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RAILWAY-INDUCED VIBRATIONS: AN EXPERIMENTAL STUDY ON VIBRATION LEVEL VARIABILITY DUE TO VEHICLE INFLUENCE

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Abstract

Globally, there is a growing shift toward prioritizing rail transport over other modes of transportation to drastically reduce CO2 emissions. However, the prediction and control of ground-borne noise and vibrations remain critical environmental challenges in urban railway operations. This paper presents an extensive evaluation of vibration levels at the source, using a recently completed railway line in Portugal as a case study. Measurements from a wide set of similar trains enabled a detailed non-deterministic analysis of vibration variability. The findings offer valuable insights to enhance the accuracy of future prediction models and support sustainable railway development.

Keywords: Railway traffic, vibrations, experimental analysis, vehicle-induced variability.

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1 INTRODUCTION

The issue of excessive vibration and noise levels associated with the operation of railway infrastructures is of great relevance and a major concern for infrastructure managers, from the design phase of a new railway line to the regular operation of existing lines. These concerns play a crucial role, especially in urban environments, raising issues regarding the comfort of residents in buildings adjacent to the infrastructure, interference with vibration-sensitive equipment, or, in extreme cases, architectural damage to surrounding ancient buildings [1].

To effectively predict and mitigate these negative effects, it is essential to understand the key parameters that contribute to the generation and propagation of ground-borne vibrations induced by railway traffic. These parameters include train characteristics (such as speed, axle load or wheel roughness), track type and conditions (e.g., slab track, ballasted track, rail irregularities) and soil properties (such as stratification, stiffness or damping). Over the past years, several studies have been conducted to evaluate the influence of these parameters on vibration levels [2-7]. These studies have provided valuable insights into how different factors interact and affect the propagation of vibrations in various railway environments.

Most of these studies are conducted in a deterministic way, which assumes a fixed set of input conditions and provides a single predicted outcome. While this approach can be useful for simplified assessments, it does not account for the natural variability present in railway operations.

Thus, the present study aims to experimentally assess the impact of the vehicle in a non-deterministic way, considering multiple passages of vehicles of the same typology. It is important to note that some key factors in the generation of vibrations induced by railway traffic include the vehicle's speed, typology, mass distribution, and the condition/maintenance of its wheels.

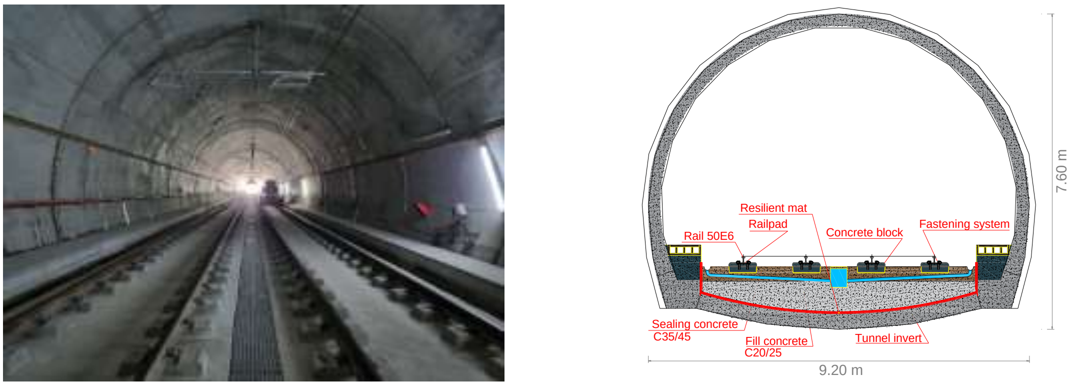
2 CASE STUDY DESCRIPTION

The Metro do Porto system comprises a network of railway lines serving the city of Porto and its surrounding metropolitan area. Among these, the Yellow Line connects Hospital São João in Porto to Santo Ovídeo in Vila Nova de Gaia. In June 2024, a 3.2 km extension was inaugurated, further extending the route to Vila D'Este. This new segment incorporates a variety of cross-sectional types, including viaduct, tunnel, trench, and surface-level segments, reflecting the diverse urban and topographical challenges along the route. Figure 1 illustrates the layout of this newly extended segment and its urban integration.

Figure 1: Yellow line of the Metro do Porto network (Santo Ovídeo-Vila D’Este).

The tunnels of the Yellow Line are constructed at varying depths below the ground surface. The distance from the railhead to the ground surface ranges from approximately 9 meters at the tunnel extremes to over 30 meters, reflecting the topographic configuration of the natural ground.

The installed railway track corresponds to a classical floating slab track system, where continuously welded 50E6 rails rest on precast concrete blocks bonded to the slab. A resilient layer was placed beneath the slab, with an average thickness of 60 cm. Figure 2 displays the cross-section with the main track components identified.



a) b)

Figure 2: Track-tunnel system: a) photographic view; b) schematic representation.

Regarding the rolling stock, the main vehicle operating on this specific line is the Eurotram. As shown in Figure 3, this is a double light rail vehicle composed of 3 modules and 4 bogies. Each bogie has 2 axles, with the end bogies transmitting a maximum axle load of 6 tons to the infrastructure, while the intermediate bogie axles transmit a load of 11 tons. The maximum unsprung mass for this vehicle is 1960 kg. The operating speed on the track section relevant to this study is limited to 60 km/h.

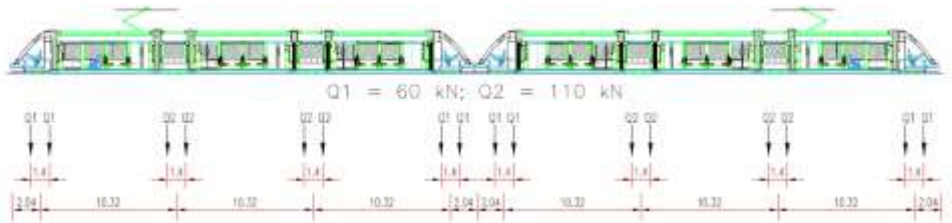


Figure 3: Geometrical configuration and axle loads of the vehicle EuroTram.

3 EXPERIMENTAL MEASUREMENTS

3.1 SETUP

In accordance with the initially defined objectives, a section inside the tunnel was monitored, with the monitoring scheme adopted shown in Figure 4. As can be seen, four accelerometers were installed to measure vibration records during the passage of metro vehicles, with one sensor located on the sleeper (S19), two sensors placed on the slab (S15 and S17), and the last one positioned on the tunnel wall (S10).

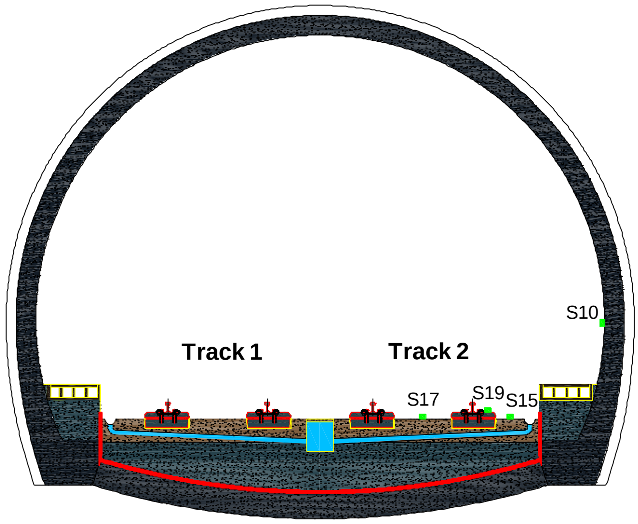


Figure 4: Vibration monitoring scheme inside the tunnel.

Due to the impossibility of operators remaining inside the tunnel during line operation, autonomous, non-synchronized battery-powered units were employed, each capable of independently recording events in three orthogonal directions. The acquisition units consist of MEMS accelerometers, with a vibration amplitude range of ±8G. Figure 5 presents illustrative photographs of the adopted equipment and its positioning.

Figure 5: Photographic record of the sensors used for vibration measurement at the track and tunnel wall level.

3.2 VIBRATION RECORDS

As previously mentioned, vibrations were measured on the railway track and tunnel wall due to the passage of railway traffic. As an example, Figure 6 presents the time history of the vibration velocity in the vertical direction induced by the passage of a vehicle traveling on Track 2. The time evolution of the Running RMS curve is also represented over the time record.

As can be observed, the vibration velocity values in the vertical direction are of the same order of magnitude on both the sleeper and the slab, with a significant attenuation when compared to the time record on the tunnel wall. This attenuation was expected due to material and geometric damping phenomena, but it is even more pronounced due to the implementation of a resilient mat under the track slab, which induces significant attenuation at higher frequencies.

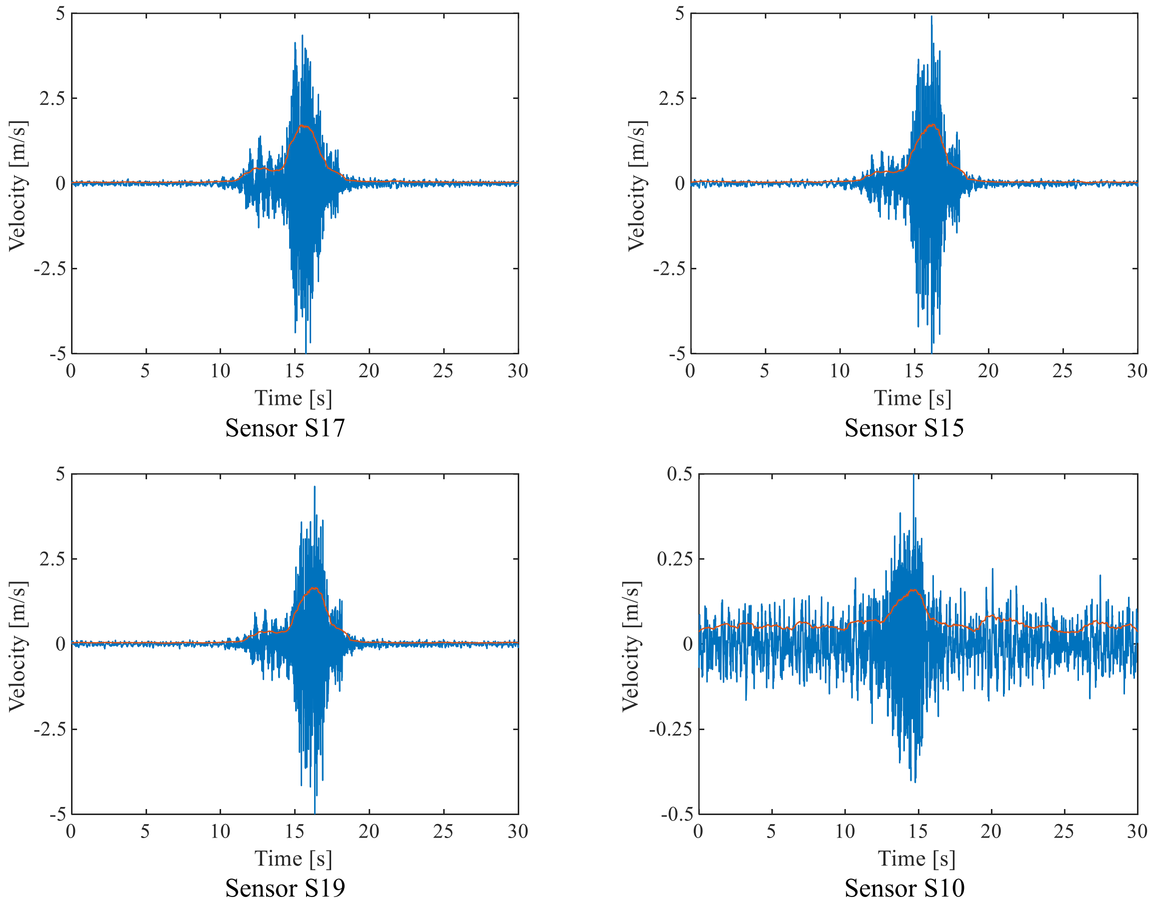
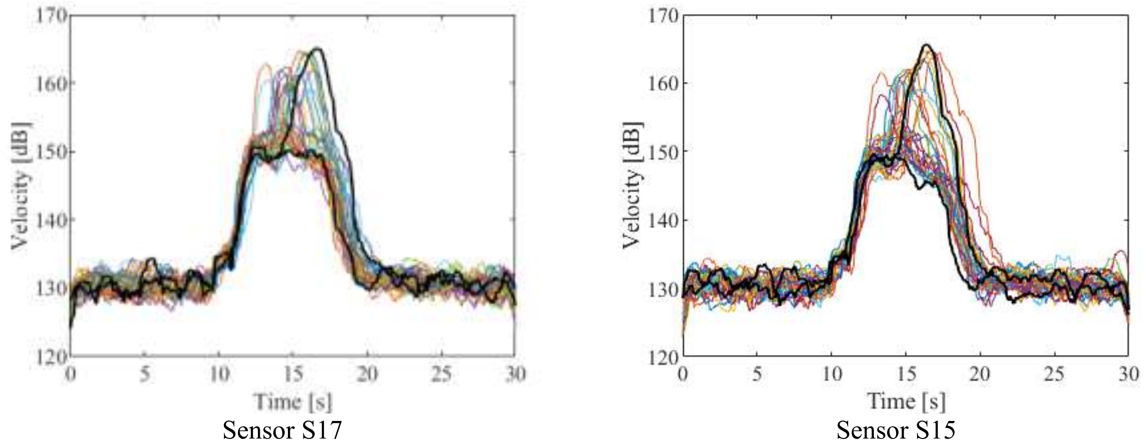
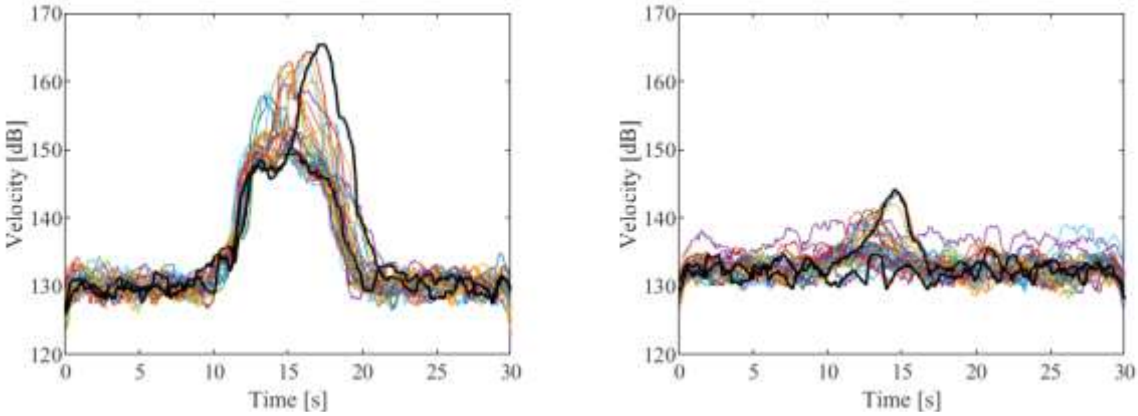


Figure 6: Record of the vertical velocity of vibration induced by a vehicle travelling on Track 2.

To assess the variability of the response due to the passage of different vehicles, Figure 7 presents the Running RMS curves of the velocity in the vertical direction. A total of 32 vehicles traveling on Track 2 were considered. The train speed remained relatively constant across all passages, with a maximum speed of 60 km/h.





Sensor S19 Sensor S10

Figure 7: Running RMS curves of the vertical vibration velocity for different vehicle passages.

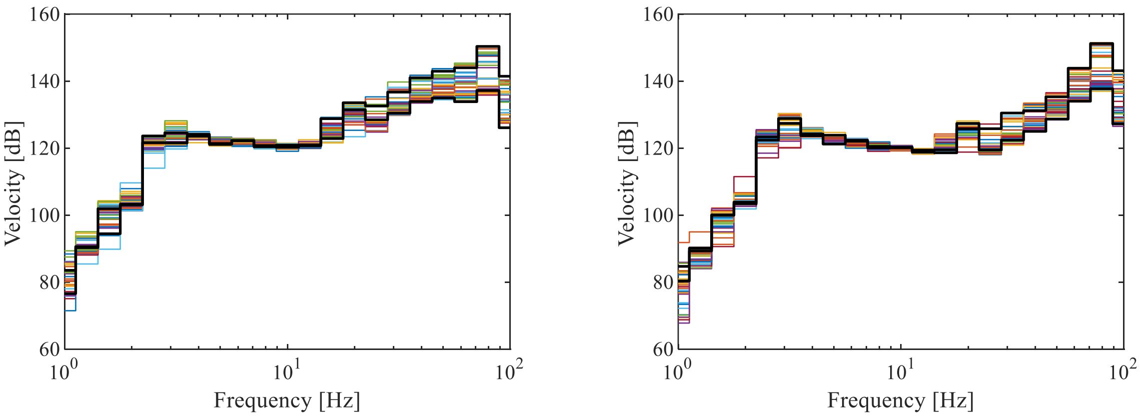
As observed, there is a considerable dispersion in the results, which can be attributed to differing vehicle conditions. Specifically, differences of up to 15 dB are recorded at the observation points on the slab and sleeper, as summarized in Table 1, where the key information is presented.

A brief note should be made regarding the results from sensor S10, located on the tunnel wall. The data is not entirely clear across all vehicles due to lower vibration levels, influenced by the presence of the resilient layer and the reduced sensitivity of the sensors used. Nevertheless, a high variability in the response remains evident.

Table 1: Key indicators regarding the maximum values of the different Running RMS curves.

Sensor	Mean	Maximum	Minimum
S17	157	165	157
S15	156	165	149
S19	156	165	150
S10	138	144	135

When analyzing the frequency content in the form of one-third octave bands, some dispersion across the spectrum is also evident, with a particular impact at higher frequencies, as shown in Figure 8 for two sensors.



Sensor S17 Sensor S15

Figure 8: One-third octave band curves of the vertical vibration velocity for different vehicle passages.

4 CONCLUSIONS

The present paper presents an experimental study on the variability of vibration levels at the source, considering the influence of the vehicle. The study focuses on a recently constructed railway line in the city of Porto, Portugal, where sensors were used to monitor a tunnel cross-section over an entire day of operation. More than 30 vehicle passages were evaluated in a single track.

From the results presented, it is clear that vehicle conditions have a significant impact on the generated vibration levels. Although it was not possible to identify in detail the parameters with the greatest influence, it is assumed that the condition of the wheels plays a key role in the observed variability.

This highlights the need for further research to better understand the relationship between vehicle conditions and vibration levels, so that these factors can be considered in the design phase of new railway lines and the maintenance of existing infrastructure.

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