Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 72 (2023) 973–980

Transportation Research Procedia

www.elsevier.com/locate/procedia

Transport Research Arena (TRA) Conference

Soil vibration and auralisation software tools for application in railways

Pascal Bouvet[a]*, David Thompson[b], Reto Pieren[c], Geert Degrande[d], Andreas Nuber[e], Martha Garcia[f]

[a]*Vibratec, 28 Chemin du petit bois, F-69131,Ecully, France*
[b]*Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[c]*Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland*
[d]*KU Leuven, Department of Civil Engineering, Kasteelpark Arenberg 40, B-3001 Leuven, Belgium*
[e]*Wölfel Engineering GmbH + Co. KG, Max-Planck Strasse 15, D-97204 Höchberg, Germany*
[f]*UNIFE, Avenue Louise 221, B-1050 Bruxelles, Belgium*

Abstract

The main objective of the SILVARSTAR Shift2Rail project is to develop validated software tools in the field of ground vibration and auralisation. The first project work stream focuses on the prediction of ground vibration through the development of a hybrid approach, combining numerical prediction with experimental results. The general framework adopted expresses the vibration level in a building as the product of terms describing the source, the propagation through the soil and the receiver. In the second work stream, auralisation and Virtual Reality (VR) software tools are developed based on physical models to synthesise railway noise in high quality. The novel auralisation and VR tools enable perception-based evaluation of noise mitigation technologies and an effective demonstration of different noise scenarios, including noise mitigation measures and vehicle design variants.

Keywords: Noise ; Railway Induced Vibration ; Auralisation ; Virtual Reality.

---

1. Introduction

Although rail is a sustainable and climate-friendly mode of transport, noise and vibration remain particular environmental concerns. People living near railways are becoming increasingly sensitive and unable to tolerate high noise and vibration levels. SILVARSTAR aims to provide the railway community with proven software tools and

---

* Corresponding author. Tel.: +33 6 15 73 20 50.
E-mail address: pascal.bouvet@vibratec.fr

10.1016/j.trpro.2023.11.525

methodologies to assess the noise and vibration environmental impact of railway traffic at a system level. The project has two work streams addressing these challenges.

The first work stream focuses on the **prediction of ground vibration** through the development and validation of a hybrid approach, combining numerical prediction with experimental results. A prototype of this hybrid numerical / experimental prediction tool is being developed and will then be implemented in existing noise mapping software. The prediction tool includes a database of experimental and numerical data to support the proposed hybrid prediction tool for railway ground vibration.

In the second work stream**, auralisation and Virtual Reality (VR)** software tools are developed based on a physics-based model to synthesise railway noise in high quality. A novel audio-visual VR tool enables demonstrations of railway noise mitigation measures. The auralisation model is linked to 3D visualisation software to realise immersive audio-visual VR experiences of railway scenes extending the applicability of the simulation beyond the state of the art.

2. Ground vibration

2.1. Concept and framework

In common with FTA guideline [Quagliata et al., 2018] and international standards [ISO 14837-1:2005] dealing with the prediction of railway induced ground vibration, the proposed SILVARSTAR modelling approach is based on the assumption that the vibration in each one-third octave frequency band can be expressed as the product of source, propagation and receiver terms. The vibration level in a building $A(f)$ at frequency f is written as the product of a source term $S(f)$ for the vehicle-track interaction, a propagation term $P(f)$ for the soil and a receiver term $R(f)$ for the building:

$$A(f) = S(f)\ P(f)\ R(f) \qquad (1)$$

or equivalent as a sum of terms in decibels. Each of these frequency-dependent terms can be represented by numerical predictions or by experimental data. One advantage is that a hybrid approach is possible combining experimental data with numerical predictions, providing increased flexibility and applicability. The SILVARSTAR prediction tool [Degrande et al., 2021] provides three calculation schemes (fully numerical using a modular approach, fully empirical, and hybrid) which are briefly described below. Note that equation (1) omits Doppler effects due to moving sources. However, it is expected to provide reasonable results when the train speed is relatively low compared with the wave velocities in the soil, while maintaining low calculation times.

- **Fully numerical prediction scheme using a modular approach**

An analytical train-track interaction model is integrated in the prediction tool in order to compute the wheel-rail contact forces as well as the force transmitted to the ground. The vehicle is represented by a simple multi-body model including the car body, the bogie frame and the wheelsets, separated by primary and secondary suspensions (Fig. 1a). Ballasted (Fig. 1b) and slab track models are included in the prediction tool. The resilient layers are represented by spring-damper systems with a constant loss factor: rail pads, under-sleeper pads, ballast, and slab mat. The rails and the slab are represented by Euler-Bernoulli beams. The sleepers are represented as a continuous layer of masses.

The track is coupled to the ground over a finite width (Fig. 1c). The ground is represented by impedances in the frequency-wavenumber domain that are pre-computed for a range of soil parameters using the MOTIV [Ntotsios et al., 2019] and TRAFFIC models [Lombaert et al., 2012]. These cover homogeneous and layered soils.

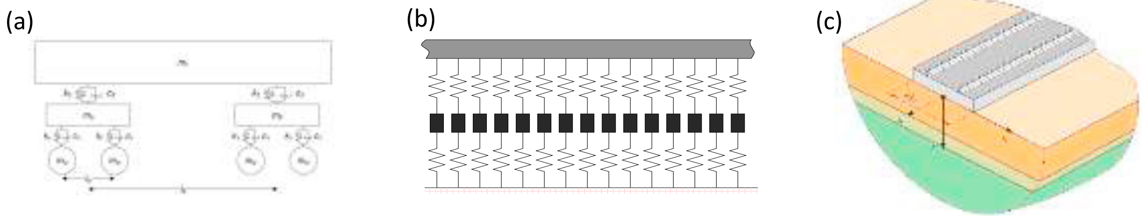

Fig. 1. (a) Vehicle model; (b) ballasted track model; (c) example of soil model.

The train-track interaction problem is solved in the frequency domain, considering the unevenness excitation, the vehicle and track compliances. The force transmitted to the subgrade is then estimated in the wavenumber domain and the free field ground response is calculated using pre-computed soil transfer functions, obtained using the same models. The response due to a train passage is then obtained by summation of the contribution of each axle. The transfer to the building is treated in the same way as in the empirical prediction scheme presented below.

- **Fully empirical prediction scheme**

The empirical procedure is based on FTA guideline [Quagliata et al., 2018] which conforms to the ISO 14837-1:2005 framework. The detailed vibration assessment predicts the vibration velocity level $L_v(x_b)$ at a receiver x_b in the building (see Fig. 2). It is expressed in decibels in one-third octave bands, resulting in a summation of the source, propagation, and receiver terms, rather than a product as per equation (1):

$$L_v(x_b) = L_F(X, x_1) + TM_L(X, x_1) + C_b(x_1, x_b) \tag{2}$$

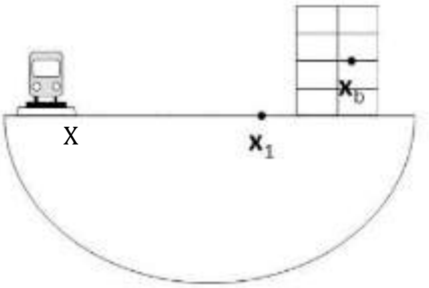

Fig. 2 Source, soil and receiver points

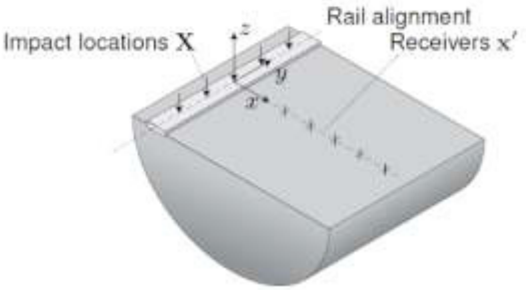

Fig. 3 Excitation and receiver point locations for TM_L measurements

The first term in equation (2), $L_F(X, x_1)$, is the equivalent force density level. The second term $TM_L(X, x_1)$ is the line source transfer mobility and is a measure for the vibration energy that is transmitted through the soil relative to the force density of the source. This transfer mobility can be derived from the superposition of measured point source transfer mobility levels $TM_P(X,\ x_1)$ for a series of n equidistant source points X_k with spacing h (see Fig. 3):

$$TM_L(X, x_1) \ = \ 10\, log_{10}\left[\ h\ \sum_{k=1}^{n}\ 10^{\frac{TM_P(X_k, x_1)}{10}}\right] \tag{3}$$

The third term $C_b(x_1, x_b)$ is the receiver term or the building's coupling loss; it is computed as a combination of adjustment factors. These describe the transmission of vibration from free field to the building foundation, from the foundation to the various floors and the radiation of sound into the rooms from the floor vibration. Rearranging equation (2) (with the omission of the building's coupling loss term) gives a convenient method of indirectly determining the equivalent force density $\mathrm{L_F}(\mathrm{X}, \mathrm{x_1})$ from the measured vibration level during train pass-by and line source transfer mobility measurements:

$$L_F(X, x_1) = L_v(x_1) - TM_L(X, x_1) \tag{4}$$

- **Hybrid prediction schemes**

Hybrid prediction schemes are also included in which numerical and empirical data are combined, following Equation (2), providing more flexibility than purely experimental or numerical models. Two options are available: a numerical source model combined with an empirical propagation term and an empirical source model combined with a numerical propagation term. More details on hybrid approaches can be found in references. More details on hybrid approaches can be found in references [Verbraken, 2013] and [Nélain et al., 2019].

2.2. Validation of the prototype vibration prediction tool

In a first step, a numerical verification is carried out by comparing the results obtained with the SILVARSTAR prototype vibration prediction tool to a state-of-the-art software for ground vibration prediction (TRAFFIC model). The frequency-based approach used in the vibration prediction tool relies on various modelling assumptions. For the results presented in Fig. 4, identical modelling assumptions are considered for both models in order to make results comparable:

- The track compliance is computed for a stationary load.
- The axle loads are applied at a fixed positions instead of moving along the track with the train displacement. This corresponds to a low speed approximation for which the Doppler effect is neglected.
- The axle loads are assumed to be incoherent.

The influence of these assumptions is detailed in [Thompson et al., 2022b]. The comparison is presented in terms of line source transfer mobility, vibration level and force density for a ballasted track supported by soft, medium and stiff soil (Fig. 4). The results computed with the prototype tool and TRAFFIC are in very good agreement.

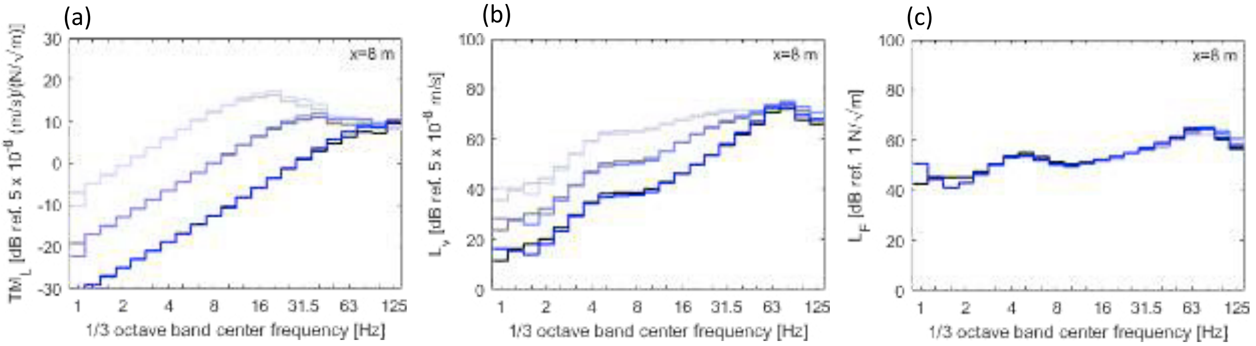

Fig. 4. IC train running at 150 km/h on a ballasted track supported by soft, medium and stiff soil (light to dark lines). Receiver located at 8 m from the track. Results are computed with TRAFFIC (gray lines) and the prototype vibration prediction tool (blue lines)
(a) Line source transfer mobility; (b) ground vibration level; (c) Force density L_F

In a second step, the results from an extensive measurement campaign at a site in Lincent (Belgium) are used for the validation exercise. The case history presented here consists of a high speed line with a ballasted track on monobloc sleepers and IC-A trains operating at about 200 km/h. Fig. 5 plots the ground vibration level spectra, measured and computed from the SILVARSTAR numerical model. The difference between numerical and experimental results below 25 Hz is due to the stationary train assumption (ignoring quasi-static components). The agreement between measurements and simulations is in the usual range (+/- 6 dB per one-third octave band). However, the global vibration level at different distance from the track is correctly estimated, with difference up to 2 dB (Table 1). More details on validation are given in [Degrande et al., 2022].

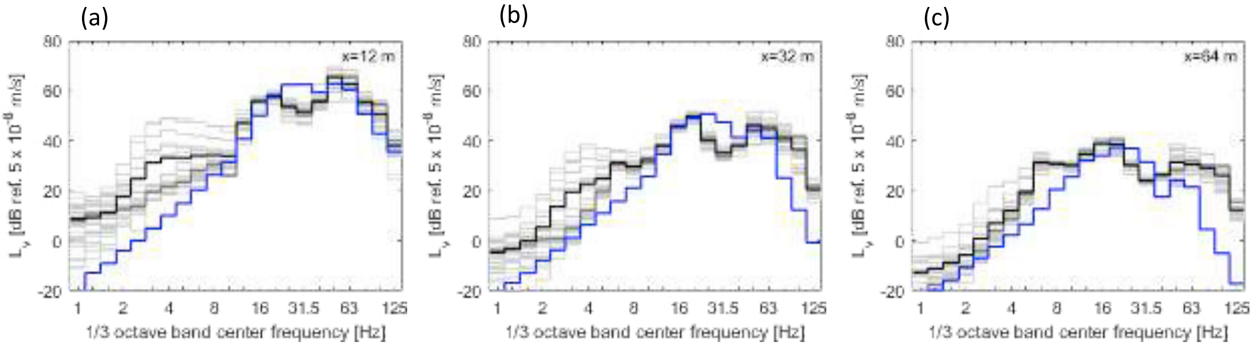

Fig. 5. Vibration level for receivers at (a) 12 m, (b) 32 m, (c) 64 m from the track at Lincent. 26 passages of IC-A trains between 178 and 218 km/h measured (grey lines) and average vibration level (black line). Vibration level predicted with the prototype tool (blue line).

Table 1. Measured and predicted global vibration level Lv [dB ref. 5×10^{-8} m/s] at 12 m, 32 m, and 64 m from the track at Lincent during the passage of an IC-A train running at 198 km/h.

Receiver location x	12 m	32 m	64 m
Measured	68.9	54.2	44.3
Predicted with the prototype tool	69.3	55.3	42.3

2.3. Database

To ensure that the prediction tool is capable of rapid large-scale calculations and is accessible to a wide range of users, it is built around an extensive database of both measured and pre-computed data [Thompson et al., 2022a]. The database includes sets of data describing vehicles, tracks, unevenness, and soil and building transfer functions. In each case the user can augment the database with their own data.

Parameters describing trains are selected to correspond to various generic train types (high-speed train, intercity, metro, tram with resilient or monobloc wheels, freight). Most of the trains are based on the same nominal vehicle model. Similarly, parameters describing tracks are provided that correspond to mainline and urban tracks, both ballasted and slab tracks. A range of unevenness spectra are provided and are selected to correspond to categories within the existing CNOSSOS-EU noise assessment methodology, although the wavelength range for ground vibration is different from airborne noise. For the soil, numerical data are provided in the form of pre-computed impedance and transfer functions. Different soil conditions are considered, distinguishing between homogeneous soils (ranging from “soft” to “stiff”) and layered soils (seven cases typical for different European countries). Experimental data from well documented cases are also included in the database. The receiver (the building) is described by sets of building correction factors for different types of building (house, small building, tall building). These factors, obtained from the RIVAS project [Villot et al., 2012], describe the transmission of vibration from free field to the building foundation, from the foundation to the various floors and the radiation of sound into the rooms from the floor vibration.

2.4. Software development

The ground vibration prediction tool is now fully integrated with the existing noise mapping software IMMI developed by Wölfel. This results in a unique software platform that will allow engineers to perform noise and vibration environmental impact studies within the same integrated software environment. The prediction tool enables the assessment of vibration levels for both large-scale studies and more detailed investigations to support the assessment of noise and vibration impacts of new and upgraded railway lines.

The user will perform vibration analysis following a step-wise methodology. First, the geometry of the line will be imported in the main interface, along with the geometrical definition of the buildings. The user starts with a 2D map including the railway line and buildings (Fig. 6a). The line is subsequently divided into sections; for each section, the user selects source, propagation and receiver terms from predefined lists that are included in the database or available as imported data. In the next step, the prediction tool computes the vibration level on the ground adjacent to the buildings and the vibration and noise levels inside the buildings for each section. The compatibility of output with respect to external GIS software will be ensured, so that the results can easily be exported to GIS formatted data and visualized in the IMMI software (2D and 3D maps, Fig. 6b).

For preliminary vibration assessment, the user will benefit from the integrated databases (train, track, soil and building) to perform a fast assessment of the affected corridor. For detailed vibration assessment, the user will be able to import external results to assess noise and vibration level with higher precision.

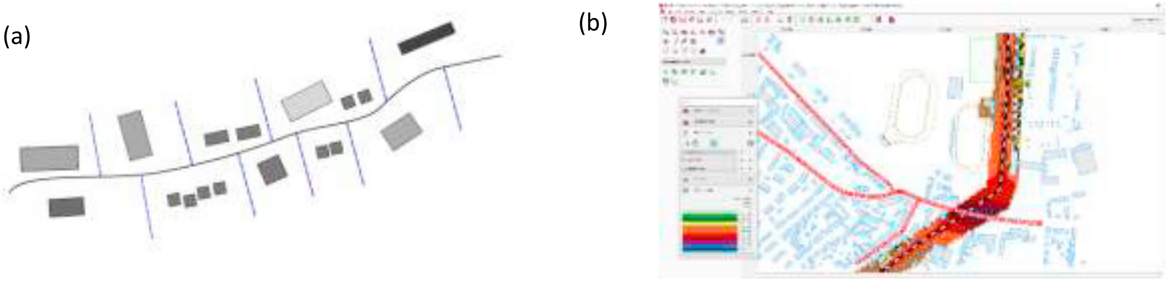

Fig. 6. (a) Definition of sections along a railway line; (b) Visualisation on 2D maps.

3. Auralisation and visualisation

3.1. Concept of the VR demonstrator

Auralisation combined with visualisation allows users to audibly experience situations that do not necessarily exist (yet). The objective of the VR demonstrator [Pieren et al, 2021 and Pieren et al, 2022] is to create an audio-visual environment that can be used for the evaluation of different scenarios of railway noise. The tool allows the user to choose between different: environments (e.g., rural, urban), mitigation measures (e.g. barriers, rail & wheel dampers), type of trains (e.g. regional, intercity), track types (e.g. ballasted, slab) and observer locations. Based on the input parameters, a set of audio-visual simulations that can be compared with each other is generated.

3.2. Railway noise auralisation

The auralisation method follows a source-path-receiver concept, according to a physic-based approach. The proposed model includes contributions from rolling noise, impact noise, traction, auxiliary systems, and aerodynamic noise. It allows pass-by parameters such as speed, roughness, wheel flats and track design to be modified. Sound sources are modelled by a collection of distinct point or line sources located in the virtual environment (Fig. 7a). Based on source specifications, source signals are generated by parametric sound synthesis. Based on the TWINS model, different structural transfer paths for rolling noise are considered in order to integrate mitigation measures such as wheel and rail dampers. Propagation effects from the source location to the observer point are simulated by processing the source signals with propagation filters. Shielding by a conventional noise barriers or low-height barriers is simulated using analytical edge diffraction models. Ground reflection is explicitly considered to account for the effect of a possible track embankment, different receiver heights or changes in ground cover. To provide directional information to the listener, the reproduction renderer considers the directions of the incident sounds at the observer point and the observer orientation to calculate the reproduction channel signals (Fig. 7b). At this processing stage recordings of ambient sounds are integrated.

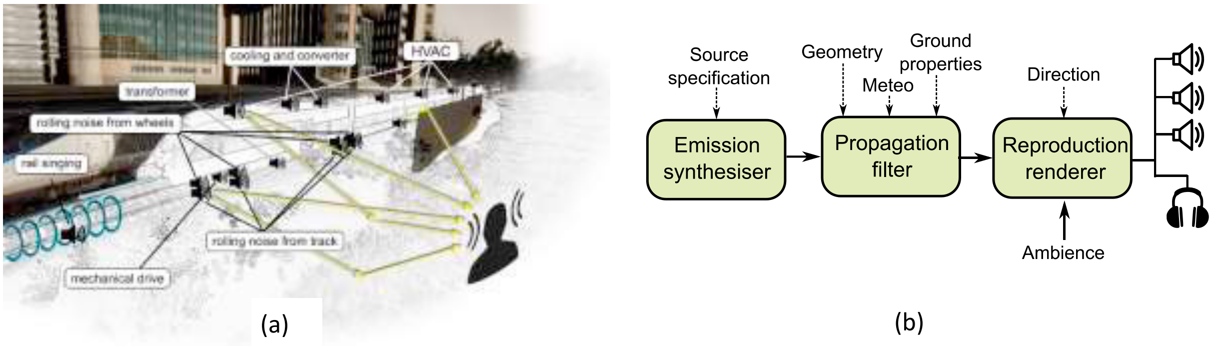

Fig. 7 (a) Rail vehicle pass-by noise auralisation concept using a collection of static and moving virtual sound sources; (b) Flow diagram of the physics-based train pass-by auralisation process.

3.3. Virtual reality demonstrator

Audio-visual reproduction is achieved via a Head Mounted Display (HMD) and calibrated headphones (Fig. 8a). To attain high immersion and plausibility of the VR experience, the sounds are binaurally rendered allowing the user to localise sound sources in the virtual space. A first set of scenarios and noise mitigation measures has been implemented in the VR prototype. The user can dive in a scenario, freely rotate their head and dynamically switch between different variants (e.g., with or without noise barriers, Fig. 8b).

Fig. 8 (a) VR station with a user wearing a HMD and headphones; (b) Rural VR environment with an approaching regional train and virtual buttons for scenario switching (scenario with or without barriers)

4. Conclusion

The new hybrid prediction model for railway ground vibration allows for either numerical or empirical calculations for each of the source, the propagation and the receiver elements. It relies on a database of both measured and pre-computed data to allow rapid calculations to be performed. In the following project phase, the prototype version will be validated against measurements and computations and will be integrated in an industrial noise mapping software program (IMMI). This will allow engineers to perform noise and vibration environmental impact studies on a large scale within the same integrated software environment.

The novel auralisation and VR tools enable perception-based virtual testing of noise mitigation technologies and an effective demonstration of different noise scenarios, including noise mitigation measures and vehicle design variants. In the current project phase, refinements are made to the signal synthesis and propagation filtering, and the catalogue of scenarios and noise mitigation measures will be expanded. This will support decision-making and facilitate communication with stakeholders through VR prior to project delivery. The new auralisation and VR software tools will be released as fully functional freeware applications.

Acknowledgements

The work presented in this paper has received funding from the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation programme (grant agreement no. 101015442). The contents of this publication only reflect the authors' views; the Joint Undertaking is not responsible for any use that may be made of the information contained in the paper.

References

Degrande, G., Lombaert, G., Ntotsios, E., Thompson, D., Nélain, B., Bouvet, P., Grabau, S., Blaul, J., Nuber, A., 2021. State-of-the-art and concept of the vibration prediction tool. SILVARSTAR Deliverable D1.1 (https://silvarstar.eu/).

Degrande, G., *et al.*, 2022, Validation of the prototype vibration prediction tool against documented cases. SILVARSTAR Deliverable D1.3 (https://silvarstar.eu/).

International Organization for Standardization. ISO 14837-1:2005 Mechanical vibration - Ground-borne noise and vibration arising from rail systems - Part 1: General guidance, 2005.

Lombaert G., François S., Degrande. G., 2012. TRAFFIC Matlab toolbox for traffic induced vibrations. Report BWM-2012-10, Department of Civil Engineering, KU Leuven. User's Guide Traffic 5.2.

Nélain, B. *et al.*, 2019. Towards hybrid models for the prediction of railway induced vibration: numerical verification of two methodologies. Proceedings of IWRN13, Ghent, Belgium. https://doi.org/10.1007/978-3-030-70289-2_46

Ntotsios, E., Thompson, D., Hussein, M.F.M., 2019. A comparison of ground vibration due to ballasted and slab tracks. Transportation Geotechnics 21, 100256, 2019. https://doi.org/10.1016/j.trgeo.2019.100256

Pieren, R., Georgiou, F., Thompson, D., Heutschi, K., Squicciarini, G., Rissmann, M., Bouvet, P., 2021. Methodology for auralisation and virtual reality of railway noise. SILVARSTAR Deliverable D4.1, November 2021 (https://silvarstar.eu/).

Pieren, R. et al., 2022. Auralisation of combined mitigation measures in railway pass-by noise. Proceedings of Internoise 2022, Glasgow.

Quagliata, A., Ahearn, M., Boeker, E., Roof, C., Meister, L., Singleton H., 2018. Transit Noise and Vibration Impact Assessment Manual. FTA 0123, U.S. Department of Transportation, Federal Transit Administration, John A. Volpe National Transportation Systems Center. (https://www.transit.dot.gov).

Thompson, D., *et al*., 2022a. Database for vibration emission, ground transmission and building transfer functions. SILVARSTAR Deliverable D2.1, January 2022 (https://silvarstar.eu/).

Thompson, D., *et al*., 2022b. The influence of model assumptions in a hybrid prediction tool for railway induced vibration. Proceedings of Internoise 2022, Glasgow.

Verbraken, H., 2013. Prediction of railway induced vibration by means of numerical, empirical, and hybrid methods. PhD thesis, Department of Civil Engineering, KU Leuven.

Villot, M., Guigou, C., Jean P., Picard, N., 2012. Definition of appropriate procedures to predict exposure in buildings and estimate annoyance, RIVAS project (SCP0-GA-2010-265754), Deliverable D1.6, June 2012.