Université de Mons
**Faculté Polytechnique – Service de Mécanique Rationnelle, Dynamique et Vibrations**
31, Bld Dolez - B-7000 MONS (Belgique)
065/37 42 15 – georges.kouroussis@umons.ac.be


S. Ouakka, O. Verlinden, G. Kouroussis, Mitigation measures dedicated to railway-induced ground vibration: an analysis of recent advances, *Proceedings of the 27th International Congress on Sound and Vibration*, virtual conference, July 11–15, 2021.

27th International Congress on Sound and Vibration
The annual congress of the International Institute of Acoustics and Vibration (IIAV)
11-16 July, 2021
ICSV27
**Annual Congress of the International Institute of Acoustics and Vibration (IIAV)**

# MITIGATION MEASURES DEDICATED TO RAILWAY-INDUCED GROUND VIBRATION: AN ANALYSIS OF RECENT ADVANCES

Slimane Ouakka, Olivier Verlinden, Georges Kouroussis
*Department of Theoretical Mechanics, Dynamics and Vibrations, Faculty of Engineering, University of Mons, Mons, Belgium*
*email: slimane.ouakka@umons.ac.be*

During the last decades, rail traffic has been subjected to considerable attention and criticism regarding vibrations. Nowadays it is becoming increasingly common for railway networks to be built and developed in urban areas, close to buildings, and the issue of railway-inducted ground vibration in these urban areas is of significant concern to residents. Proposing mitigation solutions need a thorough investigation of the source of vibrations, as well as the path of vibration propagation through the soil and the associated amplification. This paper provides a review of the various mitigation measures recently proposed by railway specialist. The main focus of the review is on meth-ods for developing anti-vibration solutions and analyses for characterizing the vibration level re-duction. An overview of the vibration generation and railway-induced ground vibration is also presented.

Keywords: mitigation systems, railway, ground vibration.

## 1. Introduction

Railway transportation plays a central role in the contemporary society, and their importance is expected to increase in the coming years since is among the most sustainable means of transport that can be a feasible alternative to the oil-based transportations. The expansion and development of railway lines lead the surrounding area to be affected by the effects of the train passage, in the form of induced ground-borne vibration and/or ground-borne noise. These effects have been to a certain extent a limitation for the development of railways, especially in urban areas where significant levels of vibration to which residents in proximity to the lines are subjected.

Ground-borne vibration and noise have been both a subject of concern in public opinion due to the caused annoyance [1], that influence the daily life of the exposed people (e.g. sleep, communication etc.). Furthermore, the prospected amplification in the European and the global railway grid in order to meet the needs in the transportation of freight and goods within the low carbon targets will certainly convey to an increase in the number of trains which in turn will lead to an enhancement in the annoyance [2]. Besides, recent study and investigation have highlighted in addition to the annoyance, some permanent effects on the health of the exposed people [3-4]. To better understand the ground-borne effects, several types of research and investigations have been conducted in the last decade. The International Union of Railways (UIC) in 2017 gave a general overview of the state of the art in induced vibration [5]. Whereas, other research has focusing on their source [6-7], and the consequences on the nearby structures [8-9].

Due to the nature of the problem, as can be easily understood in the aforementioned research, the use of numerical simulation (virtual prototyping) is necessary in order to reproduce the railway environment, which would otherwise require very expensive laboratory tests. For example, the model developed by Kouroussis et al. [10,11] represents a promising way to consider the whole vehicle/track/soil/receiver system by working in two steps to separate each subsystem and to easily each contribution (Figure 1).

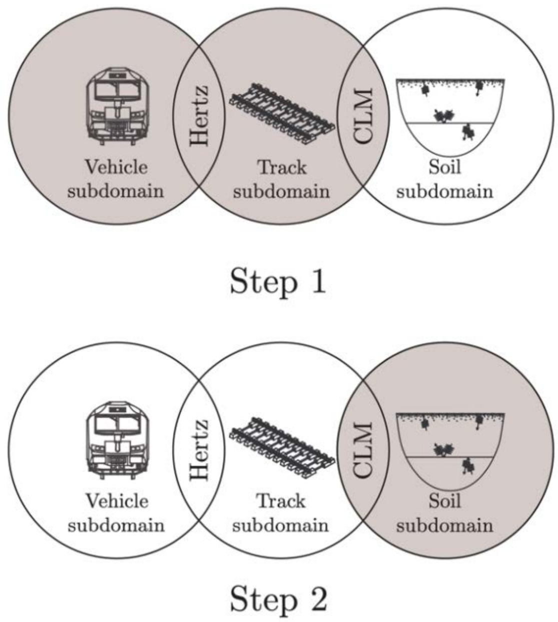


Figure 1: Two-step approach of the model considered in [10,11].

Afterwards, it is important to develop strategies on how to reduce ground vibration effects. Mitigation systems, of which this paper gives a review providing the recent advancements, are different and can be applied in all the interesting parts (i.e. vehicle, track and propagation path). Some studies in how to mitigate the effects of the railway passage have been conducted in the last years [8,12]; at the same time, due to the complexity of the problem, there are many other ways for improvement as will be discussed in the following sections.

## 2. Ground-borne vibrations and noise

In this section, the characteristics and the effects of vibrations coming from rail traffic will be presented objectively, since how they are treated might change from country to country based on the local law. Different standards and guidelines are available in the literature to define adequate procedures and assessments.

Generally, vibrations are generated in surface and underground railway from the contact between the train wheel and the track, then they travel the ground and transfer to surrounding buildings, where they can be felt by the humans in the form of vibrations (ground-borne vibrations) or sound (ground-borne noise) as can be seen in Figure 2. At the same time, in addition to their effects on humans, these can also be relevant for the functioning of sensitive equipment but are far too low to cause structural or cosmetic damage to buildings [5].

The two effects as mentioned are both generated by the interaction between train, track and subsoil. The difference between the two is that the ground-borne vibration is the vibration of the structure (frequency range between 1 and 100 Hz) and the ground-borne noise is the sound generated inside the building by its oscillation caused by the ground vibration (frequency range between 20 and 250 Hz), hence it is straightforward to understand that the phenomena occur simultaneously. However, these two effects are not to be confused with Air-borne noise where the sounds travel through the air, and this will not be discussed in this paper.

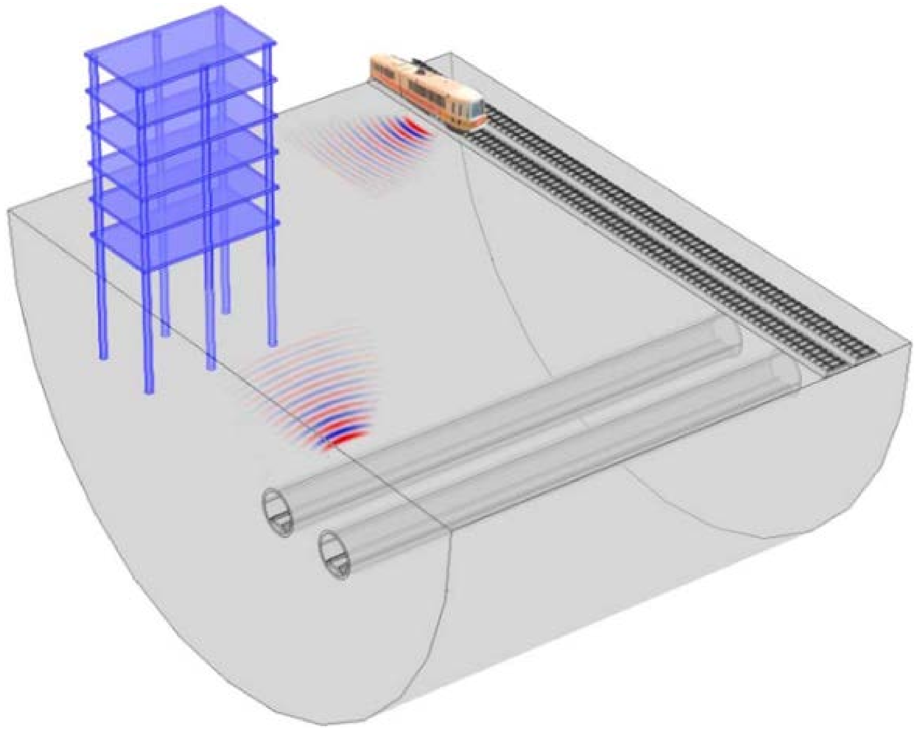

Figure 2: Surface and underground ground-borne propagation [13].

## 2.1 Assessment of the vibration

The vibration coming from the rail traffic as anticipated is treated according to the country and standards considered. A major standardisation effort is being made, to produce one comprehensive ISO standard, namely ISO 14837, which in the end will include 35 parts defining different elements.

Generally, the assessment is carried out in all three directions and the highest value or the average one are used as referment. At the same time for the assessment, it is important also to take into account if are freight or passenger trains. Passenger trains, in turn, can be subdivided into classical trains or modern high-speed trains that can have a shift above 10 Hz when the speed exceeds 300 km/h as can be noticed in Table 1.

Generally, freight rail cause more frequent and greater magnitude vibration than the passenger ones, because of different reasons such as single suspension system, longer, less maintenance and they run during the night when people's sensitivity increases.

Table 1: Frequency of typical vibration for each of the generating mechanisms, depending on train speed [5].

| Vehicle Speed | 40 km/h | 80 km/h | 160 km/h |
|---|---|---|---|
| Moving load (axle spacing approx. 1.8 m) | 3 Hz | 5 Hz | 11 Hz |
| Track unevenness | ≥ 1 Hz ≤ 100 Hz | ≥ 2 Hz ≤ 200 Hz | ≥ 4 Hz ≤ 400 Hz |
| Rail corrugation | Approx. 500 Hz | Approx. 1000 Hz | Approx. 2000 Hz |
| Wheel unevenness | ≥ 4 Hz | ≥ 8 Hz | ≥ 15 Hz |
| Wheel polygonization (wavelength of 0.1 m) | Approx. 100 Hz | Approx. 200 Hz | Approx. 400 Hz |
| Inter bogie spacing (assuming approx. 8 m) | Approx. 1 Hz | Approx. 3 Hz | Approx. 5 Hz |
| Sleeper spacing (0.6 m) | Multitudes of 16 Hz | Multitudes of 32 Hz | Multitudes of 64 Hz |

## 2.2 Waves propagation

Vibration generated in the wheel-track contact propagates through the soil from the track to the adjacent constructions, in the form of waves. The waves that can travel in the ground are of three types: Rayleigh waves, compression waves (P-waves) and shear waves (S-waves). Compression waves are the waves with the highest propagation velocity but with the lowest energy transmitted. Rayleigh waves are the most important for the excitation of buildings, these are also known as surface waves because they occur at the surface of the soil, at the lowest velocity.

## 2.3 Impact of vibration

The impact of the ground-borne vibration may have different effects depending on the intensity of the signal. Some vibrations are classified as feelable vibrations, those are below the threshold of perception, however, this is not the case of ground-borne noise that is always present and noticeable.

The ground-borne effects are generally of two types:

- damage to buildings,
- annoyance to humans.

Ruin to buildings due to vibrations coming from the traffic rail are very rare and in case of occurrence are mostly cosmetic damages, these type of effects are taken into account for example by British Standard BS 7385-2 Code.

On the contrary, more important is the disturbance caused by railway passage to humans. According to the ISO 2632, the threshold of perception expressed in RMS values lies at a vibration strength of approximately 1 mm/s at 1 Hz and 0.1 mm/s at 10 Hz and higher; and ground-borne vibration level caused by the rail traffic ranges between 10 to 80 Hz. However, it is important to notice that differences between individuals may occur depending on their sensitivity. In ISO 2631-1:1997, the absolute threshold of perception of weighted vertical vibration is stated to be around 0.015 $m/s^2$. To the vibration is to add the noise coming from the movement that the vibration itself is causing, the so-called ground-borne noise, for which the acceptable level can be derived from legal limits for environmental noise, which are 35 to 40 dB(A) during the day and 25 to 30 dB(A) during night time. Recently, some studies have state also some permanent effects in human health caused by these vibrations in addition to the only annoyance [3].

# 3. Mitigation systems

To arrest and/or reduce the negative effect of ground-borne noise and vibration different methods have been tested in the past years. This improvement can be applied just to new infrastructure but others also in exiting, the different methodologies are to be compared both with their feasibility and the costs to be able to gustily them.

The mitigation systems can be applied at the source in all three parts of the railway system, on the vehicle, on the track and the transmission path (soil). It is also possible to improve directly at the receivers (i.e. buildings), but these are out of the objective of the paper. Many of those have been tested in laboratories using scale models, but to the nature of the problem computer simulation after calibration are the right solution. Their effectiveness is expressed in [dB] as insertion loss, i.e. the difference in vibration, between the original configuration and the application of the measure.

For simplicity the parts of the railway have been subdivided into just the mean three subsystems, however depending on the different techniques used these components change from one to another. However, it is of significant importance, in order to evaluate the improvement, to separate between new lines and retrofitting existing lines, and the separation be among surface rails and underground ones. Given the purpose of these measures, which have to deviate and/or damp the propagation of vibration waves, recent material such as Meta-material could be an important means in the achievement and improvement of these measures. Meta-materials are artificial and/or composition of natural materials engineered in order to gain proprieties that are not available in nature.

## 3.1 Improvement in the vehicle

Different are the measures that can be applied to the means of transportation are of different kinds and importance depending on their technologies. These measures have to deal with the reduction of the effects of the rail passage but at the same time have to maintain the train passengers comfort at the high standards.

The importance of improvement of the vehicle is crucial for the ground-borne vibration since as have been stated already the production of this effect is between the track and wheel contact, the latter is a component of the train.

Indeed RIVAS report D5.5 [14] considers the main mitigation measures to and control of the mitigation in the following points:

- Improving wheel roundness
- Reduction of the unsprung mass

The estimation of these measures is difficult to assess in a general way, and a combination of them can help to reach a reduction up to 10 dB [5].

When the main contributor in the vehicle is identified, it is possible to design the vehicle so as the dynamic forces acting on the track is reduced. Figure 4 shows the positive effect of changing the stiffness of resilient wheel equipping trams to reduce the transmitted ground vibrations. This also demonstrates the real interest of a compound vehicle/track/soil model in the design of this kind of wheel [15]. Recently, the possibility to use dynamics vibration absorber was proposed in [8] by quantifying numerically the vibration attenuation when the absorber is placed in the vehicle instead of the track.

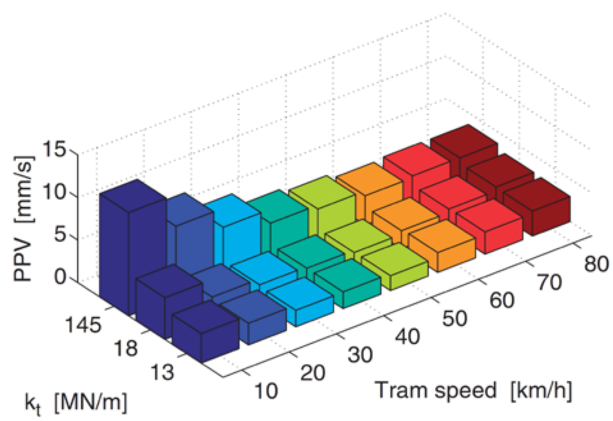


Figure 3: Effect of changing wheel resilient material stiffness on ground vibration level. Comparison of vibration indicators as a function of the wheel stiffness in the case of the T2000 tram circulating in the Brussels Region [15].

## 3.2 Improvement in the track

In the track, it is more relevant to the kind of technologies of the track itself, since we have different typologies in the actual world railway infrastructure system. Following the possible improvements will be explained while discussing also the possible problem and the type of track where these can occur [5].

Irregularity in the track and the ballast can be an important source of vibration. Indeed, a good track alignment can provide a 10 dB reduction for the ground-borne noise for speeds at 320 km/h, therefore, maintenance plays an important role in the vibration mitigation.

Rail fasteners are used mostly, even if several improvements have been made over the years are the one presented a long time ago, named Resilient Rail Fasteners. However, with the recent application of new designs where the rail is supported by resilient blocks such as in the Thameslink project in London it has been possible to have a reduction of 13 dB]in ground-borne noise.

Embedded rail systems are also an alternative, generally, here the rail is embedded in a concrete slab with a wedge on either side to keep the rail in place, this technology might be effective for ground-borne noise reduction, around 2.5 dB.

Other important improvements can be done just under the track, such as under the sleepers by inserting pads with an expected reduction of 8 -20 dB; or ballast mats that can be applied to both the surface and underground systems and here the reduction ranges from 3 to 15 dB.

It is important to have in mind that track mitigation measures are often characterised by a transmissibility curve (Fig. 5) as a function of the frequency. Three zones can be distinguished: zone 1 when the transmissibility is close to 1 (no effect of the mitigation measure); zone 2 when the transmissibility is greater than 1 (negative effect of the mitigation measure) and zone 3 when the transmissibility is lower than 1 (positive effect of the mitigation measure). Notice that for zone 3, the smaller the damping ratio, the greater the vibration attenuation. The choice of support stiffness is, however, limited by the allowable vertical static displacements under the axle loads of the train and some excitation frequency (covering zone 2) may be amplified. Such effects were generally observed for floating-slab systems [16,17].

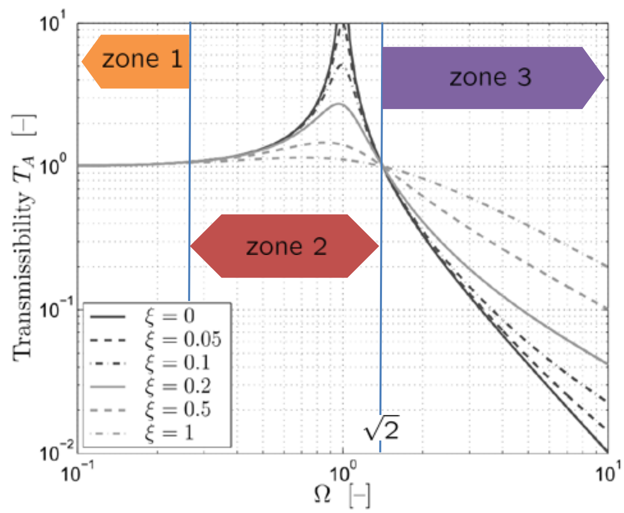


Figure 4: The force transmissibility of a viscously damped single degree of freedom system as a function of the frequency ratio Ω and the damping ratio ξ.

### 3.3 Improvement in the ground

Whereas measures in the transmission path are generally applied in the surface train, where surface waves are the main contributor for the ground-borne effects, because for the P- and S-waves and the parts of the buildings that are below the ground level these measures would not be worthwhile. Besides, for the measures in the transmission path, FEM plays an important role in their prediction, however with calibration using field measurements.

The aim of the measures insert between the track and the adjacent building is to act as a barrier for the waves. The barrier is generally an introduction of material in the soil, that thanks to its characteristics such as density and/or stiffness can deviate the waves from the surrounding soil. The materials of which are composed of the available barriers are the following:

- an elastic mat;
- air, in case of a trench;
- water, in case of a ditch;
- concrete or sheet piling, in case of a wave impending block.

For example, subgrade configuration affects the transmission path: embankment with specific material stiffness can play the role of a waveguide by trapping energy within it (Fig. 6). Other studies demonstrated similar results [19,20]. Similarly, developing guided waves travelling in soil medium represents a promising innovative antivibration method (e.g. phononic crystal barriers [21]).

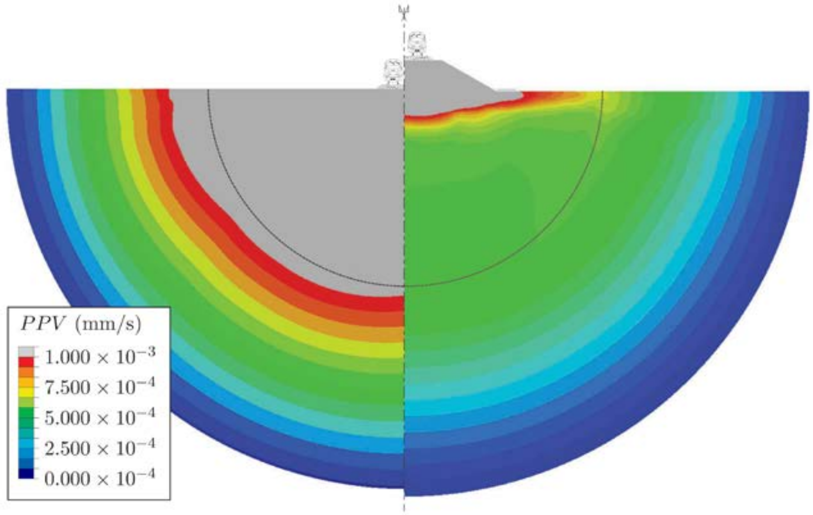


Figure 5: Numerical visualization (longitudinal planar view) of the ground peak particle velocity generated by the passage of a Thalys high-speed train on track at-grade (left view) and the embankment (right view) [18].

## 4. Discussion and conclusion

This paper analysed the different mitigation solutions in order to contrast the railway-inducted ground vibration; that as discussed in the paper is becoming increasingly common and important, considering the negative effects on the population and the increment expected for the railway infrastructure. The applicable measures in the railway infrastructure to mitigate the ground-borne noise and vibration have been presented, showing that improvements can be gained by applying them to each of the three parts (i.e. vehicle, track and transmission path). With proper analysis, the three types of mitigation measure offer a considerable reduction potential in induced ground vibration. The key challenge in predictive modelling is to select the appropriate approach, possible by finding a direct correlation between the excitation forces and the ground vibration motion.

## Acknowledgement

This work was financially supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No INSPIRE-813424.

## REFERENCES

1 Maclachlan, L., Ögren, M., Kempen, E., Alkhateeb, L. H., Persson, W. Annoyance in Response to Vibrations from Railways, *International Journal of Environmental Research and Public Health*, **15** (9), 1887, (2018).

2 Gidlöf-Gunnarsson, A., Ögren, M., Jerson, T., Öhrström, E. Railway noise annoyance and the importance of number of trains, ground vibration, and building situational factors, *Noise & Health a Bimonthly Inter-disciplinary International Journal*, **14** (59), 190-201, (2012).

3 Croy, I., Smith, M. G., Waye, K. P. Effects of train noise and vibration on human heart rate during sleep: an experimental study, *BMJ Open*, (2013).

4 Maclachlan, L., Waye, K. P., Pedersen, E. Exploring Perception of Vibrations from Rail: An Interview Study, *International Journal of Environmental Research and Public Health,* **14** (11), 1302, (2017).

5 Satis, P.V. (November 2017) Railway Induced Vibration - State of the Art Report. [Online.] available: https://uic.org/IMG/pdf/vibration_report_v2.pdf.

6 Kouroussis, G., Connolly, D.P., Verlinden, O. Railway-induced ground vibrations – a review of vehicle effect, *International Journal of Rail Transportation,* **2** (2), 69-110, (2014).

7 Kouroussis, G., Vogiatzis, K. E., Connolly, D. P. A combined numerical/experimental prediction method for urban railway vibration, *Soil Dynamics and Earthquake Engineering*, **97**, 377–386, (2017).

8 Kouroussis, G., Zhu, S., Olivier, B., Ainalis, D., Zhai, W. Urban railway ground vibrations induced by localized defects: using dynamic vibration absorbers as a mitigation solution, *Journal of Zhejiang University – Science A*, **20** (2), 83–97, (2019).

9 Kouroussis, G., Vogiatzis, K. E., Kassomenos, P. The effect of transportation vibration on the urban acoustic environment, *Science of the Total Environment*, **650** (Part 2), 2640, (2019).

10 Kouroussis, G., Verlinden, O., Conti, C. A two-step time simulation of ground vibrations induced by the railway traffic, *Journal of Mechanical Engineering Science*; **226** (2):545–72, (2012).

11 Kouroussis, G., Van Parys, L., Conti, C., Verlinden, O., Using three-dimensional finite element analysis in time domain to model railway-induced ground vibrations, *Advances in Engineering Software*, **70**, 63–76, (2014).

12 Lombaert, G., Degrande, G., François, S., Thompson, D. J. Ground-borne vibration due to railway traffic: A review of excitation mechanisms, prediction methods and mitigation measures, *Noise and Vibration Mitigation for Rail Transportation Systems*, Springer Berlin Heidelberg, 253–287, (2015).

13 Thompson, D. J., Kouroussis, G., Ntotsios, E. Modelling, simulation and evaluation of ground vibration caused by rail vehicles, *Vehicle System Dynamics*, **57** (7), 936–983, (2019).

14 Nielsen, J., Mirza, A., Cervello, S., Huber, P., Müller, R., Nelain, B., Ruest, P. Reducing train-induced ground-borne vibration by vehicle design and maintenance, *International Journal of Rail Transportation*, 2015, 3 (1), 17–39, (2015).

15 Kouroussis, G., Verlinden, O., Conti, C. Efficiency of resilient wheels on the alleviation of railway ground vibrations, *Journal of Rail and Rapid Transit*, **226** (4), 381–396, (2012).

16 Vogiatzis, K., Kouroussis, G. Prediction and efficient control of vibration mitigation using floating slabs: Practical application at Athens metro lines 2 and 3, *International Journal of Rail Transportation*, 3 (4), 215–232, (2015).

17 Zhu, S., Wang, J., Cai, C., Wang, K., Zhai, W., Yang, J., Yan, H. Development of a vibration attenuation track at low frequencies for urban rail transit, *Computer-Aided Civil and Infrastructure Engineering*, **32** (9), 713–726, (2017).

18 Olivier, B., Connolly, D. P., Costa, P. A., Kouroussis, G. The effect of embankment on high speed rail ground vibrations, *International Journal of Rail Transportation*, **4** (4), 229–246, (2016).

19 Connolly, D., Giannopoulos, A., Forde, M. Numerical modelling of ground borne vibrations from high speed rail lines on embankments, *Soil Dynamics and Earthquake Engineering*, **46**, 13–19, (2013).

20 Lyratzakis, A., Tsompanakis, Y., Psarropoulos, P. N. Efficient mitigation of high-speed trains induced vibrations of railway embankments using expanded polystyrene blocks, *Transportation Geotechnics*, **22**, 100312, (2020).

21 Albino, C., Godinho, L., Amado-Mendes, P., Alves-Costa, P., Diad da-Costa, D., Soares, D. 3D FEM analysis of the effect of buried phononic crystal barriers on vibration mitigation, *Engineering Structures*, **196**, 109340, (2019).