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Railway Induced Groundborne Noise And Vibration From Lines In Tunnel, Paris Rer E "Eole" Project

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ABSTRACT

Construction of the RER E "EOLE" tunnel line in Paris (France) between St-Lazare station and Paris West has started in 2018. Ground-borne noise and vibration levels generated by operational trains have been carefully considered to prevent nearby buildings' occupants from being exposed to noise annoyance. This paper describes the steps taken to predict ground-borne noise from train operation in a tunnel. The tunnel is located under 1870's era buildings, on Boulevard Haussmann, Paris. A model for predicting ground-borne noise and vibration from the operational railway was used, including a numerical FEM/BEM model of the soil and foundations and an empirical transfer function for this Haussmann-style building type.

Keywords: Railway, Vibrations, Tunnel.
I-INCE Classification of Subject Number: 76

1. INTRODUCTION

EOLE, the extension of the RER E railway line towards Paris-West, links Tournan/Chelles in the East and Mantes-la-Jolie in the West. The new railway consists of the construction of an 8 km single bore tunnel running at a depth of 25 to 50 m. The tunnel follows a 19th century boulevard with a typical Haussmann-era architecture. In such cases, ground-borne noise and vibration from train services might disturb occupants of buildings with deeply buried foundations. This paper presents a prediction model of ground-borne noise and vibration using numerical calculations for the tunnel-foundations transmission and an empirical transfer function for the foundation-floor transmission within Haussmann-style buildings. The topic of foundations to floor transmission for at-grade railway has been dealt with in RIVAS [2] project, but little information exists on the foundations to floor transfer functions near tunnel sections. One of the issues of predicting ground-borne noise and vibration consists in modelling the transfer function between vibration of the foundations and ground-borne noise within Haussmann-style buildings near a tunnel section. This transfer function had to be estimated from measured field data to fill the existing gap in the literature.

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2. GROUND-BORNE NOISE MODEL CONSTRUCTION

A prediction model of vibration levels on foundations including numerical models of the tunnel structure, the soil layers and the building foundations with MEFISSTO (CSTB Software [1]) is used. An empirical transfer function between vibration of the foundations and vibration of upper levels floors within Haussmann-style buildings is used. The ground-borne noise resulting from structure vibration is evaluated using a relationship between sound level and vibration at the floor center drawn from RIVAS [2].

The calculation process and a cross-section profile are presented Fig. 1.1 and Fig. 1.2. The calculation process starts from the tunnel wall velocity spectrum and leads to the floor velocity and ground-borne noise as shown. The building foundations is located at 7 m above the tunnel. The building structure consists of 5 underground concrete levels and of 6 masonry levels.

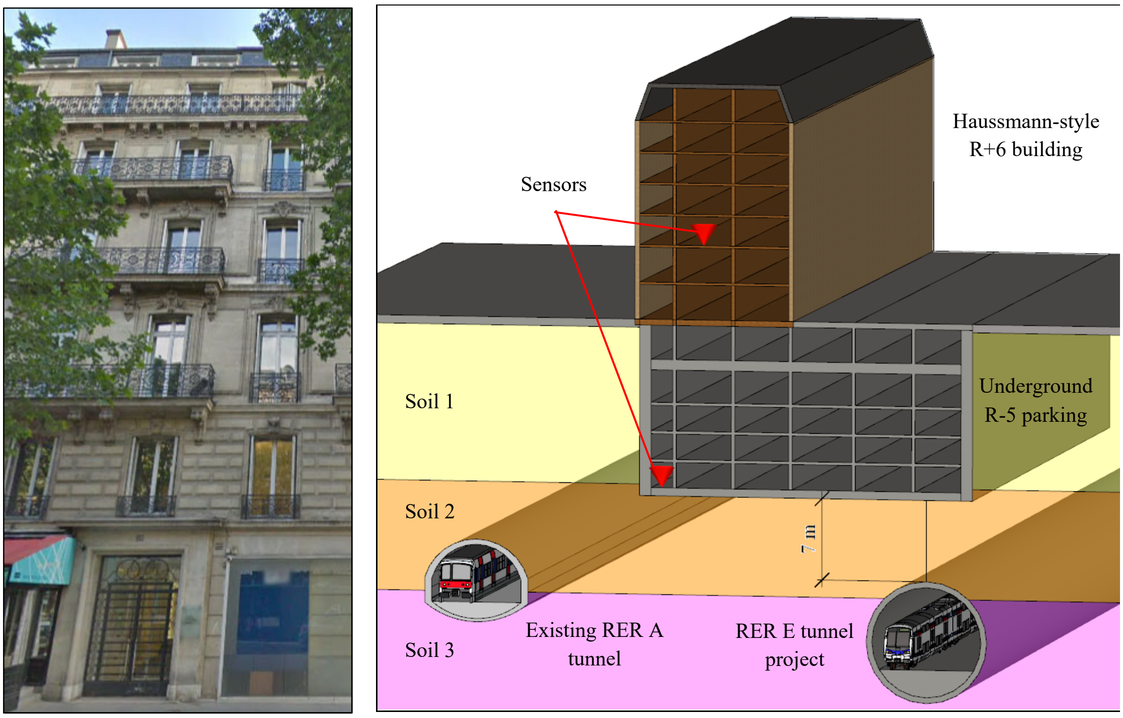


Figure 1.1: Façade and cross-section profile

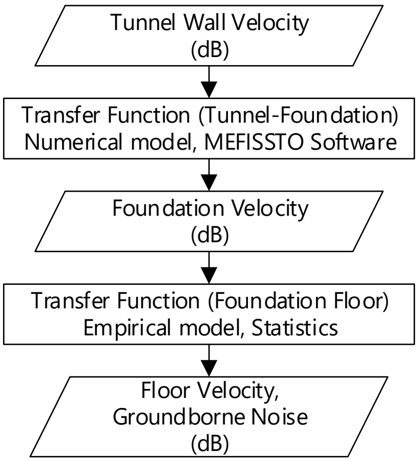


Figure 1.2: Calculation process

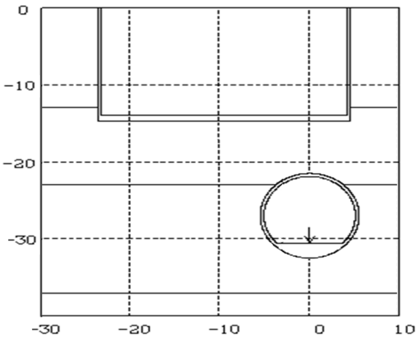
2.1 Numerical modelling of the tunnel/ground/foundation

A two steps procedure is used to predict groundborne vibration in buildings close to a tunnel. First, the tunnel's response to a running train is evaluated ; this part is not fully described in this paper but briefly discussed in Section 4.1). In a second step, the soil and building foundations response is computed.

A 2.5 D FEM-BEM tunnel/ground/foundations model (CSTB MEFISSTO Software [1]) is used to calculate a velocity level difference between tunnel wall and building foundations. Input data for this model is the tunnel wall velocity during train pass-by expressed as 1/3 octave band spectrum, as well as ground and concrete structures properties.

Ground conditions and geometry of the tunnel and building structures are shown in Figure 2.1. The simplified building geometry is limited to the outer wall and foundations slab in contact with the ground, without basement floors. This simplified geometry allows for the calculation of the foundations velocity level. Given the lack of adequate information, the underground and upper storeys are not modelled. The building floor velocity levels are not computed : indeed, each complex storey floor differs from one another (cf. Fig. 4).

Calculation results are given in Figure 2.2, and expressed as a velocity level difference between the tunnel wall and the foundations.



Propagation Medium	Density ρ (kN/m^3) / Dynamic Young Modulus E (GPa) / Poisson's ratio ν (-) / Loss factor η (-)			
Soil 1 (0 m to -13 m)	20	0.2	0.3	0.08
Soil 2 (-13 m to -23 m)	19	3.5	0.35	0.08
Soil 3 (-23 m to -37)	24	7.5	0.35	0.08
Soil 4 (-37 to -∞)	18	0.6	0.46	0.08
Concrete	23.5	28	0.15	0.01

Figure 2.1: MEFISSTO model geometry and parameters

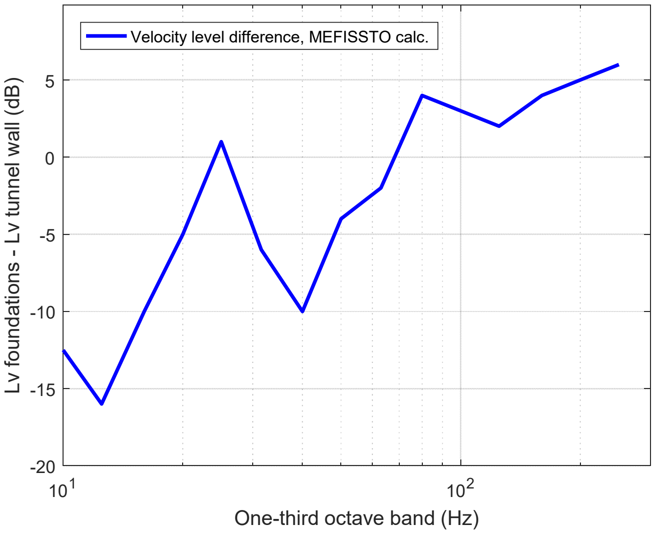


Figure 2.2: Velocity level difference between foundations and tunnel wall, 2.5D MEFISSTO result.

2.2 Empirical foundations to floor transfer function

Field measurements of vibration levels of the building foundations and the mid-span of floors were conducted inside 6 Haussmann-style buildings located close to a railway tunnel (RER A). The difference of velocity level spectra between foundations and floor is measured during train pass-by. For each location, 8 measurements are meshed from foundations to the top storey (up to 7 levels in one building). Sensors are placed near the corner of the building for the foundations, and at mid-span of each floor. The data acquisition system consists of 8 tri-axe accelerometers sampled at 1024 Hz. Velocity levels spectra are obtained by integration from the acceleration spectra.

The average difference of vertical velocity levels $Lv_{eq,Tp}$[1] between foundations and the floor (Level 2) is calculated for each third octave band and for each building. A statistical treatment of these measurements is carried out by calculating the mean value and standard deviation of 6 measurements taken in each building at mid-span floor, on the second storey (Level 2).

The empirical foundations to floor transfer function spectrum used in the model is the "mean value + 1 standard deviation" of the 6 buildings (cf. Fig. 3). This leads to an overestimation of the floor velocity level of approximately +3 to +7 dB compared to the measured data mean value. The floor response variability (deviation from the mean) reflects the frame construction diversity and floor construction diversity, in Haussmann-era buildings.

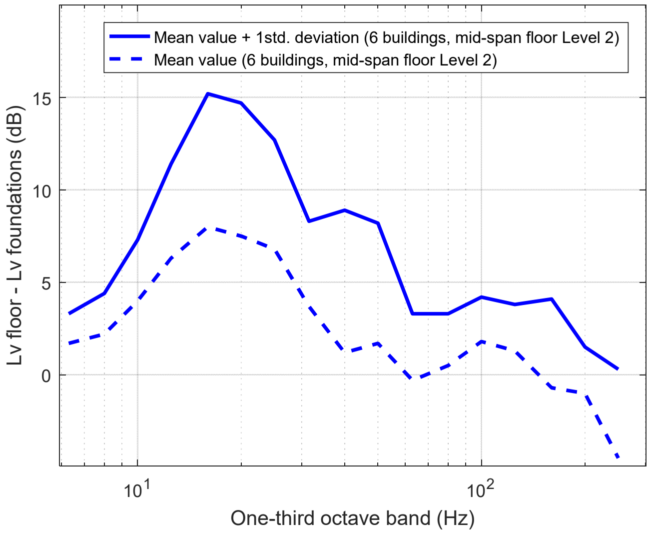


Figure 3: Empirical foundations to floor transfer function for Haussmann-style buildings

2.3 Empirical floor vibration to ground-borne noise transfer function

A simplified transfer function between room space average sound level and floor velocity level at mid span is drawn from RIVAS [2]. RIVAS proposals for predictions concerning floor vibration to ground-borne noise are :

- For concrete floors and heavy wood floors : $Lp_{\text{average room}} \approx Lv_{\text{mid span floor}} + 7$ dB
- For lightweight wood floors : $Lp_{\text{average room}} \approx Lv_{\text{mid span floor}}$ -3 dB

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[1] $Lv_{eq,Tp}$: averaged equivalent velocity level during train pass-by as described for acoustics measurements of $L_{pAeq,Tp}$ in ISO 3095:2013 Acoustics - Railway applications - Measurement of noise emitted by railbound vehicles

Based on the RIVAS proposals, the transfer function used in this paper to calculate roomspace average sound level for the heavy (loaded) Haussmann-style wood floor is (for each one-third octave band) :

$$Lp_{\text{average room}} \approx Lv_{\text{mid span floor}} + 7\text{ dB} \quad \text{(Equation 1)}$$

[dB réf 2.10^{-5} Pa] [dB réf 5.10^{-8} m/s]

(Assuming the room is normally furnished, Reverberation Time = 0.5 s, taking into account that both heavy floor and heavy ceiling radiate noise and neglecting vertical walls radiation, cf. ISO 14837-31 [8])

Typical Haussmann-style floors consist in boards, beams, filling with construction rubble, wood lathwork and decorative "staff" ceiling work (powdered lime and marble) as shown in Fig. 4.

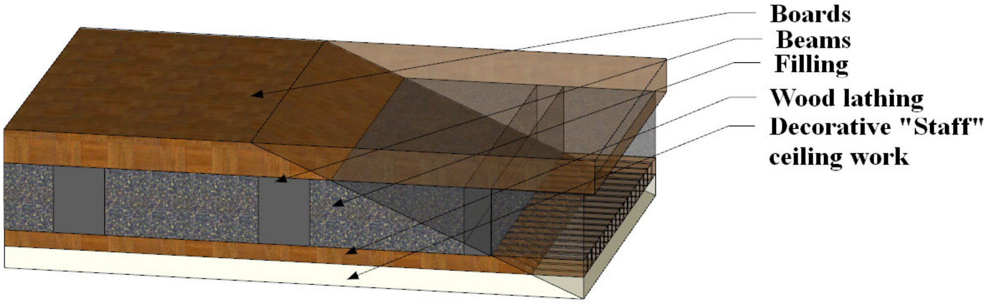

Figure 4: Typical Haussmann-era floor

3. EXAMPLE OF FLOOR VELOCITY AND GROUND-BORNE NOISE LEVELS CALCULATION

The described model is applied to a Haussmann-style building and his 5 levels underground car park (cf. Fig 1.2). The train source corresponds to an RER line E "MI2N"-type train operating at 120 km/h in a double slab-track tunnel. The track consists of welded rails fastened on sleepers with a resilient under sleeper pad (STEDEF track). Input data of the model is the velocity level on the tunnel wall in the horizontal direction shown in Fig. 5; the source excitation aspects are discussed below in Section 4.1. Building foundations velocity level is calculated with MEFISSTO (cf. § 2.1). Mid-span floor velocity level is calculated using the empirical foundations to floor transfer function (cf. § 2.2). Ground-borne noise (*id est* average roomspace noise) is calculated from mid-span floor velocity level following Equation 1.

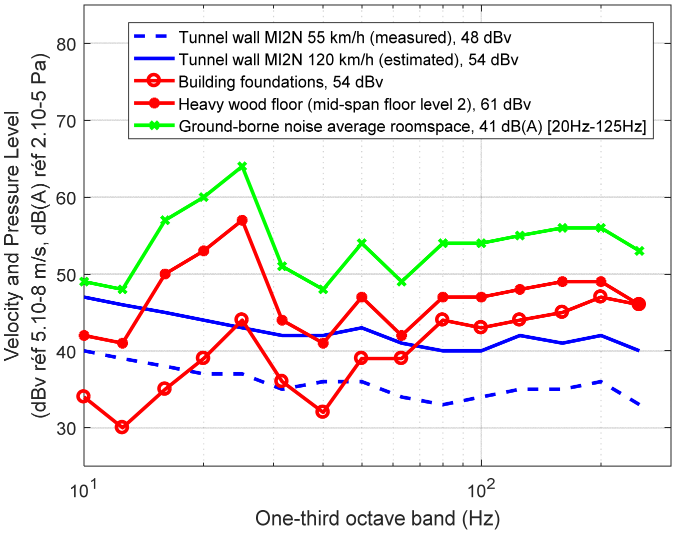

Figure 5: Calculation results, Tunnel wall, Foundations and Floor Velocity Levels, Ground-borne Noise, Measured Data at Tunnel Wall

4.1 DISCUSSION

4.1.1 Limitations of the method

It is important to emphasise that in the context of environmental impact assessment, an adequate margin of uncertainty should be applied to the calculation results to ensure the reliability of the prediction.

4.1.2 Absence of source model

This method does not include emission. Train-track interaction as well as tunnel-ground conditions influence velocity levels of the tunnel wall. Input data for the model depends mainly on the roughness of rail running surfaces, ground conditions and track system :

- Rail roughness for the presented example (cf. Fig. 5) corresponds to 7 years of service. Rail roughness has been measured and is below the ISO 3095:2013 limit spectrum.
- Stiffer ground conditions would reduce velocity level on the tunnel wall.
- Lowering sleeper pads stiffness would lower the track resonance and reduce velocity level on the tunnel wall.

In order to calculate the change in vibration response in accordance with the project design (i.e. relative change to the track system), it is necessary to combine this method with a prediction model for tunnel response including train/track/tunnel characteristics. For more information regarding the latter, the reader is referred to the literature ([3],[4],[5],[6]).

4.1.3 Representativeness of measurements taken on the tunnel wall

Model input data consists of a velocity level measured on the tunnel wall at an existent section of the RER E railway. The train speed at measurement location is 55 km/h. 4 measurements are placed over a 100 m tunnel section. These 4 measurements on the tunnel wall are averaged to define the tunnel wall velocity level input at 55 km/h (horizontal direction). In this paper, an increase of +6.5 dB is applied to the 55 hm/h measurement for each one-third octave band (without frequency shift) to obtain a simplified estimation of the tunnel wall velocity level at 120 km/h. The indicator used for this purpose is the $Lv_{eq,Tp}$[2] mean value for 15 MI2N train services.

4.2 COMPARISON WITH AN EXISTING EMPIRICAL FOUNDATIONS TO FLOOR TRANSFER FUNCTION (RIVAS)

In RIVAS project, an experimental procedure is described to predict railway vibration transmission for at-grade tracks.

RIVAS results include recommendations to predict ground-borne noise and vibration resulting from surface operating trains. Transfer functions measurements between vibration of the foundations and mid-span floor velocity levels are given for buildings with heavy wood floors. The existing SBB[3] data drawn from RIVAS [1] are compared in Figure 6 to field measurements for Haussmann-style foundations to floor transfer functions. This comparison shows that the obtained transfer function for Haussmann-style buildings (with underground train source) reduces the predicted floor vibration level by 6 dB at floor resonance compared to RIVAS SBB data (with at-grade train source). Given the relatively low number of measurements available, the empirical Haussmann-style transfer function described should be compared to additional measurements to confirm this trend. The differences between both transfer functions could be related not only to floors construction, but also to the train location (underground or at-grade), because the foundations are excited in different ways.

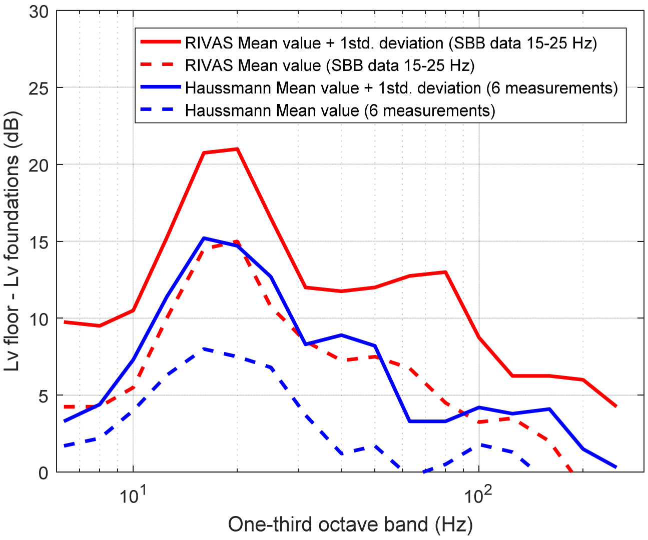

Figure 6: Velocity level difference between floor (mid-span) and foundation. Statistical transfer function in dB (mean value and mean value + 1 standard deviation) for range 15-25Hz of floor resonant frequencies.

5. CONCLUSIONS AND OPEN POINTS

A typical foundations to floor transfer function for Haussmann-style buildings located near a tunnel section is derived from 6 measurements in buildings. This transfer function is integrated in a ground-borne noise prediction model.

This hybrid numerical and empirical method allows to improve the accuracy of the prediction model by an adequate characterization of the vibration transfer inside

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[2] $L_{Veq,Tp}$: averaged equivalent velocity level during train pass-by as described for acoustics measurements of $L_{pAeq,Tp}$ in ISO 3095:2013 Acoustics - Railway applications - Measurement of noise emitted by railbound vehicles

[3] SBB : Swiss Federal Railways

Haussmann-style buildings. The obtained empirical foundations to floor transfer function for underground railway is compared to the RIVAS data for at-grade railway. This comparison shows that the obtained transfer function for Haussmann-style buildings near a tunnel section reduces predicted floor vibration level by 6 dB at floor resonance compared to RIVAS SBB data.

The focus of this paper is on the building response to underground railway. Integration of the train dynamic excitation would be required to complete the prediction model, which could then be applied to a new track design and tunnel/soil interaction.

It would be interesting to compare these results with field measurements on the same buildings after tunnel is finished and train circulating as well as on similar type construction all over Europe.

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