



ENHANCING RAILWAY SUPERSTRUCTURE PERFORMANCE WITH UNDER SLEEPER PADS: A CROATIAN INFRASTRUCTURE PERSPECTIVE

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Abstract

The Croatian railway network forms part of four Trans-European transport corridors and is currently undergoing one of the largest investment cycles in its history, with significant works planned in the 2026 to 2030 period. International lines must satisfy load model D4, which imposes strict requirements on the superstructure and demands the use of high-quality crushed-stone ballast with Los Angeles abrasion resistance $LA_{RB}16$. Only a limited number of Croatian quarries can supply ballast of this quality, and large parts of the country, particularly Istria, Lika and Dalmatia, are deprived of suitable eruptive stone deposits. Transport distances from the few remaining sources frequently exceed the cost of the material itself, posing a growing economic and environmental burden. In parallel, international experience has shown that under sleeper pads (USPs) reduce the peak contact pressure at the sleeper-ballast interface, distribute vertical stresses more homogeneously, slow ballast degradation and extend tamping intervals - an effect confirmed by more than 1,500 instrumented cross-sections on Austrian main lines. More importantly, research demonstrates that the reduced stress level enables the use of ballast with lower abrasion resistance, reduced angularity or higher fines content without compromising track performance. This paper combines a review of the current ballast supply situation in Croatia, including the relevant regulations, qualifying quarries and the Los Angeles test methodology, with a synthesis of the operational and experimental evidence on the role of USPs. The discussion concludes that USPs should not be regarded merely as a track-protection measure, but as a key enabler for adaptive ballast specifications, supporting a more resilient, sustainable and economically viable development of the Croatian railway network.

Keywords: railway ballast, under sleeper pads, testing, performance, Croatian railway network

1 Introduction

Ballasted track remains the dominant superstructure form on the Croatian railway network and on the great majority of European main lines. The long-term performance of such tracks depends heavily on the quality of the crushed-stone ballast and on the way vertical loads are transferred from the sleeper to the ballast bed. As traffic loads on the international corridors of the Republic of Croatia increase to satisfy the requirements of load model D4 (22.5 t/axle, 8.0 t/m), the demand for high-quality ballast is rising in parallel with major investment in track renewal and modernisation. At the same time, the number of Croatian quarries able to supply ballast that meets the most stringent abrasion-resistance class ($LA_{RB}16$) is limited, and transport distances continue to grow.

This situation has led infrastructure managers and researchers across Europe to look for measures that either reduce the loading on the ballast, extend its service life, or relax the quality requirements without compromising safety. Under sleeper pads (USPs) - resilient elastomeric layers placed between the concrete sleeper and the ballast - have emerged as one of the most promising solutions in all three respects.

The aim of this paper is twofold. It first summarises the present state of the Croatian railway network, the regulatory framework governing ballast quality and the testing methodology used to verify it. It then reviews international evidence on the influence of under sleeper pads on ballast contact pressure, settlement behaviour and tamping intervals, with particular attention to the reduced stress level produced by USPs in respect to ballast quality requirements.

2 Croatian railway network and investments

2.1 Trans-European corridors

With the accession of Croatia to the European Union, the Croatian railway network became part of the Trans-European Transport Network (TEN-T). TEN-T corridors are of major importance for the development of railway transport in Croatia because they connect the country with key European economic and transport flows. Due to its geographical position between Central Europe, the Balkans, and the Adriatic Sea, Croatia serves as an important transit state within the European railway system. The most significant railway routes in Croatia are part of the Mediterranean Corridor and the Rhine–Danube Corridor, linking major urban and freight centres such as Zagreb, Rijeka, Vinkovci, and Osijek with neighbouring EU member states and international markets. Through the TEN-T framework, Croatia has been modernising railway infrastructure by improving interoperability, electrification, signalling systems, and operational speeds in accordance with European standards. The railway network is especially important for strengthening the role of the Port of Rijeka as a gateway for Central Europe and for shifting freight transport from roads to more sustainable rail transport. A major development occurred with the revised TEN-T Regulation adopted by the European Union and implemented during 2025, which expanded and reorganised the European Transport Corridors. Croatia gained increased strategic importance through the introduction of the new Western Balkans–Eastern Mediterranean Corridor, connecting the Western Balkans more directly with the EU core transport network. This corridor expansion improved Croatia’s role as a bridge between Southeast Europe and the rest of the European Union while also creating stronger links toward neighbouring non-EU Balkan countries. In addition, the updated TEN-T guidelines included additional Croatian transport hubs and routes within the expanded European network structure, further strengthening the country’s position in future railway planning and cross-border connectivity [1]. The 2025 expansion therefore represents not only an infrastructure policy change, but also a significant geopolitical and economic opportunity for Croatia’s railway sector and its long-term integration into a sustainable European transport system. The total length of railway lines in the Republic of Croatia amounts to 2,617 km. According to their importance they are classified into international lines (1,460 km), regional lines (626 km) and lines of local importance (531 km). In accordance with the relevant Regulation (Official Gazette NN 84/21).

2.2 Investment cycle in railways in Croatia

In recent years the Croatian railway sector has been the subject of an exceptional investment cycle, encompassing both the construction of new infrastructure and the renewal of existing lines, together with the modernisation of the wider rail system. Design and construction activities are currently in progress on virtually all lines of international, regional and local significance.

The total planned investment in railway infrastructure for the period 2026-2028 amounts to approximately EUR 1.37 billion, as shown in figure 1. A more detailed graphical overview of the projects currently underway is provided by HŽ Infrastruktura [2].

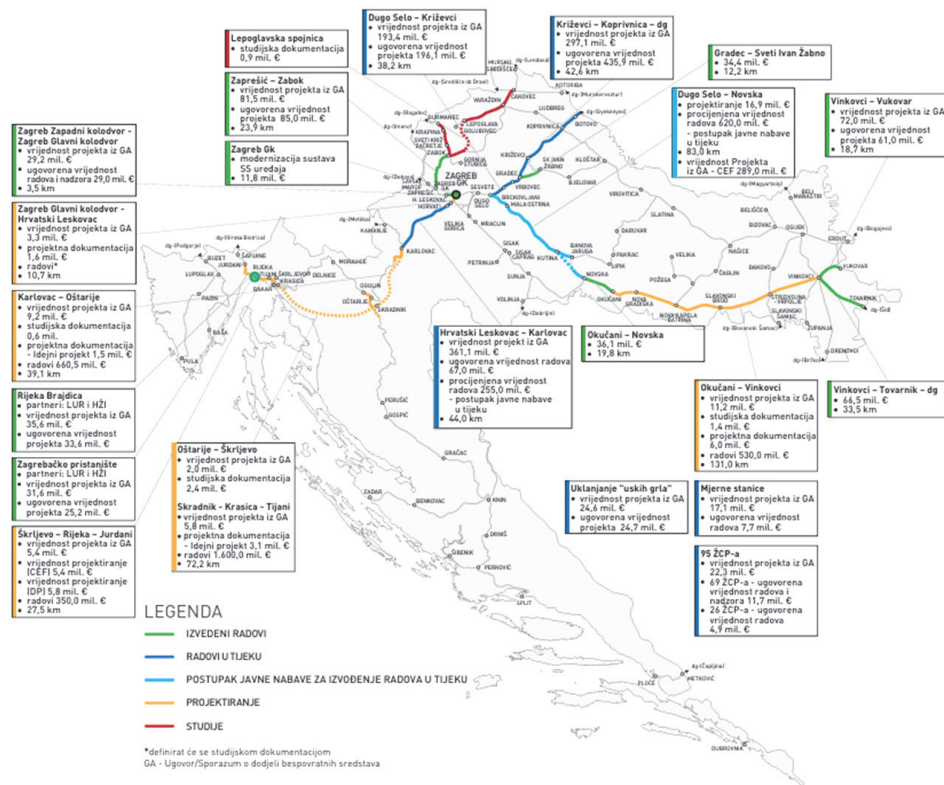


Figure 1 Overview of railway infrastructure projects in Croatia, co-financed from EU Cohesion Funds, NPOO and CEF, including works and study/design documentation; original legend in Croatian [2]

3 Technical regulations and ballast quality requirements

The Regulation on technical conditions for the safety of railway traffic prescribes the technical conditions required for safe, orderly, regular and uninterrupted railway operation, as well as the essential functional conditions for railway infrastructure subsystems that the railway lines in the Republic of Croatia must satisfy [3]. The Regulation stipulates that, for international traffic, the superstructure and substructure of upgraded and/or reconstructed lines intended for mixed and freight traffic must, at the permitted speed, satisfy load model D4 (22.5 t/axle, 8.0 t/m). This requirement applies to more than 50% of the lines operated by HŽ Infrastruktura. Such loads call for substantial investment in the existing infrastructure in order to meet all the parameters laid down by international standards. The most common problems on the substructure concern the strengthening and widening of the track body, as well as the strengthening or replacement of existing bridges and culverts.

The loads transferred to the substructure originate not only from rail traffic itself, but also from the heavier superstructure grid required to satisfy load model D4, which is built using concrete or wooden sleepers and UIC60 rails. Such a track superstructure and traffic load can be supported only by a ballast bed consisting of crushed stone with an abrasion resistance of $LA_{RB} 16$. In its Technical conditions for the production and delivery of railway ballast, HŽ Infrastruktura has prescribed that ballast of category $LA_{RB} 16$ must be used in the construction of all lines intended for international traffic and in all switch and crossing areas. The use of $LA_{RB} 20$ ballast on international lines is permitted only in maintenance operations on sections where stone of that quality has previously been installed [4].

4 Quarries supplying railway ballast in Croatia

Only a small number of Croatian quarries currently meet the $LA_{RB} 16$ abrasion resistance requirement for railway ballast. The large planned infrastructure investments are accompanied by high demand for ballast, which the existing quarries struggle to meet both in production capacity and in logistics. Quarries are often located several hundred kilometres from the worksite, and delivery costs frequently exceed several times the unit cost of the material at the quarry itself. Quarries supplying railway ballast of $LA_{RB} 16$ quality are located in the northern and eastern parts of the country, whereas Istria, Lika and Dalmatia are essentially deprived of suitable eruptive stone deposits. HŽ Infrastruktura currently obtains railway ballast for its projects from the following quarries: Psunj (Okučani), Bojna (Petrinja), Radlovac (Orahovica) and Fužinski Benkovac.

5 Los Angeles abrasion test

5.1 Purpose of the test

The Los Angeles abrasion testing apparatus is used to measure the resistance of coarse aggregate (ballast) to friction and impact under standardised conditions, expressed as the loss of mass in per cent. The Los Angeles abrasion loss method is a key indicator of the quality of crushed-stone materials and is closely correlated with compressive strength, resistance to wear and the durability of concrete, asphalt mixtures and unbound base materials. In general, aggregates with low wear losses are hard and exhibit good resistance to abrasion and good durability. Conversely, stone materials with a high proportion of weak particles or susceptibility to weathering exhibit very poor results in abrasion and crushing tests [5].

5.2 Apparatus

The Los Angeles testing apparatus, shown in figure 2 together with the steel charging balls used during the test, consists of a sample cylinder with an internal diameter of $710 \text{ mm} \pm 5 \text{ mm}$ and an internal length of $510 \text{ mm} \pm 5 \text{ mm}$. The cylinder is closed at both ends and fitted with a steel cover over a charging opening. Together with the aggregate, steel balls with a diameter of approximately 46.8 mm and a mass in the range of 390 g to 445 g are placed inside the cylinder, so that the total mass of the charge is between $4,690 \text{ g}$ and $4,860 \text{ g}$. The cylinder rotates at a speed between 31 and 33 rpm.



Figure 2 Los Angeles abrasion testing apparatus with steel charging balls [5]

5.3 Test procedure and Los Angeles coefficient

The test procedure consists of placing $10,000 \pm 100$ g of ballast into the steel drum together with an abrasive charge of twelve steel balls (diameter 45 – 49 mm, mass 400 – 445 g, total mass 4,690 to 4,860 g). The drum is rotated 1,000 times around its axis at a constant speed of 31 to 33 rpm. Sieving on a 1.6 mm sieve is then used to determine the difference between the initial mass and the mass of the aggregate retained on the sieve. The Los Angeles coefficient is computed according to the following equation:

$$LA = (10000 - m) / 100 \quad (1)$$

where LA is the Los Angeles coefficient and m is the mass of the fraction retained on the 1.6 mm sieve, expressed in grams [6]. The lower the LA coefficient, the higher the abrasion resistance of the tested ballast. Category $LA_{RB} 16$, required by HŽ Infrastruktura for international lines, corresponds to a maximum LA value of 16%.

6 Under sleeper pads and ballast contact pressure

6.1 Effect on contact pressure and ballast degradation

The long-term performance of ballasted railway track systems is strongly influenced by the magnitude and distribution of contact pressures at the sleeper-ballast interface. Excessive ballast contact pressure accelerates ballast degradation, settlement and fouling, leading to increased maintenance demand and reduced track availability. Under sleeper pads introduce a resilient elastic layer between the concrete sleeper and the ballast, altering the load transfer mechanism and reducing peak contact stresses. As illustrated in figure 3, the pad allows the ballast stones to embed into its surface, which significantly enlarges the effective contact area between sleeper and ballast and, in consequence, reduces the peak contact pressure transmitted to individual stones.

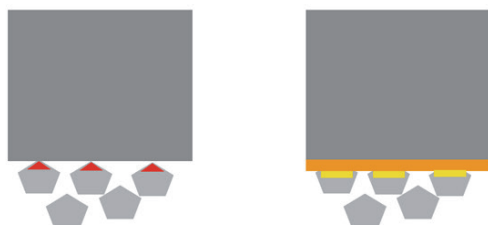


Figure 3 Illustration of increased ballast embedment through the application of USPs (Source: Getzner Werkstoffe GmbH)

Numerous laboratory tests, full-scale track trials and numerical simulations have demonstrated that USPs lead to a more homogeneous distribution of vertical stresses and to a significantly lower maximum ballast contact pressure. As shown in figure 4, the contact area between sleeper and ballast can be increased by approximately a factor of ten when an elastoplastic PUR USP is used, which corresponds to a reduction of the ballast contact pressure of the order of 85%. This reduction directly slows particle breakage and ballast attrition, contributing to longer tamping intervals and improved life-cycle performance of the ballasted track system. Railway operators including ÖBB and DB have reported positive operational experience, particularly on highly loaded main lines and on sections with restrictive maintenance windows [7, 8].

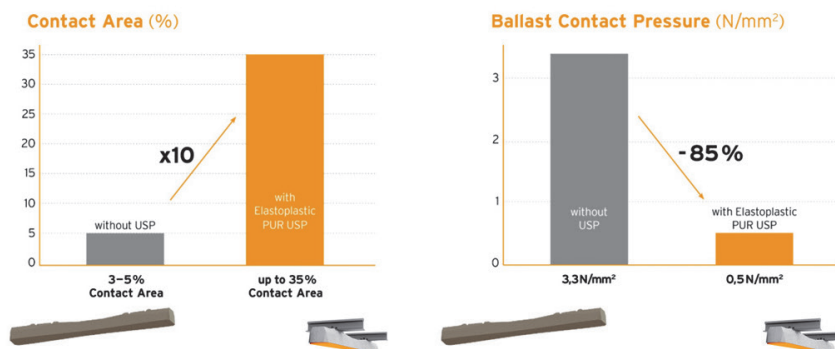
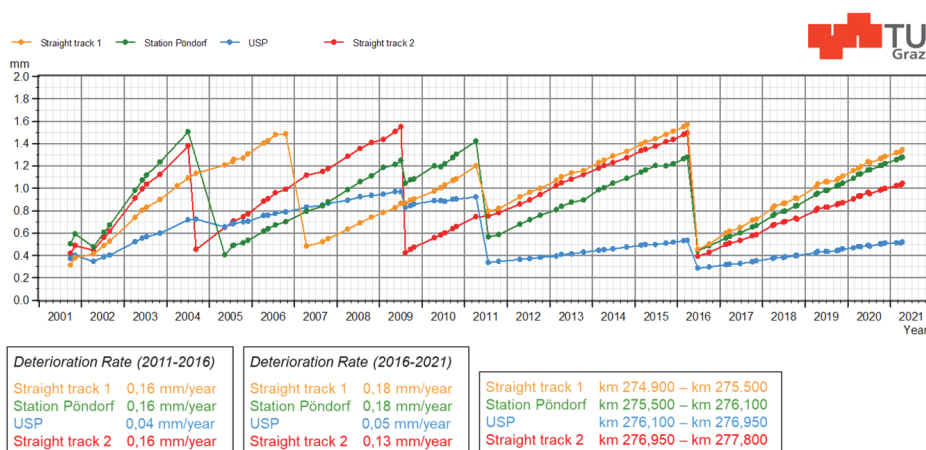


Figure 4 With introduction of USP: Increasing the contact area results in a decrease of ballast contact pressure (Source: Getzner Werkstoffe GmbH)

The evaluation of more than 1,500 cross-sections on Austrian lines with traffic loads exceeding 20 MGT, equipped with Getzner under sleeper pads of type SLB 3007 G, has shown an increase of the tamping intervals by a factor of approximately 2.75. The long-term settlement records reproduced in figure 5, originally compiled by TU Graz from the ÖBB network, clearly illustrate the markedly slower deterioration rate of the section equipped with USPs compared with the adjacent ballasted sections without pads [7].



Source: ÖBB network, Austria 225 kN axle load, 20 MGT/year

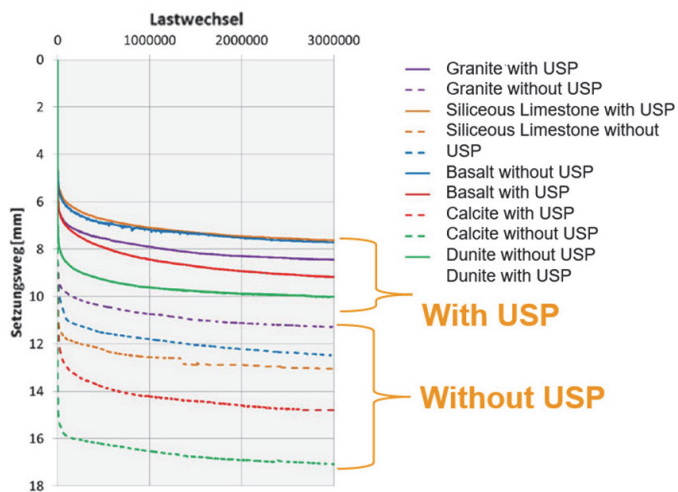
Figure 5 Comparison of track settlements at different track sections of the ÖBB network (Source: TU Graz)

6.2 Track stiffness and dynamic behaviour

Beyond the simple reduction of contact pressure, USPs also influence overall track stiffness and dynamic behaviour. By reducing stiffness contrasts between adjacent track sections, USPs help to mitigate transition problems at structures such as bridges, tunnels and switches and crossings. Several operators have highlighted the benefits of USPs in reducing differential settlement and track geometry deterioration in such critical zones [7]. These benefits, however, are closely linked to the selection of pad stiffness as a function of sleeper type, axle load and traffic mix. A system-level design approach, in which the pad is tailored to the specific track configuration, is therefore essential in order to fully exploit the potential of USPs.

6.3 Relaxation of ballast quality requirements through USPs

A particularly relevant consequence of the reduced ballast contact pressure provided by USPs is the potential to relax ballast quality requirements without compromising track performance. This concept has been investigated in depth by Berghold at Graz University of Technology, whose research demonstrates that the use of USPs can compensate for weaker ballast properties by lowering the stress levels below critical degradation thresholds [9]. Berghold's work, based on settlement tests in a large-scale ballast box and on hammer-impact tests on individual ballast stones, indicates that under defined boundary conditions ballasted tracks equipped with USPs can tolerate lower abrasion resistance, reduced angularity or higher fines content while still meeting the relevant performance and safety criteria. As shown in figure 6, the difference in cumulative settlement between high-quality and lower-quality ballast materials (granite, basalt, siliceous limestone, calcite, dunite) is markedly smaller when USPs are inserted than in the configuration without pads, where the lower-quality ballast degrades much faster than the high-quality reference.



Source: Armin Berghold, Dipl.-Ing. (2016)

Figure 6 Settlement tests for different ballast materials with and without USP [9]

Likewise, the hammer-impact tests carried out by Berghold (figure 7) show that the breakage rate of individual stones - quantified by the mass of particles smaller than 22.4 mm produced under a standard impact - is significantly reduced when the loading point is supported by an USP, which spreads the impact over a larger area. For weaker stone such as calcite and dunite, the reduction factor reaches values of 1.75 and 2.75 respectively. In combination, these two test series indicate that the controlling failure mechanisms of ballast - progressive crushing of contact points and abrasion between particles - can be effectively mitigated by USPs [9].

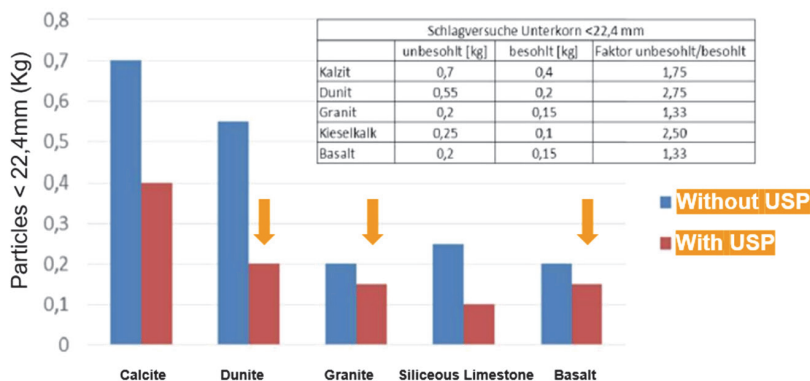


Figure 7 Hammer-impact tests for different ballast materials with and without USP [9]

6.4 Ballast and USP as a coupled system

The combined evidence from operational experience on the ÖBB and DB networks and from the laboratory-scale investigations carried out at Graz University of Technology supports a framework in which the ballast and the under sleeper pad are evaluated as a coupled mechanical system, rather than as isolated components. In such a framework the stiffness, thickness and surface profile of the pad and the petrographic and geometric properties of the ballast (abrasion resistance, angularity, fines content, particle size distribution) are co-design variables. The appropriate combination is the one that keeps the contact stress and the resulting cumulative settlement below the limits associated with the relevant traffic mix and maintenance regime. Adopting this coupled-system view has important practical consequences: ballast specifications can be defined in terms of the long-term performance of the entire sleeper-pad-ballast assembly rather than as standalone material limits; the pad becomes an active design parameter for life-cycle cost optimisation, on a par with the ballast quality class; and an increase in pad compliance can be balanced against a relaxation of the abrasion-resistance or angularity requirements imposed on the ballast, opening the door to the use of locally available materials that would otherwise fail to satisfy current standards.

7 Economic and environmental implications

The possibility of using ballast with relaxed quality requirements has significant economic and environmental implications, particularly in countries such as Croatia where the supply of high-quality LA_{RB}16 ballast is geographically uneven. High-quality ballast resources are becoming increasingly scarce across Europe, while transport distances and material costs continue to rise. Allowing the controlled use of lower-quality or alternative ballast materials - enabled by the pressure-reducing effect of USPs - offers a pathway towards a more sustainable railway infrastructure.

For Croatian conditions, this approach is especially attractive in regions where local stone is of inferior abrasion resistance but is readily available close to the worksite. Substituting long-distance transport of LA_{RB}16 material with locally sourced LA_{RB}20 or comparable ballast, in combination with USPs of appropriately selected stiffness, could materially reduce the carbon footprint of new construction and renewal works, lower transport costs and ease the pressure on the few productive LA_{RB}16 quarries.

The economic case is further reinforced by the documented increase in tamping intervals on lines equipped with USPs, which translates into reduced life-cycle maintenance costs and improved track availability - both highly relevant for the heavily loaded Croatian RH1 and RH2 corridors. Taken together, the operational and experimental evidence summarised above suggests that under sleeper pads should not be viewed solely as a track-protection measure. They act, more fundamentally, as a key enabler for adaptive ballast specifications - that is, for a regulatory and design environment in which ballast quality requirements are matched to the contact-stress level actually transmitted to the ballast, rather than fixed in absolute terms. Such an adaptive framework supports resilience against fluctuations in the availability of high-quality stone, promotes the sustainable use of regional resources, and contributes to long-term cost optimisation in modern railway networks.

8 Further steps: proposal for a Croatian instrumented test section

The transfer of the operational and laboratory evidence into Croatian railway practice would greatly benefit from field validation on a real-scale test section, designed following the methodology of Berghold [9] and of similar long-term programmes on European main lines [7, 8]. The proposal is a 2 × 2 factorial trial on a representative renewal section of corridor RH1 or RH2 (load model D4, ≥ 20 MGT/year) with four adjacent segments of 80-120 m each: A (LA_{RB}16, no USP, reference); B (LA_{RB}16, with USP); C (LA_{RB}20, no USP); and D (LA_{RB}20, with USP). Ballast for segments C and D would be sourced from a region currently underserved by LA_{RB}16 supply. The measurement campaign should incorporate the following techniques, used in in-track USP trials:

- Insertion loss between USP segments (B, D) and matched reference segments (A, C) under controlled train pass-bys or controlled impulse/sweep excitation; the matching of reference segments - sleeper type, ballast condition, subgrade, alignment, curve radius - documented prior to measurement.
- Vibration measurement per DIN 45672-2 with assessment per DIN 45672-1; sensors at rail head, rail foot, sleeper end, ballast shoulder and ground positions of increasing offset, evaluated in one-third-octave band spectra.
- In-situ track receptance via instrumented-hammer FRF at the sleeper, used to cross-check the laboratory dynamic-stiffness values obtained on USP specimens per EN 16730 and DIN 45673-6.
- Track decay rate per EN 15461 where rolling-noise effects are in scope, since USPs modify the sleeper contribution to track decay.
- Ground-borne vibration in the surroundings within the ISO 14837-1 framework, with building-side assessment per DIN 4150-2 and DIN 4150-3, ISO 2631-2 or the applicable national equivalent.
- Long-term track-geometry and settlement evolution by track-recording car following the methodological lines established by the RIVAS WP3 and SILVARSTAR projects, complemented by geodetic monitoring at fixed sleeper points and periodic ballast sampling.

9 Conclusion

The current Croatian regulation requires LA_{RB}16 ballast on all international lines and switch and crossing areas, yet only a limited number of quarries - concentrated in the north and east of the country - can supply ballast of this quality. Large parts of Croatia (Istria, Lika and Dalmatia) lack suitable eruptive stone deposits altogether, which significantly increases transport distances and the cost of supplying ballast to construction sites.

Under sleeper pads have been shown, through laboratory testing, full-scale trials and operational experience by major European infrastructure managers, to reduce peak ballast contact pressure, homogenise stress distribution, slow particle breakage and extend tamping intervals by a factor of the order of 2 – 3. They also mitigate stiffness contrasts at transitions such as bridges, tunnels and switches. The presented research demonstrates that the reduced stress level provided by USPs makes it possible, under defined boundary conditions, to tolerate ballast with lower abrasion resistance, reduced angularity or higher fines content without exceeding critical settlement and degradation thresholds. USPs therefore act as an enabler for adaptive ballast specifications, rather than only as a track-protection measure. Applied to Croatian conditions, this finding suggests that a coordinated combination of suitably specified under sleeper pads with locally available ballast of relaxed quality could substantially reduce transport-related costs and emissions, improve the use of regional stone resources and extend maintenance intervals on the heavily loaded RH1 and RH2 corridors. Further work, including site-specific pad design, controlled field trials and an explicit update of the existing technical conditions for the production and delivery of railway ballast, is recommended in order to integrate this approach into Croatian railway practice.

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SAFE ROAD INFRASTRUCTURE DESIGN AND MONITORING

