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Review of Ground-Borne Vibration Mitigation in High-Speed Rail Systems through various Modifications

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Abstract- High-speed rail systems generate significant ground-borne vibrations that can lead to structural damage, discomfort to nearby residents, and accelerated deterioration of railway components. This review investigates various vibration mitigation strategies used in high-speed rail infrastructure, focusing on track and material modifications. Key techniques include the application of resilient rail pads, ballast mats, floating slab tracks, and subgrade treatments. Each method's effectiveness is analyzed based on experimental findings, numerical simulations, and field data. Among these, resilient rail pads are highlighted for their practicality and ease of implementation, offering effective vibration isolation without extensive structural changes. However, the success of mitigation efforts depends on factors such as train speed, soil conditions, and system design. The paper concludes looking at what we still don't know and suggests using several different solutions together to get better results. This review aims to guide engineers and researchers in developing efficient, site-specific vibration control solutions for high-speed rail systems.

Keywords: High-speed rail (HSR), Ground-borne vibrations, Vibration mitigation, Track infrastructure, Structural modifications, Environmental impact.

I. INTRODUCTION

High-speed rail (HSR) has revolutionized transportation by offering fast, efficient, and environmentally friendly alternatives to traditional travel. However, one of the critical side effects of high-speed rail operations is the generation of ground- borne vibrations. These vibrations happen because of the way the train wheels move against the track infrastructure and can be transmitted through the track structure into the surrounding soil and built environment. While often imperceptible at low levels, such vibrations cause various consequences when train speeds exceed 250 km/h, including damage to nearby buildings, degradation of track components, and reduced passenger comfort.

The increasing density of urban development near rail corridors further exacerbates the challenges associated with ground-borne vibrations. Causes of ground vibration include soft marine clay layers, high train speeds, dynamic train-track interaction, low soil stiffness, wave amplification in soft soils, and inadequate damping near high-speed rail tracks.[1]As a result, mitigating these vibrations has become a priority in both the design of new high-speed rail systems and the upgrading of existing ones. Causes of damage include high axle loads, inadequate rail pad stiffness, poor sleeper design, excessive vibrations, thermal variations, material fatigue, improper maintenance, and dynamic train-track interactions leading to infrastructure degradation. [2]

A wide range of mitigation strategies has been explored to address this issue, involving modifications to the track structure, rail fastenings, subgrade treatments, and even rolling stock design. The rapid expansion of high-speed railways necessitates effective noise prediction and control methods to ensure ecological safety for nearby residents, emphasizing source-based mitigation strategies and validated international practices. Among these strategies, the use of resilient components—such as rail pads, ballast mats, and floating slabs—has proven effective in reducing vibration transmission.

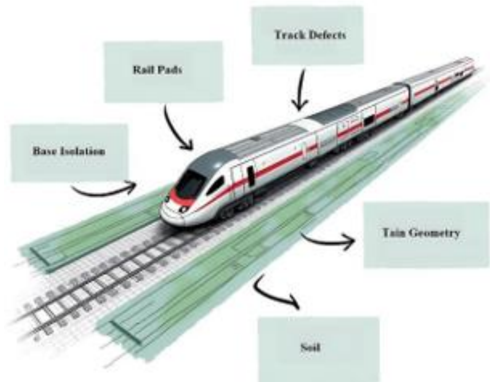

Figure 1: Factors Influencing Ground-Borne Vibrations in High-Speed Rail Systems

These solutions aim to modify the dynamic behavior of the track system by introducing damping and flexibility. Additionally, the integration of advanced materials and computational modeling techniques has further enabled targeted and efficient design of vibration control measures. Train- induced vibration mainly results from quasi-static wheel loads, with dominant frequencies linked to train geometry. This review paper explores the current state of ground-borne vibration mitigation in HSR systems through various structural and material modifications. The aim is to present a comparative analysis of mitigation methods, highlight recent advancements, and identify areas for future research. The primary source of these vibrations is the irregular contact between train through free field, and impact on nearby buildings.

II. INSTALLATION SOURCE & TRANSMISSION OF GROUND BORNE VIBRATIONS

Ground-borne vibrations in high-speed rail systems are a result of dynamic interactions between moving trains and track infrastructure. Increased vibration with speed, significant frequencies linked to train structure, and slower attenuation with distance, affecting human comfort. [5] After the vibrations start, they spread through the entire track system, which typically consists of rails, rail fastenings, sleepers, ballast (in ballasted tracks), or concrete slabs (in slab tracks), followed by subgrade and natural soil. The structural elements of the track influence how vibration energy is transferred and dissipated. For example, rail pads and baseplates affect local vibration levels through their stiffness and damping properties. The transfer of ground-borne vibrations is highly dependent on soil characteristics such as density, elasticity, damping capacity, and layering.

Softer soils tend to amplify low-frequency vibrations, while stiffer soils may transmit higher frequencies more effectively. Understanding both the generation and transmission mechanisms of these vibrations is essential for developing mitigation solutions such as rail pad optimization, base isolation, ground improvement, and the use of wave barriers to reduce adverse environmental and structural effects. Soil reinforcement and train geometry influence the critical speed and dynamic behavior of high-speed rail systems, emphasizing improved ground treatment techniques and more accurate critical speed estimation methods for enhanced stability. Numerical investigations reveal that vertical track irregularities wheels and the rail, caused by factors such as wheel or rail surface imperfections, track discontinuities, rail joints, or sudden changes in stiffness.

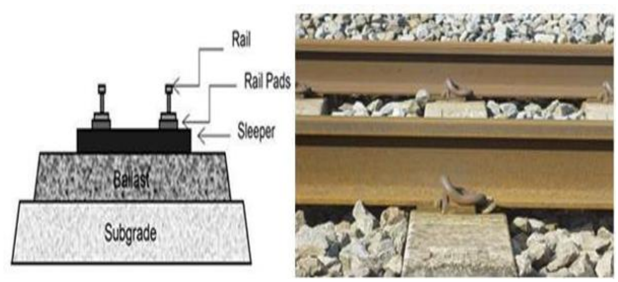

Figure 2: Rail System Configuration

Ground-borne vibrations from high-speed trains generate higher vibrations, while embankments reduce them, and horizontal vibrations are significant at greater distances. As train speeds increase, the dynamic forces at the wheel-rail interface also increase, often leading to greater excitation of vibration energy into the supporting structures and the ground. Causes studied include increased dynamic loads from high- speed trains, interaction with existing track structures, soil properties, train speed, vibration propagation significantly affect dynamic responses, reducing safety at high speeds. Larger bridge spans lessen this impact, but severe irregularities like TI4 risk ballast destabilization and wheel set detachment, compromising train safety.

III. OVERVIEW OF VIBRATION MITIGATION TECHNIQUES

Ground vibrations from high-speed rail over soft marine clay using a 2D finite element approach in ABAQUS. Results show peak vibrations occur near the Rayleigh wave velocity, with safe PPV limits identified for structures and vibration levels analyzed in decibels to assess human comfort and structural safety.[1] This specific type of vibration absorber does a great job of keeping the rails steady. The single layered absorber lowers vertical displacement and acceleration by 65–68%, while the three-layered design achieves a greater reduction of 70–72%.

Technique	Mechanism	Effectiveness	Cost	Ease of Implementation	Common Applications
Resilient Rail Pads	Dampen vibrations between rail and sleeper	High	Low to Moderate	Easy	Urban lines, track upgrades
Ballast Mats	Isolate track from subgrade using resilient layers	High	Moderate	Moderate	New construction, vibration-sensitive areas
Floating Slab Track	Mass-spring system to absorb and isolate vibrations	Very High	High	Complex	Tunnels, dense urban environments
Under Sleeper Pads	Absorb vibrations at sleeper-ballast interface	Moderate	Moderate	Moderate	Retrofitting, medium-speed lines
Soil Stabilization	Increase stiffness	Low to Moderate	Low to Moderate	Easy to Moderate	Areas with poor soil conditions
Tuned Mass Dampers	Dynamic vibration absorbers tuned to dominant frequencies	High	High	Complex	Bridges, elevated structures

Overall, the three-layered absorber provides slightly better vibration control, enhancing rail system stability and performance. [2] Rail pad stiffness reduction lowers ballast stress, improves load distribution, and enhances track lifespan with minimal deep-layer deformation. This study investigates how a resilient baseplate affects slab track vibration and noise. Lab tests and modeling show baseplate flexibility improves accuracy, while rail pad stiffness greatly influences vibration above 1 kHz.[3] [4] Problems like loose supports or a soft foundation make vibrations much worse on high-speed tracks.. Numerical models show such irregularities worsen responses, aiding defect detection through vibration analysis.

Base-isolated buildings respond to vibrations from railway traffic, showing that base isolation effectively reduces vibration transmission and enhances building comfort and safety. A comparison of EPDM and HDPE railway pads shows that EPDM pads significantly reduce dynamic vibration frequencies—by 58% for single-layer and 71% for double-layer configurations thereby enhancing track vibration control and performance. [6] Finite element modeling with Gaussian process regression to estimate rail pad and ballast stiffness efficiently from field hammer tests, achieving high accuracy and speed using limited data and sensors. This paper presents an experimental study on ground-borne vibrations from high-speed rail lines across different earthwork profiles, revealing that cutting profiles generate the highest vibration levels while embankments result in the lowest. Contrary to common assumptions, the analysis shows that horizontal vibrations can be more significant than vertical ones at greater distances from the track, emphasizing the need to consider both directions in vibration assessment. A 2.5D FEM study shows combined seismic and high-speed train loads amplify ground vibrations, especially at higher speeds. Softer soil worsens effects, while stiffer ground and slower trains reduce risks. [7]

Traditional ballasted track requires frequent maintenance due to drainage deficiencies and weak subgrade, leading to high costs. This study investigates the effect of two different rail profiles—bull headed and flat footed— on the fatigue behavior of a track slab using modal, transient, and fatigue analysis.[8] Uses of spectral element method and optimization to simulate ground and building vibrations from high-speed trains, validating results with experiments and analyzing structural and vehicle influence on vibration response. Rail pads provide essential track flexibility and vibration damping. This study uses hands-on tests to find out service conditions affect pad materials' mechanical behavior, aiding dynamic modeling and long-term infrastructure performance prediction.[9]

A study in Greece found that using softer pads on the tracks helped stop cracks from forming in concrete sleepers, extending the track's life and lowering noise emissions, improving railway sustainability and performance.[10] Vibrations and noise from urban rail transport have impact on nearby residents' health, and proposes risk assessments and forecasts. It evaluates protective measures like sub- ballast mats, showing their effectiveness in reducing health risks and ensuring compliance with sanitary and epidemiological standards for urban populations. Rail noise reduction using constrained damped dynamic vibration absorbers through finite element modeling. Results show significant vibration reduction: single-layered absorbers reduced vertical displacement and acceleration by 65–68%, while three-layered absorbers achieved a 70–72% reduction, demonstrating their effectiveness in minimizing rail- induced noise and vibrations.

Tram track insulation, lubrication in curves, welded rails with compensators, and analyzes their structural, mechanical, and economic effectiveness through various investigations.[11] Mesh-type rail pads (NMTRP and MTHDRP) designed to enhance damping and reduce stress in urban rail systems. Finite element and experimental analysis show MTHDRP offers superior vibration reduction, lower stress levels, and better dynamic stiffness retention, making it more effective than traditional rail pads for long-term performance.[12] Vehicle-track-viaduct model using frequency domain analysis to evaluate CRTS-III damping tracks, showing significant reductions in acceleration and noise, with the viaduct top plate as the main noise source.

Introducing a negative stiffness DVA (NSDVA) for floating slab tracks, achieving effective vibration reduction with low mass ratio, overcoming space limitations, and outperforming traditional DVAs (dynamic vibration absorber) through optimized design and FEM analysis. Introducing high-speed trains in Portugal requires enhanced rail maintenance and performance evaluation. Vibration tests, including one in Lisbon, helped develop numerical models simulating train- induced vibrations. Calibrated with real data, simulations using the Thalys HST showed no significant increase in vibration levels, suggesting compatibility with current tracks under studied conditions. The lack of reliable models for predicting rail pad dynamic stiffness under real conditions by combining extensive laboratory testing with machine learning. Gradient Boosting proved most accurate. Results reveal toe load as a key factor, suggesting updates to current standards and aiding track design and maintenance optimization.

Novel Filled Damping Block Mesh-Type Rail Pad (NFDBMTRP) with improved damping and uniform stress distribution, reducing vibration and enhancing safety, durability, and stability in heavy haul railway operations.[13] Vibration energy in railways can be harvested using electromagnetic, piezoelectric, turbo electric, and hydraulic methods, each with specific strengths and weaknesses. Despite progress, challenges like system stability, durability, and cost still need to be addressed through further research.

Scope Rail, a vibration prediction tool using 3D finite element modeling and machine learning to accurately forecast structural vibrations and indoor noise near high-speed rail, improving environmental assessments and cost efficiency. Varying ballast/subgrade stiffness affects track degradation. Key factors increasing energy dissipation and wear include high train speeds, stiffness variation, soft soils, and stiff rail pads. [14]

A two-step 2D model is developed to predict ground vibrations from high-speed trains on bridges. Validated by field data, it effectively analyzes vibration impacts under various soil conditions for environmental assessment. High-speed trains induce dynamic forces that degrade ballasted tracks and raise maintenance needs. This study uses field data and a 3D model to analyze track behavior, highlighting rail pad stiffness as key to reducing ballast stress. Optimized stiffness improves durability while balancing displacement and stiffness, offering insights for sustainable track management. An elastic side- supporting sleeper track (ESSDT) is introduced with a vibration reduction device (VRFMD), effectively reducing vibration and adjusting natural frequency, enhancing stability and resonance control in urban rail systems. Frictional heat at the wheel-rail interface during braking and acceleration accelerates wear and deformation.

This study validates a 3D thermo mechanical FE model simulating high slip ratio conditions. With flash temperatures up to 360 °C, the model closely matches experimental data, enabling accurate prediction of thermal effects in wheel-rail interactions. [15] Under Sleeper Pads (USPs) improve track resilience but may increase rail and sleeper vibrations, especially under high-frequency impacts, leading to potential noise, ballast movement, and reduced lateral track resistance. This study examines 3D rail vibrations under fastening constraints up to 5000 Hz using experiments and finite element modeling. Operating deflection shapes and wavelet methods identify vibration modes. The validated model reveals that fastening parameters influence vibration frequencies, amplitudes, and wave propagation, offering effective strategies for rail vibration control.

This study analyzes vibration transmission in multi-layer track-bridge systems for 24 m, 32 m, and 40 m spans under 400 km/h train loads. Using a refined model, it finds increased acceleration and contact forces with speed and load, especially for the 40 m span, highlighting span- dependent dynamic behavior and performance limits. Identifying polyurethane-based pads as most effective for vibration isolation, maintaining stiffness, and showing strong potential for ballasted track systems noise and vibration reduction. Stiff rail pads increase sleeper stress, reducing track life also influences noise, reduced by 6% using dampers.

IV. FUTURE RESEARCH DIRECTION

Advanced Material Development:
Future studies should quantitatively evaluate novel polymer composites and elastomeric blends by measuring parameters such as dynamic modulus, damping ratio, and fatigue life under controlled load–speed spectra. Establishing clear relationships between material microstructure and mechanical response will help optimize durability and vibration attenuation.

Optimization of Rail Pad Stiffness:
Research should focus on the development of adjustable or smart rail pads capable of modulating stiffness by ±20–40% in real time. Quantitative assessment of their effect on vibration levels (e.g., reduction in acceleration peaks by 5–10 dB) and noise radiation across high-speed and metro systems is required.

Machine Learning Integration:
Machine learning algorithms should be expanded for real-time prediction of rail pad stiffness degradation, based on large datasets of acceleration, displacement, and temperature. Quantitative validation using prediction accuracy, RMSE, and correlation with field measurements will strengthen reliability.

Negative Stiffness DVA Expansion:
Future work should apply NSDVA principles to ballasted, slab, and bridge track structures and validate performance via 3D FEM simulations.

Quantitative targets may include vibration reduction of 8–15 dB in the vertical frequency range of 20–80 Hz, followed by laboratory and field measurements.

Multi-Layer Vibration Absorbers:
Lightweight multi-layer DVAs should be designed for constrained urban environments. Research must quantify performance across train speeds (40–350 km/h), focusing on transmissibility reduction, damping enhancement, and long-term stiffness stability under cyclic loads.

Under Sleeper Pad (USP) Improvement:
USP development should aim to minimize ballast dilation while maintaining lateral resistance within acceptable limits. Quantitative studies must evaluate noise reduction, track geometry retention, and ballast settlement rates compared with conventional systems.

Energy Harvesting Opportunities:
Investigate piezoelectric or electromagnetic harvesters that can convert track vibrations into usable electrical energy. Quantitative performance indicators may include harvested energy density (mW/m), efficiency under variable train speeds, and operational durability.

Customized Urban vs. Heavy-Haul Solutions:
Future research must quantify the distinct load ranges, frequency spectra, and environmental conditions of urban transit versus heavy-haul systems. Tailored rail pads or absorbers should be benchmarked through measurable outcomes such as vibration reduction, stiffness retention, and noise mitigation.

Hybrid Track Insulation Techniques:
Combining ESSDT, VRFMD, and mesh-type pads can create adaptive systems. Studies must quantify improvements using frequency response functions, transmissibility curves, and dynamic stiffness comparisons under controlled excitation scenarios.

Standard Updates and Guidelines:
Recommend revisions to railway design standards by integrating quantitative parameters such as toe load variation, dynamic stiffness ranges, and allowable acceleration limits. Evidence-based thresholds derived from experimental and field data should guide future policy development.

V. CONCLUSION

Effective Vibration Mitigation:
Resilient rail pads, ballast mats, floating slab tracks, and subgrade improvement methods consistently reduce vibration levels by approximately 5–15 dB, depending on track and soil conditions.

Rail Pads as a Practical Solution:
Among available techniques, resilient rail pads offer a favorable balance of cost, ease of installation, and measurable vibration attenuation, making them suitable for widespread implementation.

Requirement for Integrated Approaches:
No single solution is universally effective; combining multiple techniques (e.g., rail pads + ballast mats + track insulation) improves vibration control and infrastructure durability.

Need for Quantitative Validation:
Future solutions must be supported by numerical modeling, field measurements, and measurable performance indicators such as transmissibility, dynamic stiffness, and vibration attenuation.

Implications for Infrastructure and Community:
Effective vibration reduction enhances track longevity, structural safety, ride comfort, and minimizes the impact on nearby residents and sensitive structures.

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