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Railway External Noise Analysis and Mitigation with a Proposed Multi Channel Diagnostic Framework

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Abstract. Railway external noise becomes more difficult to diagnose as train speed rises because wheel-rail, aerodynamic, structural, and environmental contributions overlap in both time and frequency. This study combines a literature-based comparison of mitigation measures with Python analysis of three single-channel train pass-by recordings. The review links the TWINS wheel-rail framework, computational fluid dynamics for aerodynamic sources, and acoustic imaging methods to practical source-, path-, and receiver-side control. Time waveforms, fast Fourier transforms, spectrograms, and one-third-octave bands show persistent energy between 500 and 1000 Hz, but the 300 km/h recording does not display the aerodynamic dominance expected from speed-based theory. Because microphone position, reflection, wind, wheel and rail condition, and the use of one recording channel can all change the apparent spectrum, the measurements are interpreted as band-based indicators rather than definitive source separation. The comparison also shows that noise control requires trade-offs among acoustic performance, maintenance, cost, and operating conditions. A future diagnostic architecture is therefore proposed using synchronised microphone and vibration arrays, moving-source beamforming, source-separation algorithms, and edge feature extraction before wireless transmission. This extension would connect physical noise models with spatially resolved measurements and more reliable intervention decisions.

Keywords: railway noise, TWINS, computational fluid dynamics, time-frequency analysis, microphone array, beamforming, source separation, edge sensing

1. Introduction

Railway noise is produced by several mechanisms whose relative importance changes with speed and operating condition. At low and medium speeds, surface roughness at the wheel-rail contact excites coupled wheel, rail, and track vibration, which then radiates rolling noise [1-4]. At higher speeds, unsteady flow around bogies, pantographs, inter-coach gaps, and other exposed components increases aerodynamic noise; its sound power rises more steeply with speed than rolling noise [1, 2]. These mechanisms often overlap in a pass-by recording, so a measured spectral peak cannot automatically be assigned to one physical source.

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Engineering control follows three routes. Source measures reduce wheel-rail excitation, structural radiation, or flow-induced sound. Propagation measures use vertical, semi-enclosed, or fully enclosed barriers. Receiver-side measures improve facade and window insulation where trackside modification is impractical. Their value depends on more than nominal decibel reduction: maintenance demand, cost, spatial coverage, train speed, source height, and operating environment can change the preferred solution. Reliable source diagnosis is therefore a prerequisite for selecting a proportionate intervention.

This study addresses two connected questions. First, what can single-channel time-, frequency-, and time-frequency analysis reveal about three train pass-by recordings, and where does source attribution become unreliable? Second, how should the evidence from TWINS-type wheel-rail modelling, computational fluid dynamics (CFD), acoustic localisation, and mitigation studies be combined into a practical decision framework? The paper analyses the available recordings, compares source-, path-, and receiver-side controls, and then proposes a multi-channel acoustic-vibration sensing system to improve source localisation and diagnostic reliability.

2. Methodology

The literature review covers railway-noise mechanisms, analysis methods, and mitigation studies published mainly from 2000 to 2025. Searches used combinations of railway noise, wheel-rail noise, TWINS, high-speed train aerodynamic noise, CFD, microphone array, beamforming, time-frequency analysis, and noise control. Sources were screened for relevance, methodological transparency, authority, and applicability to real operating conditions. The selected mitigation evidence was organised into source-control, propagation-path, and receiver-side measures and compared using reported A-weighted reductions or insertion losses, applicable conditions, maintenance requirements, cost implications, and spatial coverage. TWINS, CFD, and array-acoustic studies were used as interpretive frameworks; this project did not run a TWINS or CFD simulation and did not collect microphone-array data.

Three WAV recordings were processed in Python using NumPy, SciPy, and Matplotlib. Each file was converted to mono and normalised before time-waveform inspection, Hamming-windowed fast Fourier transform analysis, spectrogram calculation, and one-third-octave aggregation using ISO 266 centre frequencies. A 0.5 s sliding-energy calculation was used to locate the main pass-by interval. Spectral subtraction, with the background estimate taken from quieter segments, was applied only as a signal-processing demonstration. It does not represent a physical reduction achieved by an engineering intervention. The reported band energies are dimensionless values derived from normalised recordings; without acoustic calibration they cannot be interpreted as sound pressure levels or compared directly across different recording setups. Likewise, the labels 'wheel-rail' and 'aerodynamic' refer to operational frequency-band proxies based on the reviewed literature, not independently identified sources. These restrictions are essential when interpreting the ratios and the apparently large reductions after spectral subtraction.

3. Literature review

3.1. Types of railway noise and their causes

The TWINS framework explains rolling noise as a chain from combined wheel and rail roughness to contact-force excitation, coupled wheel-track vibration, and acoustic radiation [3, 4]. It is valuable because it links measurable physical inputs to component-level predictions, allowing engineers to

DOI: 10.54254/2755-2721/2027.37699

test how rail grinding, wheel condition, track support, and dampers change the radiated sound. Its predictions nevertheless depend on reliable roughness spectra, track and wheel mobility, contact filtering, and radiation parameters. A field recording that lacks these inputs can be compared with TWINS-based frequency expectations, but it cannot validate the model by spectrum alone. At higher speeds, aerodynamic sources emerge from unsteady flow around bogies, pantographs, inter-coach gaps, and cavities. Wind-tunnel experiments, CFD, and field measurements indicate that source strength and location vary with geometry, flow condition, and source height [1, 2, 5]. The change from rolling to aerodynamic dominance is therefore a trend rather than a universal threshold observable in every single-microphone recording.

3.2. Existing methods for noise analysis

Modern railway-noise analysis combines physical modelling, numerical simulation, and signal processing. FFT and one-third-octave analysis provide compact descriptions of spectral energy, while spectrograms and wavelet methods show how non-stationary components change during a pass-by [6, 7]. TWINS-type models describe wheel-rail excitation and radiation, whereas CFD coupled with an acoustic analogy can identify flow structures and estimate aerodynamic sound from components such as bogies and pantographs [1, 2, 5]. A single microphone records the superposition of all sources and propagation effects at one point. A synchronised microphone array instead retains phase and spatial information, allowing beamforming or inverse methods to estimate where sound originates. These methods are complementary: modelling predicts mechanisms, time-frequency analysis identifies when and where energy occurs in the spectrum, and arrays test whether that energy is spatially consistent with a proposed source.

3.3. Noise-reduction methods in existing research

Source control reduces excitation or radiation before sound enters the propagation path. In a metro curve affected by rail corrugation, Zhao et al. reported a 3 dB reduction after rail grinding and a further 8 dB reduction after rail dampers were installed [8]. The result shows why surface condition and structural vibration should be considered together: grinding reduces the roughness input, while dampers reduce the rail response and radiation. The reported benefit is tied to that track and corrugation condition, so maintenance interval and site-specific dynamics remain important.

Where source treatment is insufficient, barriers alter the propagation path. Zhang et al. evaluated a semi-closed noise barrier on a high-speed railway bridge using field measurements and numerical analysis [9]. Relative to a 3.15 m vertical barrier, the semi-closed design provided about 6 dB of additional reduction under the tested service conditions. The study demonstrates that enclosure geometry can improve shielding for elevated or high-position sources, although the benefit depends on bridge geometry, receiver position, and train operation.

Receiver-side treatment is used when track or barrier modification is impractical. Alonso et al. examined facade and window retrofits ranging from improved sealing to replacement glazing [10]. Because windows are commonly the weakest acoustic element in a facade, targeted upgrades can improve indoor exposure without modifying the railway. This approach does not reduce outdoor sound and must be assessed alongside ventilation, facade construction, and the required indoor criterion.

The three control routes solve different parts of the problem. Source measures can benefit a wide area but require access, maintenance, or vehicle redesign. Barriers protect receivers within a defined acoustic shadow but introduce structural, financial, and visual constraints. Receiver-side retrofits are

DOI: 10.54254/2755-2721/2027.37699

local and comparatively independent of railway operations, yet they protect only treated indoor spaces. An integrated strategy should therefore begin with source diagnosis and then combine measures according to speed, site geometry, affected population, maintenance capability, and cost.

3.4. Summary and research gap

Existing studies provide strong evidence for individual mitigation technologies, but two gaps remain. First, reported decibel reductions are often tied to a particular train, track, geometry, or measurement procedure, which limits direct comparison across source-, path-, and receiver-side measures. Second, many diagnostic interpretations rely on spectra from one or a small number of microphones even though wheel-rail and aerodynamic sources overlap and move relative to the observer. This study therefore combines a practical mitigation comparison with a critical test of single-channel source attribution. The unexpected high-speed result is treated as evidence of measurement ambiguity rather than proof that an established source model is wrong.

4. Results and analysis

The three recordings represent a slowly passing train, a close-range fast pass-by, and a train reported to travel at 300 km/h. The figures show time waveforms, FFT spectra, one-third-octave bands, and spectrograms. Because the files were not obtained with a shared calibrated measurement protocol, the analysis emphasises within-recording spectral patterns. Absolute energy comparisons between scenarios and source labels assigned from frequency bands are treated cautiously.

4.1. Analysis of a slow passing train

The slowly passing train has three prominent time-domain peaks at approximately 9.5, 11.6, and 13.4 s (Figure 1). The operational wheel-rail and aerodynamic bands contain normalised energies of 1.481 x 10^-3 and 1.699 x 10^-3, respectively, giving a ratio of 0.872 (Figure 2). This near-unity ratio means that the two predefined bands contain comparable energy; it does not demonstrate that two physical sources contribute equally. The one-third-octave spectrum peaks at 500, 630, and 800 Hz (Figure 3), consistent with frequencies often associated with rolling noise [3, 4]. Spectral subtraction reduces the two band energies to 6.232 x 10^-8 and 1.301 x 10^-8 and changes their ratio to 4.755 (Figure 4). The scale of this reduction shows the sensitivity of the algorithm to its background estimate and should not be reported as engineering noise-control performance.

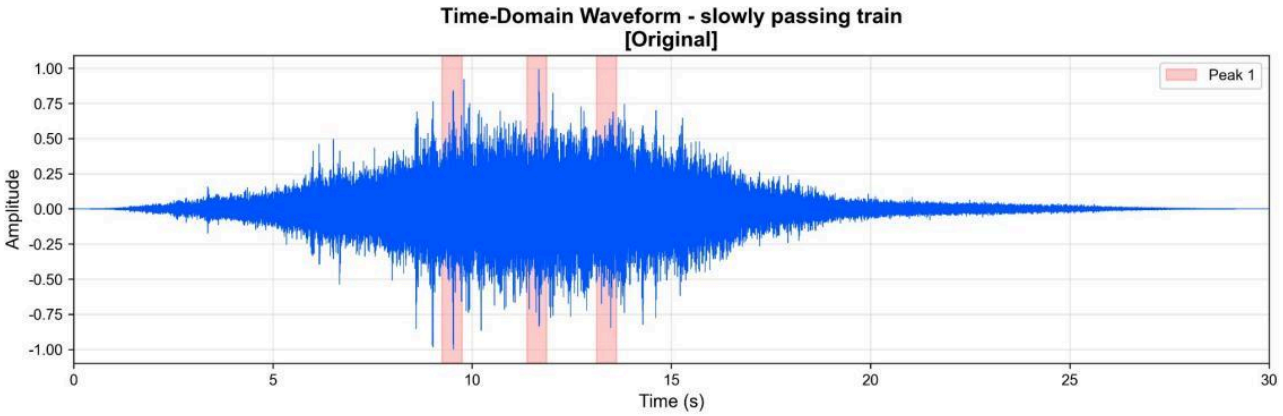


Figure 1. Time-domain waveform of the slowly passing train (original)

DOI: 10.54254/2755-2721/2027.37699

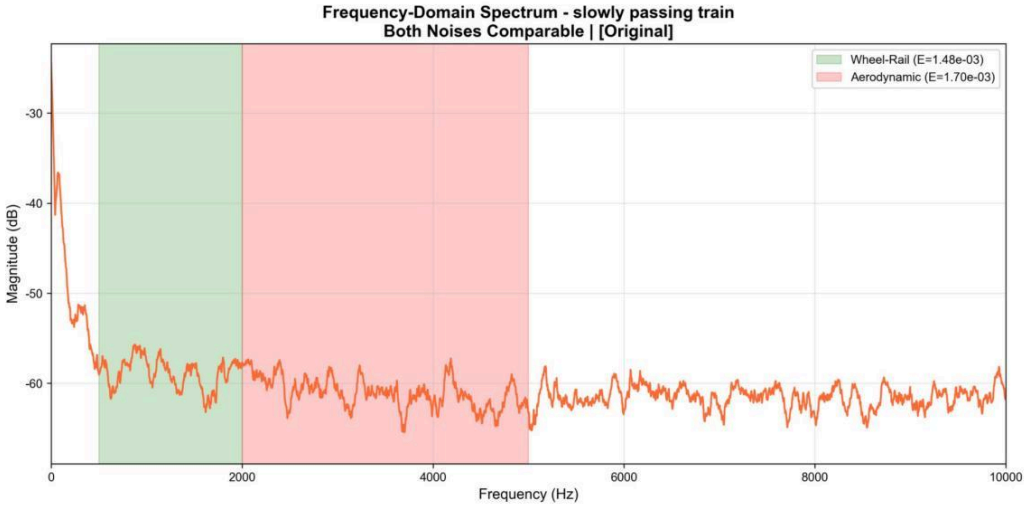


Figure 2. Frequency-domain spectrum of the slowly passing train (original)

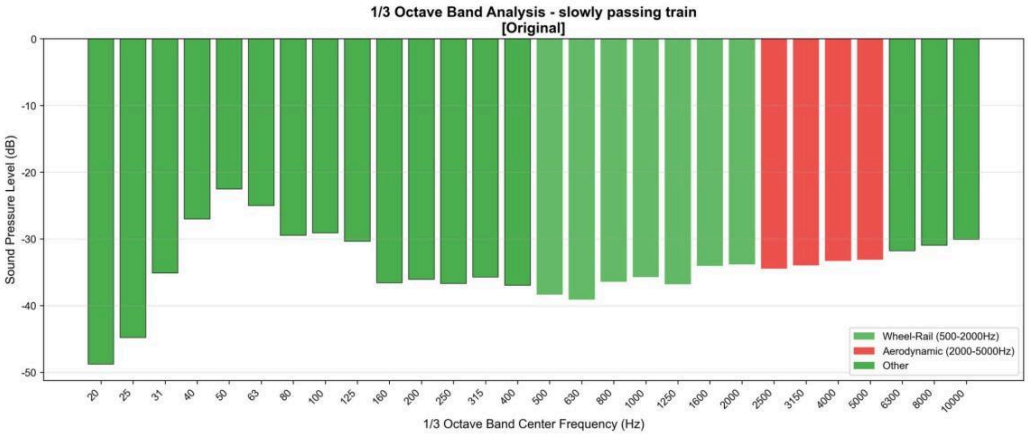


Figure 3. One-third octave band spectrum of the slowly passing train (original)

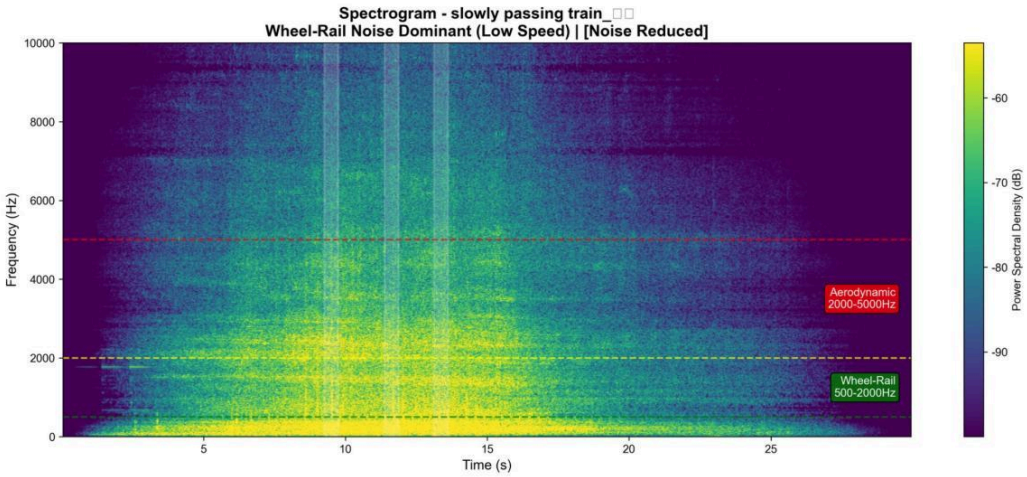


Figure 4. Spectrogram of the slowly passing train after spectral subtraction

DOI: 10.54254/2755-2721/2027.37699

4.2. Analysis of the close-range fast passing train

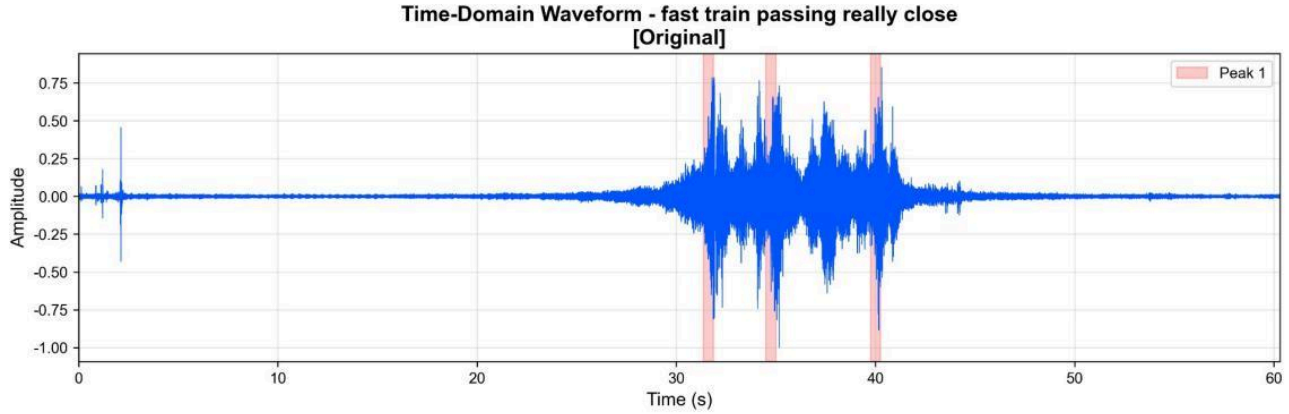


Figure 5. Time-domain waveform of the close-range fast passing train (original)

The close-range fast pass-by has much larger recorded amplitudes than the slow case, but the difference cannot be attributed to train speed alone because microphone distance, gain, and calibration were not controlled. Within this file, the predefined wheel-rail and aerodynamic bands contain normalised energies of 5.148 x 10^2 and 2.785 x 10^1, producing a ratio of 18.486 (Figure 5). The result indicates strong concentration in the band associated with wheel-rail radiation, consistent with the microphone's close position, but it is not a spatial separation of wheel and aerodynamic sources.

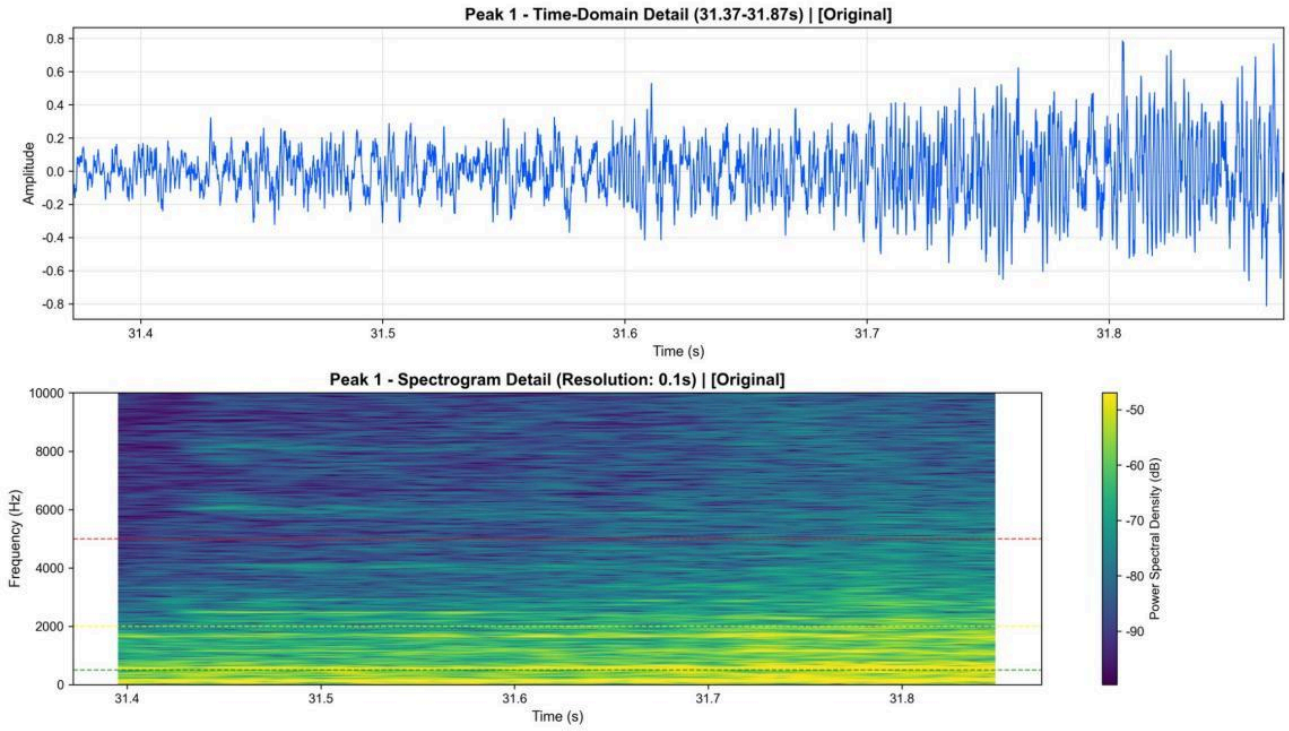


Figure 6. Close-up of Peak 1 in the close-range fast passing train recording

DOI: 10.54254/2755-2721/2027.37699

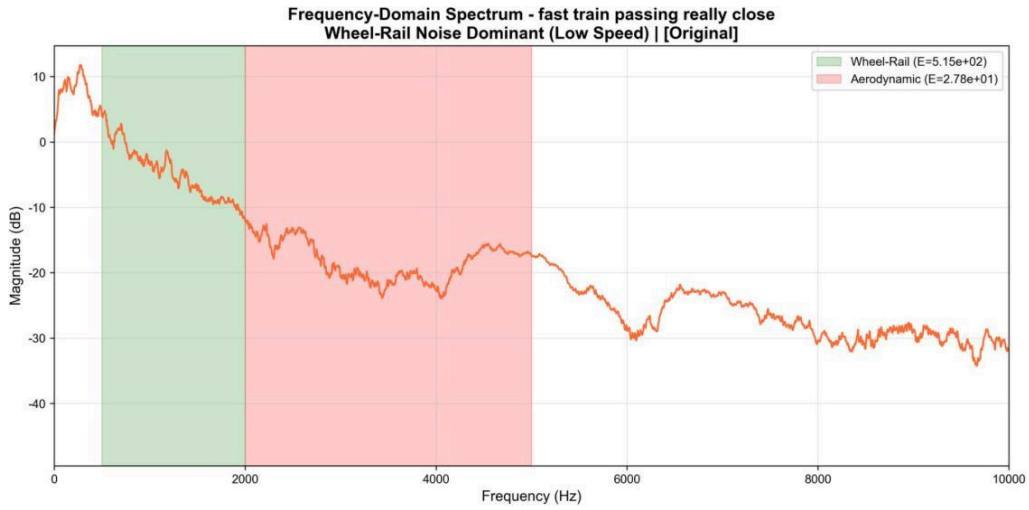


Figure 7. Frequency-domain spectrum of the close-range fast passing train (original)

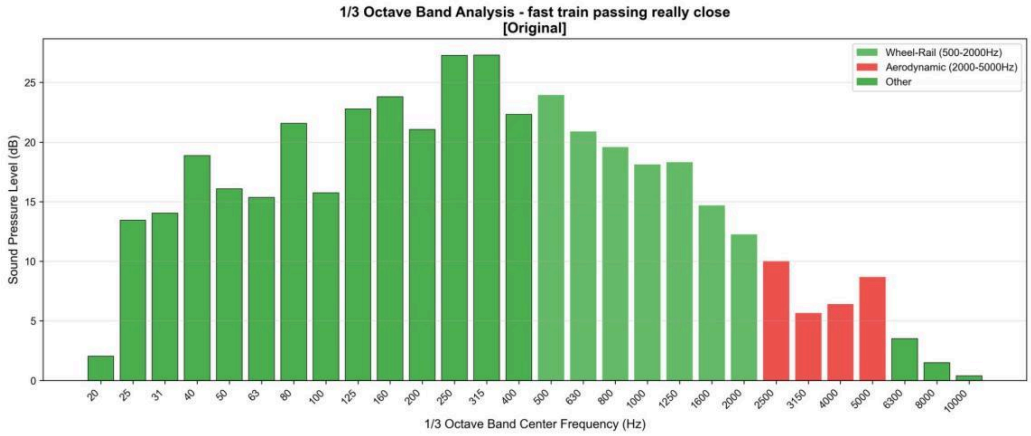


Figure 8. One-third-octave-band spectrum of the close-range fast passing train (original)

Sharp peaks occur at approximately 31.6, 34.8, and 40.0 s, consistent with discrete high-amplitude events during the pass-by (Figure 6). Energy is concentrated between 500 and 2000 Hz, with prominent one-third-octave bands at 630 and 800 Hz (Figures 7 and 8). These frequencies are compatible with rolling-noise descriptions in the literature [3, 4], although the recording alone cannot determine whether each peak corresponds to a particular wheelset or structural component. After spectral subtraction, the operational band energies fall to 3.982 x 10^-3 and 5.809 x 10^-4. This five-order change reflects algorithmic suppression of the recorded signal, not a measured reduction from a physical mitigation device.

DOI: 10.54254/2755-2721/2027.37699

4.3. Analysis of a high speed train at 300 km/h

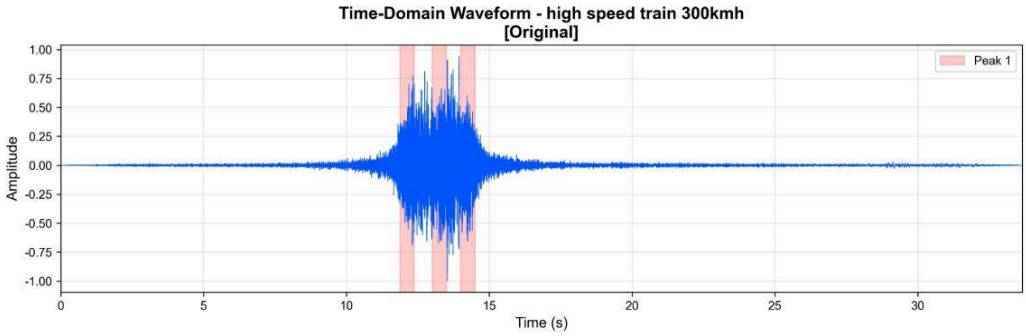


Figure 9. Time-domain waveform of the 300 km/h high-speed train (original)

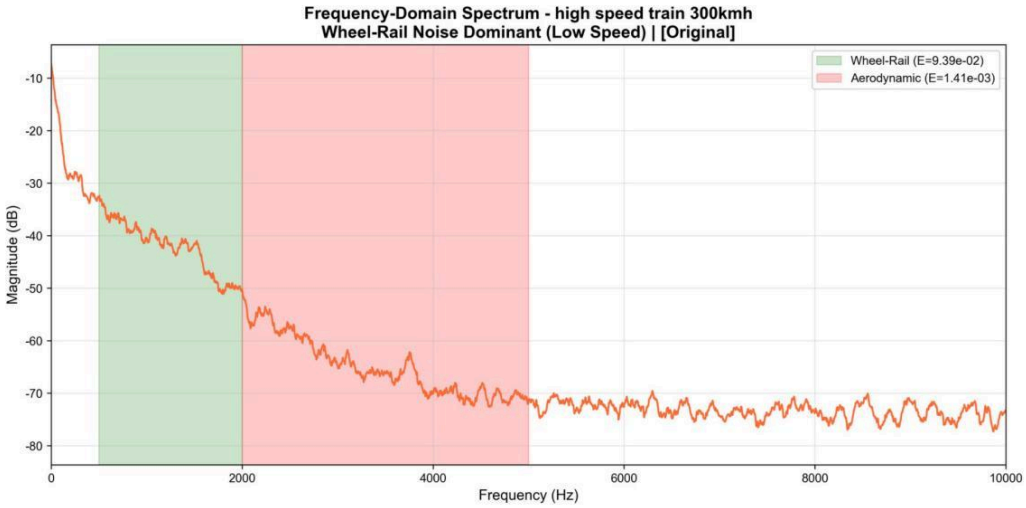


Figure 10. Frequency-domain spectrum of the 300 km/h high-speed train (original)

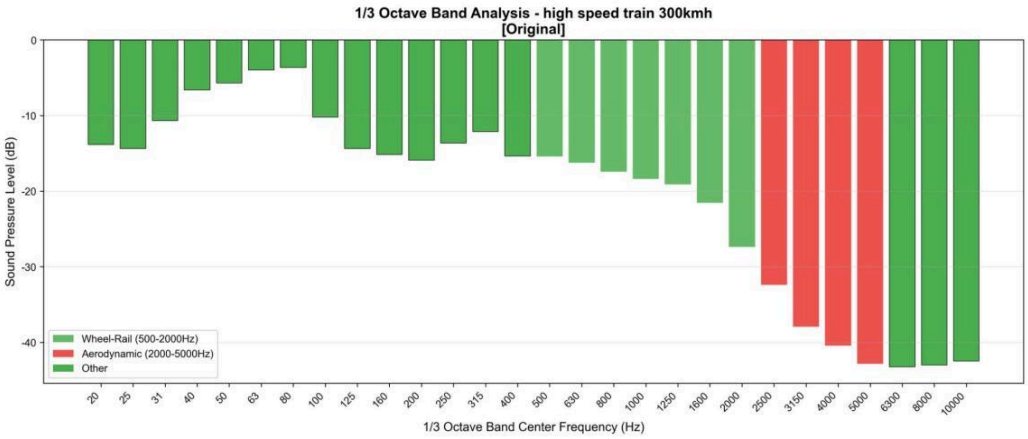


Figure 11. One-third-octave-band spectrum of the 300 km/h high-speed train (original)

DOI: 10.54254/2755-2721/2027.37699

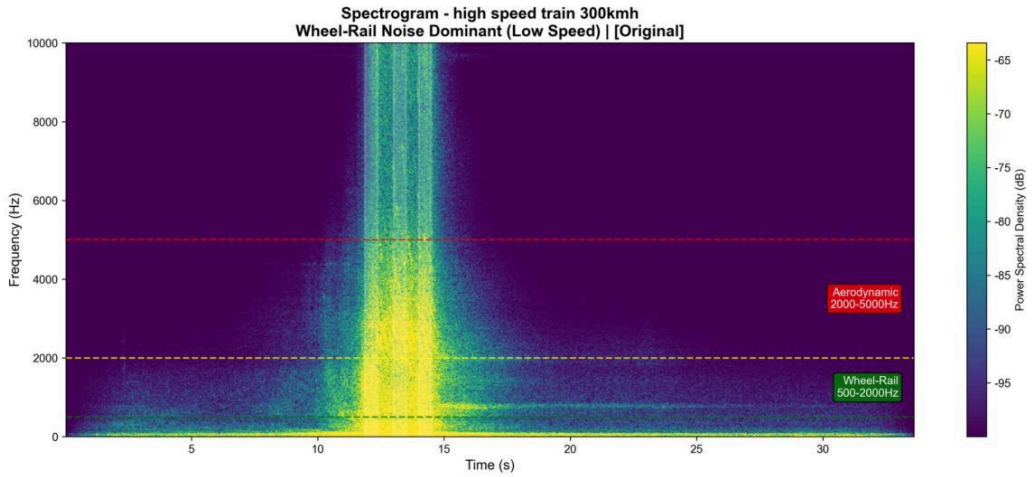


Figure 12. Spectrogram of the 300 km/h high-speed train (original)

The 300 km/h recording does not show the aerodynamic dominance expected from general speed-scaling arguments. The predefined wheel-rail and aerodynamic bands contain normalised energies of 9.393 x 10^-2 and 1.406 x 10^-3, respectively, giving a ratio of 66.790 (Figures 9 and 10). This is an apparent spectral result, not a direct measurement of separate source powers. A trackside microphone close to the rail can emphasise rolling noise, while source directivity, ground or building reflections, wind, roughness, wheel condition, and recording gain can alter the observed spectrum. Severe surface roughness can also increase rolling-noise radiation [4]. The discrepancy therefore exposes the limits of applying a speed-based source rule without information about sensor geometry and operating condition.

Most energy lies between 500 and 1000 Hz, with one-third-octave peaks at 630 and 800 Hz (Figure 11). The spectrogram shows how this energy concentrates around the pass-by interval (Figure 12), but it provides no spatial information. Spectral subtraction removes almost all energy in these bands. Such over-suppression confirms that the processed signal cannot be used to estimate the performance of a barrier, rail treatment, or aerodynamic modification. It also illustrates why a single channel and a single denoising rule are insufficient when several non-stationary sources overlap.

4.4. Comparison across the three recordings

Across all three recordings, substantial energy occurs in the 500-1000 Hz region associated with wheel-rail radiation in previous studies [3, 4]. The ratios differ sharply, but the files were recorded under different and incompletely documented conditions, so the differences cannot be assigned solely to speed or source strength. The spectral-subtraction results are similarly unsuitable as physical reduction rates because the algorithm removes components that resemble the estimated background. The most defensible finding is methodological: time-frequency analysis identifies when dominant bands occur, whereas reliable source attribution requires spatial measurements, vibration evidence, or a validated physical model.

4.5. Limitations of single channel source attribution

A single microphone preserves amplitude and frequency but discards the spatial phase relationships needed to localise a moving source. Frequency-band attribution is also non-unique: wheel, rail, bogie, and aerodynamic components can occupy overlapping bands, and reflections can shift the

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apparent balance. The present analysis can therefore identify candidate mechanisms and anomalous recordings, but it cannot estimate independent source powers.

This limitation explains the high-speed discrepancy and defines the next research step. Multiple synchronised microphones would enable moving-source beamforming, while accelerometers on the rail, fastener, or nearby structure would provide a separate observation of mechanical excitation. Agreement among an acoustic source map, vibration coherence, and the frequency ranges predicted by TWINS or CFD would provide much stronger evidence than any one spectrum.

5. Discussion

The literature and recording analysis together support two decisions. Noise mitigation must match the dominant physical mechanism and operating context, and the diagnostic method must be strong enough to distinguish candidate sources. The following comparison therefore considers both intervention trade-offs and the sensing architecture needed to make a more reliable choice.

5.1. Source control measures

Source control acts on noise generation and can benefit all receivers along the affected section. For rolling noise, rail grinding, rail dampers, resilient wheels, low-stiffness fasteners, and track absorbers target roughness excitation or structural radiation. Reported reductions commonly range from about 3 to 10 dB(A), depending on the measure and test condition [8, 11, 12]. Their effectiveness can deteriorate as wheel and rail surfaces change, so inspection and maintenance are part of the engineering cost. At high speed, bogie fairings, pantograph optimisation, and other geometric changes aim to reduce flow separation and pressure fluctuations [1, 2]. These measures may require vehicle redesign and should be assessed against drag, access, safety, durability, and maintenance constraints.

5.2. Path control measures

Path control is appropriate when source modification is insufficient or impractical. Conventional vertical barriers can provide useful insertion loss, but performance depends on barrier height, source height, diffraction, and receiver position [11]. Semi-enclosed and fully enclosed barriers can protect a larger vertical source region and may be more effective for high-speed lines [9, 13, 14]. Their acoustic benefit must be weighed against construction cost, structural loading, access, visual impact, and the limited area inside the acoustic shadow. Differences between field and review values also show why nominal reductions should not be transferred between sites without comparable geometry and measurement conditions.

5.3. Receiver-side control measures

Receiver-side control improves the sound insulation of buildings without changing outdoor railway noise. Gap sealing, secondary glazing, and high-performance double or triple glazing can help indoor spaces meet applicable limits [10]. This approach is useful where track access is constrained or only a small number of buildings require protection. Its main limitation is restricted coverage: outdoor spaces remain exposed, and performance depends on facade construction, ventilation requirements, workmanship, and occupant use. It is therefore a complement to source and path control rather than a general substitute for them.

DOI: 10.54254/2755-2721/2027.37699

5.4. Comparative summary and integration

Table 1 summarises the mitigation evidence. Source control offers the widest spatial benefit but carries maintenance or redesign costs. Barriers provide targeted protection but introduce geometric, structural, financial, and visual constraints. Receiver measures can be proportionate for isolated buildings but leave the outdoor environment unchanged. Economic assessment should compare the cost of prevention with the social cost of continuing exposure [15]. For a new high-speed line, aerodynamic design and appropriately configured barriers can be planned together. For an existing urban railway, condition-based wheel-rail maintenance, local barriers, and targeted facade treatment may be more feasible. In both cases, the quality of source diagnosis determines whether expenditure addresses the actual mechanism.

Table 1. Comparative summary of railway-noise mitigation strategies

Mitigation category	Specific measure	Typical noise reduction (dB(A))	Applicable speed range	Key advantages	Key limitations
Source control	Rail grinding	5-8	All	Universal effect; targets root cause	Requires regular maintenance
Source control	Rail dampers	5-8	All	Targets rail vibration and radiation	Costly installation
Source control	Resilient wheels	6-10	All	High effectiveness	High cost; vehicle-specific
Source control	Track absorbers	3-5	All	Effective for track-radiated noise	Moderate effectiveness
Path control	Vertical barrier	6-15 (lower at high speed)	All	Protects specific areas effectively	Localised effect; visual impact
Path control	Semi-enclosed barrier	>4 at high speed	All	Better than vertical barriers at high speed	Higher cost and visual impact
Path control	Fully enclosed barrier	4.5-6 field / 15-25 review	All	Highest potential effectiveness	Very high cost; major visual impact
Receiver-side control	Window retrofitting	Meets indoor target	All	Protects indoor occupants	No outdoor benefit; building-specific

5.5. Proposed multi channel diagnostic framework

The proposed measurement system combines a trackside microphone array with vibration sensors mounted at selected rail, fastener, or support locations. A tachometer or reliable speed and position record would support moving-source correction, while wind, temperature, and sensor geometry would be logged for each pass. Railway microphone-array studies demonstrate that spatial sampling can locate sources on moving trains, and broader acoustic-imaging research shows that synchronised channels improve spatial resolution and background-noise rejection compared with one microphone [16, 17].

DOI: 10.54254/2755-2721/2027.37699

Processing would proceed in four stages. First, all channels would be calibrated, time-synchronised, filtered, and divided into pass-by windows. Second, short-time spectra, one-third-octave features, and cross-spectral matrices would describe the event. Third, moving-source beamforming would produce frequency-dependent source maps, while sparse or independent-component methods would estimate overlapping contributions [18, 19]. Fourth, acoustic maps would be compared with vibration coherence and with TWINS- or CFD-informed source regions. A component would be classified only when spatial, spectral, and mechanical evidence were mutually consistent.

An edge processor could perform event detection, quality checks, and feature extraction before wireless transmission, reducing bandwidth and allowing long-term monitoring [20]. Selected raw multi-channel windows should still be retained so that later algorithms can be audited or rerun. The main design trade-offs are array aperture versus portability, channel count versus synchronisation and cost, local computation versus power consumption, and feature-only transmission versus future reanalysis. Validation should use a calibrated reference source, repeated passes, documented weather and geometry, and paired measurements before and after a real intervention. Relevant performance measures include localisation error, source-separation stability, repeatability of band levels, data reduction, latency, and power use.

Table 2. Proposed diagnostic chain from physical mechanism to engineering decision

Layer	Function	Evidence and trade-off
Physical models	TWINS for rolling noise; CFD and acoustic analogy for aerodynamic noise	Mechanism-based expectations; sensitive to model inputs
Sensing	Synchronised microphone and vibration arrays with speed, position, and weather metadata	Adds spatial and mechanical evidence; increases hardware and calibration demands
Signal processing	Time-frequency features, cross-spectra, beamforming, and source separation	Improves localisation and separation; depends on array geometry and assumptions
Edge layer	Event detection, quality control, and feature extraction before wireless transfer	Reduces bandwidth and latency; feature selection can limit later reanalysis
Validation	Repeated calibrated passes and paired tests before and after mitigation	Supports reproducible intervention decisions; requires controlled field access

This architecture converts the limitation found in the present recordings into a testable engineering programme. It also keeps mitigation assessment and diagnosis connected: a rail treatment should change vibration-coherent rolling-noise sources, an aerodynamic modification should change mapped body sources, and a barrier should alter the transfer path rather than the source itself.

DOI: 10.54254/2755-2721/2027.37699

6. Conclusion

This study combined a literature-based mitigation comparison with time-, frequency-, and time-frequency analysis of three train pass-by recordings. The recordings consistently contained substantial energy between 500 and 1000 Hz, but the 300 km/h file did not show the aerodynamic dominance expected from general speed-scaling theory. The result does not invalidate TWINS or aerodynamic-noise models. It shows that a spectrum from one uncalibrated microphone is shaped by source position, propagation, reflection, environmental condition, wheel and rail state, and the measurement chain.

The mitigation review confirms that engineering decisions involve trade-offs among acoustic performance, maintenance, cost, spatial coverage, and operating condition. Source measures address generation but require maintenance or redesign; barriers protect defined zones but depend on geometry and can be expensive; receiver treatments improve indoor exposure without reducing outdoor sound. Spectral subtraction should not be confused with these physical interventions, because its near-total energy removal in the present recordings reflects aggressive signal processing rather than measured environmental noise reduction.

The proposed next stage is a synchronised acoustic-vibration array that connects mechanism models with spatial evidence. Beamforming would localise moving acoustic sources, vibration channels would identify structure-borne excitation, and source-separation methods would test overlapping components. Edge processors could detect pass-by events and transmit calibrated features together with selected raw windows for later verification. Repeated, calibrated before-and-after measurements would then allow TWINS- and CFD-informed hypotheses to be tested and would provide a stronger basis for choosing technically effective and economically proportionate railway-noise controls.

References

[1] Zhang, T., Chen, Z., Xiao, X., & Sheng, X. (2024). A review on the research of noise generation mechanism and control technology in high-speed trains. *Journal of Sound and Vibration, 571*, 118123.

[2] Yan, H., Jiang, K., Fu, Z., & Liu, J. (2022). A review of recent research into the causes and control of noise during high-speed train movement. *Journal of Low Frequency Noise, Vibration and Active Control, 41*(2), 547–567.

[3] Thompson, D. J., & Jones, C. J. C. (2000). A review of the modelling of wheel/rail noise generation. *Journal of Sound and Vibration, 231*(3), 519–536.

[4] Thompson, D. J. (1996). On the relationship between wheel and rail surface roughness and rolling noise. *Journal of Sound and Vibration, 193*(1), 149–160.

[5] Deng, T., Liu, Q., Chen, Z., & Hua, X. (2014). Analysis of external noise spectrum of high speed railway. *Journal of Central South University, 21*, 4753–4761.

[6] Kumar, A., Singh, A. K., & Kumar, P. (2019). 50 years of FFT algorithms and applications. *Journal of the Franklin Institute, 356*(14), 7449–7483.

[7] Jáuregui, J. C., Reséndiz, J. R., Thenozhi, S., Szalay, T., Jacsó, Á., & Takács, M. (2018). Frequency and time-frequency analysis of cutting force and vibration signals for tool condition monitoring. *IEEE Access, 6*, 6400–6410.

[8] Zhao, G., Liu, W., Zhang, W., & Wang, Y. (2017). Internal noise reduction in railway vehicles by means of rail grinding and rail dampers. *Applied Acoustics, 118*, 44–52.

[9] Zhang, J., Xiao, X., Sheng, X., & Wang, Y. (2019). Acoustic performance of a semi-closed noise barrier installed on a high-speed railway bridge: Measurement and analysis considering actual service conditions. *Applied Acoustics, 156*, 194–204.

[10] Alonso, A., Patricio, J., Vivian, D., & del Rey, R. (2021). Acoustic retrofit strategies of windows in facades of residential buildings: Requirements and recommendations to reduce exposure to environmental noise. *Building and Environment, 207*, 108488.

[11] Sheng, X., Li, T., & Zhang, J. (2023). Recent advances on research into high-speed railway noise. *Journal of Modern Transportation, 31*(1), 1–21.

DOI: 10.54254/2755-2721/2027.37699

[12] Luo, H., Liu, X., Cai, C., & Li, X. (2023). Experimental evaluation and numerical interpretation of various noise mitigation strategies for in-service elevated suburban rail. *Journal of Sound and Vibration, 544*, 117390.
[13] Zhang, J., Sheng, X., & Xiao, X. (2025). Study on the noise reduction effect of sound barriers on the aerodynamic noise of high-speed trains. *Journal of Sound and Vibration, 592*, 118819.
[14] Zhang, L., Wang, Y., Li, X., & Liu, Y. (2024). A review on the research of noise generation mechanism and control technology in high-speed trains. *Intelligent Transportation Infrastructure, 2*(1), 1–21.
[15] Brons, M., van der Veen, R., & van Wee, B. (2003). Railroad noise: Economic valuation and policy. *Transportation Research Part D: Transport and Environment, 8*(3), 169–184.
[16] Barsikow, B. (1996). Experiences with various configurations of microphone arrays used to locate sound sources on railway trains operated by the DB AG. *Journal of Sound and Vibration, 193*(1), 283–293.
[17] Merino-Martinez, R., Sijtsma, P., Snellen, M., et al. (2019). A review of acoustic imaging methods using phased microphone arrays. *CEAS Aeronautical Journal, 10*, 197–230. doi:10.1007/s13272-019-00383-4.
[18] Zea, E., Fernandez-Grande, E., & Lopez Arteaga, I. (2020). Sparsity-driven separation of railway rolling noise with a microphone array. *Proceedings of e-Forum Acusticum*.
[19] Hyvarinen, A., & Oja, E. (2000). Independent component analysis: Algorithms and applications. *Neural Networks, 13*(4-5), 411–430. doi:10.1016/S0893-6080(00)00026-5.
[20] Shi, W., Cao, J., Zhang, Q., Li, Y., & Xu, L. (2016). Edge computing: Vision and challenges. *IEEE Internet of Things Journal, 3*(5), 637–646. doi:10.1109/JIOT.2016.2579198.