

Technologies for Minimizing Track Degradation and Additional Dynamic Effects at Permanent Way-Railway Bridge Stiffness Transitions [†]

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Abstract

Railway tracks at bridge approaches experience significant vertical stiffness transitions, leading to adverse effects such as settlement and increased dynamic loads, accelerating track degradation. This study explores various structural solutions, including geosynthetics, reinforced ballast, transition slabs, under sleeper pads (USPs), under ballast mats (UBMs), jet grouting, and special rail fasteners. Despite their application, these solutions often fail due to their static nature. This paper introduces an adaptive approach using special rail fasteners with real-time adjustable stiffness. This system dynamically modifies rail support characteristics based on train speed and track conditions, improving track durability, ride quality, and maintenance strategies. The findings demonstrate the potential of adaptive systems to enhance railway infrastructure performance.

Keywords: railway bridge transition; track stiffness; dynamic fastening system; track settlement; smart rail support



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1. Introduction

Vertical stiffness transition is one of the most significant challenges in railway infrastructure. It manifests in the interface between a flexible railway track and a bridge superstructure, more critically at the bridge abutment. Given this region's placement between a soft, compressible soil foundation and a stiffer, unyielding bridge structure, it is described as a “trouble spot.” As trains pass through these regions, the abrupt change in support stiffness results in many problems. A possible settlement of the flexible track section, coupled with the unyielding rigid bridge, will result in uneven longitudinal track bedding. Dynamically applied train loads will be amplified in this region as suspension systems become increasingly overloaded, causing aggravated track component vibrations. Among others, these components include rail joints and fasteners. In the long term, this can cause misaligned tracks, requiring higher maintenance levels and exposing safety-related concerns. Existing solutions, i.e., (i) gradually stiffening geosynthetics transitions, (ii) reinforced ballast layers, (iii) transition slabs, (iv) under sleeper pads, (v) under ballast mats, (vi) special soil improvements, e.g., jet grouting, as well as (vii) special rail fasteners, seek to ease the problem but fail due to their static nature and incapacity to respond in real-time to varying train loads. Monitoring systems can identify these factors but are left without fixable modifications; they simply report damage without preventing it. The real

answer may lie in adaptive rail support and fastening systems that can dynamically adjust their stiffness based on the load using technologies like hydraulic, pneumatic, or magnetic mechanisms. These adaptive systems could react instantly to train movements, cushioning vibrations, maintaining even support, and extending the track's lifespan.

The paper is structured as follows: Section 2 presents the existing solutions for managing stiffness transitions, Section 3 explores the proposed adaptive approaches, and the derived conclusions are provided in Section 4.

2. Literature Review

This section presents solutions currently implemented to address vertical stiffness transitions. These solutions are primarily applied to railway bridges but may also be designed and constructed in special cases, such as grade crossings or connecting track structures of varying configurations. In the case of grade crossings, these solutions are necessary if the crossing's superstructure is ballastless—for example, an embedded rail system—while the adjacent track section features conventional ballast.

In mainline railway tracks, the primary focus is also on managing the transition between ballastless and ballasted track superstructures. A notable example is Line 1 of the Budapest tram network, where seven different superstructure types, as specified by BKV Ltd. (Budapest Transport Privately Held Corporation), alternate.

Sections 2.1–2.7 aim to present the most common configurations, not all available.

2.1. Gradual Stiffness Transitions Using Geosynthetics

Geosynthetic materials enhance the interaction between soil and the connection zones between flexible tracks and rigid structures. This approach improves the bearing capacity, compression modulus, and overall stability of the track foundation, bringing its stiffness closer to that of bridge abutments. However, a perfect match is impossible due to the significant stiffness difference, and transitions must be managed stepwise using partial sections [1].

Commonly used geosynthetics, such as geogrids or geocomposites, are primarily designed to control differential settlement and reduce excessive stresses on the rails [2]. Their effectiveness depends on installation parameters, including material type, quality, and structural configuration, but they provide only static stiffness enhancement [3]. Once installed, their properties cannot be adjusted during railway operation. If the underlying layers deform due to design flaws, overloading, etc., it leads to permanent damage [4].

Restoration typically requires dismantling, reinforcement, or multiple rounds of geometric correction involving extra ballast. Unfortunately, this approach is often symptomatic and may not guarantee a durable solution. Similar problems can occur without reinforcement, particularly when addressing “water pockets” or drainage issues without resolving the underlying cause [5].

2.2. Reinforced Ballast Layers

The primary purpose of reinforced ballast layers is to enhance load-bearing capacity and limit or reduce deformation in railway transition zones. Reinforcement techniques—such as bonded (glued) ballast [6], among others—increase the stiffness of the ballast layer and, consequently, the entire track structure. This improvement primarily affects vertical stiffness but, in some instances, can also enhance lateral stiffness, providing more stable support and lateral restraint for the track.

This approach is becoming increasingly popular because research results indicate that reinforced ballast reduces stress concentrations at transitions, improves settlement control, and thereby enhances overall railway performance [7]. The bonded ballast solution

can only be implemented in a stepwise arrangement, making subsequent modifications impossible, as detailed in Section 2.1.

Although reinforced ballast designs can approximate the required stiffness transition profiles quite effectively—albeit in a static manner—their significant drawback is that they tend to accelerate ballast particle degradation (i.e., breakage). This degradation leads to plastic settlements and track deformations, which may increase maintenance needs [2,7].

It is important to note that ballast degradation can be mitigated using specialized solutions (see Sections 2.4 and 2.5) or by enhancing the physical properties of the ballast material itself (i.e., using higher-quality stone, such as basalt or granite, instead of andesite). However, even these measures cannot entirely eliminate the problem [8].

Another concern is that track geometry corrections in bonded ballast sections are often challenging or impossible. Structural bonding—such as bonding in lower layers—can be adequate, as can bonded beams on the curves' outer and/or inner sides. However, bonding in the upper layers between and alongside sleepers severely limits the ability to perform track geometry adjustments, allowing only minimal modifications [6,9].

2.3. Transition Slabs

Transition slabs (also known as specialized “floating slabs”) serve to connect different track systems—primarily a flexible system and a significantly more rigid one—to rigid structures, effectively creating a “bridge” between the two. These slabs partially absorb and distribute longitudinal and transverse stresses caused by temperature variations [7]. In an optimal design, transition slabs can secure connections while significantly increasing the risk of structural damage due to vibrations generated by passing trains. These slab structures effectively dampen harmful vibrations affecting structural elements and the resulting displacements and movements [10].

However, the effectiveness of transition slabs in managing vertical stiffness variations depends on other design considerations and their relationship to the overall railway system. The mechanical properties of the slabs are also influenced by the underlying materials (layer structure, embedded granular materials, etc.) and the loading conditions [10]. While transition slabs can significantly improve the situation at transitions, they can also become potential failure points if improperly designed. This highlights the necessity for assessment and adaptation to operational requirements.

One major drawback of transition slabs is that they tend to “shift” the problem from the cross-section of the bridge abutment to the cross-section at the beginning of the transition slab. This occurs because there remains a significant difference in vertical stiffness between the conventional ballasted track structure and the transition slab. Compared to the solutions discussed in Section 2.1 (where the problem persisted at the bridge abutment cross-section), the resulting issues primarily appear at the far end of the transition slab.

2.4. Under-Sleeper Pads (USPs)

Under-sleeper pads (USPs) are designed to improve load distribution between sleepers and the ballast, thereby reducing the dynamic impacts of trains. This effect helps maintain track geometry as accurately and consistently as possible while minimizing vibrations. These factors are crucial for extending the lifespan of railway infrastructure and reducing the frequency and extent of maintenance activities [11]. Relying on USPs with variable stiffness provides an especially innovative solution for the problem [12].

It is essential to note that by reducing the vertical stresses transmitted to ballast (i.e., particles), USPs also help mitigate ballast particle degradation and wear.

However, USPs cannot be considered a complete solution for the topic addressed in this article. Relying solely on USPs cannot fully resolve the problem. They should only be used as a supplementary measure with other solutions (see Section 2.8).

2.5. Under-Ballast Mats (UBMs)

Applying under-ballast mats (UBMs) in transition zones between railway tracks and bridges has become increasingly popular as a potential solution for managing stiffness transitions. UBMs effectively reduce track stiffness, thereby mitigating dynamic forces and minimizing vibrations transmitted to structural elements. This is particularly beneficial for maintaining passenger comfort and extending track lifespan [13–15]. In practice, UBMs are primarily placed on the bridge side of the transition zone to lower the high vertical stiffness values typically present there.

Additionally, UBMs help minimize ballast degradation, which is often exacerbated by sudden support changes in transition zones [15,16]. Field application experiences highlight the need for careful design and material selection to optimize performance [17,18]. Integrating UBMs with geogrids can enhance stability but may also increase installation costs and complexity [16,17]. UBMs are not worth using as a unique reinforcing material; see Sections 2.4 and 2.8.

2.6. Jet Grouting

Jet grouting technology represents a significant technological innovation and solution in the field of soil improvement, particularly at the interfaces between railway tracks and bridges. This advanced technology involves injecting a high-pressure, cement-based mixture into the soil, enhancing the soil's structure, strength, density, and load-bearing capacity. Such improvements are crucial for managing stiffness transitions arising from differences in soil properties, support behaviors, and other factors between tracks and bridge abutments or structures [19,20].

The primary advantage of jet grouting is its ability to effectively strengthen weak soils, increasing the stability and load-bearing capacity of railway systems [21,22]. Moreover, it minimizes disruption to surrounding structures—if any—compared to traditional methods, making it an ideal solution for urban, densely built environments where existing infrastructure is present [23,24].

On the other hand, challenges associated with jet grouting include variability in the diameter and integrity of the grouted columns, which can lead to uneven or inadequate performance [25]. Additionally, the economic aspects of jet grouting—such as costs, the time required for site-specific adjustments, and the potential for long-term maintenance issues (although these are generally uncommon)—require careful consideration [26,27].

Experience from various applications highlights the benefits of improved soil cohesion and reduced deformation. At the same time, it underscores the necessity of rigorous preliminary assessments and post-installation monitoring to ensure the desired performance is achieved [28,29].

2.7. Special Rail Fasteners

Given that this topic is a central focus of the current article (featuring even more specialized configurations than the solutions presented above), the authors have chosen to analyze this segment in greater detail, as discussed in the following sections.

Applying special rail fasteners at the interfaces between railway tracks and bridges can enhance stiffness transitions, particularly in terms of vertical and longitudinal stiffness, while reducing noise and vibrations. Special fasteners like Zero Longitudinal Restraint (ZLR) and Reduced Longitudinal Restraint (RLR) systems minimize axial (longitudinal)

stresses during train passage, improving track dynamics [30–32]. These fasteners reduce dynamic forces, enhancing ride comfort and safety.

However, implementing these technologies requires precise design to avoid excessive rigidity, which may worsen vibration issues or increase wear [32,33]. Optimal stiffness can lower noise, but overly stiff fasteners may amplify noise under harmonic loading [34,35]. Adjustable fasteners are promising for transition zones but require careful monitoring to maintain effectiveness [36].

Resilient rail fasteners with resilient elements and rail pads reduce vibrations, ensuring smooth transitions and minimizing track deformation risks [37,38]. Such designs lower dynamic force transmission to bridge structures, enhancing stability [39]. Longitudinal stiffness is also crucial, affecting resistance and load transfer between rails and structures. Well-designed fasteners adapt to differential movements caused by temperature or load variations [40,41].

Advanced materials in fasteners can significantly reduce noise, as their frequency-dependent properties target specific vibration frequencies [42]. This reduces environmental noise, improves passenger comfort, and extends infrastructure lifespan by minimizing fatigue [43]. However, high-quality materials and precision manufacturing can increase costs. Implementing these systems in existing railways involves a learning curve and potential additional costs [40,41].

Despite their higher costs, special fasteners have shown positive results, with reports of improved ride comfort and reduced maintenance in high-dynamic-load zones. European high-speed railway case studies demonstrate the effectiveness of adjustable fasteners in transition zones [40,41].

2.8. Mixed-Combined Solutions

A combination of the different solutions presented in Section 2 can also be implemented. As predicted, better results can be achieved with the combined solutions than with them individually. For example, use a transition slab and USP, but other effective combinations can be implemented (e.g., USP + UBM + transition slab).

3. Possible Future Adaptive Solutions Related to Rail Fasteners

Transforming railway maintenance operations, adaptive rail fastening technology solves problems in stiffness transition zones where dynamic loads are most problematic [44]. Modern fastening systems utilize advanced materials, real-time monitoring, and sophisticated numerical models to protect the infrastructure under challenging operational conditions proactively [44,45]. Continued development is imperative to refine these technologies, helping to safeguard an efficient railway network.

The initial idea originated from Cui et al. [46], who presented a solution involving a structure made of MRE (magnetorheological elastomer) material. This structure is positioned beneath the base plate, and its stiffness—both static and dynamic—can be adjusted based on the variation of the electrical current passing through it.

The authors of this article have further developed this concept. At this stage, the idea exists only at the conceptual design level, and further research is necessary to establish the mathematical-physical-dynamical and control frameworks and ensure that the solution can be tested and potentially implemented in real-world applications.

According to the concept, the proposed solution is as follows:

1. The MRE or hydraulic/pneumatic elements must be installed beneath the rail fastenings in the transition zone and along the bridge abutment sections.
2. A more modern, expensive solution is possible by installing them under every rail fastening along the entire bridge length.

3. Sensors must be installed—considering redundancy—before, within, and after the transition zones (at both ends of the bridge) over an appropriate length (approximately min. 50–100 m before and after the transition zones) to measure the approaching vehicle and the dynamic characteristics it generates.
4. From the precise collection of these dynamic data (vehicle type, vehicle speed, vehicle mass, vibrations, vibration accelerations) and the elastic and plastic deformations caused by vehicle passages, it will be possible to calculate in advance the most ideal stiffness characteristics in the transition zones for each passing train to minimize dynamic impacts and reduce plastic deformation.
5. The (MRE) elements must be connected to an electronic network to allow individual regulation according to the ideal profiles calculated and predicted from the measured characteristics specified in point 4.
6. It is worth mentioning that the lowest train speed should be max. 5 km/h, and the highest speed has to be 160 to 350 km/h, depending on the line speed. The sudden changes must be managed, i.e., safety braking or unexpected cases.
7. A training database must be created based on the results of multiple measurement series conducted through various vehicle passages and their evaluations, using an appropriate mathematical-physical-dynamic model to achieve the most ideal results and settings for each case.
8. The solution can be supported by learning algorithms and artificial intelligence-based computational methods.
9. Future research will/should include a full theoretical development of the system.

4. Conclusions

This study tackled the problem of vertical stiffness transitions at railway bridges, a key factor affecting track geometry, dynamic stability, and lifespan. Conventional solutions were critically reviewed. While widely used, these static methods often struggle to address the complex, dynamic interactions between flexible track systems and rigid bridge structures. A significant contribution to this research is introducing an adaptive approach using MREs/hydraulic/pneumatic elements and intelligent rail fastening systems. This innovative solution enables real-time adjustment of rail support stiffness based on train speed and load, significantly reducing dynamic forces, minimizing plastic deformations, and lowering maintenance demands. This system enhances ride quality and extends track life by continuously optimizing stiffness transitions. Further research should focus on refining mathematical models, developing robust control algorithms and, e.g., fuzzy method solutions [47,48], and conducting full-scale tests [49,50] to validate the system's performance. This study lays the basis for a new generation of smart infrastructure capable of maintaining optimal performance under varying conditions. The solution presented could also help to optimize the energy consumption of vehicles [51], and the use of special rail welds in the transition zone could be considered [52].

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