CETRA^{2026} 27-30 May 2026, Bol, Island Brač, Croatia
9th International Conference on Road and Rail Infrastructure

INNOVATIVE SINGLE-AXLE BOGIE DESIGN FOR A REGIONAL RAIL VEHICLE

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Abstract

Rail transport is widely recognized as a leader in sustainable mobility, offering substantial environmental benefits and reduced carbon emissions compared to other transportation modes. However, the modernization of railway vehicles remains a critical challenge, particularly in regions where outdated fleets continue to operate. This study presents design and a comprehensive structural analysis of a new single-axle bogie for regional railway vehicles. The proposed design incorporates a frame constructed from S355J2 weldable steel. The finite element analysis was performed to evaluate the structural integrity and the frame simulating the real vertical loads encountered during operations. The maximum stress levels remain below the material's tensile strength limit of 355 MPa, ensuring safety and durability. The maximum displacement was of 1.16 mm, indicating a well-balanced design that provides sufficient torsional flexibility to absorb vertical track irregularities while maintaining adequate stiffness for lateral stability. The results conclusively demonstrate that the bogie frame design meets all required strength and deformation specifications. This innovative solution offers significant potential for modernizing regional rail transport systems, promoting safer, more reliable, and environmentally sustainable railway operations. By addressing the specific needs of regional trains while incorporating advanced materials and suspension technologies, this design represents a promising approach to upgrading aging railway fleets and enhancing overall transportation efficiency in the sustainable mobility sector.

Keywords: bogie, design, rail vehicle, finite element method

1 Introduction

Railway transport is widely recognized as one of the most sustainable modes of transport, particularly regarding its environmental performance [1, 2]. In a period characterized by rapid technological development and continuous transformation of transport systems, the pursuit of innovative solutions aimed at improving operational efficiency, system reliability, and environmental responsibility has become increasingly important [3, 4]. Nevertheless, the popularity of railway transport among passengers is largely driven by additional factors, including a high level of travel comfort, operational safety, relatively extensive network coverage, and competitive journey times [5, 6]. A central objective in contemporary railway vehicle development is development of railway vehicles that meets requirements of performance, passenger comfort, and environments. Therefore, growing public demand for rail transport is accompanied by increasing expectations for modern, safe, and comfortable vehicles, with low-floor accessibility.

A significant challenge remains the prevalence of aging rail vehicles in many countries, where vehicles often operate beyond their intended service life. To reduce investment costs, operators frequently rely on modernization programs to extend the lifespan of older vehicles

DOI: https://doi.org/10.5592/CO/CETRA.2026.1851

typically not low-floor. However, such an approach does not provide a long-term solution. The sustainable development and increasing attractiveness of railway transport can be most effectively ensured through the introduction of newly designed, modern, low-floor vehicles offering enhanced comfort and safety [7, 8]. These requirements are effectively addressed by regional rail vehicles equipped with independent traction systems and single-axle bogies, enabling operation on local non-electrified railway lines. This vehicle concept constitutes an innovative response to the demands of the modern railway sector offering increased flexibility in network utilization, improved passenger comfort, and a reduced environmental footprint [9, 10]. As the bogie plays a decisive role in determining ride quality and operational safety [11-15], this research is concentrated on a conceptual design of an innovative single-axle bogie specifically intended for this category of rail vehicles.

2 Current situation in the Czech Republic and Slovak Republic

Historically, class 810 diesel multiple units have been the most widely deployed rail vehicles in the Czech and Slovak Republics, particularly on non-electrified regional lines. They were produced between 1974 and 1984 at the Vagonka Studénka plant and designed with two powered axles, higher engine power, and improved passenger comfort. Each unit accommodated 55 seated and about 40 standing passengers and primarily served connections between small municipalities or regional towns and major urban centers where road transport is less efficient. In total, around 600 vehicles were delivered to České dráhy and Železničná spoločnosť Slovensko, with an additional 100 units supplied to Hungary. Following extended periods of operation, several modernization programs were implemented. The ŽOS Zvolen company (Slovakia) upgraded the vehicles to class 813, while Pars Šumperk (Czech Republic) introduced the Regionova class 814. An overview individual versions of the rail vehicle is shown in figure 1.

Figure 1 a) the original vehicle 810-class, b) the modernized vehicle 814-class Regionova, c) the modernized vehicle 813-class

While the differences between these variants are relatively minor, notable distinctions include the use of a TEDOM combustion engine in the Regionova units and MAN engines in the 813 class. Variations of a bogie design are similarly limited and mainly associated with differences in transmission systems. More pronounced differences are observed in the vehicle bodies. All these vehicles operate on single-axle bogies. The primary suspension system employs coil springs with wheelset guidance realized by pins, while the secondary suspension is provided by vertical links that also allow limited bogie rotation during curve negotiation.

3 Design of the single-axle bogie

During real-world operation, bogie structures and their frames are exposed to a wide spectrum of load conditions influenced by passenger occupancy, track quality expressed through deviations from ideal geometry, localized track deformation, and various additional operational factors. Consequently, the resulting load conditions are highly variable and cannot be accurately described using deterministic load functions. A representative substitute load spectrum is defined and applied in the testing of newly developed bogie designs. This spectrum also serves as the basis for structural design and, increasingly, for virtual testing and optimization procedures [15, 16]. The applied loading conditions are defined by regulatory frameworks, including UIC guidelines, European and national standards, or internal specifications of the vehicle operator, always reflecting the intended service conditions of the vehicle. The proposed bogie design is based on a wheel diameter of 840 mm and is intended for a normal-gauge track of 1, 435 mm. A three-dimensional model of the single-axle bogie is depicted in figure 2.

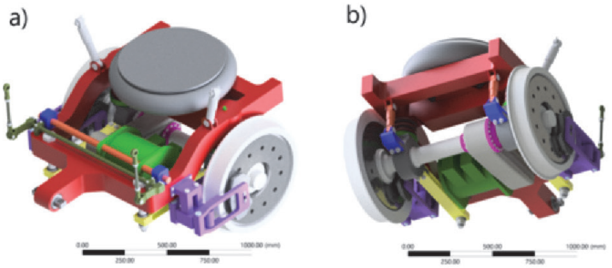

Figure 2 Single-axle rail bogie: a) front view, b) bottom-view

The single-axle bogie incorporates structural elements required for reliable support and guidance of the vehicle body [17, 18]. Traction forces are transmitted through a central pivot. The rear section of the bogie frame is equipped with mounting brackets for a pair of dampers responsible for attenuating oscillatory motion arising from suspension deflection and bogie vibration during operation. These dampers provide damping between the wheelset bearing housings and the bogie frame at the locations of the primary suspension springs. An additional pair of dampers connects the vehicle body to the bogie frame in the vertical direction, where oscillations primarily originate from the secondary suspension system. One limitation of this configuration is positioning of the secondary suspension air spring at a relatively large distance from the pivot. As a result, the vehicle mass is not transmitted exclusively through the air spring; a part of the load is instead carried by the pivot. This leads to increased mechanical loading of the pivot and a marginal reduction of ride comfort. A bottom-view arrangement includes the axle-mounted gearbox, traction motor, wheelset with integrated brake discs, primary suspension springs located between the bogie frame and bearing housings, flat belt wheelset guidance, and the dampers forming a dissipative connection between the bearing housings and the bogie frame.

3.1 A bogie frame structure

The bogie frame constitutes the principal load-bearing element of the running gear and serves as the foundation for mounting all remaining bogie components. An internal frame configuration was selected primarily to achieve weight reduction. The structure is designed as a welded beam-type assembly composed of two longitudinal beams, which are downwardly offset at the front section. The designed bogie frame is shown in figure 3.

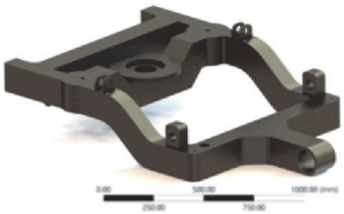

Figure 3 A designed bogie frame

An additional longitudinal beam terminates at the pivot location. The transverse beam features a central offset to minimize spatial requirements for the installation of the secondary suspension air spring. End beams contribute to the transverse stiffness of the frame and provide attachment points for wheelset guidance pins and damper brackets. The selected belt-type wheelset guidance system has been adopted from conventional passenger coaches, where it has demonstrated long-term operational reliability across tens of thousands of vehicles. These belts are typically arranged on both sides of the bogie, parallel to the longitudinal beams. Depending on the application, the belts may be manufactured from steel or composite materials [19, 20]. Their transverse stiffness is high, resulting in minimal lateral deformation. Because the belt-type guidance arrangement largely eliminates multiple pin joints and contact pairs that typically experience fretting, clearance growth, and lubrication-related degradation, the long-term maintenance burden may be reduced. Therefore, from a lifecycle perspective, belt-type guidance may reduce wear in the guidance joints but it increases the importance of belt-condition monitoring and scheduled replacement.

Key advantages of flat belt guidance include low mass and compact spatial requirements. From a structural standpoint, the bogie frame is fabricated from S355J2 structural steel with guaranteed weldability in accordance with EN 10 025-2 [21], using rectangular profiles with a wall thickness of 12 mm. Subsequent strength analysis confirmed that this thickness represents an optimal compromise between structural integrity and material efficiency. The selection of the secondary suspension system was guided by the intended operational profile of the vehicle. An air spring was therefore chosen as the most suitable solution. Its primary advantage lies in the ability to regulate internal pressure, ensuring that buffer height remains within prescribed limits despite changes in static load. Additionally, air suspension provides favorable compliance characteristics, which are particularly important for lightweight regional vehicles subject to fluctuating passenger loads.

4 Assessment of the structural strength

The primary aim of the numerical analysis was to verify the structural integrity of the designed bogie frame under boundary conditions that realistically represent the operational load modes. The strength assessment was conducted as a static analysis focusing on vertical loading of the bogie frame and was performed using the finite element method (FEM). While the present assessment is based on a static vertical load case, extending the study to dynamic loading and fatigue under real track irregularities would provide additional, practically relevant insights. Measured or standardized track geometry spectra combined with vehicle speed would yield time histories of forces transmitted through the springs, pivot, axlebox areas and guidance elements, capturing dynamic amplification and occasional peak loads that static averaging can miss. This would allow identification of resonance-sensitive regions via modal and transient response analysis, and it would clarify whether the observed stress and deformation margins remain valid under realistic excitation (e.g. dip joints, turnout irregularities). The simulations were carried out in the ANSYS software, which is widely employed for solving problems in structural mechanics, dynamics, and fluid mechanics [22-25].

The principal advantage of numerical simulation methods is their capability to analyze complex geometries that would be impractical to evaluate analytically. However, computational effort and analysis duration are strongly dependent on available hardware resources, and any modification to the model requires repetition of the entire simulation process. The strength analysis incorporated several boundary conditions. The vertical load of 99, 695.1 N was applied at the position of the secondary suspension air spring, corresponding to the average gravitational load transmitted from the vehicle body to a single bogie.

An illustration of the defined boundary conditions and the bogie frame mesh are depicted in figure 4. The finite element mesh of the bogie frame consisted of elements with a nominal size of 12 mm, resulting in 216, 439 elements and 395, 794 nodes.

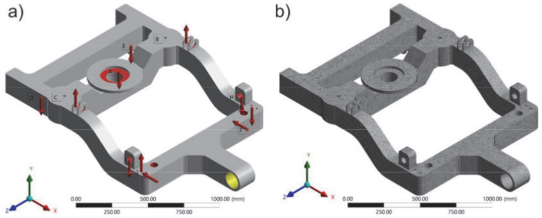

Figure 4 a) the boundary conditions for defined for calculation, b) the created finite element model of the bogie frame

This results to the total load of approximately 199, 390 N distributed across both bogies. Additional loads included a 7, 000 N force representing the weight of the traction system, a 15, 000 N load applied to the motor mounting brackets, and 8, 000 N loads applied to the damper mounting brackets for both suspension stages. In regions with complex geometry or expected stress concentrations, the mesh was locally refined using smaller elements automatically generated by the software, thereby improving the accuracy of the results.

The resulting stress distribution is shown in figure 5a and the calculated deflections are in figure 5b. The stresses are evaluated using the von Mises criterion. It demonstrates that the bogie frame satisfies the strength requirements, as the maximum equivalent stress remained below the yield strength limit of 355 MPa. The displacement analysis revealed a maximum deformation of approximately 1.16 mm. Higher deformation values indicate increased torsional flexibility of the bogie frame, which enhances the ability to absorb vertical track irregularities. Conversely, lower deformation values correspond to greater torsional stiffness and improved lateral stability.

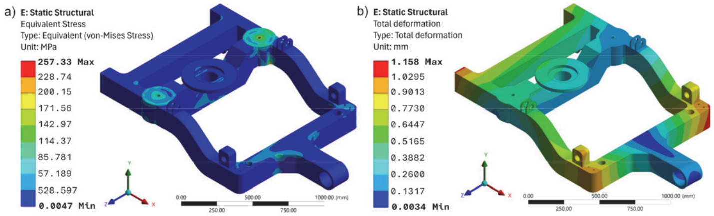

Figure 5 a) a distribution of stresses in the bogie frame structure, b) calculated deflections of the bogie frame structure

5 Conclusion

This study addressed the conceptual design and structural assessment of an innovative single-axle bogie intended for regional rail vehicles. The work was motivated by an analysis of the current state of railway transport in the Czech and Slovak Republics, where aging rail vehicles remains prevalent, particularly in the form of the 810-class diesel multiple units and their modernized derivatives. Based on the identified shortcomings, the development of new low-floor regional rail vehicles capable of efficient operation on local lines while maintaining high standards of comfort, safety, and environmental performance was proposed. The bogie represents a critical subsystem in such vehicles, exerting a substantial influence on ride behavior, stability, and passenger comfort. Accordingly, the primary focus of this work was placed on the design of a single-axle bogie and its load-bearing frame.

The proposed bogie design incorporates coil-spring primary suspension, flat belt wheelset guidance, and air-spring-based secondary suspension, enabling automatic adjustment of vehicle height in response to load variations. A comprehensive strength analysis of the bogie frame was performed using the finite element method in ANSYS under static loading conditions reflecting the gravitational effects of the vehicle body and onboard equipment. The results confirmed that the proposed structure meets all strength criteria, as the maximum von Mises stress remained below the material yield limit. Furthermore, the observed deformation levels indicate adequate torsional compliance, contributing to effective absorption of vertical track irregularities and improved ride comfort. Based on these findings, it can be concluded that the proposed single-axle bogie constitutes a technically viable solution suitable for implementation in modern regional rail vehicles.

Acknowledgement

This publication was also supported by the project KEGA 028ŽU-4/2026 and VEGA 1/0308/24.

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