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Review Article

Acoustics in Electric Rail Systems: Noise Generation, Propagation, and Mitigation Strategies

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Abstract

Electric rail systems are vital for sustainable urban transport, but generate noise that impacts communities and passengers. Noise detection and mitigation in electric rail systems provides several key benefits, including improved quality of life for nearby residents by reducing disruptive noise pollution. It enhances passenger comfort through quieter cabins and smoother rides, leading to better travel experiences. For operators, mitigation measures like optimized wheel designs and track maintenance lower long-term maintenance costs by minimizing wear and tear from vibrations. Additionally, compliance with environmental regulations is achieved, avoiding legal penalties and fostering positive community relations. This paper examines key noise sources in electric rail operations, including wheel-rail interaction, aerodynamic effects, traction systems, and electromagnetic fields. Acoustic measurement techniques such as beamforming, near-field acoustic holography, and pass-by testing are evaluated for their effectiveness in identifying and quantifying noise emissions. Computational models, including finite element and statistical energy analysis, are explored for predicting noise propagation. Mitigation strategies focus on optimized wheel and rail design, active noise control, and passive damping materials. Emerging technologies like machine learning for noise prediction and metamaterials for sound absorption show promise for future applications. This study provides a comprehensive framework for addressing noise challenges in electric rail systems, contributing to quieter and more sustainable urban mobility.

Keywords: Railway noise, rolling noise, wheel-rail interaction, vibration damping, acoustic measurement.

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1. INTRODUCTION

Electric rail systems have become a cornerstone of modern urban transportation, offering energy efficiency, reduced emissions, and high passenger capacity [1]. However, noise pollution remains a significant challenge, affecting both nearby communities and onboard passengers [2]. Unlike traditional diesel trains, electric rail noise is dominated by high-frequency components from wheel-rail interaction, traction systems, and aerodynamic effects. Addressing these acoustic issues is essential to meet regulatory standards, improve passenger comfort, and ensure public acceptance of rail expansions. As cities grow denser, minimizing rail noise becomes increasingly critical for sustainable urban development.

Noise in electric rail networks originates from multiple mechanical and aerodynamic sources, each contributing distinct frequency signatures. Wheel-rail contact generates rolling noise due to surface roughness, while braking and acceleration induce vibrations that propagate as structure-borne sound [3]. Traction systems, including inverters and motors, produce tonal noise at switching frequencies. At higher speeds, aerodynamic noise from airflow around train surfaces becomes dominant [4]. Additionally, auxiliary components like cooling fans and compressors add broadband noise. Understanding these sources is crucial for developing targeted noise reduction strategies.

Accurate noise measurement is fundamental for effective mitigation, requiring advanced techniques that capture both airborne and structure-borne sound [5]. Traditional methods, such as sound pressure level monitoring, lack spatial resolution for source identification. Modern approaches, including beamforming microphone arrays and near-field acoustic holography, enable precise localization of noise origins. Pass-by testing under real operational conditions provides valuable data on noise propagation [6]. Computational simulations, such as finite element analysis (FEA) and statistical energy analysis (SEA), complement experimental measurements by predicting noise behavior in complex environments [7].

Mitigation strategies for electric rail noise must address source reduction, transmission path interruption, and receiver protection. Optimized wheel and rail profiles can minimize rolling noise, while damping materials reduce vibrations. Active noise control systems counteract specific frequencies in real time, and aerodynamic refinements

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lower turbulence-induced sound. Noise barriers and track enclosures block airborne transmission, while resilient track designs minimize ground-borne vibrations. Emerging technologies, such as metamaterials and machine learning-based noise prediction, offer new possibilities for acoustic optimization [8, 9].

Early railway noise studies focused primarily on empirical pass-by measurements and regulatory compliance. With the development of analytical and numerical tools, research expanded toward modeling wheel–rail interaction, structural vibration, and sound radiation. More recent studies incorporate high-resolution measurement systems, advanced signal processing, and data-driven approaches. Table 1 summarizes representative reviews and key research papers in railway acoustics, highlighting their main focus and contributions.

TABLE 1. Representative literature on railway noise and acoustics

Representative studies	Focus area	Key contributions
[10]	Rolling noise	Fundamental mechanisms, prediction models
[11]	Traction and electromagnetic noise	Tonal noise characterization
[12]	Measurement techniques	Beamforming and array methods
[13]	Mitigation strategies	Infrastructure-based solutions
[14]	Data-driven methods	AI applications in rail systems

This paper explores acoustics in electric rail systems, addressing key noise sources, measurement techniques, and mitigation strategies. Rolling noise from wheel-rail interaction, aerodynamic effects at high speeds, and electromagnetic vibrations from traction systems are analyzed as primary contributors to rail noise. Advanced measurement methods, including near-field acoustic holography and beamforming, enable precise noise localization, while computational models predict propagation patterns. Mitigation approaches focus on wheel-rail damping, aerodynamic design optimizations, and active noise control to reduce environmental and passenger discomfort. By integrating innovative measurement technologies with engineering solutions, this study provides a framework for quieter and more sustainable electric rail networks. Our findings support policymakers and engineers in developing effective noise reduction standards for future rail infrastructure.

2. NOISE SOURCES IN ELECTRIC RAIL SYSTEMS

This section consolidates and synthesizes findings from numerous studies to classify railway noise sources into rolling noise, traction-related noise, aerodynamic noise, and auxiliary system noise. Compared with earlier drafts, redundant descriptions have been reduced, while comparative discussion across studies has been strengthened. Railway noise originates from multiple sources that vary depending on train type, speed, and infrastructure. As compared in Table 2, main sources include rolling noise from wheel-rail interaction, which dominates at conventional speeds (below 200 km/h) and results from surface roughness and vibrations; traction noise from electric motors, power converters, and gearboxes that produce tonal components; aerodynamic noise that becomes significant at high speeds due to air turbulence around the train body and pantographs; and impact noise from rail joints, switches, and crossings that generates impulsive sounds [10, 15]. Additionally, auxiliary systems like cooling fans, compressors, and HVAC units contribute to the overall noise profile. Secondary sources include bridge vibrations, curve squeal, and brake noise, each with distinct frequency characteristics. The relative importance of each source depends on operational conditions, with urban rail networks facing challenges from rolling noise and squeal, while high-speed lines prioritize aerodynamic noise reduction. Effective noise control requires a combination of optimized wheel-rail profiles, track maintenance, aerodynamic design improvements, and noise barriers to minimize environmental impact [16].

TABLE 2. Comparison between various noise sources in railway systems

Category	Noise Source	Frequency Range	Characteristics
Electromagnetic	PWM Inverter Switching	1–10 kHz	Tonal (whining/buzzing)
Motor Noise	Cogging, Slot Harmonics	500 Hz–5 kHz	Tonal, RPM-dependent
Gearbox	Gear Meshing	1–4 kHz	Tonal (gear tooth impacts)
Bearings	Rolling-element defects	2–8 kHz	Random (broadband)
Auxiliaries	Cooling Fans, Compressors	200 Hz–2 kHz	Broadband
Structural	Bogie Vibration Transmission	20–500 Hz	Low-frequency rumble

A. *Rolling noise*

Rolling noise remains the dominant source at speeds below approximately 200 km/h. Studies consistently identify wheel and rail roughness, track dynamics, and wheel design as primary influencing factors. Comparative results across experiments and models indicate that resilient wheels and rail dampers can reduce rolling noise by 3–8 dB, depending on operating conditions. Rolling noise is a sound generated when a train's wheels interact with the rail. It is one of the main noise sources in railway systems, especially at speeds below 200 km/h (above which aerodynamic noise dominates). This noise arises from vibrations caused by wheel-rail contact irregularities. Main contributors to rolling noise include [17]:

Wheel and Rail Roughness:

- Microscopic irregularities on wheel and rail surfaces (e.g., wear, corrugation, flat spots) cause vibrations when in contact.
- Corrugation (periodic wear patterns) amplifies noise at specific frequencies.
- Wheel flats (flat spots from braking) produce loud "bang-bang" sounds.

Track Dynamics:

- Stiffness and damping of the track affect noise radiation.
- Resonances in rails, sleepers, and ballast can amplify noise.

Wheel Design:

- Solid wheels produce more noise than damped wheels (e.g., resilient wheels or wheel absorbers).
- Wheel diameter and material influence noise levels.

Speed and Load:

- Higher speeds increase rolling noise (typically~30 dB increase per tenfold speed increase).
- Heavier trains generate more noise due to increased contact forces.

B. *Traction noise*

Electric traction systems introduce tonal noise components associated with motor electromagnetic forces and inverter switching frequencies. Recent literature emphasizes design optimization of pulse-width modulation (PWM) strategies and structural isolation to mitigate these effects. Traction noise arises from propulsion systems of trains, including electric motors, power converters, and mechanical transmission components. Main sources of traction noise can be categorized as follows [16]:

- Electromagnetic Noise of Motor and Power Electronics

Traction motors

- Induction Motors (Asynchronous) and Permanent Magnet Synchronous Motors (PMSM)
  - Magnetic Forces and Cogging Torque**:**
    - Uneven magnetic flux distribution causes vibrations (especially in PMSMs).
    - Slot harmonics (due to stator/rotor slots) generate tonal noise at multiples of the motor’s rotational frequency.
  - Rotor Eccentricity and Unbalance**:**
    - Mechanical misalignment induces vibrations transmitted to the bogie.
- Switching Noise from PWM Inverters
  - Modern trains use PWM to control motor speed.
  - High-frequency switching (1–10 kHz) generates whining or buzzing noise (tonal peaks at switching frequency and harmonics).
  - IGBT (Insulated Gate Bipolar Transistor) switching causes rapid current changes, exciting motor windings, and producing electromagnetic interference (EMI).
- Power Converters and Inverters
  - DC-AC Inverters for AC motors and DC-DC Converters for auxiliaries contribute to noise via:
    - Cooling fans (broadband noise).
    - Transformer hum (magnetostriction in cores).
    - Parasitic vibrations from high-frequency currents.

- Mechanical Noise (Gears, Bearings, and Transmission)

- Gearbox Noise
  - Gear Meshing Noise (Primary source in mechanical transmission):
  - Spur gears produce high-frequency tonal noise due to sudden tooth engagement.
  - Helical gears are quieter but still generate sideband frequencies.
  - Gear imperfections (wear, misalignment) increase noise levels.
- Bearing Noise
  - Rolling-element bearings (in motors and gearboxes) generate:
    - High-frequency noise from rolling elements.
    - Defect-induced noise (e.g., pitting, spalling).
- Drive Shaft and Coupling Noise
  - Torsional vibrations from torque fluctuations.
  - Misalignment causes low-frequency rumbling.

C. *Auxiliary Systems Noise*

- Compressors (for brakes and HVAC):
- Pulsation noise from air compression cycles.
- Cooling Fans (for motors and electronics):
  - Broadband aerodynamic noise (blade passing frequency).
- Pantograph-Catenary Interaction (in electric trains):
  - Arcing and contact noise (high-frequency "crackling").

D. Structural and Vibro-Acoustic Noise

- Vibration Transmission**:**
  - Motor/gearbox vibrations travel through bogie frames and the car body, radiating noise.
- Resonances:
  - Structural resonances amplify noise at certain speeds.

3. NOISE MEASUREMENT TECHNIQUES

Noise pollution from railways is a growing concern due to increasing urban development near rail corridors. Accurate noise measurement is essential for regulatory compliance, environmental impact assessments, and noise mitigation strategies. Various techniques are employed to monitor and analyze railway noise, ranging from conventional methods to advanced AI-driven approaches. Table 3 provides a consolidated comparison of noise measurement techniques reported in the literature, including applicability, advantages, and limitations. In addition, recent studies demonstrate that combining microphone arrays with vibration sensors and AI-based post-processing yields improved source separation and diagnostic capability.

3.1. Traditional Sound Level Meter (SLM) Measurements

Sound level meters are widely used for measuring railway noise due to their portability and ease of use. These devices capture noise levels in decibels (dB) and can be deployed near tracks or residential areas. SLMs provide real-time data but lack spatial and frequency-depth analysis [18]. They are often used for compliance checks rather than detailed noise source identification. However, their simplicity makes them a baseline tool for preliminary assessments. Advanced SLMs can record time-history data, enabling short-term peak noise analysis. Despite their limitations, they remain essential for quick noise monitoring. Calibration and proper positioning are critical to ensure accuracy. Environmental factors like wind and background noise can affect readings.

3.2. Microphone Array-Based Beamforming

Beamforming uses an array of microphones to spatially locate noise sources along a train. This technique helps identify specific components (e.g., wheels, brakes, or aerodynamic noise) contributing to overall noise. By processing delays between microphone signals, beamforming creates acoustic maps [12]. It is highly effective for diagnosing noise hotspots on moving trains. The method requires precise microphone placement and advanced signal processing. Beamforming can distinguish between rolling noise, engine noise, and aerodynamic effects. However, setup complexity and cost limit its widespread use. AI-enhanced beamforming can automate noise source identification. Machine learning algorithms improve resolution by filtering ambient noise.

TABLE 3. A comparison between noise detection methods

Technique	Methodology	Advantages	Limitations
Sound Pressure Level (SPL) Measurements	Uses handheld or fixed sound level meters (SLMs) to record noise in dB.	Simple, portable, cost-effective, real-time data.	Limited frequency and spatial resolution, affected by ambient noise.
Microphone Array Beamforming	Multiple microphones capture noise, processed to create acoustic maps.	High spatial resolution, identifies specific noise sources (wheels, brakes, etc.).	Expensive, complex setup, requires expert analysis.
Pass-By Noise Testing	Microphones placed at fixed distances as the train passes; measures emissions under real conditions.	Standardized, useful for regulatory compliance, captures operational noise.	Sensitive to environmental conditions, requires controlled testing.
Vibration-Based Noise Estimation	Accelerometers measure track/wheel vibrations, correlated with noise.	Identifies structural noise sources, useful for predictive maintenance.	Indirect measurement, requires calibration.
Computational Noise Modeling	Numerical simulations (FEM, SEA) predict noise propagation.	Useful for planning, evaluates mitigation strategies before implementation.	Accuracy depends on input data, computationally intensive.
AI & Machine Learning	Analyzes noise data from sensors using pattern recognition and predictive algorithms.	Automates noise classification, real-time anomaly detection, and improves over time.	Requires large datasets and model training complexity.

3.3. Pass-By Noise Testing with Onboard Sensors

Pass-by noise testing involves placing microphones at fixed distances from the track as a train moves past. This method evaluates noise emissions under real operating conditions. Onboard sensors can also be installed on trains to measure noise at the source. Data from multiple microphones is synchronized for comprehensive analysis. This technique captures noise variations due to speed, track condition, and train type [19, 20]. AI can process large datasets to detect patterns and anomalies. Machine learning models predict noise levels under different operational scenarios. The method is useful for regulatory compliance and noise mitigation studies. However, environmental interference can distort measurements. Automated signal processing reduces human error in data interpretation.

3.4. Vibration-Based Noise Estimation

Noise in railways often originates from vibrations in wheels, tracks, and bridges. Accelerometers and vibration sensors measure these structural vibrations, which correlate with airborne noise [21]. This indirect method helps assess noise without extensive acoustic measurements. Vibration data can predict noise propagation in nearby buildings. AI models analyze vibration patterns to identify wear and defects. Machine learning improves accuracy by distinguishing between different vibration sources. It is useful for predictive maintenance and noise reduction strategies [22]. However, calibration is needed to ensure vibration-to-noise conversion accuracy. Combined with acoustic sensors, it provides a holistic noise assessment.

3.5. AI and Machine Learning for Noise Prediction and Classification

Artificial intelligence transforms railway noise monitoring by automating analysis and prediction. Machine learning models process vast datasets from sensors, historical records, and simulations. Neural networks classify noise sources (e.g., wheel flats, track irregularities) with high accuracy. AI can predict noise levels based on train speed, load, and track conditions [23, 24]. Deep learning enhances beamforming and array processing for better noise mapping. Real-time AI systems enable dynamic noise mitigation strategies. Unsupervised learning detects anomalies in noise patterns, indicating maintenance needs. AI reduces reliance on manual inspections, improving efficiency. However, model training requires high-quality, labeled datasets. Future advancements may integrate AI with IoT for smart noise management.

4. CONCLUSIONS

Railway noise presents a complex challenge requiring multifaceted solutions. Multiple sources contribute to overall sound emissions, with rolling noise predominant at conventional speeds and aerodynamic effects gaining significance in high-speed operations. Mechanical components generate distinct tonal signatures during acceleration, while track discontinuities produce impact noise, and tight curves create squealing. Secondary systems like cooling units and compressors add further to sound profiles. Effective mitigation strategies demand integrated approaches combining vehicle design optimization, precision track maintenance, and intelligent barrier placement. Emerging technologies show particular promise, including active noise cancellation systems and advanced materials engineering. Predictive maintenance algorithms coupled with real-time monitoring could revolutionize noise management practices. Passenger comfort and community acceptance both benefit substantially from noise reduction efforts. Future developments should focus on balancing operational requirements with environmental considerations. Sustainable rail growth depends on continued innovation in acoustic engineering and proactive noise control measures. Such advancements will ensure rail transport maintains its competitive edge while minimizing acoustic environmental impact.

REFERENCES

[1] M. Brenna, F. Foiadelli, D. Zaninelli, Electrical railway transportation systems, John Wiley & Sons, 2018.

[2] F. Bunn, P.H.T. Zannin, Assessment of railway noise in an urban setting, Applied acoustics, 104 (2016) 16-23.

[3] J.C. Nielsen, A. Pieringer, D.J. Thompson, P.T. Torstensson, Wheel–rail impact loads, noise and vibration: a review of excitation mechanisms, prediction methods and mitigation measures, in: Noise and Vibration Mitigation for Rail Transportation Systems: Proceedings of the 13th International Workshop on Railway Noise, 16-20 September 2019, Ghent, Belgium, Springer, 2021, pp. 3-40.

[4] D. Liu, C. Wang, J. Gonzalez-Libreros, Y. Tu, L. Elfgren, G. Sas, A review on aerodynamic load and dynamic behavior of railway noise barriers when high-speed trains pass, Journal of Wind Engineering and Industrial Aerodynamics, 239 (2023) 105458.

[5] B. Tutmez, A. Baranovskii, Quantifying uncertainty in railway noise measurement, Measurement, 137 (2019) 1-6.

[6] K.B. Ginn, K. Haddad, Noise source identification techniques: simple to advanced applications, Acoustics 2012, (2012).

[7] M. Xie, F. Yao, L. Li, Y. Li, Research status and development trend of energy finite element analysis: a review, Journal of Vibroengineering, 25 (2023) 247-268.

[8] J.Y. Yoon, S. Pyo, A review of mitigation measures for reducing railway rolling noise from an infrastructure point of view, International Journal of Railway, 12 (2019) 1-9.

[9] S. Ouakka, O. Verlinden, G. Kouroussis, Railway ground vibration and mitigation measures: benchmarking of best practices, Railway Engineering Science, 30 (2022) 1-22.

[10] D. Thompson, Railway Noise and Vibration: Mechanisms, Modelling and Means of Control, Elsevier Science, 2008.

[11] X. Zhang, H.G. Jonasson, Directivity of railway noise sources, Journal of Sound and Vibration, 293 (2006) 995-1006.

[12] G. Licitra, F. Artuso, M. Bernardini, A. Moro, F. Fidecaro, L. Fredianelli, Acoustic Beamforming Algorithms and Their Applications in Environmental Noise, Current Pollution Reports, 9 (2023) 486-509.

[13] J. Yoon, S. Pyo, A Review of Mitigation Measures for Reducing Railway Rolling Noise from an Infrastructure Point of View, International Journal of Railway, 12 (2019) 1-9.

[14] K. Oh, M. Yoo, N. Jin, J. Ko, J. Seo, H. Joo, M. Ko, A Review of Deep Learning Applications for Railway Safety, in: Applied Sciences, 2022, pp. 10572.

[15] D. Thompson, G. Squicciarini, E. Ntotsios, L. Baeza, Noise and vibration from railway vehicles, in: Handbook of Railway Vehicle Dynamics, Second Edition, CRC Press, 2019, pp. 521-578.

[16] X. Zhang, H.G. Jonasson, Directivity of railway noise sources, Journal of Sound and Vibration, 293 (2006) 995-1006.

[17] D. Thompson, P. Gautier, Review of research into wheel/rail rolling noise reduction, Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 220 (2006) 385-408.

[18] B.S. Kumar, V. Chowdary, Railway Noise Pollution in Urban Environments, in: N. Garg, C. Gautam, S. Rab, M. Wan, R. Agarwal, S. Yadav (Eds.) Handbook of Vibroacoustics, Noise and Harshness, Springer Nature Singapore, Singapore, 2024, pp. 1-38.

[19] M. Ottley, A. Stoker, S. Dobson, N. Lynar, Identifying noise levels of individual rail pass by events, in: Noise and Vibration Mitigation for Rail Transportation Systems: Proceedings of the 12th International Workshop on Railway Noise, 12-16 September 2016, Terrigal, Australia, Springer, 2018, pp. 205-213.

[20] X. Sheng, S. Zhang, X. Xiao, Y. He, Recent advances on research into high-speed railway noise, Intelligent Transportation Infrastructure, 2 (2023) liad015.
[21] M. Belding, A. Enshaeian, P. Rizzo, Vibration-based approach to measure rail stress: Modeling and first field test, Sensors, 22 (2022) 7447.
[22] K. Elansari, A. Idrissi, H. Tifernine, Machine Learning to Predict Railway Infrastructure Defects, in: Modern Artificial Intelligence and Data Science 2024: Tools, Techniques and Systems, Springer, 2024, pp. 391-406.
[23] K. Oh, M. Yoo, N. Jin, J. Ko, J. Seo, H. Joo, M. Ko, A review of deep learning applications for railway safety, Applied Sciences, 12 (2022) 10572.
[24] M.J. Pappaterra, F. Flammini, V. Vittorini, N. Bešinović, A systematic review of artificial intelligence public datasets for railway applications, Infrastructures, 6 (2021) 136.