

Article

Lightweight Design and Topology Optimization of a Railway Motor Support Under Manufacturing and Adaptive Stress Constraints

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Abstract

The study investigates the combined effects of material selection, manufacturing constraints, and a dynamic stress constraint function on the resulting material distribution achieved through a structural optimization process, while ensuring full compliance with the relevant European assessment standards for railway bogie. A high-fidelity finite element model of the complete bogie system was developed to accurately reproduce the operational loads and the structural interactions between the motor support and its surrounding components. The proposed methodology integrates topology optimization within a manufacturability-oriented framework, enabling a systematic evaluation of the influence of material properties, draw direction, and minimum feature size on the optimized configuration. In this context, an adaptive stress coefficient, derived from the performance of the original component, was introduced and proved effective in improving both the material distribution and the resulting stress levels of the optimized design. The results demonstrate that the combined consideration of material selection, manufacturing constraints, and adaptive stress control leads to a structurally efficient and production-feasible design. Three different materials were tested, showing consistent stress distributions and mass savings across all cases. The innovative optimized configuration achieved over 16% mass reduction while maintaining admissible stress levels. The proposed approach provides a generalizable and standard-compliant framework for future applications of topology optimization in railway engineering.

Keywords: topology optimization; lightweight design; manufacturing constraints; adaptive stress constraint; sensitivity analysis; railway vehicle design



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1. Introduction

In the current context of railway engineering, the need for lightweight yet structurally sound components is increasingly pressing, as it directly contributes to energy efficiency, reduced track wear, and improved dynamic performance. Nevertheless, optimization-based design processes, and, in particular, topology optimization, are still not explicitly included in the reference European standards, which primarily rely on traditional verification methods. This gap limits the adoption of more advanced design approaches in industrial practice, despite their proven potential. At the same time, the rapid and reliable development of innovative solutions must comply with the strict structural and safety requirements imposed by the assessment of complex assemblies such as railway bogies. To address these limitations, the present study proposes a methodology that integrates topology optimization within a standard-compliant design framework, through the analysis of

the influence of material selection, manufacturing constraints, and stress-related influence coefficients on the optimized structural response. Structural optimization techniques, and particularly topology optimization, have already found extensive application in several engineering fields. Topology optimization is widely applied to automotive body structures, particularly in the early design stages, to achieve lightweight and high-performance vehicles [1]. Case studies demonstrate significant mass reductions and improved structural integrity through these methods, applied to metallic and composite structure [2–6]. Also manufacturing techniques were studied and improved adopting similar techniques [7–11]. Structural and topology optimization, when integrated with additive manufacturing (AM), is transforming the design and production of turbomachinery components by enabling lightweight, high-performance, and geometrically complex parts [12–18]. In the railway sector, the literature analysis shows that application of structural optimization remains relatively limited despite growing interest in recent years. Railway vehicles are inherently complex systems, composed of multiple structural components that must simultaneously satisfy different mechanical and functional requirements under highly variable loading conditions. Researchers have addressed the lightweight design of railway car bodies through structural optimization approaches, proposing approaches characterized by static [19–21] and dynamic [22,23] behavior of the system. The increasing use of composite materials in car body structures has stimulated a large number of studies on their optimization, investigating a wide range of configurations, including both laminated and sandwich structures [24–30]. Literature shows as most optimization applications involving manufacturing constraints are applied to general engineering cases [31–35], with limited attention devoted to the sensitivity of such constraints and a predominant focus on the final optimization outcome. Moving to the railway domain, research activities are significantly fewer, mainly due to the higher complexity of the application and the fact that optimization-based design has not yet become an established practice in this field. Different types of optimizations were explored in [36–39], evaluating the presence of manufacturing constraints, testing metallic and composite materials. Focusing on railway bogie frames, topological optimization methods, manufacturing constraints and a combination with a multibody environment were presented in [40–43]. The literature, particularly regarding the application of topology optimization in the railway sector, shows only a limited number of studies, mostly focused on the final result rather than on the influence of individual key parameters on the optimization outcome. The present research aims to fill this gap by proposing a comprehensive evaluation of the topology optimization process applied to a key component of a railway vehicle. The study investigates the combined effects of material selection, manufacturing constraints, and a dynamic stress constraint function on the resulting material distribution, while ensuring full compliance with the relevant European assessment standards. This work is intended to serve as a reference framework for future applications of topology optimization in the railway field.

2. Material and Methodology

2.1. Materials' Description

In this study, three materials were selected and compared for the design and optimization of the motor support: the alloyed steel G18NiMoCr3, the austempered ductile iron (ADI) GJS-1050-6, and the aluminum alloy Al-Cu4MnMg. Their characteristics are reported in Table 1. Each of these materials presents distinctive mechanical and technological characteristics, making them suitable for different design and manufacturing approaches. The steel G18NiMoCr3 [44–46] is a high-strength material commonly used in critical railway components, characterized by excellent toughness, fatigue resistance, and dimensional stability under dynamic loading. Its main drawback lies in its relatively

high density and manufacturing cost, which may limit its use in lightweight applications. The GJS-1050-6 cast iron [47–49] on the other hand, represents a compromise solution that combines good mechanical strength with enhanced damping properties and favorable castability. The austempering treatment improves its toughness and fatigue resistance compared to conventional ductile irons, making it suitable for complex geometries obtained by casting. However, its brittleness under extreme loads and its limited weldability may restrict its use in certain operating conditions. Finally, the Al-Cu4MnMg alloy [50] offers a clear advantage in terms of weight reduction, thanks to its low density, while maintaining good strength-to-weight ratio and corrosion resistance. Nevertheless, its lower stiffness and fatigue strength compared to ferrous alloys may represent a limitation in applications subjected to severe mechanical loads. The comparative evaluation of these three materials, therefore, provides a comprehensive understanding of the trade-offs between mechanical performance, manufacturability, and weight efficiency, enabling the identification of the most suitable material for the optimized design of the railway motor support.

Table 1. Mechanical properties of the selected materials.

Material	Young's Modulus [MPa]	Poisson's Ratio	Shear Modulus [MPa]	Density [kg/m ³]	Yield Strength [MPa]	Ultimate Strength [MPa]
G18NiMoCr3	206,800	0.29	80,155	7820	700	830
GJS-1050-6	170,000	0.27	66,929	7200	700	1050
Al-Cu4MnMg	72,000	0.33	27,068	2790	310	370

2.2. Methodology

The present study is based on an extensive numerical campaign aimed at achieving the structural innovation of a motor support mounted on the bogie frame of a railway vehicle. To investigate this complex component within its operational environment, a high-fidelity finite element (FE) model of the complete bogie system was developed, including all main subsystems such as the primary suspension and wheelsets. This comprehensive modeling framework enabled an accurate evaluation of the motor support behavior under realistic load conditions and its interaction with the surrounding structures. The adopted methodology follows a multi-step approach designed to ensure both technical soundness and manufacturability throughout the topology optimization process. In the first phase, a rigorous assessment of the original component was carried out according to the relevant European standards. This preliminary study identified the critical stress regions, clarified functional requirements, and established feasible manufacturing and design constraints. On this basis, the design space, where geometry could be modified, and the non-design space, corresponding to interfaces that must remain unaltered for proper system integration, were precisely defined. The second phase focused on the structural topology optimization. A sensitivity analysis was conducted to investigate the influence of three key parameters: material selection, manufacturing constraint (single draw direction), and minimum feature size. This parametric exploration enabled a systematic evaluation of how these factors affect the distribution of material, structural stiffness, and total mass of the optimized support. The analysis provided a clear understanding of the trade-offs between performance and manufacturability, guiding the definition of an innovative yet production-feasible configuration. An additional innovative feature introduced in this study concerns the definition of a material utilization coefficient, denoted as k , developed to introduce an adaptive control of the optimized configuration stress level with respect to the original design. This coefficient acts as a scaling factor applied to the material allowable

stress during the optimization process, ensuring that the stress distribution within the optimized geometry remains within a predefined utilization range. The value of k is estimated from the preliminary analysis of the original component, allowing the optimization to start from the actual performance level of the existing system and to target a controlled increase in material efficiency. Moreover, a maximum limit is imposed to avoid excessive material exploitation, thereby maintaining a safety margin during the structural optimization process. This adaptive criterion allows the algorithm to enhance structural performance while ensuring the reliability and manufacturability of the resulting geometry. In the third phase, the optimized geometry was reconstructed in detail, ensuring full compatibility with the surrounding systems. The FE model was subsequently updated to reflect the new geometry, allowing a comparative numerical validation across multiple material options. This step confirmed the consistency and robustness of the proposed design. Among the novel aspects of this methodology are the systematic integration of a high-fidelity full-bogie model within the topology optimization loop, the combined assessment of material-dependent and manufacturing constraints, and the introduction of the adaptive material utilization coefficient k as a design control factor. Together, these features establish a generalizable framework for lightweight design and structural optimization of railway components, bridging the gap between conceptual topology results and industrial-grade feasibility.

2.3. Description of the Support

The motor support, characterized by a slender and elongated geometry, is positioned at the end of the longitudinal beam on the outer side of the bogie, where the traction motors are installed according to the design of the propulsion system. The original configuration of the support features an L-shaped structure, constrained through two main interfaces that ensure proper load transmission to the bogie frame. These interfaces were originally designed as bolt connections, and this feature has been intentionally preserved throughout the innovation process to maintain ease of assembly and replacement. The support also includes two eyelets that serve as the attachment points for the motor itself. In the redesigned configuration, these interfaces were carefully retained and integrated within the optimized geometry, ensuring full compatibility with the existing system architecture and enabling direct substitution of the original component without the need for structural modifications. Figure 1 illustrates a detailed CAD representation of the motor support, where the interfaces with the bogie frame and the motor are highlighted in red; these regions define the non-design space considered in the optimization process. The overall positioning of the support within the complete finite element model is shown in Figure 2.

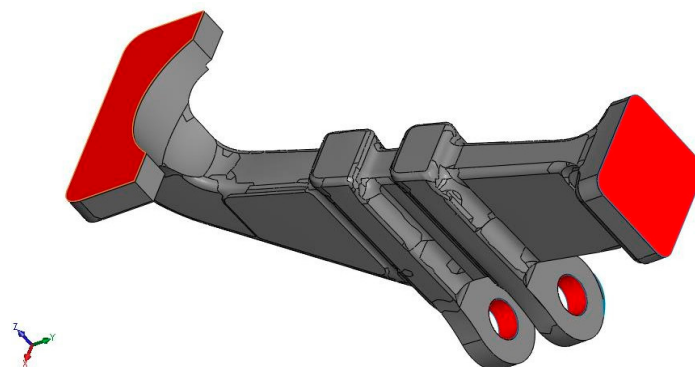


Figure 1. CAD representation of the motor support.

2.4. Bogie System: High Fidelity FE Model

Figure 2 presents the finite element (FE) model of the original motor bogie frame, developed as a high-fidelity representation of the entire structural system. Each component

was modeled using the most appropriate element formulation (0D, 1D, or 3D), based on its geometric complexity and functional role. Given the substantial thickness and three-dimensional configuration of the bogie frame, the use of 2D shell elements (QUAD type) was deemed unsuitable. Consequently, all the primary structural parts, including longitudinal beams, cross members, and the motor supports, were discretized with second-order tetrahedral elements (TETRA10), with local mesh refinement applied to the most critical regions. All the supports, including the redesigned motor support, were connected to the bogie frame through contact formulations defined as FREEZE (bonded) interfaces. This approach enforces linear kinematic compatibility, ensuring complete stress transfer, both in terms of forces and moment, between the connected parts. The bonded contact prevents any relative sliding or separation between surfaces, thereby guaranteeing numerical stability and accurate stress redistribution. This modeling choice offered an optimal balance between computational efficiency and physical realism, allowing the modification or substitution of individual components without compromising the integrity of the global assembly, provided that the contact interfaces were preserved. The load conditions were applied using combinations of concentrated forces, surface pressures, and RBE3 elements, depending on the type and position of the applied loads. The RBE3 elements were particularly useful in distributing loads among multiple nodes without introducing artificial stiffness into the model. The wheelsets were modeled using one-dimensional beam elements with appropriate sectional properties, ensuring realistic mass and inertia while maintaining the correct flexural behavior. The primary suspension system, placed between the wheelsets and the bogie frame, was also modeled using 1D elements, following the same rationale, to preserve the compliance of the suspension connection without introducing excessive stiffness. The global boundary conditions of the bogie were defined according to an isostatic scheme, with reference constraints applied at the four-wheel contact points located at the axle ends. The model consisted of 1,783,000 elements and 2,171,000 nodes.

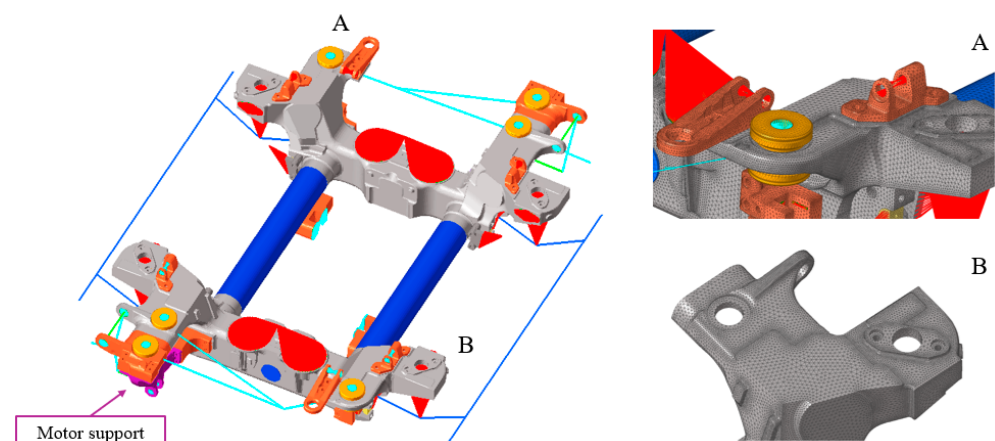


Figure 2. High-fidelity FE model of bogie system.

2.5. Optimization Settings

The optimization procedure was developed with the primary goal of minimizing the weighted compliance across all defined load cases. Compliance, representing the total strain energy stored in the structure under loading, provides an inverse measure of stiffness: the lower the compliance, the higher the global stiffness of the component. This formulation enables the definition of an efficient optimization problem, targeting a lightweight yet structurally robust configuration. Prior to launching the optimization, the motor support model was carefully prepared to ensure compatibility with the optimization solver. The geometry was reconstructed through detailed CAD modeling and subsequently

meshed, ensuring adequate resolution in critical regions. The material domain was slightly expanded to give the algorithm sufficient design freedom to redistribute material effectively while keeping the overall dimensions within the physical constraints of the component. A clear distinction between design and non-design regions was established to guide the optimization process. The design space defined the volume where the solver could remove or retain material, whereas the non-design space, corresponding to the mounting interfaces with the bogie frame and the motor attachment points, was excluded from any modification. As shown in Figure 3, the reconstructed and meshed motor support highlights in red the non-design areas, which represent the functional interfaces to be preserved. This configuration ensured that the optimized motor support remained fully interchangeable with the original component, allowing independent design iterations without requiring structural modifications to the bogie frame.

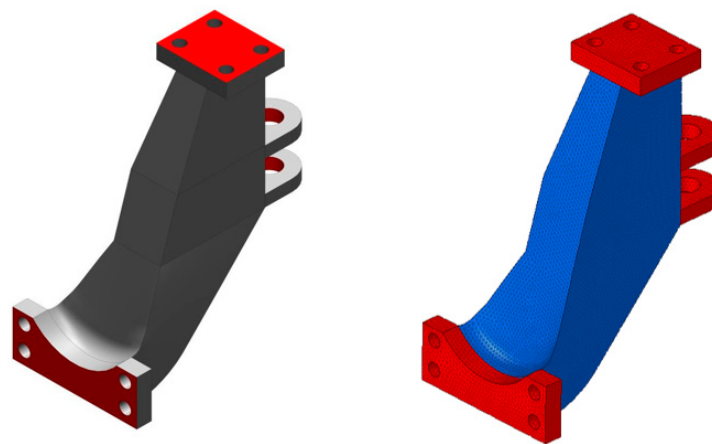


Figure 3. FE model of the motor support set for structural optimization.

In the optimization setup, summarized in Table 2, the principal constraint was defined in terms of the mass fraction, representing the ratio between the final mass of the optimized structure and the initial mass of the design domain. This parameter was fixed below 0.5, a threshold commonly adopted in topology optimization to ensure substantial material reduction while maintaining adequate structural integrity. Beyond this global constraint, an additional stress-based condition was introduced to control the mechanical response of the evolving topology. Specifically, the equivalent von Mises stress distribution $\sigma_{eq}(\rho)$ was constrained to remain below a material-dependent limit defined as $k\sigma_{(permissible_init)}$, where the coefficient k represents an influence factor derived from the preliminary assessment of the original component. This constraint, which will be detailed in the following section, allows the optimization process to account for the actual utilization level of the material while preventing excessive local stress concentrations, thus ensuring both mechanical soundness and design robustness. In addition to this, the influence of material properties and manufacturing limitations was systematically investigated to achieve a more realistic and robust optimization framework. The manufacturing constraints were introduced to emulate actual production conditions, including a single draw direction, which governs the orientation along which material can be removed, replicating the demolding direction of a cast or machined component, and a minimum feature size parameter, defined to prevent the formation of excessively small geometrical details that could hinder manufacturability. Following a series of sensitivity analysis, the minimum feature size was set to 10 mm, which provided an effective compromise between geometric resolution and technological feasibility. This modeling strategy ensured a physically consistent and production-oriented optimization process, yielding a manufacturable and structurally efficient configuration.

The parametric analysis performed on the optimization parameters, mass fraction, material type, extraction direction, and feature size, represent one of the main innovative aspects of the present work. Their systematic evaluation, combined with the integration of the adaptive stress constraint, offers valuable insights into the interplay between mechanical performance and manufacturing feasibility, highlighting the robustness and practical relevance of the proposed optimization strategy for lightweight railway components.

Table 2. Optimization settings.

Parameters and Settings of Optimization Problem		
Global settings	Objective	min (Weighted compliance)
	Mass constraint	Mass fraction < 0.5
	Stress constraint	$\sigma_{eq}(\rho) \leq k\sigma_{permissible_init}$
Technological settings	Minimum feature size	10 mm
	Draw single	Removing material along a reference direction

3. Results and Discussion

3.1. Analysis Setting and Preliminary Results

The finite element simulations were conducted employing a high-fidelity structural model of the bogie subsystem, developed to accurately reproduce the geometric and mechanical behavior of the motor support and its interfaces with the surrounding frame. The numerical analysis was performed under loading conditions consistent with the prescriptions of the reference European standard EN 13749:2021 [51] for railway running gear, ensuring full compliance with the normative framework governing structural verification and safety. Particular emphasis was placed on the load cases identified as the most demanding for the support, which are summarized in Table 3. All computations were executed on a dedicated workstation equipped with an Intel® Xeon® Gold 6244 CPU @ 3.60 GHz and 32 GB of RAM, providing adequate computational efficiency and numerical stability across the entire simulation campaign within the Altair Environment. The preliminary assessment of the original motor support configuration represented a key phase of the research activity, as it enabled a rigorous understanding of the stress distribution, stiffness behavior, and load paths characterizing the component under service-like conditions. This stage provided the necessary insight to guide the subsequent topology optimization in a physically informed manner, identifying both the regions of structural overdesign and the potential zones where material redistribution could be most beneficial. Such a methodology, grounded in detailed preliminary evaluation, constitutes a fundamental prerequisite for any reliable and effective implementation of advanced structural optimization strategies. The baseline configuration exhibited an overall sound structural performance, with the maximum utilization coefficient, defined as the ratio between the computed equivalent stress (σ_c) and the admissible limit of the reference steel material, remaining well below critical levels, never exceeding 0.5. This outcome confirms the conservative nature of the initial design and simultaneously reveals a considerable margin for optimization, allowing the same structural function to be achieved with a more efficient material layout and a potentially significant mass reduction.

3.2. Sensitivity Analysis Framework

In order to systematically investigate the influence of material properties and manufacturing constraints on the optimization outcome, a dedicated sensitivity analysis was performed. The procedure followed a factorial approach in which three key parameters

were varied within predefined ranges: (1) the material, which affects the stiffness-to-density ratio and, consequently, the achievable lightweight potential; (2) the draw direction, which defines the manufacturability constraint associated with material removal during casting or machining; (3) the minimum feature size, which governs the smallest geometrical element that can be produced within realistic technological limits. Each optimization case was defined by a unique combination of these parameters, generating a structured matrix of numerical tests that enabled a clear interpretation of their individual and combined effects. Table 4 summarizes the optimization configuration test.

Table 3. Load scenarios.

Scenario of Load (SL)	Description
SL 1—Turnout (Switch Passage)	The applied loads originate from the carbody weight, bogie inertia, and mounted equipment during vehicle passage over turnouts. The constraints are applied at the wheel contact points.
SL 2—Curving	The applied loads result from the combined effects of the carbody, bogie inertia, and onboard equipment under curved track operation, with a distribution pattern different from LC1. Constraints are applied at the wheel locations.
SL 3—Coupling Impact	The applied loads derive from the vehicle coupling event, generating an acceleration equivalent to 3 g on the bogie mass. Constraints are applied at the wheel contact points.
SL 4—Lifting Condition	The applied loads correspond to vehicle lifting operations, with the bogies suspended below the carbody. Constraints are applied at the wheel contact regions.
SL 5—Short-Circuit Condition	The applied loads are induced by a short-circuit event occurring in the traction motor. Constraints are applied at the wheel positions.
SL 6—Inertial Masses	The applied loads are associated with the inertial effects of the suspended masses acting on the bogie frame. Constraints are applied at the wheel locations.
SL 7—Dampers Action	The applied loads originate from the reaction forces transmitted by the damping devices. Constraints are applied at the wheel contact points.

Table 4. Summary of optimization campaign tests.

Case ID	Material	Draw	Min. Feature Size [mm]	Constraint Setup	Test Objective
Opt.1	G18NiMoCr3	Z-axis	25	Mass fraction < 0.5	Material sensitivity
Opt.2	GJS-1050-6	Z-axis	25	Mass fraction < 0.5	Material sensitivity
Opt.3	Al-Cu4MnMg	Z-axis	25	Mass fraction < 0.5	Material sensitivity
Opt.4	GJS-1050-6	X-axis	25	Mass fraction < 0.5	Manufacturing constraint—draw direction
Opt.5	GJS-1050-6	Z-axis	10	Mass fraction < 0.5	Manufacturing constraint—feature size

This structured approach enabled the identification of distinct behavioral trends: the first group of tests (Opt.1–Opt.3) isolated the role of material properties under identical boundary and manufacturing conditions, whereas the second group (Opt.4–Opt.5) quantified the influence of technological constraints on the topology outcome. In all cases, the same objective function and global mass constraint were adopted, ensuring comparability of the results and the isolation of each parameter’s effect. Such a systematic parametrization of the optimization space provided a clear and reproducible basis for analyzing the relation-

ship between mechanical properties, manufacturing feasibility, and final mass efficiency, as discussed in the following subsection.

3.3. Optimization Algorithm and Stress Formulation

The optimization process was performed using a gradient-based algorithm [52], which represents one of the most established and computationally efficient approaches for topology optimization problems. This method iteratively updates the material distribution within the design domain by evaluating the sensitivity of the objective function and the constraints with respect to the design variables, typically defined as element-wise material densities. At each iteration, the algorithm computes the gradient of the objective function, in this case, the structural compliance, and applies a penalization scheme to progressively drive the solution toward a discrete 0–1 material layout. The general formulation of the topology optimization problem can be expressed as

$$\min_{\rho} f(\rho) = \int_{\Omega} \sigma_{ij}(\rho) \varepsilon_{ij}(\rho) d\Omega \quad (1a)$$

$$\frac{V(\rho)}{V_0} \leq \alpha \quad (1b)$$

$$\sigma_{eq}(\rho) \leq k\sigma_{allowed} \quad (1c)$$

$$0 < \rho_{min} \leq \rho(x) \leq 1 \quad (1d)$$

where $\rho(x)$ is the material density at each finite element, σ_{ij} and ε_{ij} are the local stress and strain tensors, $V(\rho)$ and V_0 denote the current and initial design volumes, and α represents the prescribed mass fraction constraint. The additional stress constraint $\sigma_{eq}(\rho) \leq k\sigma_{permissible_init}$ is introduced to ensure that the maximum equivalent von Mises stress within the design domain remains below the allowable limit defined for the selected material, thus preserving structural integrity during the optimization process. This formulation allows the algorithm to simultaneously minimize structural compliance (maximize stiffness) and enforce both global mass and local stress constraints. The gradient-based method efficiently converges toward an optimized material distribution satisfying the imposed manufacturing and performance requirements, providing a stable and computationally robust solution for the motor support design problem. Focusing on one of the novel points of the present research activity, to further enhance the physical consistency and reliability of the optimization process, an additional constraint was introduced on the equivalent von Mises stress, formulated in terms of a variable permissible stress threshold. Unlike conventional approaches, where the allowable stress is fixed according to material properties, the present study defines a dynamic stress limit that accounts for the actual utilization level of the original component. Specifically, the permissible stress limit in the optimization phase, denoted $k\sigma_{permissible_init}$, scaled through an “influence factor” k estimated from the preliminary structural analysis of the non-optimized motor support. The coefficient k represents a utilization-based correction factor derived from the ratio between the maximum equivalent stress in the original component (σ_{c_orig}) and the allowable stress of the same material ($\sigma_{permissible_init}$), increased by 20% to promote a controlled performance enhancement. This increase corresponds to a conventional safety margin commonly adopted in railway engineering practice, typically ranging between 1.0 and 1.2, and was selected through a tuning process to ensure structural robustness while preserving the effectiveness of the optimization procedure. Its formulation can be expressed as

$$k = \begin{cases} \frac{\sigma_{c_orig}}{\sigma_{permissible_init}} * 1.2, & \text{if } \frac{\sigma_{c_orig}}{\sigma_{permissible_init}} * 1.2 \leq 0.85 \\ 0.85, & \text{if } \frac{\sigma_{c_orig}}{\sigma_{permissible_init}} * 1.2 > 0.85 \end{cases} \quad (2)$$

This condition ensures that the optimization process begins from the actual performance level of the existing design, incremented by a controlled safety margin, while maintaining a strict upper limit corresponding to 85% of the material's permissible stress. The resulting adaptive constraint provides a realistic yet safe boundary for the optimization algorithm, avoiding excessive stress concentrations that could compromise structural integrity or fatigue life. From a methodological standpoint, this approach bridges the gap between numerical optimization and engineering practice, introducing a feedback-based stress regulation mechanism. By linking the optimization constraint directly to the pre-existing stress state of the real component, the process inherently captures the design's initial safety margin and transforms it into an effective performance scaling parameter. This allows the optimizer to explore more aggressive lightweight configurations while preserving a predictable and verifiable stress margin, thereby enhancing both the robustness and the industrial applicability of the resulting topology. Overall, the proposed formulation represents a novel contribution to topology optimization for railway components, combining adaptive constraint tuning with material utilization control. It provides a systematic way to align optimization targets with the baseline mechanical behavior of the original system, ensuring that the achieved mass reduction does not come at the expense of structural reliability.

3.4. Optimization Process and Sensitivity Results

The present research activity focused on the structural innovation of a crucial component for railway vehicles, the motor support, within a lightweight design perspective. The optimization campaign was specifically aimed at evaluating the combined influence of the selected materials and the imposed manufacturing constraints on the resulting material distribution and, consequently, on the component mass. In addition, the impact of introducing a stress-related constraint, defined through the previously described influence coefficient k , was also assessed to quantify its effect on the optimization outcome. This approach enabled a systematic investigation of how material mechanical properties and technological limitations affect the structural efficiency achievable through topology optimization. In particular, the analyses labeled as Opt.1 to Opt.3 were devoted to the assessment of the material influence under identical boundary and optimization conditions. The three configurations correspond to the use of the original G18NiMoCr3 steel, the GJS-1050-6 ductile cast iron, and the Al-Cu4MnMg aluminum alloy, respectively. In all these cases, the manufacturing constraints were kept constant, consisting of a predefined draw direction along the global Z-axis and a minimum feature size of 25 mm, which ensured both manufacturability and numerical robustness of the resulting geometry. The obtained results revealed that, under these conditions, the effect of material selection on the optimized layout is nearly negligible. This outcome is fully consistent with theoretical expectations, since all the considered materials exhibit sufficiently high mechanical performance when compared to the stress levels observed in the preliminary finite element assessment of the original design. Consequently, both the overall material distribution and the resulting normalized mass remained substantially unchanged across the three optimizations. Only minor local variations were detected, primarily in the form of small holes or cavities located in the lower region of the support, as illustrated in Figure 4. These slight deviations, however, do not significantly affect the global stiffness or weight efficiency, confirming that, within the examined mechanical context, material substitution alone does not drive substantial improvements in the optimized configuration. Building upon these findings, the subsequent phase of the research focused on the ductile cast iron (GJS-1050-6) configuration, which was selected as the reference material for further investigation on the influence of manufacturing constraints. These analysis correspond to Opt.4 and Opt.5, respectively, and

were aimed at evaluating the sensitivity of the optimized geometry to variations in the manufacturing parameters. In Opt.4, the first parameter explored was the draw direction, which was modified from the initial vertical orientation (along the Z-axis) to an orthogonal extraction direction along the X-axis. This change produced a markedly different and strongly asymmetric material distribution, which, although technically feasible, was not considered suitable for the specific application under study. The resulting configuration exhibited a geometry similar to an open “C”-shaped section, structurally less efficient in withstanding torsional effects, for which closed-section layouts generally provide superior performance. Moreover, the mass variation associated with this configuration was minimal, offering no significant advantages in terms of weight reduction or stiffness improvement. For these reasons, this setup was not further pursued in the optimization process. The Opt.5 configuration instead focused on the minimum feature size, the second key manufacturing constraint investigated in this study. A dedicated sensitivity analysis was performed on this parameter to assess its influence on the resulting topology, progressively reducing the value from the baseline of 25 mm down to 10 mm, corresponding to a reduction in more than 100%. The results revealed that this constraint plays a crucial role in determining the final optimized shape, significantly affecting both the material distribution and the resulting mass, lower more than 12% respect to the other optimization results, as clearly illustrated in Figure 5. The 10 mm threshold was identified as the lower acceptable limit, ensuring that no structural regions would fall below a thickness compatible with mechanical integrity and manufacturability. The final configuration obtained under these settings exhibited a well-balanced and structurally efficient geometry, maintaining a continuous load-carrying path and a form compatible with the original support’s interfaces and the bogie’s loading conditions. As illustrated in Figure 5, the influence coefficient k proved to have a significant impact on the optimization results, leading to noticeable variations in the final mass. This parameter therefore represents a key factor for achieving an effective optimization process and ensuring the structural quality of the resulting configuration. It is worth emphasizing that, as detailed in the following subsection, the optimized topology was subsequently redesigned and refined to generate a manufacturable model suitable for finite element verification. This post-processing step is always crucial, as it bridges the gap between the conceptual outcome of topology optimization and the development of a functional component ready for engineering validation. In this case, starting from a fine-grained topology (with smaller feature size) and selectively adding material during the design refinement phase enabled the full exploitation of the optimization potential, leading to a structurally robust and lightweight configuration.

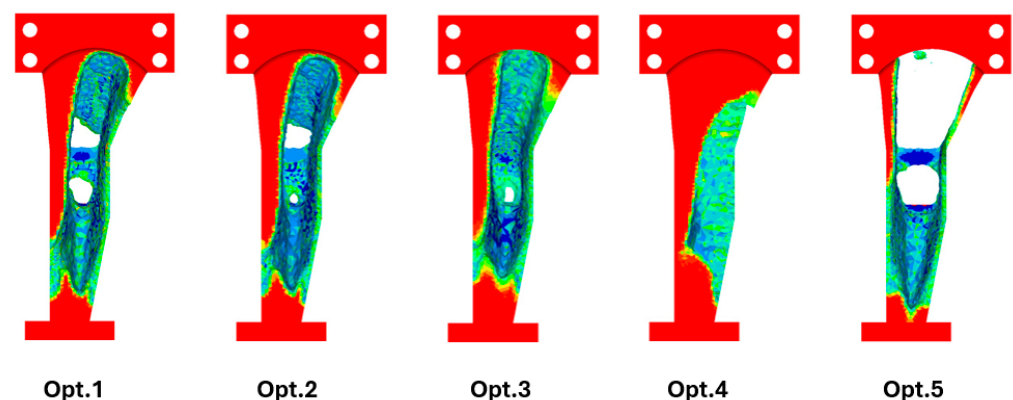


Figure 4. Final material distribution resulting from optimizations.

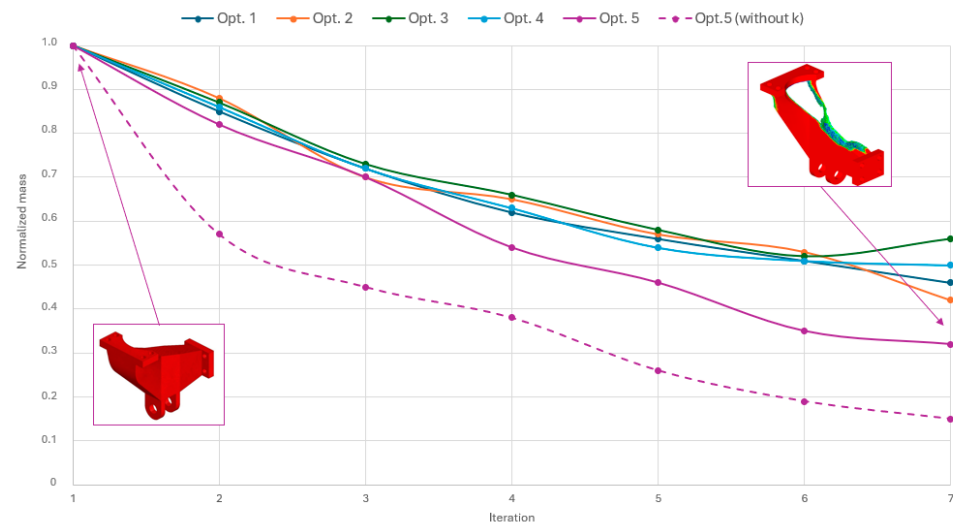


Figure 5. Evolution of mass during each optimization.

3.5. Innovated Geometry and Assessment

The final phase of the present research focused on the reconstruction of the optimized motor support geometry, bridging the gap between the conceptual topology provided by the optimizer and a manufacturable, functional component. While the topology optimization process identifies the most effective material distribution for achieving structural efficiency, the raw output often consists of complex, irregular shapes that cannot be directly realized through conventional manufacturing techniques. The main objective of this reconstruction stage is therefore to transform the optimized topology into a physically feasible geometry that preserves the functional and structural advantages identified during the numerical campaign, while being compatible with a variety of production methods, including casting and machining. In practical terms, the designer's intervention is required to generate smooth surfaces, eliminate sharp edges, and fill small cavities or thin features that are not manufacturable in reality. This ensures that the reconstructed component maintains proper load paths, preserves the interfaces with surrounding bogie subsystems, and guarantees structural integrity under operational conditions. Importantly, this phase involves selectively reintroducing a controlled portion of material to the topology, compensating for geometric simplifications or smoothing operations. Thanks to the insights provided by the optimization process, this additional material can be distributed in an optimal manner, preserving the weight efficiency achieved during the parametric analysis, as shown in Figure 6.

Finally, the fully reconstructed motor support geometries were reintroduced into the high-fidelity FE model of the complete bogie to perform a new set of numerical simulations under operational load conditions, as illustrated in Figure 7. This step allowed a rigorous verification of the structural performance of the final component, confirming that the reconstructed, manufacturable designs meet both the stiffness and stress requirements while preserving the advantages of the optimized topology. This approach ensures that the final motor support is not only theoretically optimal but also ready for practical implementation, providing a robust, innovative, and manufacturable solution for railway applications.

Table 5 reports the comparative stress results between the original steel motor support and the innovative configurations in ductile cast iron and aluminum alloy, including the estimated utilization coefficient U for each loading scenario, and calculated stress σ_c . Stress concentrations were evaluated in detail on the redesigned support to assess its new functional behavior under operational conditions. Figure 8 illustrates the equivalent stress

distribution on the original support, confirming the coherence of the stress distribution obtained on the optimized configuration.

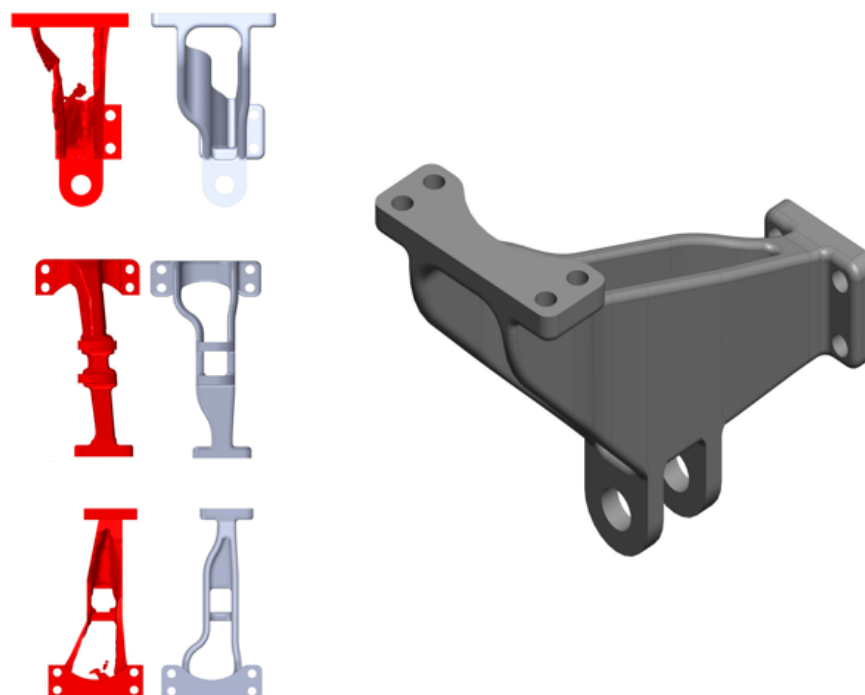


Figure 6. Building steps and final innovated geometry of motor support.

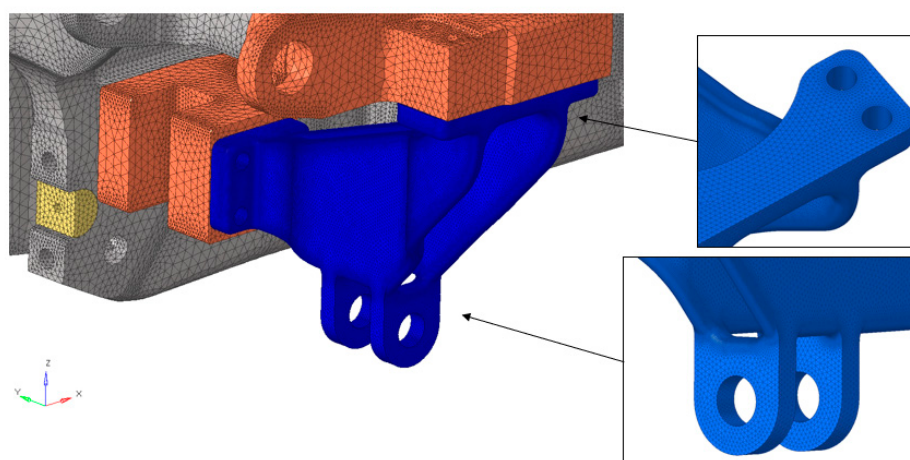


Figure 7. Local view of the innovated motor support FE model.

Table 5. Final assessment: comparison between original performance and innovated ones.

Load Case	G18NiMoCr3		GJS-1050-6		Al Cu4MnMg	
	σ_c [MPa]	U	σ_c [MPa]	U	σ_c [MPa]	U
SL1	252.0	0.48	413	0.59	367	1.18
SL2	252.8	0.48	413	0.59	367	1.18
SL3	17.3	0.03	30	0.04	16	0.05
SL4	3.8	0.01	11	0.02	6	0.02
SL5	50.3	0.10	111	0.16	56	0.18
SL6	200.3	0.38	288	0.41	217	0.70
SL7	9.0	0.02	19	0.03	11	0.04

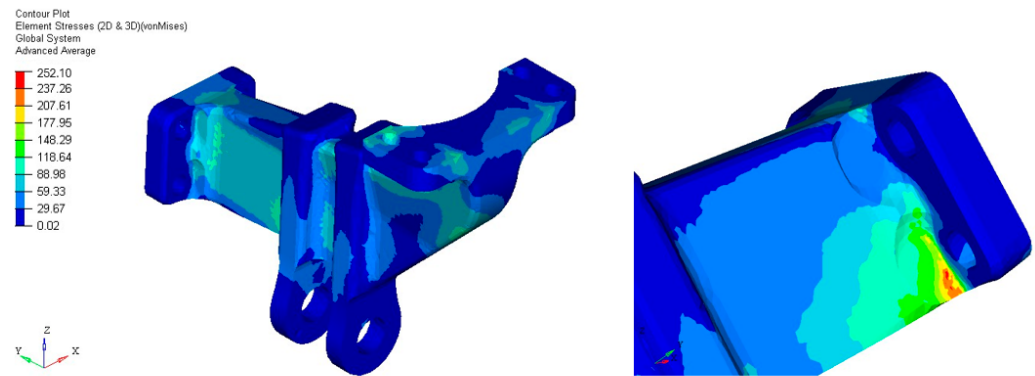


Figure 8. Stress concentration for the original motor support.

With reference to the innovated design, the most critical stress regions for both materials were located at the base of the connecting plate between the support and the bogie frame, as expected and clearly illustrated in Figure 9. It is important to highlight that, in the case of the aluminum alloy, the estimated material utilization coefficient exceeded unity, indicating that the component would theoretically operate beyond the admissible stress limit and therefore would not be acceptable. This finding guides the material selection towards ductile cast iron, which demonstrates adequate safety margins thanks to its higher allowable stress. Although not explicitly investigated in this study, it should be noted that the absence of welding in the motor support design plays a significant role in preserving structural performance. Welded components would likely exhibit local reductions in material strength and higher stress concentrations, potentially leading to critical failure regions. This observation further underscores the relevance of manufacturing-driven design choices, where casting or machining enables the realization of the optimized geometry without introducing structural weaknesses.

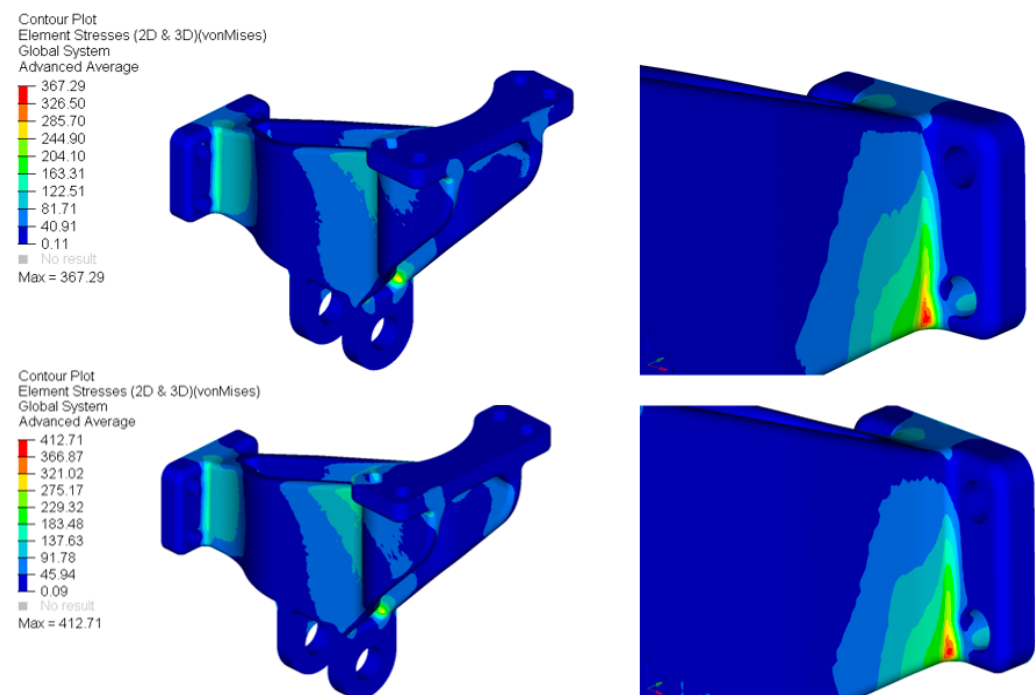


Figure 9. Stress concentration for the innovated motor support: Al Cu4MnMg at the top, GJS-1050-6 at the bottom.

Finally, the present study introduces an innovative visualization of the topology optimization results. Figure 10 presents a combined chart comparing the utilization coefficient

for all tested materials across the various loading scenarios, allowing a rapid identification of the most effective material in terms of stress performance. At the same time, a secondary y-axis is used to display a bubble chart, highlighting the studied solutions and emphasizing their differences. The original steel configuration is represented by a normalized mass of unity (bubble size proportional to mass) and is positioned towards the left of the x-axis, reflecting its lower material utilization under stress. The objective of the optimization process is to shift the solutions downwards, corresponding to reduced stress and lower material utilization (smaller bubble diameter), while simultaneously moving rightwards along the x-axis, maintaining an acceptable utilization coefficient and exploring lighter designs. This visualization strategy provides a clear and intuitive tool for evaluating both the performance of each material under all loading conditions and the characteristics of the optimized motor support configurations. By integrating mass, stress, and utilization coefficient in a single, interpretable chart, it enables a comprehensive and rapid assessment of the trade-offs inherent in the lightweight design process.

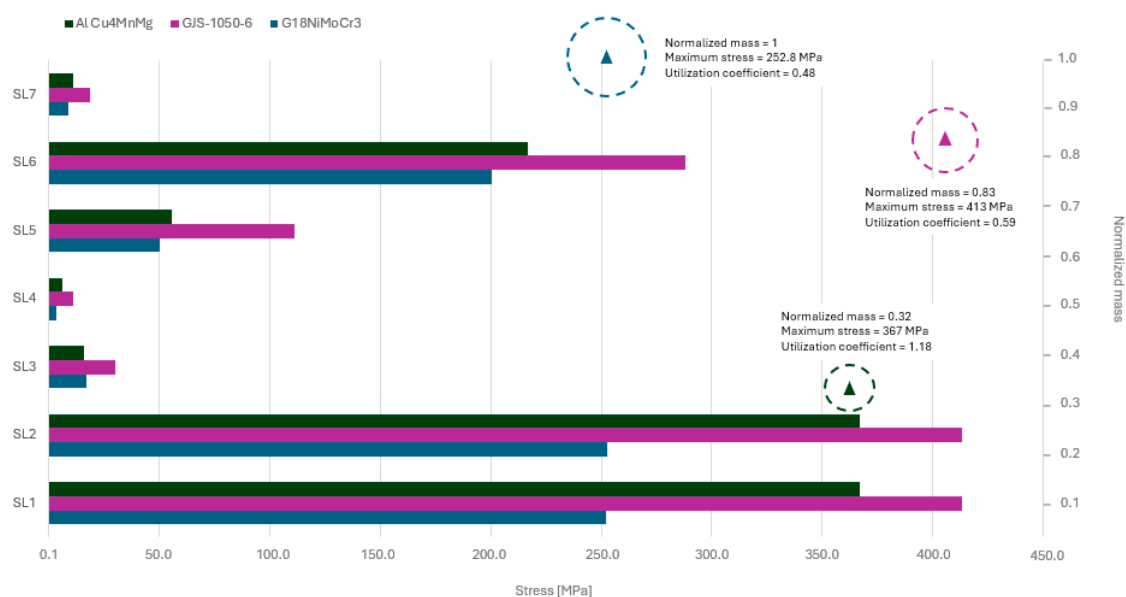


Figure 10. Optimization process final review: material selection performance for all load scenarios on the left, final optimized solutions on the right.

4. Conclusions

This study presented a methodology for the lightweight and manufacturability-oriented optimization of a motor support for railway vehicles, developed within a topology optimization framework compliant with the relevant European assessment standards. The proposed approach aimed to evaluate the combined influence of material selection, manufacturing constraints, and an adaptive stress control strategy on the resulting optimized configuration. The introduction of an influence coefficient associated with the stress field proved to be a key element in the optimization process. Defined from the performance of the original component, this coefficient effectively regulated the admissible stress level during the iterative process, leading to more balanced and realistic material distributions. The results highlighted the relatively low impact of material choice compared to manufacturing constraints, particularly the minimum feature size. When properly assessed through a dedicated sensitivity analysis on the mesh resolution, this parameter emerged as a fundamental factor in achieving a structurally efficient and well-distributed material layout. The combined evaluation of these parameters enabled the development of an effective framework for structural analysis and design innovation through topology

optimization. The resulting motor support exhibited a manufacturable geometry suitable for casting processes and achieved a mass reduction exceeding 16%, while preserving mechanical integrity and compatibility with the bogie interfaces and overall functional requirements. Future developments will focus on extending the optimization framework to include dynamic performance constraints, allowing the optimized geometry to account not only for static load conditions but also for the vibrational and modal behavior of the entire bogie system.

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