PERCEPTUAL IMPACT OF ROLLING STOCK TONALITY ON RAILWAY PASSENGERS AND NEARBY COMMUNITIES: IN-SITU STUDIES

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Abstract

Tonal noise from rolling stock is addressed in railway through dedicated indicators, but its perceptual relevance in real operation is still difficult to quantify. This paper reports in-situ perception studies performed within the European project FP4 Rail4Earth (Grant Agreement ID: 101101917).

Surveys were conducted with passengers during revenue service and with residents living near railway stations. Preliminary steps were used to define field protocols suited to realistic environments. Large participant samples and structured questionnaires were used to assess comfort and noise-related annoyance. In these real life conditions, no statistically significant relationship was observed between the tonal character of a noise and its perceived annoyance: while tonal sources were associated with low annoyance, others sources (e.g. train passengers or warning signals such as horns) were perceived as highly disturbing for the interior zones or the exterior locations investigated.

Practical considerations are proposed. During acceleration and braking, where traction noise is inherently tonal, target setting should primarily rely on overall noise level. For other interior conditions, tonality may be used as a secondary refinement via a moderate penalty added to overall level requirements when high comfort is targeted. For exterior noise, no clear tonal influence was observed, the results highlight the importance of identifying dominant noise sources and contextual factors in order to enable targeted mitigation strategies.

Keywords: railway, tonality, perception, passengers, communities

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1. Context and objectives

1.1 Background

Train equipment is the main source of tonal noise, primarily due to rotating components (e.g. fans, compressors, gearboxes, traction motors) that generate vibrations at harmonic frequencies, and electrical systems where frequency switching during power conversion introduces tonal elements. The assessment of tonal noise in railway applications is addressed by the acoustic standards EN ISO 3381:2021 and EN ISO 3095:2025 for interior and exterior noise, respectively. These standards reference the following tonality evaluation methods:

- For type testing according to EN ISO 3381 and EN ISO 3095, ISO 1996-2:2017 Annex K provides a method based on third-octave band analysis combined with a comparison to the overall sound level.
- For EN ISO 3095, when an assessment of tone audibility is requested, ISO/TS 20065:2022 provides a narrow-band analysis method and defines the tonality indicator ΔL (dB). This indicator is used throughout the present study.
- For EN ISO 3381, tonal noise may also be investigated using DIN 45681 or ISO 1996-2:2017 Annex J, which include tone-audibility assessments and associated penalties that may reach up to 6 dB.

The scope of work of the four-year FP4-Rail4EARTH, under the HORIZON-ER-JU 2022-FA4-01 call topic, is to improve the existing sustainability performance of rail ways to build a more attractive and resilient transport mode and to contribute towards the objectives of a climate neutral Europe for 2050.
Effective noise emission management is essential for the expansion of rail transport, impacting both train passengers and residents. For decades, the rail industry has managed railway noise emissions by monitoring and controlling sound pressure level. Other characteristics, such as tonality, may also significantly influence annoyance. Since the reduction of tonality has an impact on rolling stock design, a balance between comfort, cost, and performance is required.
Through several surveys, this study investigates the relation between perceived annoyance and tonal indicators. The findings aim to guide manufacturers and operators in designing rolling stock that reflects the actual perception of tonal noise.

2. Methodology

To assess the absolute contribution of tonality to annoyance, in-situ surveys were conducted under real operating conditions (onboard trains and in residential environments). This approach enables evaluation on an absolute scale, reflecting the overall comfort or discomfort experienced in daily situations, and therefore ensures high ecological validity.
Although such conditions inherently involve uncontrolled variables, their influence was mitigated by

(i) careful selection of acoustical environments,
(ii) testing during off-peak periods, and
(iii) maintaining consistency in rolling stock or location across surveys.

Data were collected using a questionnaire specifically designed and pre-tested to help participants identify tonal components and describe the associated annoyance.

3. Test cases selection

3.1 Exterior location

The selection of test sites followed two main principles:

(i) environments where railway noise is dominant, with minimal influence from other transport sources, and
(ii) locations with previously identified noise complaints when available.

Based on these criteria, two types of environments were investigated:

- surroundings of a commuter train station (§3.1.1)
- surroundings of a tramway station (§3.1.2)

3.1.1 Commuter train station - Granollers

The selected site is a suburban station located in Granollers, Spain, served primarily by regional trains, with occasional freight traffic. Approximately 12 train movements per hour were recorded (October 2024), including both passing trains (≈20%, up to 140 km/h) and stopping services or terminating services (see Figure 1), with turnaround times of about 30 minutes. The station is located in close proximity to residential buildings (≈50 m, see Figure 2). According to the infrastructure manager ADIF, the area is associated with a high level of noise complaints from residents.

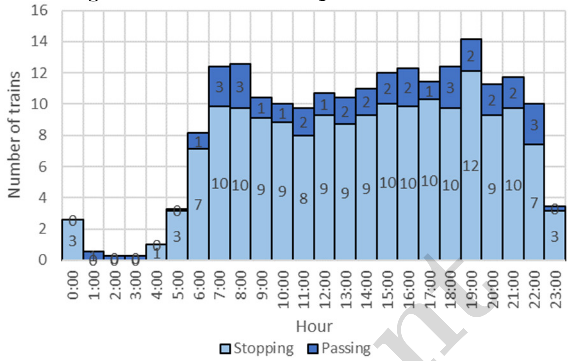

Figure 1: Distribution of train movements per hour at Granollers station (average, October 2024)

Figure 2: Granollers commuter station and surrounding residential environment

3.1.2 Tramway stop

The site is located in a densely populated urban area (see Figure 3). It is served by two tramway lines, with approximately half of the services terminating and half continuing their route. The traffic corresponds to roughly one tramway every five minutes per direction (≈ 24 trams per hour).

Figure 3: Tramway stop and surrounding urban environment

3.2 Interior locations

3.2.1 General considerations

The test environments were prequalified to ensure that the perceptual impact of tonality could be isolated. Situations with very low tonal content, strong correlation between tonality and overall level, or poorly characterized intermittent tonal events were avoided, as they would hinder interpretation.

Preliminary acoustic measurements were conducted to select relevant train interior zones. The objective was to identify paired zones with contrasting tonality levels while maintaining similar overall sound levels, enabling the specific effect of tonality on perception to be assessed.

3.2.2 Selected trains

Following a pre-analysis phase, three types of rolling stock were retained for field tests: a commuter train, a metro, and a tramway. These were selected to ensure the presence of noticeable tonal components in specific operating conditions, enabling the assessment of their perceptual impact.

Table 1 summarizes, for each train, the low and high tonality levels (ΔL, calculated according to ISO/TS 20065:2022 with time blocks of 3 s) together with the overall sound level (dBA). For the higher tonality condition, both time-averaged (AVG) and maximum (MAX) values are reported, while all other values correspond to time averages over a representative journey.

Despite the targeted selection of zones, the difference in tonality between low and high conditions remains limited (typically a few decibels). This can be attributed to:

(i) the occurrence of tonal events in specific operating phases (e.g. acceleration), whose contribution is reduced in averaged values, and

(ii) limitations of the ISO/TS 20065:2022 method, which relies on a 3 s averaging time and tends to underestimate transient tonal components.

Table 1: Zone definition of selected rolling stocks

Rolling stock	Low tonality	Higher tonality	Overall level dBA
Tramway	Avg 6 dB	Avg 10 dB Max 24 dB	69 dBA
Metro	Avg 1 dB	Avg 2 dB Max 7 dB	63 dBA
Commuter	Avg 7 dB	Avg 8 dB Max 19 dB	63 dBA

4. Preparation of tests

All tests were conducted in Spain. The questionnaires were designed and administered in Spanish.

4.1 Qualitative tests (diary tests) – for interior tests

At the beginning of the study, qualitative tests were conducted to gather passenger insights on interior noise comfort and to guide the design of the field survey questionnaire. They were implemented as an online diary administered through a mobile-phone application and completed daily over one working week. A total of 20 participants took part in the study, with half assigned to the commuter train and half to the metro. The questionnaires evolved from one day to the next, progressively addressing noise perception in greater detail. The objective was to study both overall annoyance and source-specific annoyance under real travel conditions, to evaluate the ability of passengers to distinguish between different onboard noise sources, and to extract representative verbatims. These verbatims were subsequently used to adapt the questionnaire wording to terminology familiar and understandable to passengers.

The results indicate that passengers are generally accustomed to typical train noise environments and rarely identify noise as a primary concern in spontaneous feedback. Most participants were nevertheless able to identify the main noise sources when prompted. Finally, an inter-individual variability was observed in both the perception and tolerance of interior noise.

4.2 Design of the questionnaire

Interior tests

The questionnaire was designed to be administered by an interviewer using a structured sequence of questions. It mainly consists of closed-ended questions based on rating scales, complemented by a single open-ended question. Visual support could be provided to participants to facilitate understanding of the scales.

The survey begins with general questions related to participant characteristics and trip conditions, followed by a broader assessment of onboard comfort. Within this section, interior noise is addressed alongside other comfort factors in order to limit early focus on noise and reduce potential bias. A dedicated section on interior noise then provides a general evaluation, followed by source-specific annoyance ratings using an 11-point scale:

- 0 = not annoying at all
- 10 = very annoying

The questionnaire concludes with questions addressing perceived appropriateness of the noise level, overall quietness, and tolerance thresholds.

Exterior tests

The exterior questionnaire follows a similar structured approach, beginning with general questions on the acoustic environment inside the home, including multiple noise sources to avoid premature focus on railway noise. It then addresses train-related noise more specifically, including comparative assessments with other environmental sounds and identification of the most disturbing periods.

Additional questions investigate the ability of respondents to identify specific railway noise sources and their impact on daily activities. Participants also rate the annoyance associated with different types of

train noise (e.g. acceleration, braking), as well as the annoyance caused by different train types passing through the station. To support source identification, images of the train types are presented during the interview.
Finally, information is collected on dwelling characteristics, including location and façade orientation, as well as the presence of sound insulation. Throughout the survey, participants are regularly reminded to base their responses on the noise perceived while inside their homes.

4.3 Pilot tests

Pilot campaigns were conducted for interior and exterior surveys, each representing approximately 10 % of the final sample. Their purpose was to verify questions clarity and comprehension, to estimate the completion time, and to validate the interviewer protocol. Based on these preliminary tests, minor adjustments were implemented in the questionnaires, including refinement of terminology and the addition of alternative response options.

4.4 Conduction of field tests

All field tests were conducted in accordance with the predefined sampling targets, including 50 participants per exterior test and 150 participants per rolling stock for interior surveys, resulting in a total of 450 participants.
Screening criteria were applied to ensure the relevance of the respondents. For exterior surveys, participants were required to live in the vicinity of the investigated station and to have a dwelling directly facing the railway. For interior surveys, all participants were regular users of the studied railway line.
The overall sample was balanced in terms of gender (50% male, 50% female) and age groups (18 - 34, 35 - 49, and over 50). All participants reported normal hearing conditions, with no declared hearing impairments or hyperacusis.

5. Main results

Statistical significance was assessed using Kruskal–Wallis test with a significance threshold of $p < 0.05$.

5.1 Interior test

An overview of the interior results is given in Table 2. Results are commented below the table. Rows marked with the symbol "*" correspond to tonal sources.

Table 2: Overview of interior tests results (mean values). Comfort and Agreement questions were rated from 0 (very poor) to 10 (excellent), while Annoyance questions was rated from 0 (not annoying at all) to 10 (very annoying).

	Comm.	Metro	Tram
Comfort /10	2.5/10		7.5/10
Interior comfort	6.2	8.7	8.4
Interior noise	4.6	8.0	7.4
Annoyance /10	2.5/10		7.5/10
Interior noise	4.8	2.9	3.3
Motor accel.*	2.0	1.5	2.2
Motor braking*	1.2	1.4	2.0
Air conditioning*	1.2	0.9	0.8
Rolling noise	3.5	2.4	3.4
Other passengers	7.4	3.7	4.6
Rattling noise	3.3	1.0	1.9
Announcements	2.7	2.9	1.4
Agreement /10	2.5/10		7.5/10
The sounds I hear are fitting for a train	4.4	8.5	8.2
I experience this train as quiet	4.6	8.8	8.4
This train has a tolerable noise level	4.6	8.6	8.4

Commuter train

The overall interior noise annoyance is moderate (mean value 4.8). However, the most prominent source of annoyance is attributed to other passengers (mean 7.4), clearly exceeding all railway-related noise sources. Tonal components do not show significant differences between zones when considering categorical ratings; only braking noise exhibits a statistically significant difference on the 0–10 scale, although within a low annoyance range (mean 1.2). When grouping sounds into tonal and non-tonal categories, statistically significant differences are observed on the numerical scale, but not on categorical ratings. Importantly, non-tonal sounds are perceived as more annoying than tonal ones. No significant effect of zonal tonality differences is observed.

Metro

The overall annoyance is low (mean 2.9). No significant differences between zones are found for tonal noise components, except for braking noises on the 0–10 scale, again within a low annoyance range (mean 1.4). No significant differences are observed between tonal and non-tonal noise categories. In contrast, higher annoyance levels are reported for non-railway sources such as other passengers and safety signals or announcements. As with the commuter case, zonal tonality differences do not lead to significant perceptual differences.

Tramway

The overall annoyance remains low (mean 3.3), with other passengers identified as the most disturbing source (mean 4.6). The only significant difference between zones relates to rolling noise, which is classified as non-tonal. All railway-related noise sources are rated below 4, confirming a generally low annoyance level. While some statistically significant differences are found between sound categories (tonal, non-tonal, safety signals, and passengers), tonal sounds are not perceived as more annoying than non-tonal ones. As in the other cases, no significant influence of zonal tonality differences is observed.

5.2 Exterior tests

Granollers station

The overall annoyance due to train-related noise is low, with a mean value of 3.3, which is lower than the exterior noises in their globality (mean value of 4.4).

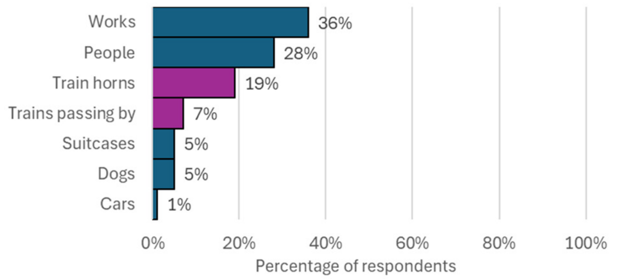

Figure 4: Noise sources identified as annoying in open-ended responses at Granollers station

Figure 4 synthetizes the identified sources of exterior noise annoyance when openly asked to the respondents and shows the percentage of respondents who mentioned each source. The external works (36 %) come first (at the time of the study works where happening on a near streets), followed by the people or animals in the street (28 %). Train-related complaints are mainly focused on the train horns (19 %) and the trains passing by (7 %).
Respondents were then asked to rate the annoyance associated with a predefined set of outdoor noise sources. Figure 7 reports the proportion of respondents assigning an annoyance rating of 5 or higher on the 0–10 scale. All respondents (100 %) reported annoyance from construction works and nearly all (92 %) from people in the street, while approximately half (44 %) reported annoyance from train traffic.

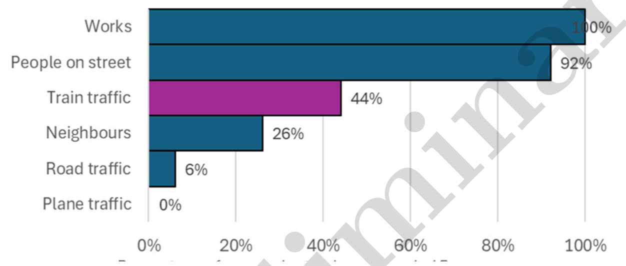

Figure 6: Share of respondents reporting annoyance ≥ 5/10 for selected train-related noise sources at Granollers station

When respondents were asked openly which train-related noises they found annoying (see Figure 8), the most frequently mentioned source was train horn activation (42 %), followed to a lesser extent by passenger suitcase noise (17 %), freight trains (17 %)

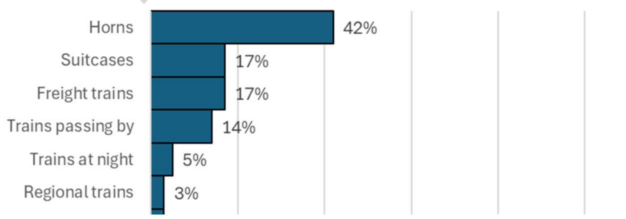

Figure 7: Share of respondents reporting annoyance ≥ 5/10 for selected outdoor noise sources at Granollers station

and passing trains (14 %).
Respondents were then asked to rate the annoyance associated with a predefined list of train-related noise sources. Figure 6 reports the proportion of respondents assigning an annoyance rating of 5 or higher on the 0–10 scale. Passenger and suitcase noise (98 %), passing trains (96 %), and train horns (94 %) were identified as the most frequently annoying sources. Other signals, such as door warnings and station announcements, were reported as annoying by about half of the respondents (52 % and 50 %, respectively). In contrast, train noise in other operating conditions was associated with lower annoyance, particularly for stationary trains (26 %) and even more so for acceleration and braking phases (2 % in each case).

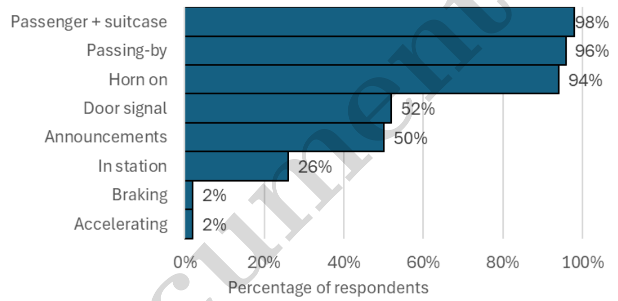

Figure 5: Noise sources identified as annoying in open-ended responses at tramway station

<u>Tramway station</u>
The overall annoyance associated with tramway-related noise is low, with a mean rating of 3.1, and remains below the annoyance reported for the overall outdoor acoustic environment (mean 4.3).
Figure 8 presents the percentage of respondents who reported annoyance for a general set of outdoor noise sources. Although the site includes a one-way road with a speed limit of 30 km/h, road traffic was found to be more annoying than tramway noise, with 64% of respondents reporting annoyance from road traffic compared with 10% for rail-related noise.

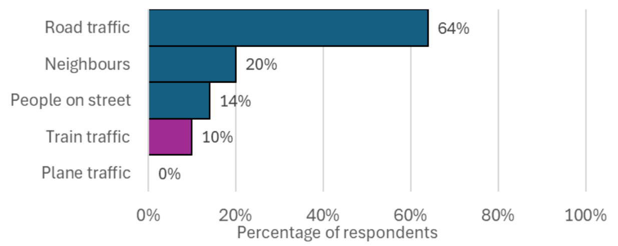

Figure 8: Distribution of train-related noise sources identified in open-ended responses at Granollers station

Tramway noise was generally perceived as a minor contributor to the overall acoustic environment: 70% of respondents rated it as less noticeable than other noise sources (0–4 on a 0–10 scale), while only 8% considered it more noticeable.

Figure 9 presents the annoyance associated with specific tramway noise sources. Among these, wheel squeal on curves was identified as the most disturbing source, with 42 % of respondents reporting annoyance, followed by pass-by noise (38 %). Braking (34 %) and acceleration (22 %) were associated with lower annoyance than pass-by events (38 %). Announcements (6 %) and warning signals (2 %) were reported as less annoying at the commuter train station.

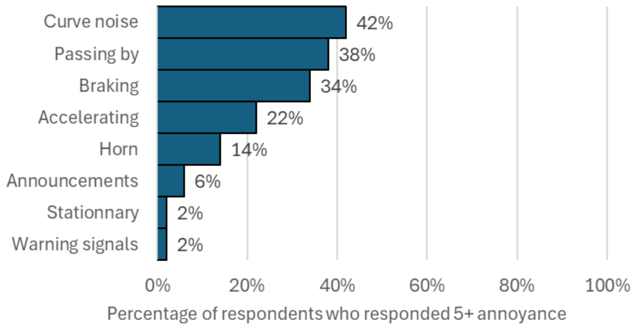

Figure 9: Share of respondents reporting annoyance ≥ 5/10 for selected train-related noise sources at tramway station

6. Conclusions

6.1 Overall conclusions

For the interior noise, the annoyance caused by tonal sounds is low. There are no statistically significant differences in ratings between areas with tonal components and those without. Similar conclusions are obtained for the exterior noise single campaign. To better understand the sources of annoyance and draw reliable conclusions, it is recommended that infrastructure managers monitor the root causes of residents' complaints.

6.2 Recommendations

Exterior noise

The two in-situ cases studied in this task did not reveal significant influence of tonality on residents' perception. The analysis confirms that the annoyance from external noise is low and does not depend on the tone, with external factors such as construction work, the passage of trains, and passenger noise generating a greater negative impact than the tonal components of the rolling stock.

Interior noise

The studies carried out within the framework of this project indicate that the tonality penalty defined in Annex J of ISO 1996-2:2017 appears to be conservative when compared with the annoyance levels reported by interviewed train passengers and considering the outputs of the laboratory study [1].

It is proposed to retain the general approach of ISO/TS 20065:2022 cited in ISO 3095:2025 when an evaluation of audibility of tones is required.

In case that the tonality audibility indicator is used to calculate a penalty for a contractual requirement (in standstill or constant speed scenario), the following approach is proposed depending on the level of tonality (a schematic representation of the thresholds is given in Figure 10).

For $\Delta L < 12$ dB

The in situ investigations show that, even for trainsets exhibiting relatively high measured tonal components, the associated annoyance is statistically non-significant or remains very low when compared with situations characterized by low tonality.

Consequently, for moderate tonality levels ($\Delta L < 12$ dB), no tonality penalty is recommended to be applied to the overall noise level.

For $\Delta L > 12$ dB

Laboratory studies conducted within this project [1] demonstrate that, for two signals with identical overall sound levels, the perceived annoyance equivalence between a purely tonal sound ($\Delta L = 24$ dB) and a purely non-tonal sound corresponds approximately to a + 6 dB difference in overall sound level.

By comparison, ISO 1996-2:2017 Annex J prescribes a 6 dB penalty for $\Delta L > 12$ dB. Based on the experimental results obtained in this project, this penalty level appears overly conservative.

Accordingly, the following revised penalty scheme is considered more representative and suitable:

- + 3 dB for $12 \text{ dB} < \Delta L \leq 24$ dB
- + 6 dB for $\Delta L > 24$ dB

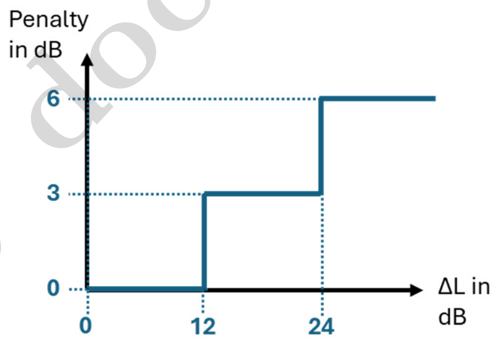

Figure 10: Proposed revised tonality penalty as a function of the tonality indicator ΔL

7. Acknowledgments

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