Vibrations induced by railway traffic: from environmental impact assessment to exploration in new railway projects

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Abstract. Prediction and control of ground-borne vibrations are one of the largest environmental challenges for railway exploration in urban areas. Nowadays, there is a shift at global level, in which investment in rail transport takes precedence over other transportation options, in a final attempt to drastically reduce CO2 emission. The expansion and improvement of the railway network, associated with the high standards of comfort required by modern societies, requires the assessment and mitigation of the environmental impact induced by the implementation of such infrastructures in nearby buildings, more specifically in their inhabitants and in the operation of sensitive equipment. Using a recently completed railway line in Porto, Portugal, as a case study, this paper aims to provide insights into the numerical studies conducted during the environmental impact assessment phase concerning vibrations induced by railway traffic.

Keywords: Railway traffic; ground-borne vibrations; prediction methodologies.

1 Introduction

Railway transport is a public mass transport system, allowing the movement of a large number of passengers (or goods) on a single journey. Although the benefits (economic, social and environmental) inherent to rail transport are evident, their exploration leads to environmental concerns, motivated by the generation and propagation of vibrations and noise that affect the comfort and life quality of the inhabitants in the vicinity of the infrastructure.

In the pursuit of such problem, several authors have focused their research on assessing the human response to rail-induced vibration and re-radiated noise, concluding, unanimously, that continued (day-to-day) exposure to these phenomena causes adverse effects, in particular, discomfort and disturbances in sleep quality [1, 2]. Nevertheless, on the long-term, a continuous exposure influences the potential development of serious health problems, such as stress and cardiovascular disorders [3].

Since modern societies are demanding higher comfort standards, the impact caused by the operation of a railway line on nearby buildings, more specifically in their inhabitants, needs to be assessed. The study of effective mitigation measures, technically and economically viable, for the control of ground-borne noise and vibrations induced by rail traffic is, therefore, a subject of high importance and relevance in the current context, for which the infrastructures managers are aware.

In this context, this paper provides a comprehensive evaluation of the expected vibration levels inside buildings for a new metro line in the Metro do Porto network. This analysis corresponds to those conducted as part of the environmental impact assessment phase.

2 International standards: ground-borne noise and vibration limits

The phenomena associated with continued exposure to ground-borne vibrations induced by railway traffic have a regulatory framework, which is directly associated with the frequency range in which they prevail. Thus, and in a frequency range 1-80 Hz, the vibration of the building is perceived as a mechanical vibration by the human body, existing international standards, as ISO 2631 (Parts 1 and 2), Norwegian Standard NS 8176 or German Standard DIN 4150, which set out practical procedures for assessing human comfort. The FTA document [4] is used as a guideline manual in the USA, providing recommendations and analysis procedures that follow the actual state of the art on the topic.

It should be noted, that the above-mentioned normative documents do not apply exclusively to problems of vibration induced by rail traffic. The exception to this practice is given by FTA manual [4], which presents recommendations to adopt in the design and performance evaluation of transport infrastructures, thus justifying the adoption of these recommendations in the development of the present study. Since re-radiated noise is a direct consequence of ground-borne vibrations, FTA manual also presents some reference values for the limits that should not be exceeded in terms of re-radiated noise. However, this relevant phenomenon and the preconized limits require further consideration, which is beyond the scope of this paper.

Table 1 presents the ground-borne noise and vibration limit values inside the building (category II), according to a general vibration assessment methodology proposed by FTA.

Table 1. Indoor Ground-Borne Vibration (GBV) and Ground-Borne Noise (GBN): impact criteria for general vibration assessment [4].

Land Use Category	**GBV Impact Levels (VdB) ($dB_{ref}=10^{-8}$ m/s)**			**GBN Impact Levels (dBA) ($dB_{ref}=2x10^{-6}$ Pa)**		
	Frequent Events	Occasional Events	Infrequent Events	Frequent Events	Occasional Events	Infrequent Events
Category II: Residences and buildings where people normally sleep.	80.1 VdB	83.1 VdB	88.1 VdB	35 dBA	38 dBA	43 dBA

Ground-borne vibration limits are expressed in terms of Running RMS (Root Mean Square) of the vibration velocity (in dB, ref. 10^{-8} m/s). Ground-borne noise limits are expressed as A-weighting sound pressure in dB units. It should be highlighted that the maximum value of the Running RMS is considerably lower than the peak particle velocity (PPV). Both values can be correlated by a crest factor that should be around 4-5 for the case of railway traffic vibrations [4].

It should be stated that the ground-borne vibration limits presented in Table 1 correspond to the values adopted by FTA/FRA [4, 5]. However, these values are in close agreement with the limits preconized by other standards/guidelines.

3 General assessment of ground-borne vibrations

3.1 Description of the methodology

The analysis methodology adopted in this study is based on the guidelines of a general assessment outlined in the technical documents of FRA/FTA. The basic principle of this methodology involves evaluating vibration attenuation curves, defined through the maximum value of the running root-mean-square (RMS) of vertical velocity, as a function of the distance from the railway infrastructure. These curves are subsequently corrected to account for the presence of buildings, considering their specific characteristics. The values dictated by these corrected attenuation curves are then compared with the limit values indicated in Table 1, based on the land use category.

In summary, the methodology adopted in the present study follows the systematic application of the following steps:

i) Evaluation of attenuation curves for the maximum RMS value of vertical velocity at the ground surface;

This step is carried out using advanced numerical modeling, which is three-dimensional in nature and includes vehicle-track interaction, different types of rolling stock, and varying levels of track irregularity amplitudes.

ii) Application of adjustment factors to the surface vibration attenuation curves to consider the dynamic properties of the building and foundation system

The result of this operation is an estimation of the maximum vibration levels inside the buildings. Subsequently, the estimated vibration levels inside the building are converted into sound pressure levels (re-radiated noise).

iii) Comparison of the maximum predicted values of RMS vertical vibration velocity with the limit values associated with the building's functionality, as indicated in Table 1.

If the limit values indicated in Table 2 are not exceeded, there is no potential of impact. However, if limit values are exceeded, there are two additional options: i) to perform a detailed analysis (experiments, detailed numerical modeling, etc.) in order to check, using a more accurate approach, if mitigation measures are required; ii) to propose mitigation measures in order to comply with the limits.

3.2 Evaluation of attenuation curves based on advanced numerical modeling

The assessment of vibration levels at the ground surface surrounding the railway system was developed using a numerical approach to the problem, employing numerical tools developed by the authors and experimentally validated [6-8].

Following such an approach requires the use of numerical models that, as accurately as possible, represent the dynamic response of the system, considering its various components. The following subsections provide a brief description of the calculation models adopted in the detailed analysis presented in subsequent sections.

In the present study, an experimentally validated 2.5D FEM-PML approach is adopted [9]. The advantage of this method resides in the fact that only a cross-section normal to the track needs to be discretized without losing the 3D character of the problem. From the computational point of view, the method is quite efficient since a small system of equations is solved several times (for different wavenumber/frequency) instead of solving an equation system with millions of degrees of freedom (as it is usual in 3D problems).

The drawback usually pointed out to the finite element approach when dealing with wave propagation problems is its inability to directly deal with unbounded domains, i.e., its intrinsic requirement of truncation of the domain. This drawback can be overcome by several approaches. In the present study, a PML (Perfectly Matched Layer) approach is adopted. Thus, the combination of the 2.5D PML approach with 2.5D FEM approach allows fulfilling the Sommerfeld's condition with a reasonable compromise between accuracy and computational effort. In more detail, the 2.5D PML is a layer that surrounds the domain of interest (discretized with FEM) and allows absorbing the reflected waves without reflection. The model is illustrated in Figure 1.

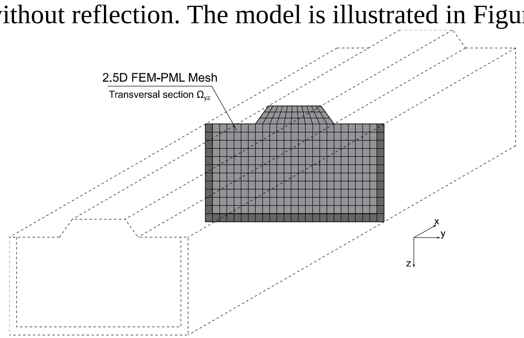

Figure 1 . Infinite and invariant structure in one direction – 2.5D FEM-PML approach.

3.3 Prediction of vibration levels inside buildings

Regarding the soil-structure dynamic interaction, there is a trend for lower building vibration with the increase of the building's mass. Light buildings are easily excited due to soil vibration, in contrast to what happens with heavier buildings where soil-structure coupling effects cannot be neglected. In the case of heavier masonry buildings, with large mass and stiffness, founded in soil layers it is common to observe lower vibration levels in the building foundation when compared with the vibration levels recorded in the free-field. On the other hand, the decrease of the ratio building stiffness versus ground stiffness gives rise to lower energy dissipation. For that reason, the soil-structure coupling loss is almost null.

The building foundation type also presents a relevant role on the soil-structure interaction mechanism. The selection of the foundation type is entirely related with the ground stiffness and mass of the buildings. Spread foundations are usually applied when dealing with buildings constructed in competent soils while deep foundations, such as piles, are the choice when the construction of the buildings falls in regions of soft soils or when the buildings' mass is very large. Therefore, it is reasonable to consider higher dynamic coupling loss for large buildings founded in pile foundations.

Following the soil-structure interaction mechanisms explained above, FTA [4] suggests the application of the adjustment factors presented in Table 2.

Table 2. Adjustment factors for soil-structure dynamic interaction [4].

Factor	Adjustment to propagation curve	
Soil-structure interaction		
Coupling to building foundation	Wood-frame houses	-5 dB
	1-2 Story Masonry	-7 dB
	3-4 Story Masonry	-10 dB
	Large masonry on piles	-10 dB
	Large masonry on spread footings	-13 dB
	Foundation in rock	0 dB

Besides the adjustment factors related with soil-structure coupling, there are other adjustments related with the receiver that must be taken into account, namely the energy loss due to material damping induced by vibration propagation along the structural elements. In a simplified way, this effect can be taken into account by considering an attenuation factor per story of the building, as presented in Table 2.

By last, and probably more relevant, adjustment factors should be applied to take into account the structural dynamics of the building. Usually, there is a considerable amplification of the vibration levels in the frequency range close to the natural frequencies of the building's slabs. This aspect is discussed in detail by Lopes et al. [9], where it is shown that if the energetic content of the excitation is high in the frequency range close to the natural frequencies of the slabs, there is a very considerable amplification of the maximum values of Running RMS. Colaço et al. [10, 11] show that this effect has repercussions not only in the vibration levels, but also in the sound pressure levels resulting from the re-radiated noise.

As evidenced, the aspects mentioned above are complex and closely related to the building dynamic response in the frequency domain. Therefore, it is difficult to quantify them through an adjustment factor applied to the maximum value of the RMS of the vertical particle velocity. However, a more detailed study where it is possible to incorporate such phenomena, would require the numerical modeling of the buildings themselves, with the inherent complexity involved and time-consuming, demanding for a geometric and material survey of each building under analysis. Thus, taking into account the listed aspects, the FTA guidelines suggest, in a simplified way, that the effects of structural amplification are met through a +6 dB adjustment factor (see Table 3).

Table 3. Adjustment factors for receiver [4].

Factor	Adjustment to propagation curve	
Building		
Floor-to-floor attenuation	1 to 5 floors above grade	-2 dB/floor
	5 to 10 floors above grade	-1 dB/floor
Amplification due to resonances of floors, walls and ceilings	+6 dB	

4 Case study: Yellow Line of the Metro do Porto network

4.1 General description

The section of the Yellow Line (Metro do Porto) between Santo Ovídeo and Vila D'Este stations features different cross-sectional types, including viaduct, tunnel, trench, and surface segments, extending over a total length of 3.2 km. Figure 2 illustrates the layout of this railway line and its urban integration. Additionally, the same figure displays the depth of the railway track (at rail level) for the trench and tunnel segments.

For this study, a representative tunnel section is considered for a general assessment of vibration levels. Figure 3 displays the cross-section with the main components indicated.

Figure 2. Yellow line of the Metro do Porto network (Santo Ovídeo-Vila D'Este).

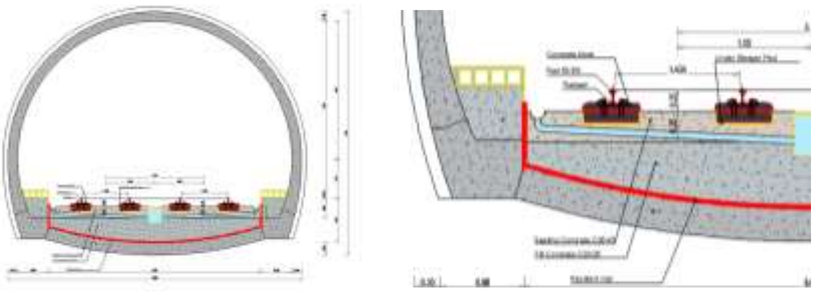

Figure 3. Track cross-section.

Regarding the rolling stock, the passage of the EuroTram vehicle, operated by Metro do Porto, at a speed of 80 km/h is considered. The geometric properties and weight per axle are detailed in Figure 4. A maximum value of 1960 kg for the unsprung masses is considered. As reported by Colaço et al. [12], this parameter is the most influential component of a train for vibration prediction purposes.

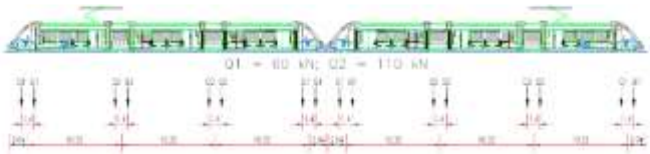

Figure 4. Geometrical configuration and axle loads of the vehicle EuroTram.

Considering train-track interaction is essential for addressing vibration generation issues. In this work, the dynamic interaction mechanism is provided by the rail unevenness. A synthetic unevenness profile was generated following the FRA approach [13].

Regarding ground characterization in the environmental impact study phase, the existing geotechnical data primarily come from SPT tests. Given that vibrations from railway traffic induce very small ground deformations, elastic and linear modeling is suitable. However, such an analysis requires characterizing the ground's deformability parameters for small deformations, typically achieved through geophysical testing. Based on existing empirical correlations and experience with similar scenarios, a parametrization of the ground for the section in question has been established, as summarized in Figure 5 and Table 4.

Table 4. Elastodynamic properties.

Layer	**Vs (m/s)**	**Vp (m/s)**	**ν (-)**	**ρ (N/m³)**	**ξ (-)**
ZGG6	250	500	0.35	2000	0.03
ZGG3	460	1350	0.2	2100	0.02
ZGG5	375	2143	0.49	2000	0.03

4.2 Environment impact assessment of vibrations

The modeling of the track-tunnel-ground system was developed using the 2.5D finite element mesh illustrated in Figure 6. Using the previously defined numerical approach, the vibration records at the ground surface are calculated and analyzed.

Figure 5. Geotechnical profile.

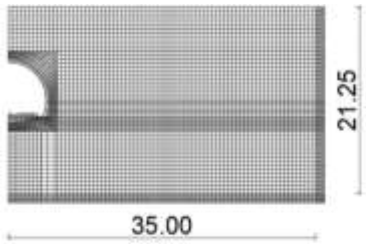

Figure 6. Finite elements mesh.

Figure 7a shows the time history of the vibration velocity for a point located at the ground surface, directly above the tunnel's plane of symmetry. The same figure also includes the Running RMS evolution, represented by the red line. Figure 7b presents the attenuation curve as a function of distance to tunnel's plane of symmetry, considering the mean values of the maximum RMS vertical velocity measured at the ground surface. The mean value results from accounting for some randomness in the generation of the unevenness profile (a track in good condition is considered for the present analysis).

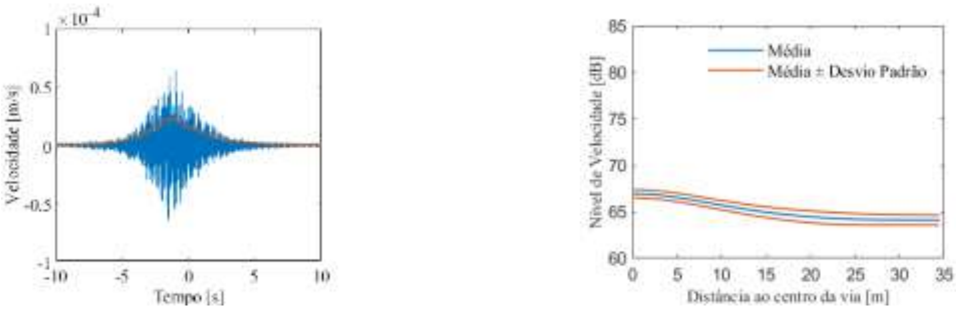

Figure 7. Vibration velocity record evaluated at the ground surface for the passage of the EuroTram vehicle.

In line with the previously presented methodology, the prediction results in free field conditions are adjusted by corrective coefficients to account for the building's dynamic response. Figure 8 compares the predicted vibration levels inside buildings at various distances with the FTA-defined limit values for residential buildings. As shown, the predicted values are substantially lower than the limit values specified for Category II buildings for this specific example.

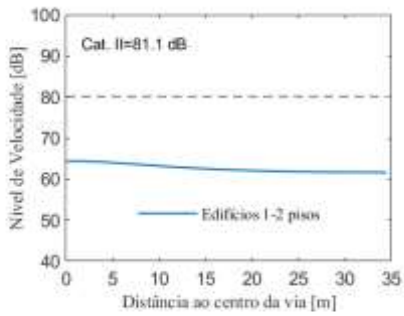

Figure 8. Prediction of vibration levels in terms of maximum Running RMS values inside a typical building.

5 Conclusions

This paper provides insights into the studies conducted during the environmental impact assessment phase concerning vibrations induced by railway traffic. To achieve this, the methodology proposed by the FTA is adapted to account for the local properties of the track-tunnel-ground system. Through the numerical modeling of this system, more reliable outcomes are achieved.

In subsequent stages of railway track design and construction, experimental studies should be conducted to confirm the initial assumptions made during the environmental impact phase. These studies are expected to guide the final design of mitigation measures, if necessary.

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