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# Definition and analysis of ground surface vibration curves induced by railway traffic

## Définition et analyse des courbes d'atténuation des vibrations induites par le trafic ferroviaire.

A. Colaço
*CONSTRUCT-FEUP, University of Porto*

R. Gomes
*Faculty of Engineering, University of Porto*

E. Fortunato*
*National Laboratory for Civil Engineering (LNEC)*

**efortunato@lnec.pt*

**ABSTRACT**: Prediction and control of ground-borne noise and vibrations are amongst the largest environmental challenges for railway exploitation in urban areas. Empirical methods based on attenuation curves, similar to those presented by the Federal Transit Administration (FTA) and the Federal Railroad Administration (FRA), could be extremely versatile for a first estimative of the vibration levels at the ground surface. Despite the value of the presented curves, these have a generalist character, not allowing to attend to the particular and specific scenarios. Furthermore, both railway technology and construction techniques adopted in other regions of the world are quite distinct from USA reality giving rise to poor predictions when applied in distinct contexts. In this way, advanced numerical modelling is a reliable alternative, allowing incorporation of the geological and geotechnical profile, type and geometric configuration of the railway track and railway vehicle specific to each case under study and, therefore, achieving a more elaborate level of detail in the analysis. On this work, a 2.5D FEM-PML (Finite Element Method – Perfectly Matched Layer) numerical approach is used to compute the ground surface vibration curves for different scenarios. From the results obtained, it is possible to state that, even being a conservative approach in some of the scenarios under consideration, the application of the empirical methodology proposed by FTA/FRA should be considered only as a first indicator, and it is recommended that more detailed analyses be performed in situations that require a higher control of the permitted vibration levels.

**RÉSUMÉ**: La prévision et le contrôle du bruit et des vibrations transmis au sol constituent l'un des plus grands défis environnementaux de l'exploitation ferroviaire en zone urbaine. Des méthodes empiriques basées sur des courbes d'atténuation, similaires à celles présentées par la *Federal Transit Administration* (FTA) et par la *Federal Railroad Administration* (FRA) pourraient être extrêmement polyvalentes pour une première estimation des niveaux de vibration à la surface du sol. Malgré la valeur des courbes présentées, celles-ci ont un caractère généraliste, ne permettant pas de s'intéresser à des scénarios particuliers et spécifiques. En outre, la technologie ferroviaire et les techniques de construction adoptées dans d'autres régions du monde sont assez différentes de la réalité américaine, ce qui donne lieu à prévisions inadéquates lorsqu'elles sont appliquées dans des contextes distincts. De cette manière, la modélisation numérique avancée constitue une alternative fiable, permettant d'incorporer le profil géologique et géotechnique, le type et la configuration géométrique de la voie ferrée et du véhicule ferroviaire spécifique à chaque cas étudié et, par conséquent, d'atteindre un niveau de détail plus élaboré dans l'analyse. Dans ce travail, une approche numérique 2,5D FEM-PML (*Finite Element Method – Perfectly Matched Layer*) est utilisée pour calculer les courbes d'atténuation des vibrations pour différents scénarios. À partir des résultats obtenus, il est possible d'affirmer que, même s'il s'agit d'une approche conservatrice dans certains des scénarios considérés, l'application de la méthodologie empirique proposée par FTA/FRA doit être considérée uniquement comme un premier indicateur, étant recommandé d'effectuer davantage analyses détaillées dans des situations qui nécessitent un contrôle plus élevé des niveaux de vibration autorisés.

**Keywords**: Railway traffic; vibrations; numerical modelling; attenuation curves.

# 1 INTRODUCTION

Based on experimental data, the Federal Transit Administration (FTA) and the Federal Railroad Administration (FRA) proposed a general vibration assessment method. The main principle of such methodology consists in the evaluation of vibration attenuation curves, defined through the maximum value of the running RMS (root-mean-square) of the vertical velocity as a function of the distance to the railway infrastructure, which are subsequently corrected to meet the presence of buildings and taking into account their specificity (Quagliata, 2018) (Hanson et al., 2012).

The ground surface vibration curves were derived from the statistical treatment of experimental results. The consideration of such curves to specific scenarios should be adapted employing adjustment factors, also of an empirical nature. These are given as single values to add to the base level preconized by the reference curves.

Despite the value of the presented curves, and as can be understood, the empirical curves reported have a generalist character, not allowing to attend to the particular and specific scenarios, as discussed in Sadeghi et al. (2019). In this way, advanced numerical modelling is a reliable alternative, allowing incorporate the geological and geotechnical profile, type and geometric configuration of the railway track and railway vehicle specific to each case under study and, therefore, achieving a more elaborate level of detail in the analysis.

# 2 NUMERICAL MODEL

Alternatively, to the solutions reported previously, ground surface vibration curves can be evaluated through advanced numerical modelling, being subsequently corrected to meet the dynamics of the existing buildings in the vicinity of the railway infrastructure. For this purpose, a validated numerical approach is used to model the train-track-(tunnel)-ground system (Lopes et al., 2016).

This approach corresponds to a sub-structured methodology, where the modelling domain is divided into a 'stationary' component, composed by the track-(tunnel)-ground system, and a 'moving' component (train), where a 2D vehicle model is adopted and only vertical excitation is considered. The interaction between both is established by coupling the vehicle contact points with the remaining system. The basic formulation of the interaction scheme is summarised in Figure 1.

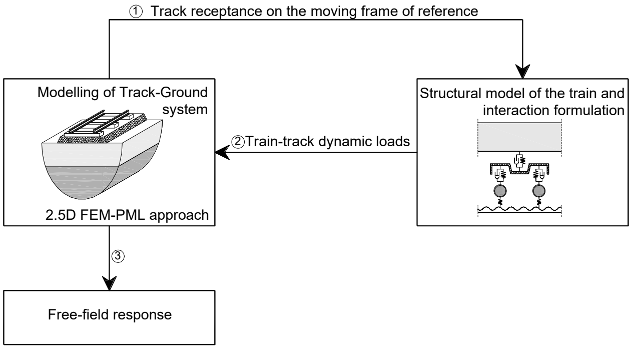


*Figure 1. Representative scheme of the numerical modelling approach.*

In terms of the track-(tunnel)-ground simulation, a 2.5D FEM-PML model is used. This formulation assumes a linear elastic behaviour of the different components and an infinite structure and invariable properties (geometrical and mechanical) in the direction of development of the track. Assuming these conditions, the three-dimensional solution of the problem is found through a 2.5D procedure based on the finite elements approach, where the analysis are carried out in the wavenumber/frequency domain. For its application, all the variables, i.e., loads (action) and displacements (response), are transformed to the wavenumber/frequency domain by means of a double Fourier transform, associated with the direction along the track and with time. Transformed quantities are functions of the Fourier images of x (longitudinal coordinate) and t (time), defined as wavenumber (k1) and frequency (ω). Moreover, a topic of particular relevance is the formulation of special procedures to treat the boundary effects inherent to the truncation of the domain associated with the finite element discretization. In order to avoid this spurious reflection of waves, a 2.5D PML approach is adopted. Full details about the mathematical formulation of the 2.5D FEM-PML model can be found in Lopes et al. (2014).

From this numerical approach, it is possible to compute vibration levels along the surface of the ground that are used to define the ground surface vibration curves.

# 3 PARAMETRIC STUDIES

## 3.1 General description

The numerical investigations in this study are based on the geometric and geomechanical properties illustrated in Figure 2. As can be seen, the scenario of analysis corresponds to a slab track in a tunnel.

To decrease computational effort, symmetry was used to reduce the modelling domain to half of its dimensions.

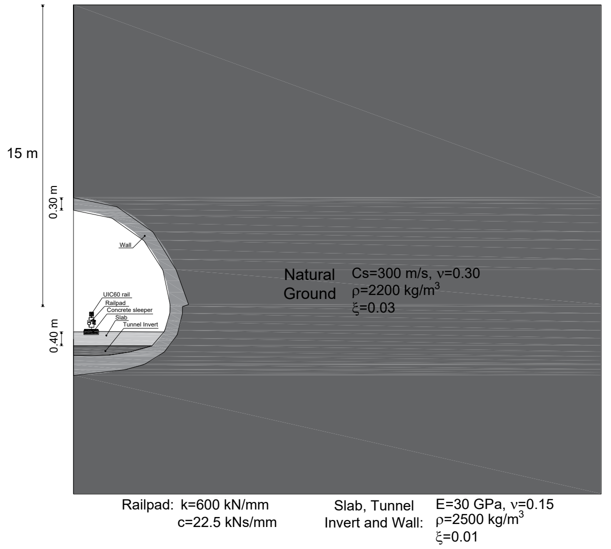


*Figure 2. Geometry and properties of the track-tunnel-ground system.*

Regarding rolling stock, the passage of the Alfa-Pendular vehicle is considered. The geometric properties and weight per axle can be found in dos Santos et al. (2016).

The train-track interaction is essential in problems involving the generation of vibrations. In the present work, the dynamic interaction mechanism is provided by the rail unevenness and the synthetic unevenness profile is generated according to the FRA proposal (Hanson et al., 2012).

The parametric studies consider two different train speeds (100 km/h and 200 km/h) and two different rail unevenness classes. At this respect, a distinction is made between the curves evaluated for a track in perfect conditions (Class 6 of the FRA classification) and a track in a not so good condition (according to Class 3 in the FRA classification).

## 3.2 Results and discussion

As initially stated, the numerical model 2.5D FEM-PML is applied for the prediction of vibration levels at the ground surface. In this way, Figure 3 presents the vertical vibration velocity for an observation point located at the ground surface, on the symmetry plane and considering the following variables: train speed equal to 200 km/h and maintenance Class 3. The ground surface vibration curves are defined through the maximum value of the running RMS (red line in Figure 3) of the vertical velocity as a function of the distance to the track.

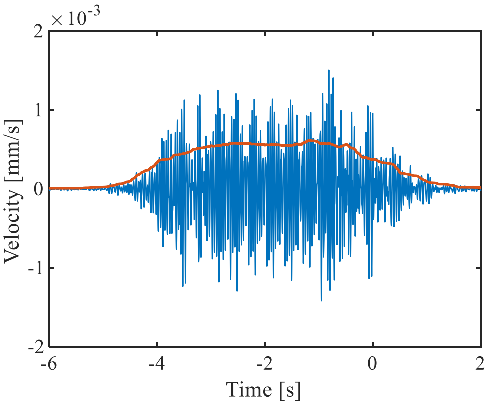


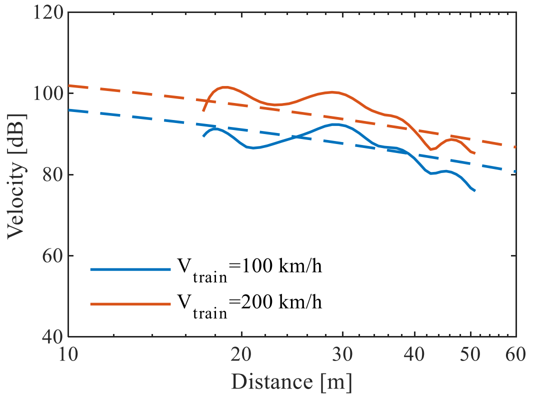
*Figure 3. Vertical vibration velocity for an observation point located at the ground surface, on the symmetry plane.*

Figure 4 presents the comparison between the vibration attenuation curves evaluated through the numerical approach and the attenuation curves proposed by FTA for the different scenarios under analysis.

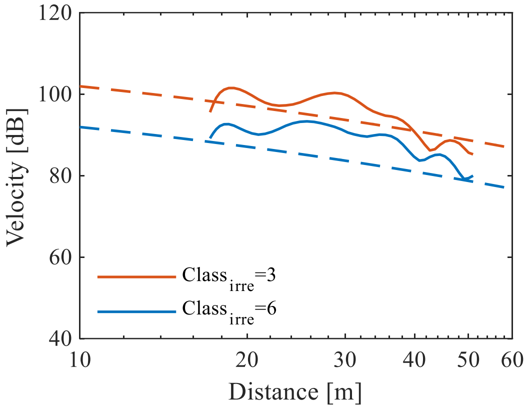
The FTA curves correspond to those defined for Rapid Transit and Light Rail Vehicles and it was assumed two adjustment factors: i) speed factor (20log(speed/speed$_{ref}$), speed$_{ref}$=50 mph); ii) track quality factor (0 dB for Class 6; +10 dB for Class 3).

As can be seen from Figure 4, and as expected, the vibration levels increase with the train speed and the degradation of the track quality. These general trends are also verified from FTA proposal through the adjustment factors adopted.

A comparison between numerical and empirical results allows to identify, for the conditions admitted, maximum deviations around 8 dB, indicating a significant difference. For some cases, the FTA curves underestimate the vibrations levels.



*a)*



*b)*

*Figure 4. Ground surface vibration curves (dB ref. $10^{-8}$ m/s): a) influence of the train speed; b) influence of the track condition (solid line – numerical result; dash line: FTA proposal).*

## 4 CONCLUSIONS

Based on the results obtained from the parametric studies conducted, it can be concluded that the application of the empirical methodology proposed by FTA should be regarded as an initial indicator. It is advisable to perform more detailed analyses in situations that require stricter control of allowed vibration levels.

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