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METHODOLOGY FOR ASSESSING STRUCTURAL NOISE ANNOYANCE IN BUILDINGS CAUSED BY RAIL TRAFFIC. COMPARATIVE ANALYSIS BETWEEN PORTUGAL AND SPAIN

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ABSTRACT

In recent years, the development of new construction materials and the publication of standards associated with new construction processes and evaluations have made it possible to construct buildings with high acoustic comfort. Alongside the construction of buildings with high sound insulation requirements, other aspects, such as structural noise, are becoming more important. This paper presents the evolution of the vibration and structural noise (ground-borne noise) descriptors in environmental impact studies derived from rail traffic in Portugal. However, these criteria are not regulated, but good practice guidelines are implemented by the management entities in order to contribute to the reduction of annoyance and, consequently, complaints from the nearby residents. In this context, a comparative analysis is carried out between the criteria used to assess low-frequency noise annoyance in two neighboring countries (Portugal and Spain), to encourage the drafting of possible Portuguese regulations in this area.

Keywords: *railway vibration, structural noise, comfort inside buildings*

1. INTRODUCTION

Noise regulations in Portugal is established by Decree-Law no. 9/2007 of 17 January, which approved the *Regulamento Geral do Ruído* (RGR) [1] . This law aims to prevent and control noise pollution, safeguarding public health and the population's well-being. Criteria are defined for assessing various noise sources likely to cause annoyance, including noise from transport infrastructures. To this end, maximum sound levels are established for outdoor environmental noise, depending on the time of day and the type of land use classification of the area. Regarding noise levels inside buildings, the only reference is to the minimum value (equal to 27 dB(A)), above which the annoyance assessment criterion applies. This regulation also does not specify any criteria for vibration levels inside buildings, and penalties to be considered when the sources being assessed have low-frequency components. Currently, in Portugal, there is still no legal obligation to comply with standards or regulations regarding vibrations that don't have the potential to cause damage to buildings, like explosions, even if they cause annoyance to occupants inside buildings.

The minimum acoustic performance criteria that buildings must meet to ensure user comfort and quality of life are established in the *Regulamento dos Requisitos Acústicos de Edifícios* [2], approved by Decree-Law No. 129/2002. This regulation applies to seven main building categories, namely: residential, mixed-use, and hotel buildings; commercial, industrial, or service buildings; educational institutions; hospitals; sports centers; passenger transport stations; and auditoriums. The criteria are defined based on sound insulation values for airborne and impact sound transmission, reverberation time, and noise levels associated with technical equipment and installations. Only in the latter case are values given for sound levels inside rooms where more noise-sensitive activities can take place. The noise sources should derive from the operation of equipment and installations inside the building and located in adjacent rooms. In this context, maximum permissible sound levels are established as follows: 27 dB(A) in bedrooms and living areas of residential buildings, 37 dB(A) in spaces where concentration and leisure activities take place (e.g., commercial, industrial, or service buildings), 30 dB(A) in hospital wards and libraries within educational institutions. These values apply under the

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assumption of continuous operation of noise sources. Additionally, penalties are imposed when noise sources exhibit tonal components, with an added correction of +3 dB(A).

In Spain, the central administration is responsible for establishing legislation at the national level; however, the implementation and enforcement of these regulations fall under the jurisdiction of the autonomous communities. Consequently, most autonomous communities have developed their own regulatory frameworks in this domain, leading to slight variations in the indices used and the corresponding limit values. This study will therefore examine the noise and vibration assessment criteria established by the autonomous communities of Madrid and Barcelona, as well as those implemented by the city of Valencia.

2. CRITERIA USED IN PORTUGAL

Even though Portugal might not have specific regulations for ground-borne vibration and noise from rail traffic, the EU Directive 2016/797 (also known as the Railway Safety Directive) provides a framework to ensure that the levels of vibration and noise generated by rail operations do not cause annoyance. It's critical for rail operators to consider these environmental impacts, and ensure that mitigation measures are implemented if necessary, particularly in areas with sensitive uses (residential, healthcare, or industrial zones). In this context, the authors published in 2019 a methodological action guide for minimising the occurrence of potential noise and vibration annoyance situations inside homes derived from the operation of the Lisbon metro. This document indicates the criteria related to vibrations and ground-borne noise limit values inside buildings for the different phases of a railway infrastructure project (construction and operation), which are explained below (exploration phase):

2.1 Ground-borne noise

To predict ground-borne noise levels in exposed dwellings, it is recommended that, for each individual metro train passage, the vibration velocity values (RMS) be analysed within one-third-octave frequency bands ranging from 16 Hz to 250 Hz:

2.1.1 Underground track

- be less than 0.02 mm/s in the most unfavourable situations where the vibrational reduction index from the slab in question to the surrounding walls (*Kij*) are very low and the transmission between elements is very high. This case occurs when the construction solutions are very heavy and most of the connections considered are rigid;

- between 0.02 - 0.025 mm/s, in intermediate situations where vibrational reduction index of the slab in question to the surrounding walls (*Kij*) already has some relevance, so there is less vibration transmission than in the previous case are medium values. This case corresponds to the most common situations.
- between 0.025 - 0.03 mm/s, in the more favorable situations where vibrational reduction of the slab in question to the surrounding walls (*Kij*) are very high, and the transmission between elements is very low. This case will occur when the constructive solutions of the walls are lightweight.

It is acceptable to assume an average value of 0.025 mm/s, representing most situations. As an alternative option, bearing in mind that low-frequency noise is somewhat complex from the point of view of human perception, a noise limit value of 27 dB(A) can be considered, calculated for the third-octave frequency bands between 16 Hz and 250 Hz), which approximately corresponds to the response of 10 per cent of the most sensitive individuals [3].

2.1.2 Surface track

For the purpose of predicting ground borne noise that may be established in compartments of dwellings and/or other buildings of sensitive use, taking into account the specificity of the situation under analysis (noise and vibrations induced by the movement of railway traffic), it is recommended that the vibration velocity values (RMS) of the horizontal partition element (floor), vertical or horizontal component, if more relevant, integrated in the one-third-octave frequency bands between 16 Hz and 250 Hz, should be less than 0.05 mm/s. Bearing in mind that the difference between the limit values for vibration velocity between the vertical and horizontal directions correspond roughly in terms of L_{Aeq} sound level (with A weighting in each third-octave frequency band between 16 Hz and 250 Hz) is approximately 9 - 10 dB, a value of L_{Aeq} = 36 dB [16-250 Hz] is recommended for ground-borne noise indoors.

This criterion is more permissive than the one recommended for tunnelled tracks, as, there is a masking effect from airborne noise coming directly from the infrastructure.

2.2 Vibration (perception)

2.2.1 Underground track

The following criteria are recommended to assess annoyance induced by continuous or intermittent vibrations inside buildings.
1. Average effective vibration velocity value of less than 0.28 mm/s;
2. Application of the ISO 2831-2 base curve (1989 version) [4], with the multiplicative factors corresponding to intermittent vibrations for residential buildings. In this case, the spectrum of vibration velocity values (RMS), in one-third-octave bands, must be less than 0.14 mm/s, for central frequencies between 8 and 80 Hz (period 8 pm-8 am), this limit increasing to 0.4 mm/s at 2 Hz, and 0.8 mm/s at 1 Hz. For the daytime period (8 am-8 pm), the vibration velocity value, vef < 0.20 mm/s, assumed for central frequency bands between 8 and 80 Hz, and increases to 0.56 mm/s for 2 Hz, and 1.12 mm/s for 1 Hz. These values are valid for the vertical or horizontal component of the velocity, if the latter is the most significant.

2.2.2 Surface track

For the perception of vibrations inside buildings, the reference values shown in Table 1 are recommended in terms of the vibration velocity values (RMS). In this table, the vibration can be considered Perceptible during the infrastructure's operating day (08-20h) and Null during the complementary period of operation.

Table 1 - Limit values for the perception of continuous vibration inside buildings

v_{rms} (mm/s)	Sensation
v_{rms}< 0,11	Null
0,11<v_{rms}< 0,28	Perceptible, bearable for short duration
0,28<v_{rms}< 1,10	Clear, annoying, may affect working conditions
v_{rms}>1,10	Very clear, very annoying, reducing working conditions

The ISO 2631-2 base curve (1989 version) can be also applied, with the multiplicative factors corresponding to intermittent vibrations for residential buildings. In this case, the spectrum of vibration velocity values (RMS) in one-third-octave bands must be less than 0.14 mm/s for centre frequencies between 8 and 80 Hz (period 20h-08h), a limit that increases to 0.4 mm/s at 2 Hz and 0.8 mm/s at 1 Hz. For the daytime period (08-20h), the effective vibration value, vef < 0.20 mm/s, assumed for centre frequency bands between 8 and 80 Hz, increases to 0.56 mm/s for 2 Hz, and 1.12 mm/s for 1 Hz. The lower value shown (0.11 mm/s) is considered the perception threshold. Although the criterion recommended for the night period (more restrictive) includes verification of the daytime criterion, in terms of corrective measures, there may be cases of operations management in which such differentiation may be applicable.

3 . CRITERIA USED IN SOME SPANISH MUNICIPALITIES

In 2003, the National Noise Law (*Ley 37/2003*) was published and developed into Royal Decree 1513/2005 [5] (on about the assessment and management of environmental noise), and Royal Decree 1367/2007 of October 19 (on acoustic zoning, quality objectives and acoustic emissions) [6]. With the updating of the European Directive on the assessment and management of environmental noise, the Royal Decree 1513/2005 has undergone some changes, specifically in its Annex II (Order PCI/1319/2018 of December 7 and Order PCM/80/2022 of February 7) and Annex III (Order PCM/542/2021 of May 31).
The aforementioned regulatory sets out the acoustic quality levels (equivalent SPLs) that ought to be met inside buildings depending on their use, as shown in Table 2. Where the indices L_d, L_e and L_n refer to the A-weighted, equivalent continuous sound level for daytime period (12 hours), evening period (4 hours) and night-time period (8 hours).
Regarding transmission between adjacent locations, without noise transmission between the emitter and the receiver through the external environment, the values indicated in Table 3 apply, depending on the type of use of the receiving location. These limit values are applied when the noise source relates to commercial, industrial activities, installations, sports or leisure establishments. The descriptor used to assess noise is the noise index $L_{keq,T}$, which corresponds to the A-weighted, equivalent continuous sound level, ($L_{Aeq,T}$), with, at least, an integration time of 5 seconds ($L_{kAeq,\ 5s}$). This value should be corrected for the presence of emergence of tonal components, low-frequency components and impulsive noise. The limits are met when the values of the acoustic indices, after assessing the existence of low-frequency components, do not exceed in any case more than 5 dB(A), the application limit values indicated in Table 3.

Table 2 - Acoustic quality objectives inside buildings, depending on their use

Building Type	Local	Ld and Le	Ln
Dwellings	Living areas Bedrooms	45 40	35 30
Hospitals	Living areas Bedrooms	45 40	35 30
Educational and Cultural Centres	Classrooms Libraries	40 35	40 35

Table 3 - The limits of sound levels transmitted to acoustically adjacent locations by any installation, establishment, activity or behavior (Real Royal Decree 1367/2007)

Building Use	Local	$L_{k,d}$ / $L_{k,e}$ Day/ Evening	$L_{k,n}$ Night
Dwellings	Living areas Bedrooms	40 35	30 25
Hospitals	Living areas Bedrooms	40 35	30 25
Educational and Cultural	Classrooms Libraries	35 30	35 30
Offices		35	35

For the assessment of low frequency noise, a detailed evaluation of the noise is carried out, introducing the appropriate corrections (Table 4) according to the following methodology:

a) Simultaneous measurement of the sound pressure level with C and A weighting.

b) Calculation of the difference between the values obtained (L_f), corrected for background noise;

c) Determining the presence or absence of low-frequency components, and the value of the correction (K_f) to be introduced, according to the values in Table 4.

Table 4 - Correction values (K_f) to be added in case of the presence of low-frequency components

$L_f = L_{Ceq,Ti} - L_{Aeq,Ti}$ (dB)	K_f (dB)
L_f>10	0
10<L_f<=15	3
L_f>15	6

However, the legislation only indicates the use of the above-mentioned correction factor (K_f) when dealing with noise sources located inside the building or in adjoining buildings. However, in view of the problem presented, assessing ground-borne noise annoyance in buildings caused by rail traffic, it was also decided in this work to incorporate this criterion.

Regarding the quality criteria for vibrations inside buildings, the values in Table 5 apply depending on the type of building use; the L_{aw} index refers to the vibration level according to the W_m weighting curve defined in the ISO 2631-2: 2003 standard. When assessing this criterion, the maximum RMS acceleration value with slow time constant and W_m frequency weighted is used (defined as Maximum Transient Vibration Value in ISO 2631-1: 1997). However, for transient vibrations, the W_m weighting is not used (because of the slow response of the lowest one-third-octave filters relative to the slow time constant). It is only limited to the case of stationary vibrations.

Table 5 - Acoustic quality objectives for vibrations transmitted to interior spaces

Building Type	Vibration Index L_{aw} dB re. 10^{-6} m/s^2	mm/s^2
Dwellings	75	5.6
Hospitals	72	4.0
Educational and Cultural centers	72	4.0

In the case of the community of Madrid and according to the *Ordenanza de Protección contra la Contaminación Acústica y Térmica* (2021 version), the acoustic quality objectives inside buildings are identical to those shown in Table 2 (noise). In the case of sound level measurements and for acoustic sources in the building (or adjacent buildings), the values from Table 6 are applied. The limits are met when the values of the acoustic indices, after assessing the existence of low-frequency components (Table 4), do not exceed in any case more than 5 dB(A), the application limit values indicated in Table 6.

For vibrations inside buildings, the values in Table 5 apply in addition to the limits imposed on four new building uses: hostels (78 dB/7,9mm/s2), offices (84 dB/15,8 mm/s^2), shops and warehouses (90 dB/31,6 mm/s^2), and industry (97 dB/70,8 mm/s^2).

Table 6 - The limits of sound levels transmitted to acoustically adjacent locations by any installation, establishment, activity or behavior (community of Madrid)

Building Use	Local	$L_{kAeq,5s}$ Day/ Evening	$L_{kAeq,5s}$ Night
Dwellings	Living areas	35	30
	Bedrooms	30	25
Hospitals	Living areas	40	30
	Bedrooms	30	25
Cultural	Cinemas, theaters	30	30
Educational	Classrooms	35	35
	Libraries	30	30
Offices	--------	35	35
Commerce	---------	50	50
Industrie	-----	55	55

In the case of the city of Valencia, the Municipal Ordinance for Protection against Acoustic Contamination, approved in February 2023, states criteria for sound levels inside buildings derived from airborne and structural transmission. Regarding airborne transmission, the most stringent values are for residential buildings (55 dB(A) during the day and evening, 45 dB(A) at night), and for hospitals and schools (45 dB(A) during the day and evening, and 35 dB(A) at night). These higher permissible values are related to the microphone position that should be placed in the window opening at the plane of the exterior facade and orientated towards the sound source. (windows open). The values for structural transmission are presented in Table 6. Also, when low-frequency components are detected in the noise measurement process, a detailed evaluation of the noise is carried out, introducing the appropriate corrections (identical to Table 4 correction values).

Like in Madrid, the values in Table 5 are also used as quality objectives for vibrations applicable to the interior habitable space of buildings intended for housing, residential, hospital, educational, or cultural uses.

Table 7. Assessment levels inside buildings, derived from structural transmission (city of Valencia)

Building Use	Local	Day/Evening dB(A)	Night dB(A)
Dwellings	Living areas	40	35
	Bedrooms	40	30
Hospitals	Living areas	45	35
	Bedrooms	40	30
Cultural	Concert halls	35	35
	Libraries	35	35
	Museums	45	45
	Exhibitions	45	45
Educacional	Classrooms	40	35
	Libraries	35	35
Offices	--------	40	40
Commerce	---------	45	45

For the autonomous region of Catalonia, Decree 176/2009, approving Law 16/2002 about protection against noise pollution, sets out the objectives for noise quality inside buildings intended for residential, hospital, educational and cultural use, identical to the ones shown in Table 2. About admissible sound levels for acoustically adjacent locations by any installation, establishment, activity or behaviors, values similar to those shown in Table 6 apply, except that in this case, the index used is the A-weighted equivalent continuous sound pressure level, corresponding to the daytime (7 am to 9 pm), evening (9 pm to 11 pm), and night-time (11 pm to 7am) periods.

Regarding the low-frequency assessment, the procedure differs slightly from the previous one. Thus, if the difference between simultaneous measurement of the sound pressure level with C and A-weighting is greater than 20 dB, a detailed assessment of low frequency components carried out, according to the following procedure:

a) Obtaining the low-frequency audible level, which is calculated for each third-octave band between 20 and 160 Hz, from the difference between the measured value of each one third octave band (unweighted) and the human hearing threshold published in ISO 226:2003.

b) Obtaining the L_B value, corresponding to the energetic sum of the values corresponding to the one-third-octave bands between 20Hz and 160Hz, and whose difference obtained in a) is greater than zero.

c) Determining the presence or absence of low-frequency components and the correction parameter K_f by applying the criteria in Table 8.

Table 8 - Correction values to be added in the presence of low-frequency components

L_B (dB)	K_f (dB)
L_B< 25 dB	0
25<=L_B<=35	3
L_B>35	6

For vibrations, and like in the city of Valencia city, the values in Table 5 are applied, corresponding to quality objectives applicable to the interior habitable space of buildings intended for housing, residential, hospital, educational, or cultural uses.

3. CASE STUDIES

3.1 Case 01

The building under evaluation is a semi-detached house, with a basement, ground floor, and first floor. The metro tunnel is located at a depth of approximately 20 m from the ground surface. The sound environment outside the residence is characterized mainly by road traffic noise and air traffic noise. Inside the house, given the sound insulation against airborne sounds provided by the walls and windows (made up of double glazing), the noise from the external sound environment is almost imperceptible. Three 01 dB Symphonie measurement systems were used (located on the railway platform, tunnel wall structure and inside the residence) and a Pulse measurement system from Bruel & Kjaer (located inside the residence) to which one microphone (GRAS 40AF microphone) and accelerometers (IMI 626A04 and PCB, model 393A03) were connected. Inside the residence, measurements were taken on the ground floor (living room, labeled as S and nº of measurement) and on the 1st floor (bedroom, labeled as Q). All measurements taken inside the house were accompanied by simultaneous and synchronized measurements of the metro train passages with the accelerometers placed on the railway platform, and in the tunnel wall structure. Tables 9, 10 and 11 present the results of vibration measurements taken on the ground floor. Tables 9 and 10 refer to individual passages of metro trains. In contrast, Table 11 shows the results obtained in three measurements, each lasting 30 minutes, with the noise levels already corrected from residual sound values.

Table 9 – Vibration values for single metro train passages in the living room (ground floor)

Nº Mes.	L_a dB	L_{aw} dB	MTVV dB	v_{rms} (mm/s) [1-80 Hz]	v_{rms} (mm/s) [16-250Hz]	ISO 2831-2
S1	73	56	**77**	0,024	0,022	Pass
S2	77	61	**81**	0,036	**0,035**	Pass
S3	77	59	**80**	0,03	**0,03**	Pass
S4	78	61	**82**	0,06	**0,057**	Pass
S5	74	57	**78**	0,028	**0,027**	Pass
S6	71	56	74	0,026	0,025	Pass

Table 10 - Vibration values and noise levels for single metro train passages in the living room (ground floor)

Nº Mes.	L_a dB	L_{aw} dB	MTVV dB	v_{rms} (mm/s) [1-80 Hz]	v_{rms} (mm/s) [16-250Hz]	ISO 2831-2	L_{Aeq} [16-250Hz]	L_f /L_B
S7	76	60	**79**	0,028	**0,028**	Pass	30	16/14
S8	74	56	**77**	0.019	0,019	Pass	27	26/13
S9	76	59	**80**	0,025	0,025	Pass	25	30/13
S10	77	60	**81**	0,028	**0,028**	Pass	26	28/10
S11	75	57	**79**	0,022	0,022	Pass	30	26/18
S12	68	60	72	0,011	0,011	Pass	24	27/11
S13	72	58	**75**	0,016	0,016	Pass	33	20/11
S14	75	57	**79**	0,022	0,022	Pass	30	26/18
S15	80	60	**77**	0,029	**0,029**	Pass	28	28/13
S16	74	61	**77**	0,021	0,021	Pass	23	29/10
S17	82	68	**85**	0,046	**0,046**	Pass	28	33/14
S18	77	59	**80**	0,029	**0,029**	Pass	26	30/13
S19	75,8	60	**79**	0,028	**0,028**	Pass	38	16/14

Table 11- Vibration values and noise levels for 30 minutes measurements (ground floor)

Period / nº passages	L_a dB	L_{aw} dB	MTVV dB	v_{rms} (mm/s) [1-80 Hz]	v_{rms} (mm/s) [16-250Hz]]	ISO 2831 -2	L_{Aeq} [16-250Hz]
6h30-7h00/5	59	42	45	0,006	0,0062	Pass	19
8h30-9h/10	66	49	70	0,009	0,0089	Pass	26
13h-13h30/11	66	49	70	0,010	0,010	Pass	21

The tables above show the results for vibration acceleration level (L_a), W_m weighted vibration acceleration level (L_{aw}), Maximum Transient Vibration Value (MTVV, calculated by multiplying 1.5 by the RMS acceleration value), and RMS velocity value (v_{rms}, in mm/s), for frequencies between 1 and 80 Hz (v_{rms} (mm/s) [1-80 Hz] and for frequencies between 16 and

250 Hz, (v_{rms} (mm/s) [16-250 Hz]). The column labeled as ISO 2831-2, presents the results of applying the base curve (1989 version) of this standard, with the multiplicative factors corresponding to intermittent vibrations for residential buildings. Tables 10 and 11 also show the A-weighted sound equivalent levels (L_{Aeq}), measured during single metro train passages (for the definition of the duration of each passage, -10dB rule was used in relation to the maximum value). These levels refer to the frequencies between 16-250 Hz. The results of the calculations for assessing the existence of low-frequency components are also shown, namely the Lf values (Royal Decree 1513/2005) and the L_B value (Catalonia, Decree 176/2009). Table 12 refers to the measurement results for the bedroom on the first floor of the house. The labels for each column have the same meaning that the previous tables.

Table 12- Vibration values and noise levels for single metro train passages in bedroom (first floor)

Nº Mes.	L_a dB	L_{aw} dB	MTVV dB	v_{rms} (mm/s) [1-80 Hz]	v_{rms} (mm/s) [16-250Hz]	ISO 2831-2	L_{Aeq} [16-250Hz]	L_f /L_B
Q1	65	47	67	0,007	0,006	Pass	17	30/4
Q2	69	52	72	0,011	0,011	Pass	18	31/ 3
Q3	70	53	73	0,013	0,013	Pass	19	30/7
Q4	65	48	69	0,007	0,007	Pass	17	30/3
Q5	71	53	**75**	0,013	0,013	Pass	21	30/9
Q6	68	60	71	0,012	0,012	Pass	20	30/8
Q7	72	54	**76**	0,015	0,015	Pass	22	28/10
Q8	85	67	**88**	0,064	**0,064**	Pass	27	34/11
Q9	80	63	**84**	0,038	**0,038**	Pass	26	33/12

3.2 Case 02

The measurements were taken on the first floor of a 4-storey urban building with a reinforced concrete structure. The vibration levels of the metro single metro train passages were measured in the center of the floor and on two side walls. The microphone was placed in the center of the room. Two measurement chains were used, each consisting of a real-time analyser with two channels, brand 01dB, model Symphonie, to which the respective microphone (GRAS 40 AF) and accelerometers (PCB model 393B04) were connected, and which carried out simultaneous measurements in 3 different directions. The ground-borne noise derived from each metro train passage was clearly audible, standing out from the residual sound. Table 13 refers to vibration and noise levels for single metro train passages in the living room (first floor)

Table 13- Vibration values and noise levels for single metro train passages in the living room (first floor)

Nº Mes.	L_a dB	L_{aw} dB	MTVV dB	v_{rms} (mm/s) [1-80 Hz]	v_{rms} (mm/s) [16-250Hz]	ISO 2831-2 [Hz]	L_{Aeq} [16-250 Hz	L_f /L_B
1	97	78	**100**	0,22	**0,22**	[20]	48	25/26
2	98	79	**101**	0,21	**0,21**	[40, 50]	47	25/26
3	98	79	**102**	0,25	**0,25**	[40, 50]	50	25/26
4	97	78	**101**	0,23	**0,24**	[40, 50]	50	25/26
5	96	77	**100**	0,20	**0,20**	[50]	48	24/26
6	97	78	**101**	0,23	**0,23**	[40, 50]	48	25/26
7	96	77	**100**	0,20	**0,20**	[50 Hz]	48	24/26
8	98	78	**101**	0,24	**0,24**	[40, 50]	50	25/26
9	97	78	**101**	0,23	**0,23**	[40, 50]	49	26/26
10	97	77	**100**	0,21	**0,21**	[40, 50]	48	25/36

4. COMPARATIVE ANALYSIS

4.1 Vibration

The bold values in the MTVV column of Tables 9,10,12, and 13 correspond to acceleration vibration levels that exceed the threshold values established in the Spanish criteria for assessing vibrations in residential buildings (as specified in Table 5). Similarly, the bold values in the v_{RMS} (mm/s) [1-80 Hz] column denote metro train passages where the measured vibration velocity surpasses the general threshold outlined in the Portuguese criteria (v_{RMS}=0.28 mm/s). However, as none of the recorded measurements exceed this limit, no bold values appear in the referenced tables. Furthermore, the values in the ISO 2631-2 column indicate a "PASS" when the measured values for each third-octave band remain below the thresholds established in the ISO 2631-2:1989 standard. If a threshold is exceeded, the corresponding frequency band is specified. Consequently, only the metro train passages listed in Table 13 (passages 1-10) fail to comply with the vibration assessment criteria applicable in Portugal. The comparison of results, particularly for Case Study 1 (as presented in Tables 8, 9, and 11), suggests a higher sensitivity of the criterion employed in Spain concerning the assessment of vibrations.

4.2 Ground-borne noise

According to Spanish regulations, the assessment of railway traffic noise inside residential spaces requires a minimum of three series of measurements. Each series must comprise multiple measurements (at least 3), with a minimum duration of five minutes per measurement. Furthermore, the time interval between consecutive

measurement series must exceed five minutes. The final noise level assessment is determined as the energy average of the three series. Based on the values presented in Table 10, the resulting noise level is 23 dB(A).
In the context of noise assessment and the comparative study, additional considerations were incorporated that are not explicitly specified in Spanish regulations. Specifically, the evaluation included the assessment of sound levels generated by an individual passage of a metro train, categorized as noise resulting from an activity, as outlined in Tables 3, 6, and 7. To achieve this, three series of measurements were conducted, each lasting longer than five seconds. The maximum recorded value from each series was retained, and the presence of low-frequency components was analyzed. The results of this assessment are presented in Table 14. The bold values in the v_{RMS} (mm/s) [16-250 Hz] column denote metro train passages where the measured vibration velocity surpasses the general threshold outlined in the Portuguese criteria for ground-borne noise. Similarly, the bold values for the L_{Aeq} columns (Real Decreto and Barcelona) indicate that the admissible sound levels are exceeded, considering the most critical situations for residential buildings during the night (equal to 30 and 25 dB(A), or 35 and 30 dB(A) in the case of the city of Valencia).

Table 14- Assessment of noise levels for individual metro trains passages

Nº Mes./ Table	v_{rms} (mm/s) [16-250 Hz]	L_{Aeq} [16-250 Hz]	L_{Aeq} Real Decreto	L_{Aeq} Barcelona
S7/9	**0,028**	30	**36**	30
S11/9	0,022	30	**36**	30
S13/9	0,016	33	**39**	33
S17/9	**0,046**	28	**34**	28
Q3/11	0,013	19	25	19
Q5/11	0,013	21	**27**	21
Q8/11	**0,064**	27	**33**	**27**
3/12	**0,25**	50	**56**	**53**
4/12	**0,24**	50	**56**	**53**
8/12	**0,24**	50	**56**	**53**

Regarding the assessment of sound levels, only the evaluation of individual metro train passages yields values exceeding the established criteria. Additionally, a greater degree of harmonization is observed between the two countries in this context.

5. CONCLUSIONS

The evaluation of vibration and ground-borne noise based on measurements presents significant challenges due to the small amplitudes involved and the presence of residual vibration and noise in the surrounding environment. However, the analysis of the two case studies provided insights into the higher sensitivity of the criterion applied in Spain for vibration assessment, which classifies vibrations based on the type of building use.
Regarding ground-borne noise, harmonization of results between the two countries is achieved only when individual pass-by values and criteria related to activity operation are considered. Additionally, differences in the criteria for evaluating low-frequency components in Spain have a direct impact on the final assessment outcomes. Nevertheless, it is important to emphasize that in both case studies, residents reported significant annoyance due to ground-borne noise.

6. REFERENCES

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