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Prediction of Railway-Induced Noise and Vibrations in Environmental Impact Studies

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Abstract

The prediction and control of vibrations and noise remain among the most significant environmental challenges associated with the operation of railway lines in urban areas. A national and global paradigm shift is currently under way, in which investment in rail transport is being prioritized over other modes as part of a decisive effort to reduce CO_2 emissions. This ongoing expansion and upgrading of the railway network, together with the increasingly stringent comfort standards expected by modern society, highlight the need to assess the impact of railway operations on nearby buildings, particularly the ground-borne noise and vibrations experienced by residents during service. This work introduces an efficient tool for the rapid prediction of vibration levels to support the environmental impact assessment of new railway projects. The tool enables the immediate identification of situations requiring more detailed analysis, through advanced numerical modelling, as opposed to those that can be dismissed at an early stage. The proposed solution features a graphical interface integrated with Geographic Information Systems, while its computational engine relies on substitution models supported by a database derived from numerically validated and experimentally verified models.

Keywords: railway traffic, ground-borne noise and vibrations, prediction tool, environmental impact assessment, machine learning, surrogate model.

1 Introduction

Managing densely populated urban areas, their mobility, and the need to combat climate change are significant societal challenges that justify current investments in expanding rail transport. Although the economic, social and environmental benefits of rail transport are clear, its implementation raises environmental concerns due to the generation and propagation of vibrations and noise that affect the comfort and quality of life of people living near railway infrastructures [1].

In recent years there has been growing interest in developing advanced numerical techniques that cover the entire chain from the vibration source (vehicle–track interaction) to the receiver (building), considering the following physical patterns: (i) vehicle motion on the track is the source of vibrations; (ii) energy propagates through the ground as elastic waves; (iii) the vibration field reaches nearby buildings, producing noise and structural vibrations.

For modelling the vehicle, simplified models based on rigid-body dynamics (multibody dynamics) are generally adequate for the intended purposes [2-4]. Regarding numerical modelling of the track-ground system, due to the generation and propagation of vibrations is inherently three-dimensional, conventional 3D models are the natural choice for analysis [5, 6]. However, such models are typically applied only to particular case studies due to their high computational cost. Therefore, by simplifying the structure as invariant and infinite in the longitudinal direction, numerical models based on the 2.5D concept are appropriate for predicting free-field vibrations while substantially reducing computational effort [7-10]. Although the relevance of including the building in the analysis is recognized, this topic has only recently received significant attention and remains less developed. Some works can be cited [11-15].

Despite the existence and relevance of the methodologies described, applying these models for a rapid assessment across the general alignment of a new railway, regarding potential impacts on inhabitants' comfort, is limited. The high computational effort required for detailed analyses prevents their broad use in early project phases. Moreover, information available at that stage is scarce, complicating the determination of input parameters needed for detailed numerical analyses.
Because of these limitations, rapid prediction methods are sometimes recommended, although there remains a gap in reliable and accurate methodologies for this purpose. Semi-empirical methods, similar to the one presented by the U.S. Federal Transit Administration (FTA), can be very versatile [16]. However, applying them to contexts different from those in which they were developed must be done cautiously, as they can yield unreliable predictions in some situations [17].

An interesting alternative is to use advanced numerical models, experimentally validated, to generate a database of vibrations. This database can then be used to train machine-learning algorithms, deriving a rapid prediction model suitable for an initial, general assessment of expected vibration levels along a new railway corridor [18, 19].

Within this scope, the present article introduces the prediction platform developed in the IntRAIL research project, which integrates machine-learning models (XGBoost) and Geographic Information Systems (GIS), providing different levels of analysis of railway-induced vibrations. These integrated tools are particularly well suited for supporting environmental impact assessments.

2 Description of the simulation platform

2.1 Generalities

The prediction platform was developed in Python and is composed of different modules corresponding to distinct analysis levels and purposes. Figure 1 shows the platform's home page, where the available modules can be identified.

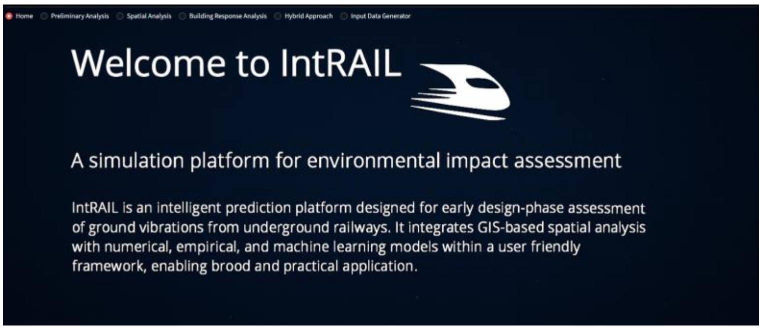

Figure 1: IntRail vibration prediction platform.

2.2 Preliminary analysis module

The first analysis module, called Preliminary Analysis, implements a simplified methodology supported by FTA studies that identifies vibration-sensitive zones induced by passing rail traffic based on source-to-receiver distance and the receiver's land-use type.

This procedure applies to all types of railway projects and is based on empirical foundations derived from observations of many railway projects where traffic-induced vibration measurements and annoyance-limit assessments were performed. As a preliminary analysis, geological and geotechnical aspects of the intervention area are not considered.

Project typology and land use are the determining factors for identifying and delimiting sensitive zones along the corridor. Four land-use categories are considered according to vibration sensitivity:

- Category I – High sensitivity: buildings where vibrations interfere with interior activities; vibration levels are generally below human perception thresholds. Examples: scientific research centres and hospital operating theatres with vibration-sensitive equipment.
- Category II – Residential: residential and lodging buildings such as homes, hotels and hospital wards.
- Category III – Institutional: schools, churches, institutions and offices without particularly vibration-sensitive equipment.
- Category IV – Historical monuments without a high sensitivity to vibrations.

For a light-rail project, the recommended distances shown in Table 1 correspond to the limit values beyond which rail traffic is not expected to induce vibration levels exceeding admissible limits for each building category (in line with FTA recommendations [16]).

Table 1: Minimum distance from track centreline by building category.

Category	Description	Minimum distance from track centreline
I	High sensitivity	175 m
II	Residencial	60 m
III	Institutional	35 m
IV	Historical	60 m

Figure 2 shows an example application of this methodology to a practical case, illustrating identification and delimitation of buildings assigned to each category along the railway alignment.

Figure 2: Railway corridor delimitation according to a preliminary analysis methodology.

This analysis level is particularly useful for a preliminary estimate of the number of buildings potentially affected by excessive vibration, allowing immediate exclusion of buildings located outside the defined corridors.

2.3 Spatial analysis

The next module produces spatial representations of vibration levels along the corridor by defining vibration maps. This functionality enables georeferenced visualization of results, facilitating global interpretation of impacts from the new alignment and identification of potentially critical zones.

A rapid model based on machine-learning algorithms was previously developed to determine the free-field response using the maximum Running RMS as the indicator. This surrogate model is based exclusively on Extreme Gradient Boosting (XGBoost), a powerful ensemble learning technique well suited for structured engineering datasets. It was trained and validated using a database generated with the 2.5D FEM-PML model [10], which encompasses multiple scenarios involving variations in rolling stock characteristics, track-tunnel configurations and ground properties.

Vibration level values are assigned to each point or cell of the geographic mesh and then integrated into a GIS to create colour maps representing spatial variation of vibration levels along the corridor and near buildings. Figure 3 show a typical resulting vibration map.

Figure 3: Example of the resulting vibration map.

This step is an essential decision-support tool, enabling preliminary assessment of the most sensitive zones and prioritization of locations for detailed analysis or experimental monitoring. The interactive graphical interface also allows automatic map updates when input parameters change (e.g., track type, foundation material, soil properties), making the analysis process more dynamic and efficient.

2.3 Structural response

Prediction of the structural response to traffic induced action is based on a methodology divided into two main modules: i) Train-track-ground module; ii) Building module.

All calculations are performed in the frequency domain and responses are analysed in 1/3 octave bands. The combination of both modules uses a decoupled formulation and is composed into three main steps.

Step 1 - Free field response calculation

Free field response evaluation relies on surrogate models and involves the following tasks:

- Generating a database from numerical modelling of the vehicle-track-ground system across multiple simulation scenarios, using Monte Carlo methods to introduce variations in input parameters;
- Using a 2.5D FEM-PML numerical models to evaluate the ground response for each scenario [10];
- Developing and training a machine learning model (XGBoost) to efficiently predict vibration levels at the ground surface in 1/3 octave bands.

Applying the machine learning model to a given case study yields the free field response u_G in 1/3 octave bands.

Step 2 - Building transfer function evaluation

For the building, the proposed methodology determines a transfer function numerically to represent its dynamic behaviour in the frequency domain, expressed in 1/3 octave bands.

Numerically, this curve can be obtained through a soil-structure interaction (SSI) approach previously developed and validated by the authors, using a 3D finite element model in the frequency domain. Equation (1) defines dynamic equilibrium in the frequency domain for an imposed motion applied at the building foundations:

$$\begin{bmatrix} K_b^{ii} & K_b^{ij} \\ K_b^{ji} & K_b^{jj} + K_s \end{bmatrix} \begin{bmatrix} u_i \\ \Delta u^b \end{bmatrix} = - \begin{bmatrix} K_b^{ii} & K_b^{ij} \\ K_b^{ji} & K_b^{jj} \end{bmatrix} \begin{bmatrix} 0 \\ u_0 \end{bmatrix} \quad (1)$$

where K_b^{ij} denotes the dynamic stiffness matrix of the structure, with indices i and j referring to interior nodes and interface (foundation) nodes of the finite element mesh, respectively. Δu^b represents the increment of displacement of the foundation degrees of freedom resulting from inertia forces generated in the building, while K_s is the dynamic stiffness matrix of the soil, evaluated using a condensed parameter model [15].

The building transfer function (TF_B) is obtained from Equation (1) by assuming u_0 as a unit harmonic displacement applied at the foundations. TF_B can thus be evaluated for any position inside the building corresponding to nodes of the finite element mesh.

Step 3 - Building response

The building response u_B is obtained by combining the free field response u_G with the building transfer function TF_B. In logarithmic scale, this relation is expressed as:

$$u_B = u_G + TF_B \quad (2)$$

This approach provides an efficient estimate of vibration levels at any point inside the building. The free field response computed by the surrogate model represents the excitation transmitted to the building foundations, while the building transfer function accounts for soil-structure coupling effects and slab amplification according to the structure's dynamic characteristics. Figure 4 presents a typical frequency dependent building transfer function.

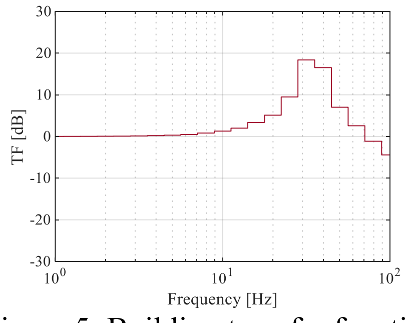

Figure 5: Building transfer function.

3 Conclusions and future developments

The presented prediction platform for traffic-induced vibrations is in the final stages of development and represents a significant advance for rapid environmental impact assessment of vibration generation and propagation from railway infrastructures. The main purpose of this paper is to present the prediction platform and its general framework.

This tool provides efficient support for environmental impact studies by enabling a quick and comprehensive assessment of expected vibration levels along an entire corridor. The implemented methodology allows early identification of the most critical zones, which can then be subject to advanced numerical analyses and/or in-situ measurement campaigns, thereby optimising resources in early project phases.

Future developments include experimental validation of the tool using measurements from experimental case studies to assess prediction reliability and calibrate the integrated machine-learning models. The database will also be expanded to include other track typologies and geotechnical conditions to increase the platform's robustness and applicability across diverse contexts.

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