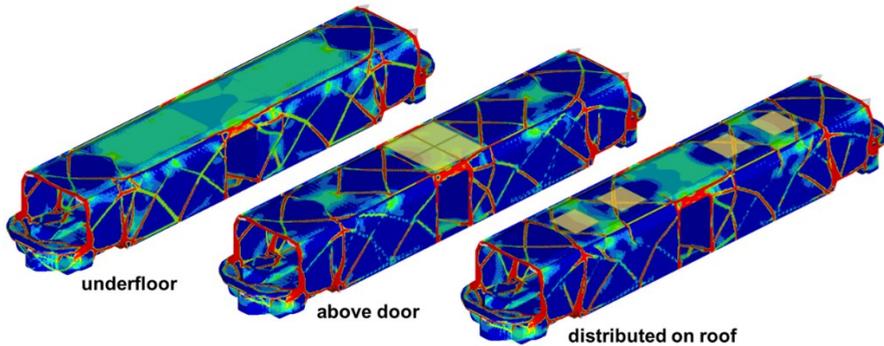

Figure 4: Car body structure for different battery locations (yellow: AC locations).

4. CONCLUSION

As part of the early development process of a small regional rail vehicle, topology optimizations were performed to determine the minimal viable car body mass for different load conditions.

Based on the frame conditions here, the analyses result for the virtual theoretically minimum achievable structural mass show that there is only a negligible mass saving potential for lighter load categories (P-IV over P-II or P-III). The same can be concluded regarding component arrangements. The location (underfloor/above doors/distributed on roof) of heavier components (e.g. four batteries with 250kg mass each) has a negligible impact on the virtual structural mass of the car body.

Based on the considered configurations, there is no significant weight difference between load categories from EN 12663-1. This finding, however, should be confirmed by performing FEM analyses on the future mechanical design of the car body.

The analyses of the structural impact of different load categories come to a similar conclusion that the three investigated P-categories lead to similar structural results with only minor differences in the load application areas themselves. P-III and P-IV are overall very similar regarding their weight and

their structure. This confirms findings from other authors (Schmauder et al., 2022) and should prompt normative boards to revaluate the necessity for distinct longitudinal loads for car body development.

The analyses comparing different battery arrangements show that the roof is mainly loaded with a shear load if no other significant loads are acting directly upon it. Moving batteries onto the roof will lead to more distinct roof structures.

Overall, the topologies show similar load paths for different load categories and equipment locations. There are repeating major structures over the length of the vehicle with only local variations, see Figure 5 where three different topology results are overlaid. The implications are clear in that different use cases/load categories for a small rail vehicle have only minimal impact on the car body weight or its optimal car body structure.

Seeing as the load paths are similar among load variations, a steel differential design could be used to best follow the force flow of the topology optimization. This could be aided by applying advanced automated design methods to derive suitable cross sections from the optimization result (Gomes Alves et al., 2022), leading to an optimal material usage, reducing the structural weight and, thus, promoting resource efficiency.

Figure 5: Overlapping structural topology results for all three different battery configurations.

ACKNOWLEDGEMENTS

REFERENCES

Gomes Alves, C., Barthel, Y., & Halsner, M. (2022). Automated Derivation of CAD Designs from Topology Optimization Results. World Congress on Railway Research (WCRR) 2022, Birmingham, UK, 2022-06-06 - 2022-06-10. https://elib.dlr.de/148477/

Malzacher, G., & Mohr, M. (2019). Lastannahmen der DIN EN 12663-1: Stand der Technik? Eisenbahn Ingenieur Kompendium 2020 (pp 66-86). DVV Media Group | Eurailpress. ISBN 0934-5930. https://elib.dlr.de/132615/

Persson, R., Lochman, L., & König, J. (2024). Regional Rail Rolling Stock Requirements & Specifications. TRA2024 Transport Research Arena, Dublin, Ireland, 2024-04-15 - 2024-04-18. https://elib.dlr.de/207557/

Schmauder, N., Malzacher, G., & Kraft, S. (2022). Inefficient design: Sensitivity analysis and numerical investigation of load cases from EN 12663-1 on railway car bodies. Proceedings of the Fifth International Conference on Railway Technology: Research, Development and Maintenance, 1. Civil-Comp Press, 2022-08-22 - 2022-08-25, Montpellier, France. https://doi.org/10.4203/ccc.1.35.1