

# Environmental Ground-Borne Noise and Vibration from Urban Light Rail Transportation During Construction and Operation

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**Abstract** Environmental vibration and ground-borne noise from light rail transport (LRT) networks consists a major impact on the urban environment. Since experiments are often difficult to obtain and to interpret especially for environmental vibration, designers and researchers generally resource numerical model to assess vibration levels and understand the complex mechanism of generation and propagation of ground vibration. In this paper, some highlights are provided on vehicle/track/soil modeling for railway-induced ground vibration, including the proper definitions of each of these subsystems. The nature of the wheel/rail interaction is also important, especially in urban area, so a case study demonstrates that local unevenness are important sources of vibrations. On the other hand, specialized prediction models and dose-response relationships for airborne rail noise during operation and construction phases of urban light rail transport networks (both underground and surficial) are needed to be evaluated, in order to quantify the impact of the technical characteristics of the noise source, the operation mode with emphasis to speed, the propagation, the implementation of quiet facades, and the number and distribution of high-level

noise events. In the present paper, two distinct case studies are presented in order to emphasize the need and the necessity of using proper tools to predict, access, monitor, and evaluate the environmental impact of LRTs to the urban acoustic environment: (a) the new Brussels Regional Express Network and (b) the new Athens Metro Line 3 extension to Piraeus port in an underground tunnel (length 7.6 km).

**Keywords** Vibration · Ground-borne noise · Airborne noise · Light rail transportation · Subway metro rail system · Tunnel boring machine

## Ground-Borne Noise and Vibration—An Environmental Hazard

It is well known that environmental noise is an unwanted unpleasant sound, loud and disruptive to hearing. Environmental vibration and noise from light rail urban networks (LRT) in particular consists a major impact on the urban environment and the way of life of inhabitants introducing annoyance and degradation of their way of life. LRT networks—both surficial and underground—in urban conditions are considered to be a sustainable mean of transportation, mainly due to the reduction of air pollutant emissions by decreasing the number of cars and heavy vehicles (i.e., busses for passenger transportation, trucks for freight) in the road network and providing a high effective transportation outcome [1]. However, an important adverse effect of their operation is the increased level of vibration and both ground-borne and airborne noise transmitted to buildings in close proximity. Induced vibration to buildings is the result of the direct transmission of ground-borne vibration [2]. There are two ways in

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which LRT traffic can induce vibration in nearby buildings [3]:

1. Ground-borne vibration and noise caused by the dynamic impact forces generated in the wheel/rail interphase due to irregularities of both wheels and tracks that can propagate in the soil and excite the foundation walls of nearby buildings, beneath ground
2. Airborne noise, caused by low frequency emissions that can excite building structural components (e.g., walls) above ground

Therefore, this urban environment degradation factor is the direct consequence of the rail vehicle forces passing from the rotating wheels into the track either for surficial or underground networks, depending on the rail vehicle's weight (static contribution) and the surface irregularities of both the wheel and the top of rail surfaces (dynamic contribution). It is therefore quite important to access the problem both during construction and operation phases of an urban LRT project. Especially regarding construction phase and during hard rock conditions, the use of tunnel boring machine (TBM) in order to minimize the inevitable disturbance to urban land uses, by shortening completion times, induce vibration and ground-borne noise, consists an important source of complaint, especially due to ground-borne noise, raising concerns of damage to structures and potentially adverse effects to vibration sensitive equipment [4].

Experiments are often difficult to obtain and/or to interpret especially for environmental vibration. This is why many researchers often use prediction methods to assess the vibration levels and, in addition, to understand the complex mechanism of generation and propagation of ground vibrations. As suggested by Kouroussis et al. [5], a whole prediction vehicle/track/soil model can be classified on either the vehicle modeling or the soil modeling. By considering that a hierarchy exists in the track models [6], an overall classification is obtained as illustrated in Fig. 1.

The vibration generated at the wheel/rail interface propagate into the track and the soil, and the way of modeling the vehicle allows considering various excitation mechanisms: Moving axle loads, either constant, harmonic, or random, neglect the dynamic interaction between the vehicle and the track and consider only the vehicle's weight as the main contribution of ground vibration. This is a relatively correct hypothesis if the vehicle studied moves on a perfect rail surface without any local defect. This is not the case in urban area where many localized defects occur in the rail and in the wheel surface. Modeling the vehicle as a combination of bodies interconnected between them (lumped mass models or multibody models) more faithfully represent the vehicle behavior and thus define a more realistic approach for the vehicle dynamics [7–9]. Track modeling is more challenging but,

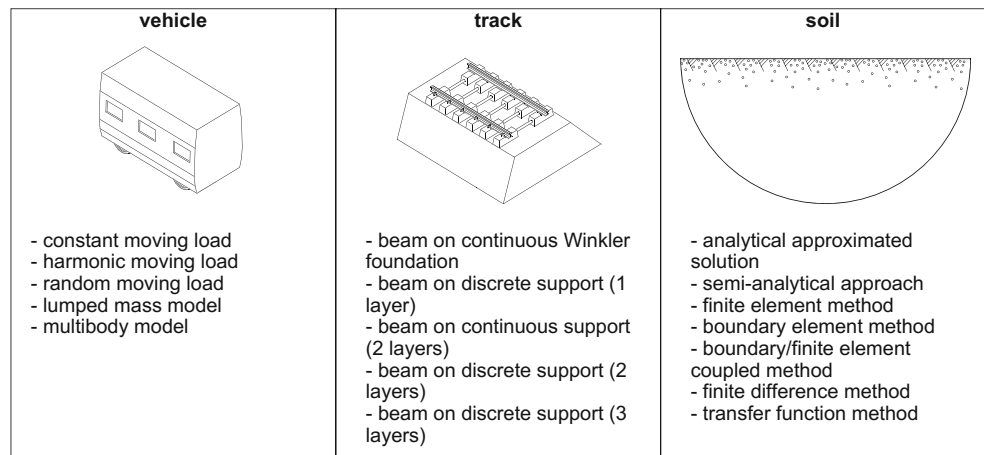
in the case of railways-induced ground vibrations, the definition of a beam lying on a discrete or continuous support remains efficient. Taking into account the discrete nature of the sleepers (instead of a continuous layer) increases the accuracy of the prediction model. The most challenging aspect remains the soil modeling which influence the quality of obtained results: Analytical solution have been proved to be non-efficient for complex modeling of soil (including multiple ground layers, realistic soil composition, coupled foundation, etc.) and the recourse of numerical tools became unavoidable. The finite element method (FEM) and the boundary element method (BEM) are the main numerical approach to model soil with the particularity to be infinite in the three directions. Research works, such as those of Galvin et al. [10], Connolly et al. [11], Frühe and Müller [12], Gardien and Stuit [13], Pyl et al. [14], Lombaert et al. [15], Triepaischajonsak et al. [16], Kouroussis and Verlinden [17], Costa et al. [18], and Vogiatzis and Kouroussis [19], proved that an accurate description of soil dynamics and track/soil interaction can be obtained using current numerical methods and usual computers.

Another specific aspect that must be retained from this analysis is the nature of the wheel/rail contact. As the source of ground vibration arises from the interaction between vehicle's wheels and the rail surface, a proper description of the dynamic phenomena is necessary, especially in the case of localized railway discontinuity [20–23]. Therefore, it is imperative that the above approach is well met by any comprehensive ground-borne vibration model that needs to determine the required mitigation measures in order to guarantee, that the allowable ground-borne vibration levels in the nearby sensitive buildings are met. For specific situations (e.g., transition zones), dedicated approaches are available for estimating the track dynamics. Alternatively, to these models needing important time and computational resources, scoping assessments represent an interesting alternative [24–26].

The field of railway airborne noise is quite large to be presented in a detailed way. Nowadays, environmental noise from urban transportation infrastructure operation, with emphasis to LRTs, is usually managed by relevant national and regional stakeholders. In Europe, especially, the Environmental Noise Directive (END) 2002/49/EC requires from all European Union Member States to determine the exposure of the population to environmental noise through Strategic Noise Mapping and to elaborate Action Plans in order to reduce noise pollution, where necessary. The END 2002/49/EC [27] aimed, therefore, to:

- Define a common and homogenous approach in order to prevent, reduce, or avoid the harmful effects due to exposure on environmental transportation noise, including annoyance, on a prioritized basis and
- Provide a basis for developing adequate mitigation measures and policies on all major environmental noise

**Fig. 1** An overview of vehicle/track and soil modeling



sources, with emphasis on road, rail, and aircraft vehicles and infrastructure, industrial equipment, and mobile machinery.

Regarding rail noise in particular, specialized dose-response relationships are needed for new sources of environmental noise such as high-speed railways entering the city, metropolitan underground and surficial tram and metro networks, in order to quantify the impact of additional factors such as, technical characteristics of the noise source, its operation mode with emphasis to speed, the implementation of quiet facades, the influence of nearby green areas, the number and distribution of high level noise events and spectral aspects (e.g., low frequency noise). According to the above Directive 2002/49/EC (annex II), the suggested assessment method for the EU noise indicators  $L_{den}$  and  $L_{night}$ , for environmental train airborne noise—as referred in Article 6—for all Member States that have no national computation methods or Member States that wish to change computation method, is the Netherlands national computation method (“Rekenen Meetvoorschrift Railverkeerslawaaai 96”, or RMR). This method provides two different calculation schemes, (a) SRM I (simplified scheme) and (b) SRM II (detailed scheme). The conditions under which each of the schemes can be used are described by the method, towards the Strategic Noise Mapping. However recently, the European Commission in cooperation with the European Union Member States has developed a common framework for noise assessment methods, called CNOSSOS-EU, which represents a harmonized and coherent approach to assess noise levels from the main sources of transport-induced noise (road traffic, railway traffic, aircraft and industrial). In 2015, CNOSSOS-EU became the new European Union Commission Directive prediction method (in form of a revised Annex II of the END), to be mandatory for all European Union Member States after 31 December 2018 [28].

A focus will be paid on a number of implementation challenges that should be faced in the context of current and

potential European Union environmental noise policy developments in view of the CNOSSOS-EU methodology becoming fully operational in the European Union Member States. CNOSSOS-EU framework expects to offer an even better and efficient way to evaluate the environmental noise levels and to propose adequate mitigation actions. Especially, regarding airborne noise mitigation from rail networks, various solutions can be implemented such as absorbing panels on the track, noise barriers next to the track, and rail dampers. Considerable positive results may be achieved this way ensuring a very good correlation between predicted and measured noise levels [29, 30].

However, the environmental vibration and ground noise parameters are not yet within the scope of the European environmental legislation, even though adverse effects during operation and construction phases are quite important in urban conditions. Especially regarding construction phase, it is clear that the limited period of the caused adverse effects may reduce the adverse effect in a time domain level, however increasing complaints of inhabitants regarding annoyance caused and even possible effects to buildings requires a more analytical approach and evaluation of possible mitigation measures. The introduction of extensive Environmental Monitoring Programs as part of the “Required Pertinent Monitoring Designs Programs” of LRT construction project specifications for the design, construction, and commissioning is therefore needed in order to ensure the protection and minimization of annoyance from construction works with emphasis to tunneling in the towards the closest sensitive receptors and the urban environment in generally.

Two distinct case studies are presented in this paper in order to emphasize to the need and necessary tools to access, monitor, and evaluate the impact of LRTs to the urban acoustic environment are as follows: (a) the new Brussels Regional Express Network (Dutch, Gewestelijk ExpresNet or GEN; French, Réseau Express Régional Bruxellois or RER) offering a rapid transit system with fast connections and increased passage frequency within a 30 km radius of Brussels, covering



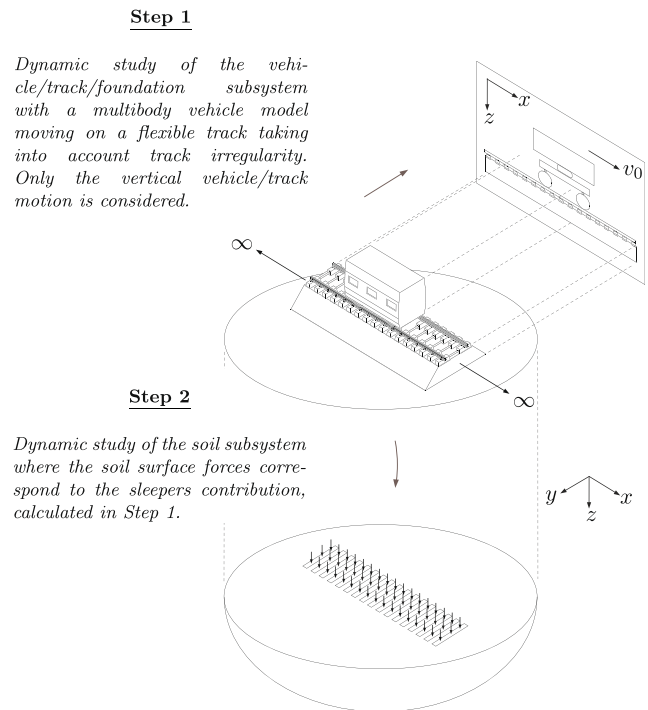
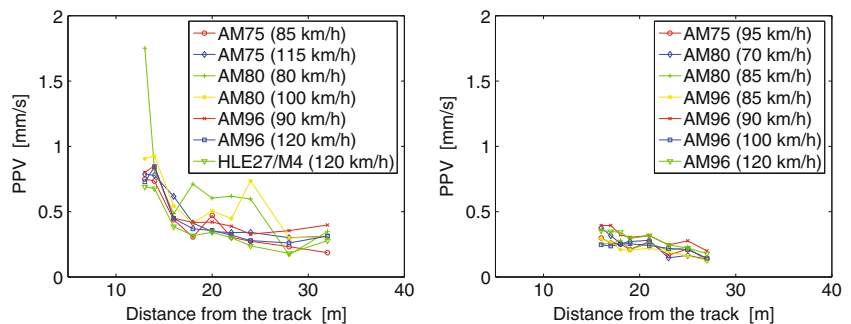
**Fig. 2** Example of existing double track railway line in Brussels

an area populated by 2.5 million habitants, and (b) the New Athens Metro Line 3 extension to the Western Athens Suburbs, towards Piraeus port an center in an underground tunnel, (length 7.6 km), with six (6) modern stations.

### Ground Vibration Induced by Intercity Train: A Study Case from Brussels

Since 1995, Brussels Region planned to build a new Brussels Regional Express Network (Dutch, Gewestelijk ExpresNet or GEN; French, Réseau Express Régional Bruxellois or RER) offering a rapid transit system with fast connections and increased passage frequency within a 30 km radius of Brussels, covering an area populated by 2.5 million habitants. To do this, most of the new networks use existing railroad lines, reducing the traffic congestion in and around Brussels. For example, the section of the Brussels-Luxembourg line L161 is planned to be updated with two supplementary tracks in order to have four (4) tracks in total (see Fig. 2). However, a few neighborhood committees were afraid and suspicious about the development of existing line, especially in terms of noise and vibration nuisances. Some complaints have been emerged during the first years of the project construction,

**Fig. 3** Measured peak particle velocity during the passing of Intercity trains in a site of Brussels: in the vicinity of a local rail joint (left) and without local rail defect (right) (reprinted with permission from [32])



**Fig. 4** Description of the used prediction model, according to a decoupling between the ballast and the soil (reprinted with permission from [34])

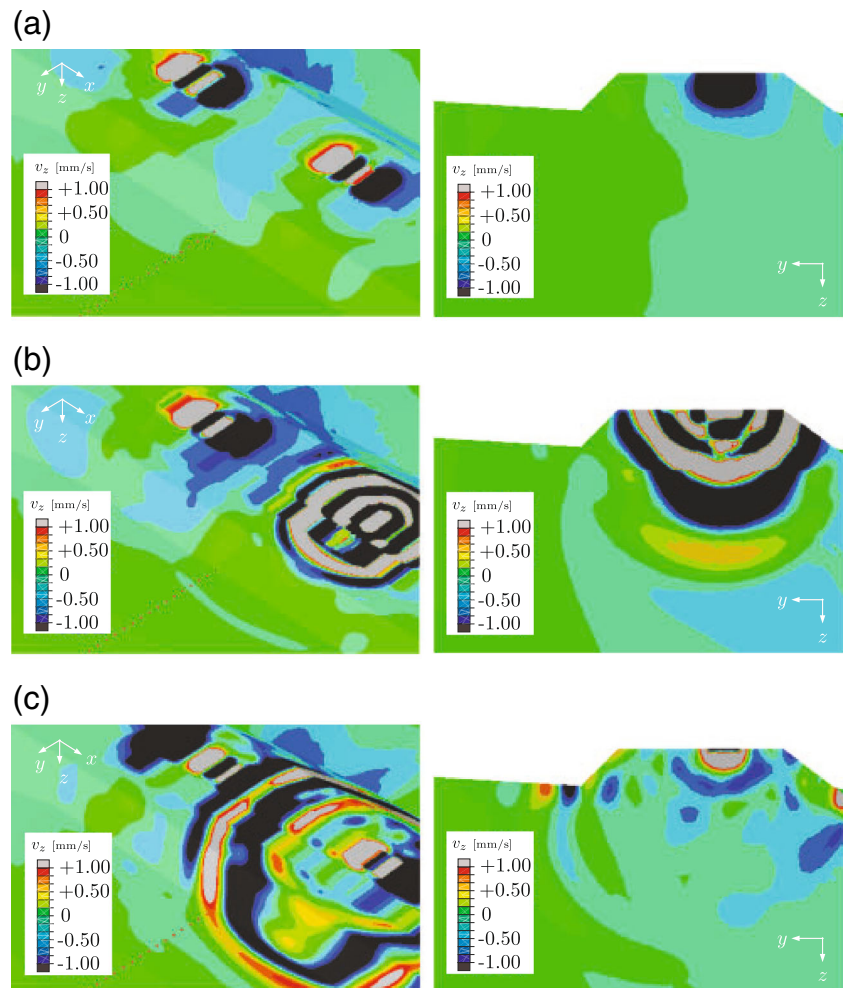
inducing some delays and postponements; the network should be put into service between 2020 and 2025.

Field trials are often used for vibration assessment in such infrastructure projects and are retained to quantify the effect of vehicle passing [31] or anti-vibration solutions [20]. They offer also a way to understand the dynamic effect of track or soil configuration on vibration level [31] Recently, the role of the site configuration was investigated in the railway line in question with the aim to assess the ground-borne vibration levels at various distances from the track when a train passes on a track with and without singular defect [32] (Fig. 3).

Nevertheless, experiments often show limitations since the complete railway line does not exist yet and multiple sources of vibration could be simultaneously recorded (the studied track was closed to domestic and high-speed roads). In that case, numerical prediction models can be used in parallel of experimental investigations, if all the site configuration



**Fig. 5** Propagation of the free-field soil vibration waves at different time instants: isometric view (*left*) and planar view along the track direction (*right*) [36]

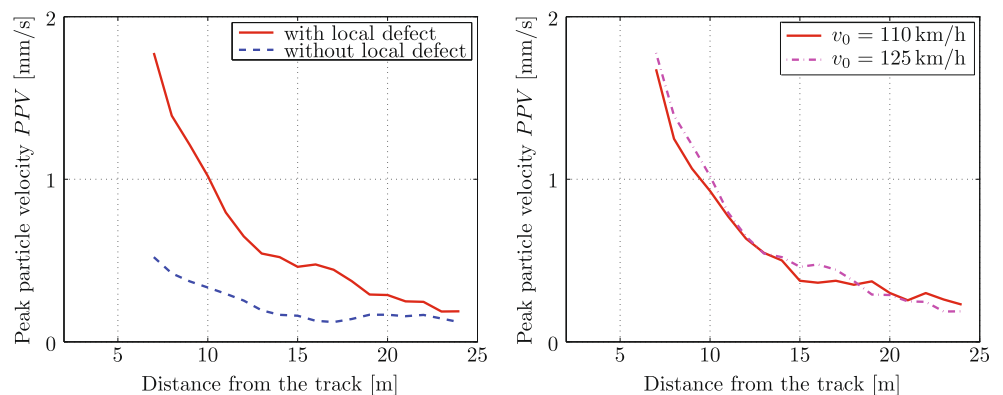


parameters are well known [16]. The choice of modeling assumptions is also of great importance since some hypotheses cannot be assumed in specific situations [33].

This section presents the numerical computation recently performed in order to quantify the vibration generated by the passing of rolling stocks (AM96) currently used in the existing L161 line. Numerical results are presented, in order to compare the findings from the experimental data from Kouroussis et al. [32].

The numerical assessment is based on an existing model validated in the past [34] offering a complete framework to evaluate the dynamics of the moving vehicle interacting with and the track, causing ground vibration level around the railway line, including free field and build environment. The proposed prediction model is based on two successive computational models in order to simplify transmission of vibration (Fig. 4): Due to the high problem complexity, the problem is split into two steps. This permits the use of the well-suited modeling approach for each

**Fig. 6** Comparison of peak particle velocity as a function of the distance from the track. Effect of the presence of a rail joint (*left*) and effect of vehicle speed (*right*)



**Fig. 7** Athens Metro Line 3 extension to Piraeus and Maniatika section



subsystem: multibody simulation for the vehicle/track subsystem (as usually performed by the train designers) and finite element analysis for the ground wave propagation (as performed in civil engineering technical department). In the first step, the dynamics of the coupled vehicle/track subsystem is simulated by considering a multibody vehicle model moving on a flexible track with a track irregularity. The normal wheel/rail forces were defined using the non-linear Hertz's theory which allows the coupling between the vehicle model and the track. The track was defined as a flexible beam discretely supported by the sleepers, including rail pads, ballast, and foundation. The second step addresses the dynamics of the soil subsystem, where the soil surface forces represent the contribution from the sleepers along with superimposition of forces computed from the first step. Compared to other more dedicated approach for modeling infinite media like soil, the finite element approach offers a way to consider complex geometries (embankment, stratified soil, non-periodic-structures, etc.). If non-reflecting boundary conditions are properly defined, the domain size can be reduced to the area of interest with reasonable computation time can be obtained [35].

A full loaded unit AM96 with six carriages was simulated in a straight line in various conditions: with and without condition of rail joint at the vicinity of the concerned region, with constant or variable speed, with and without embankment. The hypotheses adopted in the present model were verified. A complete study can be found in [36]. Only the main findings are presented in this present section. Figure 5 presents the effect of embankment configurations in terms of vibration levels. Such graphical comparison can be related to a kind of “vibration mapping” providing valuable information about the wave propagation

inside the ground generated by the passing of the train. More particularly, it appears that embankment acts a waveguide by trapping energy within it since the vibration energy is confined in the embankment and elevated vibration levels were observed when compared to the surrounding environment.

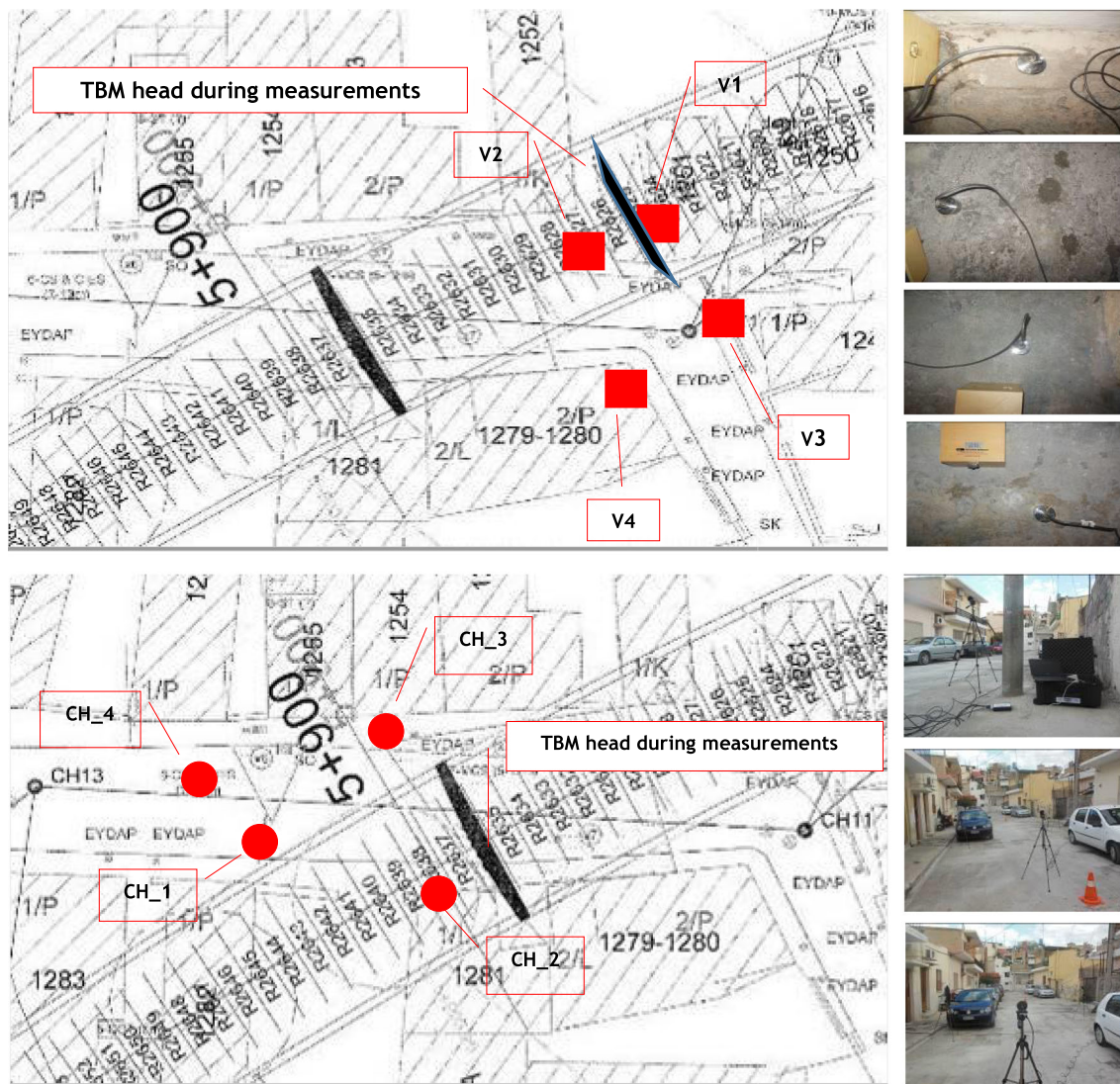
Figure 6 shows more quantitative results. The increasing in vibration due to the presence of a rail joint is clearly visible with an amplification reaching out three times the reference case (without rail joint). The effect of vehicle speed was also analyzed: In a small range of constant speed range (+13% of speed, from 110 to 125 km/h), the vibration level was almost identical but presents some local variation at specific distances from the track.

**Ground-Borne Noise from TBM Operation at Athens Metro Line 3 Extension Towards Piraeus Port**

On November 2008, ATTIKO METRO S.A. proceeded to the procurement of the project related to Athens Metro Line 3

**Table 1** Vibration velocity PPV maximum values for the relative land uses and sensitive receptors at Athens Metro

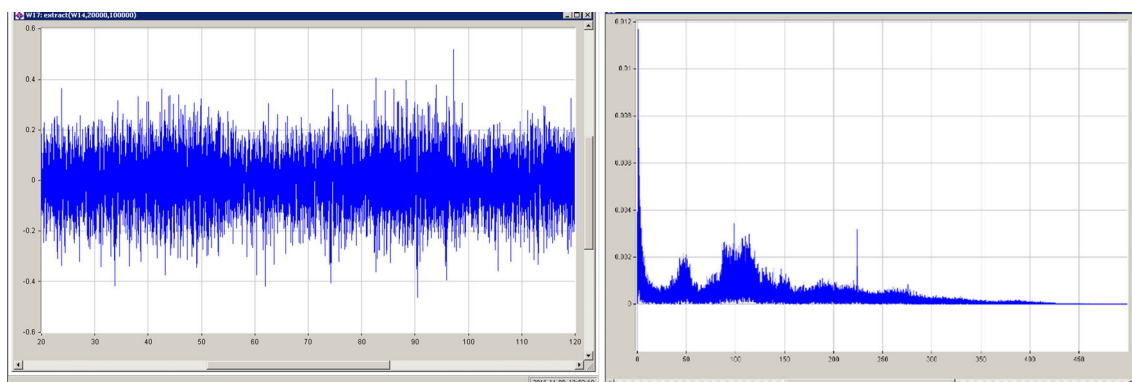
Land uses and sensitive receptors	Vibration velocity PPV <sub>z</sub>
Residential buildings	0.5 mm/s
Monuments, archeological findings, exhibits in archeological sites or museums	0.2 mm/s
Other buildings (classification according to ISO 4866)	As per DIN 4150 (Part 3) above



**Fig. 8** Athens Metro Line 3 extension to Piraeus. TBM's vibration (V1 to V4) and airborne noise (Ch 1 to Ch 4) sensors (lay out and photos)

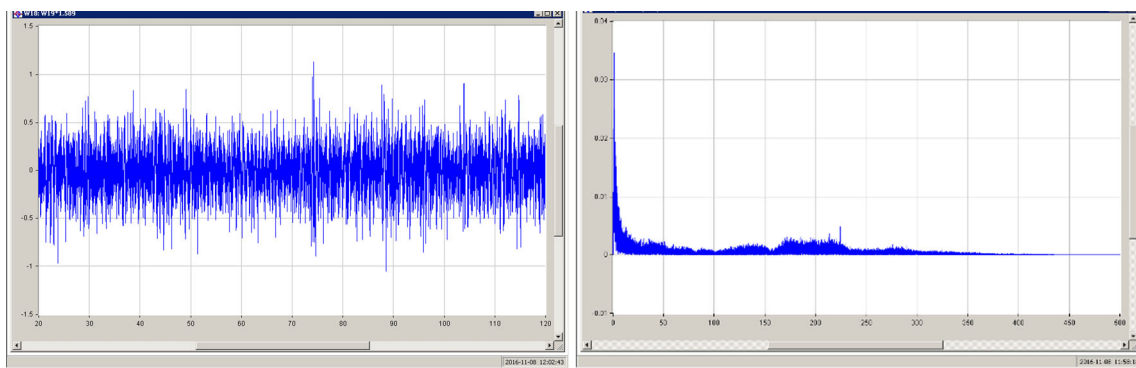
extension to the Western Suburbs, terminating in the area of Piraeus having underground tunnel (length 7.6 km) with six modern stations namely Agia Varvara, Korydallos, Nikaia, Maniatika, Piraeus, Dimotiko Theatro. On March 1st 2012,

the relevant contract was signed with the contracting joint venture J&P—AVAX S.A., GHELLA SPA, ALSTROM TRANSPORT S.A. This project constitutes an investment of EURO 730,000,000 in areas of Piraeus municipalities and



**Fig. 9** Location V1 TBM operation PPV (mm/s) time history and FFT analysis





**Fig. 10** Location V2 TBM operation PPV (mm/s) time history and FFT analysis

other municipalities in the wider area (Nikaia, Korydallos, Agia Varvara), which currently face acute traffic problems and sub-standard services, in terms of public transport networks services (Fig. 7). The metro extension to Piraeus will serve approximately 132,000 passengers on a daily basis, while covering the distance between the port and the international airport will be covered by the metro within 45 min. Additionally, once the metro becomes operational, the number of vehicles will be reduced by approximately around 23,000 on a daily basis, leading to a respective daily reduction in CO<sub>2</sub> (weight 120 t) ([www.ametro.gr](http://www.ametro.gr)) [37].

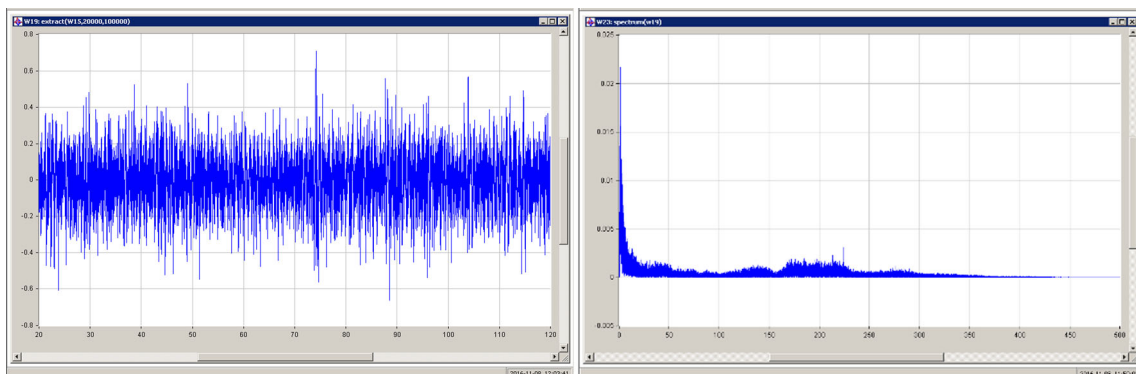
The metro tunnel is actually constructed by tunnel boring machine (TBM) in order to minimize the inevitable disturbance in functioning of the municipality services. TBM is mainly used as an alternative to usual drilling and blasting (D&B) methods in hard rock conditions. TBM has the advantages of limiting the disturbance to the surrounding ground and producing a smooth tunnel wall. This significantly reduces the cost of lining the tunnel and makes them suitable to be used in heavily urbanized areas. Even though tunneling with TBMs is much more efficient and results in shortened completion times, assuming they operate successfully, vibration from tunneling works can be a source of complaint, especially due to ground-borne noise, raising concerns of damage to structures and potentially adverse effects to vibration sensitive equipment [4]. For these reasons, monitoring of vibration levels was performed during TBM operation at the

“Maniatika section” of the Line 3 Metro extension as an environmental protection requirement of urban area. In order to assess vibration and ground-borne noise levels through the ground from the tunnel boring machine (TBM), the following criteria were enforced as per the DIN 4150 Part 3 [38]:

- Building foundation, for  $f \leq 50$  Hz, limit is set at  $\leq 3$  mm/s and for  $50 < f < 100$  Hz at  $\leq 8$  mm/s
- For all above building levels, all frequencies  $\leq 8$  mm/s

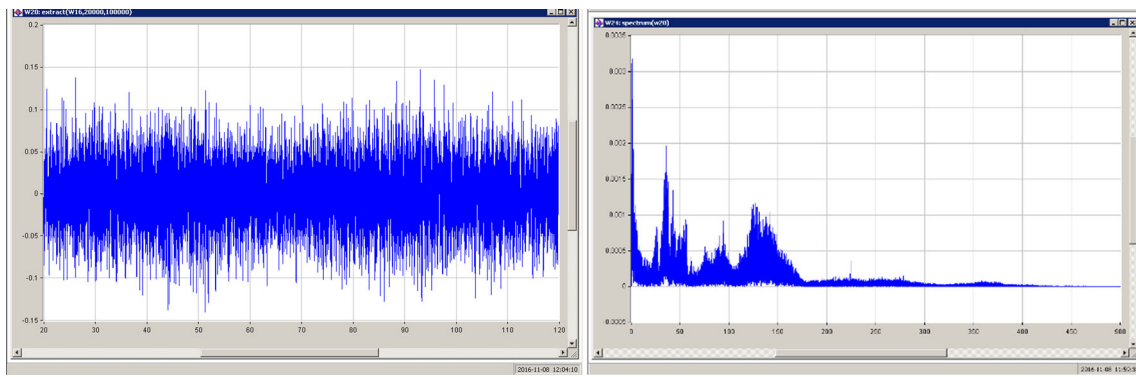
Moreover, regarding the implementation of the updated peak vibration limits (PPV in mm/s) and the velocity vector  $PPV = \sqrt{\{(PPV_x)^2 + (PPV_y)^2 + (PPV_z)^2\}}$ , the  $PPV_z$  criterion (in mm/s) was introduced with the following maximum values that were enforced for the relative land uses and sensitive receptors (Table 1).

During excavation, a full program of monitoring both peak particle velocities PPV, rms weighted acceleration and airborne noise levels were implemented during TBM operation at Maniatika section, in hard soil conditions. The relevant setup of the above special TBM’s vibration monitoring program, during the period of construction, ensures simultaneous recordings at the closest receptors of the TBM alignment axis, in real-time operation conditions using high sensitivity accelerometers WILCOXON (100 V/g), with amplifiers. The sensors operated in the frequency range of 0–450 Hz and all recordings were in



**Fig. 11** Location V3 TBM operation PPV (mm/s) time history and FFT analysis





**Fig. 12** Location V4 TBM operation PPV (mm/s) time history and FFT analysis

the area from DC up to 100 Hz. Digitization of recordings was applied by using an “anti-aliasing” at 100 Hz with sampling of 1000 Hz. The signals from the amplifiers were recorded at a multi-channel digital recorder. The real-time analysis of the signals allows the automatic calculation of  $PPV_z$  and rms [39]. The vibration velocity was calculated from the acceleration, taking into account the following formula correlating velocity and acceleration to the center frequency of each 1/3 of the octave:

$$\text{Velocity ref } 10^{-9} \text{ m/sec} = \text{Acceleration ref } 10^{-6} \text{ g} + 64 - 20 \log f$$

where  $f$  is the center frequency of each 1/3 of the octave.

This formula is based on the transformation of acceleration in dB re 10<sup>-6</sup> g to velocity in dB re 10<sup>-9</sup> m/s. For each location (as presented hereafter), the following data were recorded and analyzed:

- Vibration acceleration in time domain (m/s<sup>2</sup>)
- Vibration velocity (mm/s)
- Calculation of PPV (mm/s) for all recordings
- Calculation of the rms weighted acceleration (m/s<sup>2</sup>) and of the VDV values (according to BS6472:1992)
- Fourier analysis for the vibration velocity recordings according to DIN 4150 (Part 3)

Regarding the airborne noise monitoring program at the street level, a four-channel statistical noise monitoring station

**Table 2** Max values for all criteria during TBM operation

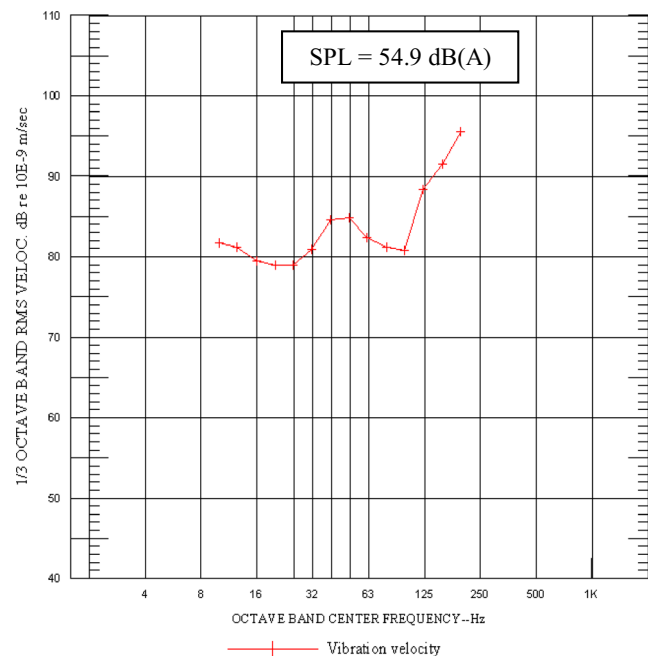
Criterion	Z (axis) for V1,V2,V3,an V4 respectively	Measurement vs limit
Max $PPV_z$ in mm/s (max value recorded for $f < 10$ Hz at 9.8 Hz and for $f 10-100$ Hz at 35.86 Hz)	0.517/1.127/0.709/0.146	Compliance as per DIN 4150 (Part 3)
rms weighted acceleration in $mm/s^2$	0.50/0.95/0.65/0.12	Compliance as per BS6472

dB4 by 01 dB was used in order to evaluate the airborne noise levels from TBM operation vs the background noise levels in the affected urban area for three time periods (series of measurements). The vibration (V1 to 4) and airborne noise (Ch. 1 to 4) sensors locations are presented in Fig. 8.

The relevant results for vibration velocity recordings during TBM operation, including Fourier analysis for the measured vibration velocity at all locations, are given in Figs. 9, 10, 11, and 12 and Table 2.

The relevant 1/3 octave band analysis for the vibration velocity at the worst case location (V2) at street level during TBM full operation, is presented in Fig. 13 with the relevant estimation for the SPL index at approx. 54.9 dB(A) including façade’s reflection.

As per the airborne noise monitoring program (three series of measurements) at the street level (four simultaneous



**Fig. 13** One-third octave band analysis for the vibration velocity at the worst case location (V2), at street level, during TBM full operation

**Table 3** SPL airborne noise in dB(A) during TBM operation

Measurement's results	CH_1		CH_2		CH_3		CH_4	
	$L_{eq}$	$L_{min}$	$L_{eq}$	$L_{min}$	$L_{eq}$	$L_{min}$	$L_{eq}$	$L_{min}$
1st series TBM operation	52.7	50.9	51.9	49.3	51.9	48.9	51.1	48.8
2nd series TBM operation	55.1	51.2	54.7	51.3	54.7	51.9	54.2	50.7
3rd series TBM operation	52.0	46.2	52.1	43.7	51.2	44.5	51.5	44.6
Average SPL from TBM operation	53.3	49.4	52.9	48.1	52.6	48.4	52.3	48.0
Background noise	38.5	36.1	36.1	33.7	38.2	35.4	37.9	35.1
SPL from TBM operation only	53.1	49.2	52.8	47.9	52.4	48.2	52.1	47.8

channels), the relevant recorded and analyzed noise levels from TBM operation are presented in Table 3.

Based on the above results, it is quite interesting to observe that SPL calculations from both ground-borne frequency analysis and direct airborne noise measurements are quite correlated for non-reflective facades condition, for all measurement locations due to the fact that the hard rock conditions create high and distinct noise signatures both on ground-borne and airborne diffusion conditions. It is however important to underline, that even if the above criteria are met, ground-borne noise and vibration from tunneling works using TBM are frequently a source of complaint, especially due to ground propagation which in these case due to the extremely hard rock soil is quite elevated. Noise concerns of damage to residential structures were recorded involving also noise annoyance and security adverse effects. For these reasons, prediction and monitoring vibration and ground-borne noise levels from TBM operation are quite a requirement for urban tunneling projects [39].

## Conclusions

LRT networks in urban conditions are considered to be a sustainable mean of transportation, providing a high effective transportation outcome, however an important adverse effect of their operation is the increased level of vibration and both ground-borne and airborne noise transmitted to buildings in close proximity. It is a fact that experiments are often difficult to obtain and/or to interpret especially for environmental vibration. Therefore, the researchers often use prediction methods to assess the vibration levels and, in addition, to understand the complex mechanism of generation and propagation of ground vibrations.

The most challenging part regarding environmental vibration prediction models aliased in-depth in order to develop a comprehensive vehicle/track model implementing input parameters which require investigation prior to execution [40]. This offers a way to treat complex problems encountered in practice where the train interacts with important local defects and quantifies the effect of these defects, according to their size and shape for any possible situation. It can be concluded

that the use of numerical model offers new insight for analyzing the vibration levels. With current calculation computers, the CPU time remains reasonable and the results obtained are valuable to analyze some specific configurations which are difficult or impossible to assess during the experiments.

In any case, the calibration of environmental vibration and ground-borne noise prediction models, by the means of in situ accurate measurements, is very important and ensures better accuracy, especially regarding the effectiveness of proposed mitigation measures [30]. Airborne noise evaluation prediction models, compared to environmental vibration ones, benefit of a higher degree of maturity. Therefore, regarding LRT airborne noise, the new CNOSSOS-EU framework within the new European Directive (revised Annex II of the END within the new Directive 2015/996/EC to be mandatory for all European Union Member States after 31 December 2018) is expected to offer an even better and efficient way to evaluate the noise level within strategic noise mapping and to propose adequate environmental noise mitigation actions, especially regarding airborne noise mitigation from urban rail networks.

Urban LRT construction (as metro and tram networks), and especially tunneling operation using TBM in hard rock soil conditions, generates environmental ground and airborne noise may cause annoyance and important adverse reactions from the population in residential zones. Therefore, it is needed to be managed effectively by implementing noise abatement actions with particular emphasis to the following [4]:

- Interruption TBM operation during quiet hours or operating the TBM with reduced thrust and/or rotation rate and possibly alternative cutter types is frequently necessary. It secures that the smooth flow of construction of the project is not impeded,
- Without use of auxiliary noisy equipment during quiet hours (e.g., drills, air compressors, earthmoving equipment) and introducing the use of alternative equipment types, as low impact hydraulic hammers replacing driven piers with bored piers,
- Prior to the use of particularly noisy/vibrating equipment as TBM, the residents of the area involved need to be notified for potential nuisance, during the night,

- Prior to the start of operations on the main underground project, an investigation of the necessity for the implementation of technical works for counteracting vibration during the period of TBM operation is suggested in order to avoid significant acoustic environment degradation.

Finally, the developed technology can be used without restrictions by all those concerned such as construction engineering companies, consultants, contractors, operators, and infrastructure managers as well as civil authorities. Therefore, a dissemination strategy for a wide-spread information transfer needs to be introduced, in order to ensure that the necessary environmental standards are met and to inform accordingly all relevant stakeholders, upgrading the management of any negative effects, by LRT operators.

### Compliance with Ethical Standards

**Conflict of Interest** The authors declare that they have no conflict of interest.

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