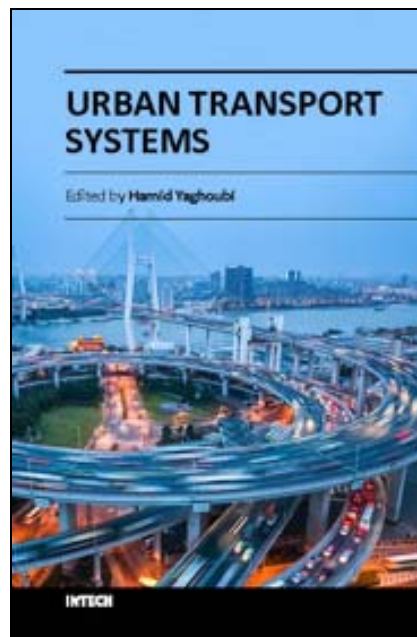


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Airborne and Ground-Borne Noise and Vibration from Urban Rail Transit Systems

Konstantinos Vogiatzis and Georges Kouroussis

Additional information is available at the end of the chapter

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Abstract

The environmental effect of ground-borne vibration and noise generated by urban rail transit systems is a growing concern in urban areas. This chapter reviews, synthesizes and benchmarks new understandings related to railway vibration and associated airborne and ground-borne noise. The aim is to provide new thinking on how to predict noise and vibration levels from numerical modelling and from readily available conventional site investigation data. Recent results from some European metropolises (Brussels, Athens, etc.) are used to illustrate the dynamic effect of urban railway vehicles. It is also proved that train type and the contact conditions at the wheel/rail interface can be influential in the generation of vibration. The use of noise-mapping-based results offers an efficient and rapid way to evaluate mitigation measures in a large scale regarding the noise exposure generated to dense urban railway traffic. It is hoped that this information may provide assistance to future researchers attempting to simulate railway vehicle vibration and noise.

Keywords: structural vibration, railway vibration, environmental noise, vibration assessment, measurement, standards, human effect, building simulation, noise mapping, LRT

1. Introduction

The rapid population growth and its concentration in urban and metropolitan areas are creating new challenges and demands to mobility. The development of railway networks is therefore unavoidable and comprises the construction of new networks and/or the extension of existing ones. This increase in mobility often causes issues, notably noise and vibration which are important and must be managed for the coming decades [1]. Indeed, this problem

is of growing importance: vibratory nuisance affects not only people (comfort and health) but also buildings (cracks as main and initial damage [2]). A recent example comes from Brussels (Belgium), which possesses a dense railway network in the city consisting of urban tramways, underground metros and regional trains and which receives numerous complaints: more than 280 complaints concerning the T2000 tram have been noted to the present day [3]. Based on this observation, comprehensive and integrated approaches are required to gain new powerful insights. Considerable efforts have been made in order to reduce the generated vibrations in the vehicle, improving the passengers' comfort, but the ground vibration problem must also be solved. In a large number of situations, the influence of vibration on structural damage in buildings and on people inside buildings can no longer be neglected. Switzerland's national railway company estimated that 1200 million euros were required to fix vibration problems across the country's network [4]. There has recently been a global development in rail infrastructure, which appears set to continue. This growth was associated to ground vibration awareness and triggering more severe standards regarding limits not to be exceeded. An active research area became evident by placing extensive efforts on predicting vibration levels with increased accuracy. This allows understanding more faithfully human perception of vibration.

The vibration of the building structure close to urban railway generates ground-borne noise, which can cause disturbance to the occupants. Sleep disturbance and annoyance, mostly related to transportation noise, comprise the main burden of environmental noise.

The mechanism of rolling noise is well mastered by the researchers in this field. The dominant source of noise is the rolling noise, generated by the interaction of rotating wheels and the rail. Both structures vibrate and radiate noise through vibro-acoustic effects. Similar mechanisms lead to impact noise and squeal noise, which are dedicated to specific studies. The other mechanisms are the aerodynamic noise—mainly due to the vehicle speed—and the machinery noise—generated by powered machines such as the electric or diesel motors, the transmission, the cooling fan and so on. Each of these sources of noise can affect people in the vicinity of railway networks.

Several and excellent books and chapters of book treat these problems in a general way, with focus on high-speed network (e.g. [5]). However, very few analyses have been done in the case of urban areas. In the authors' opinion, this created a kind of paradox that it will be explained in the next sections.

This chapter aims at reviewing recent investigations related to railway noise and vibration in urban areas and is divided into three parts:

- In a first section, the problem of railway-induced ground vibration is presented as along with two approaches—experimental and theoretical—to assess the ground vibration level, with particular focus on the modelling approach. The importance of a detailed vehicle model emphasized and the limitations of some prediction tools for urban areas are presented.
- In a second section, the problem of reducing railway noise is used to illustrate the classical approach to noise control. The various origins of airborne noise are presented, including rolling noise, aerodynamic noise and curve squeal noise, with emphasis to the main contributors in urban areas.

- In a last section, the structural noise coming for the building and ground vibration is presented. This is motivated by the misunderstanding of the people, confusing noise and vibration effects. The comfort is evaluated, followed by its effect on building performance.

2. Ground vibration and structural assessment

2.1. Position of the problem

The generation of vibrations is a consequence of the vehicle forces passing from the rotating wheels into the track. These forces depend on the moving vehicle's weight (static contribution, often called quasi-static effect) and surface irregularities at wheel and rail surfaces (representing the dynamic contribution). They contribute to the propagation of vibrations outwards from the track. The vibration level experienced is a function of this force, depending on the amplification factors of each track and soil component (all other locations within the track, soil or nearby structures), as a function of the excitation frequency. Therefore, it is imperative that both effects are well evaluated in the ground vibration assessment.

Much of the research into railway-induced ground vibrations has focused on the effect of high-speed trains on the environment. This was motivated by the so-called supercritical phenomenon which appears when a train travels close to the soil Rayleigh wave speed (critical speed depending on the soil flexibility, which may be close to that of conventional high-speed lines). Despite the large vibration levels generated by these lines which are underlain by soft soils, the distance d between the track and neighbouring structures is relatively large and the vibration attenuates rapidly. In the case of railway traffic, the attenuation is associated with a power law of the form d^{-q} , where q lies between 0.5 and 1.1, depending on the soil configuration [6]. The situation is significantly different in the case of urban transit, due to the presence of local defects which induce elevated localized vibrations (dynamic effect). In the past few years, some studies have emerged that are focused on the vehicle effects (RIVAS project, with several work packages dedicated to some mitigation measures for the vehicles [7], *CarboVibes* project focusing on freight railway lines [8]). However, by quantifying all the research projects in railway-induced ground vibration, there is a distinct lack of studies on analysing the effect of local defects on ground vibration. Despite this lack of attention, many ground-borne vibration complaints in urban environments are due to local rail and wheel surface defects (e.g. switches, rail joints, etc.).

As suggested in [9], an analogy between railway-induced ground vibrations and vibration isolation concepts can be established. When a force $f(t)$ is applied on a mechanical system, a part of this is transmitted to the foundation, depending on the characteristics of the isolation (**Figure 1(a)**). On the other hand, when a motion $u(t)$ undergoes the foundation, the equipment has also a motion $x(t)$ depending on the equipment isolator system (**Figure 1(b)**). In the railway, the vehicle/track/soil interaction is associated with the first case, as the force is defined by the wheel/rail interaction, with the quasi-static and dynamic contributions. The role of isolator is played by the track, which has the role of dispatching the forces through the discrete supports (sleepers).

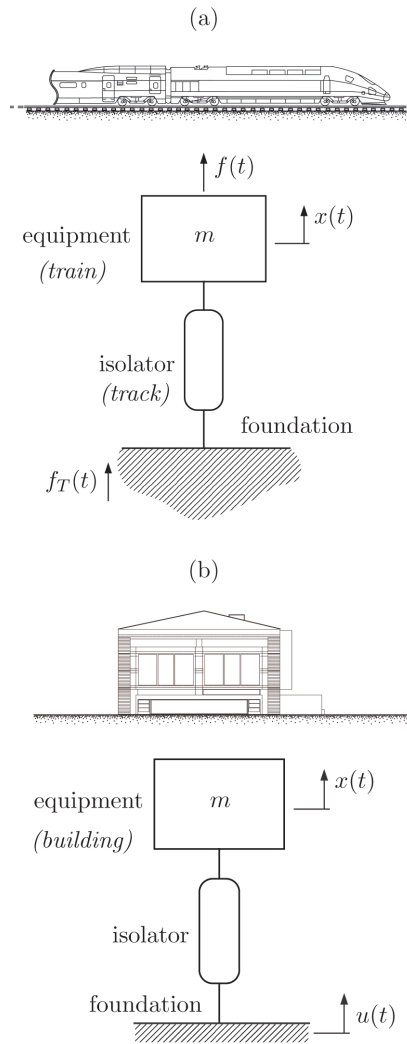


Figure 1. Schematic diagrams of the vibration isolation systems: an analogy with the railway-induced ground vibration [9]. (a) Vibration isolation where force $f(t)$ is applied by the equipment and force $f_T(t)$ is transmitted to the foundation (vehicle/track/soil dynamics). (b) Vibration isolation where motion $x(t)$ is imposed at the foundation and motion $x(t)$ is transmitted to the foundation (soil/structure interaction).

Physical experiments were the conventional means that researchers used to evaluate the effects of vehicles on their surrounding neighbourhoods. However, several cost and physical limitations remain: time and budget constraints, the difficulty involved with investigating a single effect and in cases where the site to be tested does not yet exist. Despite this, the acquisition of experimental data is interesting because it can be used to establish empirical models and

validate existing or in-development prediction models. It also serves to illustrate the essential physical interpretations gathered from experience on real lines over the last 20 years. Although many experiments are freely available in the case of high-speed trains, the case of urban railway presents few available and complete studies. However, measurement remains a quick approach for vibration evaluation when the site for analysis exists. If the site is not yet created, preliminary studies and impact surveys can be used but they are limited to other sites of similar composition.

2.2. Nature of urban networks

The vibration generated by the railway therefore depends on the type of vehicle (or network) and the quality of the rolling surface. **Figure 2** illustrates three train types according to their network. It is important to reiterate that this level classification depends not only on the vehicle speed but also on the network type. The various train/track models were classified according to their main excitation mechanisms. High-speed trains generate ground vibrations that are mainly dependent on quasi-static track deflection (effect of a moving constant axle loading), because the high-speed lines are typically characterized by very high-quality-rolling surfaces. This hypothesis is, however, valid when the vehicle speed is lower than a theoretical critical track/soil velocity (often close or greater than 500 km/h). On the contrary, a low speed and a relatively high density of singular rail surface defects (such as rail joints, crossings or switching gears) characterize the light-transit vehicles (LRT) (e.g. trams or metros). As pointed out in [10], the dynamic track deflection (induced by the dynamic interaction between the train and the track) is a main contributor to ground-wave generation. Between these two extreme cases, a combination of contributors experienced on both high-speed and urban railway lines concerns the domestic intercity trains travelling at moderate speeds. A non-negligible influence on ground vibrations is associated to quasi-static track deflection, in addition to the effects due to local defects.

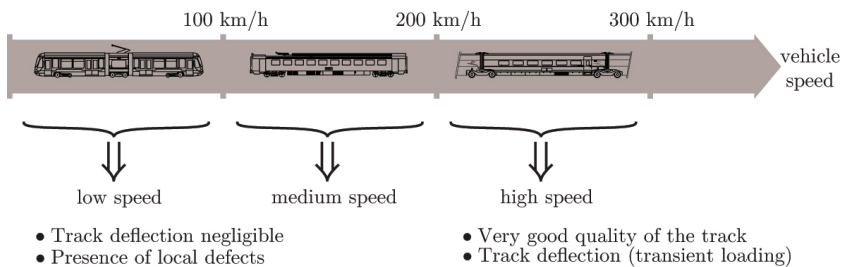


Figure 2. Main contribution to dynamic vehicle/track and soil interactions [10].

Regarding the soil modelling, various methodologies currently exist: (semi-) analytical approach, finite element method (FEM), boundary element method (BEM), among others. The FEM and BEM can be modelled as 2D or 3D problems, depending on the assumed hypothesis. When the boundary conditions mimicking the soil infinity are well defined, the FEM represents

an interesting approach due to its ability to describe the soil geometry (layer, tunnel, etc.) in detail and to easily include other structures (e.g., buildings). Compared to coupled FEM-BEM (e.g. [11]), this offers a single approach to model the soil. Furthermore, FEM software packages are already widely used in engineering.

To understand the generation and the propagation of vibrations generated by trains, we illustrate two cases in **Figure 3**: the first one assumes distributed irregularities along the track alignment; the second case is devoted to the presence of a local defect (such as rail joint, switches, crossover, turnout, etc.).

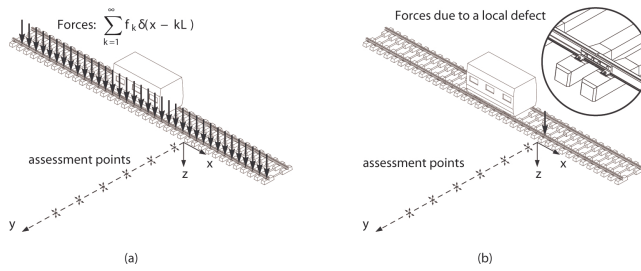


Figure 3. Generation of train forces: (a) for distributed source and (b) for local source of excitation.

In the case of distributed irregularities along the track alignment, the forces issued from the interaction between each wheel set j and the rail can be considered as the sleepers reaction covering a large distance and the excitation can be defined as the summation of the effects of each force f_k acting through the k -th sleeper in the neighbourhood

$$f_{\text{exc},j} = \sum_{k=1}^{\infty} f_k \delta(x - kL) \quad (1)$$

where L is the sleeper bay and δ the Dirac delta function. The resulting vibrations at several distances (assessment points) from the track result from the summation of the effects of each force (often called line source vibration).

In the case of a local defect (**Figure 4**), the ground vibration near railway lines is the result of the interaction of the railway vehicle and the track when the train is running over a local defect in the rail. Therefore, it is relatively reasonable to consider the single force acting on the wheel/rail-defect contact point as the only contributor to railway vibration

$$f_{\text{exc},j} = f_{\text{wheel/rail}} \quad (2)$$

Notice that the force defined by Eq. (2)—acting at the wheel/rail interface—has a location different from the force defined by Eq. (1)—at the track/soil interface, to be compliant with the

physical phenomena. Notice also that wheel flats and more generally any defect on wheel-rolling surface, are particular defects since the effect is reproduced every wheel rotation. The periodic effect of wheel-flat impact affects the whole track.

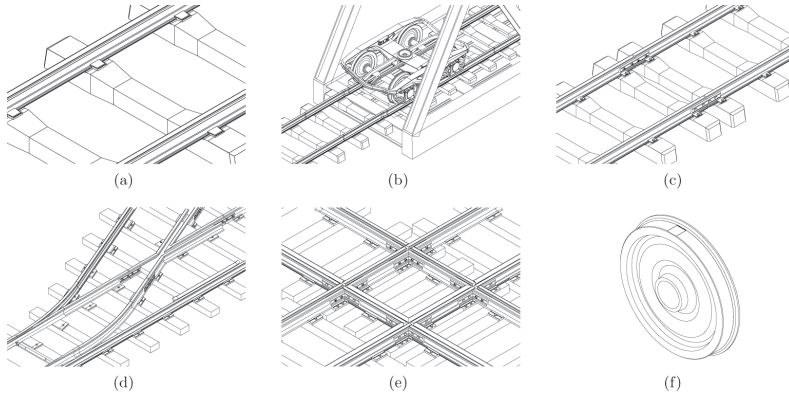


Figure 4. Overview of possible surface defects encountered in practice: (a) reference (no defect), (b) foundation transition, (c) rail joints, (d) turnout system, (e) crossing location and (f) wheel flat.

2.3. Ground-wave problem: a brief history of vibration prediction methods

The aim of a comprehensive ground-borne vibration model is to determine the required mitigation measures in order to guarantee, under examination, along these extensions, that the allowable ground-borne vibration levels in nearby buildings are met. Prediction models abound in the literature. For specific situations (transition zones), dedicated approaches are available for estimating the track dynamics. As shown in **Figure 5**, the first prediction models used a simple point source load to simulate the effect of a moving train on a track and to understand the high level of vibrations associated to the supercritical phenomenon. This was first used by Krylov [12]. Following this, many researchers have exclusively focused on high-speed lines, neglecting other cases at lower speeds. Naturally, these models were adapted to be more accurate, including the effect of track unevenness ('random axle loads', e.g. [13]). With the intent to further research the vehicle and track interaction exerted by the wheel and rail irregularities, complete vehicle/track/soil models were proposed, by defining the vehicle with lumped masses (and presented, incorrectly, as multibody models) connected by spring and damper elements representing the suspension system. The effect of detailed vehicle models was clearly discussed in [10]. The aim of this modelling approach was to be more reliable; however, the conclusion was that an accurate description can instead be obtained in simulation by considering only the unsprung and semi-sprung (bogies) masses of the train [14]. In parallel, Kouroussis et al. [15] demonstrated the benefits of including a complete model in the simulation of the ground vibration propagation induced by railway vehicles, that is, the frequency content of ground vibrations involves the signature of the dynamic modes of the vehicle and includes the effect of the sprung mass (car body). Both

results are, at a first estimate, contradictory, but the studied cases were different: in [14], the vehicle speed was relatively high (218 km/h), whereas in [15], the train studied was a tram travelling at low speed (30 km/h) running over a local defect.

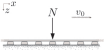
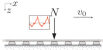
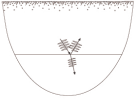
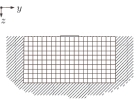
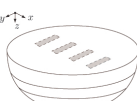
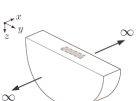
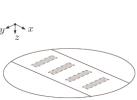
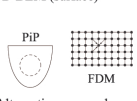
vehicle modelling →	constant axle load	random axle load	detailed model
			
soil modelling ↓			
	Krylov (1994,1998) Kaynia et al. (2000) Sheng et al. (1999,2004) Degrande and Lombaert (2001) Karlström (2006) Takemiya and Bian (2005) Maldonado et al. (2008)	Lu et al. (2006) Sheng et al. (2004) Lombaert et al. (2009)	Datoussaïd et al. (2000) Sheng et al. (2003) Lai et al. (2005) Auersch (2008) Xia et al. (2010) Lombaert et al. (2006)
analytical solution			
	Paolucci et al. (2003) Wang et al. (2004) Fujii et al. (2005) Yang et al. (2009) Vogiatzis (2012) Çelebi and Kirtel (2013)	Yang et al. (2003) Pakbaz et al. (2009)	
2D FEM			
	Hall (2003) Powrie et al. (2007) Anastasopoulos et al. (2009) Stupazzini and Paolucci (2010)		Gardien and Stuit (2003) Ju (2009) Zhai et al. (2010) Banimahd et al. (2011) Wang et al. (2012) Kouroussis et al. (2012,2013) Connolly et al. (2013) El Kacimi et al. (2013)
3D FEM			
	Sheng et al. (2006) Yang et al. (2003) François et al. (2010) Costa et al. (2010) Gao et al. (2012)		Galvin et al. (2010) Costa et al. (2012)
2.5D BEM and/or FEM			
	O'Brien and Rizos (2005) Andersen and Jones (2006) Auersch (2006) Chebli et al. (2008) Galvin and Domínguez (2009)		Galvin et al. (2010) Romero et al. (2010)
3D BEM (surface)			
	Thornely-Taylor (2004) Hussein and Hunt (2009) Jones and Hunt (2011)		
Alternative approaches			

Figure 5. Classification of recent railway-induced ground vibration models (the complete list of references can be found in Ref. [10]).

Regarding the soil modelling, analytical approaches proved their efficiency to simple case. Due to computational burden, numerical approaches were preferred these last. More particularly, BEM offers an attractive way to model infinite medium such as the soil. However, its quasi-exclusive use in the frequency domain limits the possibility to include nonlinearities and, since it uses Green's functions to efficiently calculate vibration propagation at large offsets, only simple geometries/configurations can be assessed. The FEM is an alternative method that has

gained wide acceptance in structural and vibration modelling. It has been used widely for railway vibration problems due to its versatility and to the possibility to model complex geometries. With the increase of computational capabilities these last years, FEM became on the same ranking than BEM. Moreover, the possibility to explicitly model structures/buildings close to the line makes it accessible to urban area problems.

Generally speaking, all the types of model offer valuable information. As pointed out by International Standard Organization (ISO) 14837-1 standard [16], the general circumstances of interest generally define the type of model (**Figure 6**). In the early stage of design, preliminary engineering models offer a rapid way to quantify the order of magnitude of the vibrations felt in the neighbour of railway lines. For advanced design, the need of a detailed model is obvious. Although the ISO 14837-1 standard does not provide any recommendation about which method to use in all the railway cases, it gives useful information about the frequency range within the assessment needs to be made: between 1 and 500 Hz for the effect on the buildings, from 1 to 80 Hz for the evaluation of human exposure to whole-body vibration and up to 200 Hz for sensitive equipment and sensitive tasks.

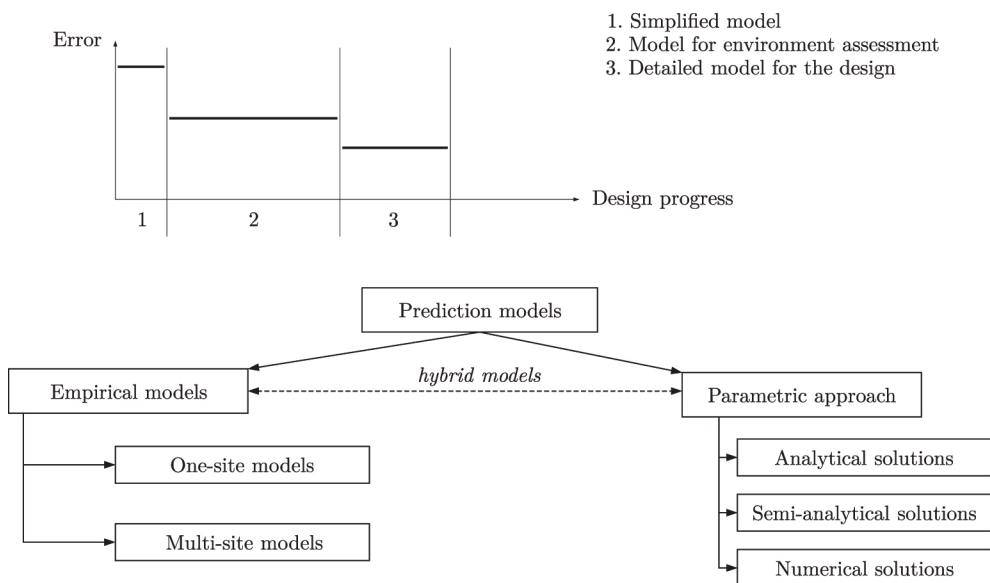


Figure 6. Synopsis of the types of model and the acceptable error in the design process.

2.4. The case of urban traffic: the 'railway paradox'

Several studies have been undertaken in order to evaluate potential vibration-mitigation measures (e.g. trenches [17]) and their effect on urban environments. The research on high-speed trains was motivated by the aforementioned supercritical phenomenon. Despite the large vibration levels generated by these lines, which are underlain by soft soils, the distance

between the track and its neighbouring structures is relatively high and the vibration amplitude attenuates rapidly. The situation is significantly different in the case of urban transit for numerous reasons such as:

- the distance d between track and buildings is relatively close;
- the contribution of the vehicle's weight and speed (quasistatic effects) is generally low and
- the presence of local defects induces elevated vibrations (dynamic effects) with a different power law.

These differences have produced some contradictory works (that the authors may call 'railway paradox'). The train constructors perform in-depth analysis of the vehicle dynamics by quantifying the vehicle's stability, comfort, behaviour on curved tracks, 3D wheel/rail interactions and motion with complex nonlinear suspensions. This is generally undertaken using multibody simulation (MBS) software tools (using commercial packages such as ADAMS, SIMPACK or Madymo) working with detailed models. The simulation of a complete process that takes into account the track and the soil is not performed: the track and therefore the soil, is modelled to be rigid. Recently, the possibility for these packages to couple the vehicle MBS model with an FEM model of the track using either co-simulation techniques (e.g. [18]) or modal reduction [19] was investigated. Currently, the track/soil vibrations are rarely considered from the initial design stages, even though it is the ideal moment to make ground vibration assessments and to analyse potential vibration-mitigation solutions. On the other hand, train/network operators consider only axle loads from the vehicle. The main reason for this discrepancy is certainly the different approaches adopted by these methodologies: MBS for the vehicle (almost always calculated in time domain) and FEM/BEM for the track/soil subsystem (static analysis or steady-state dynamics, usually calculated in the frequency domain).

This attitude produced a way of thinking to approach the issue based on the soil, considering it to be the principal cause of high-ground vibration levels (e.g. in high-speed lines, it is not the train which has an excessive speed, but the soil which has a low rigidity). Therefore, vibration-reduction measures on the transmission path (track-soil-receiver) have received considerable attention in recent years [20]. Although they represent a sustainable noise and vibration-mitigation measure (ideal candidates for retrofitting existing lines as their installation does not require track closures), they do not include the possibility to act directly on the problem source (in mechanics or in acoustics, it is well known that the first way to solve a problem is to act directly on its source). To illustrate this, a recent example that Kouroussis et al. studied [21] focused on the effect of localized railway defects in urban areas. Although wave number domain-modelling approaches are well suited to predict vibration levels on standard railway lines due to track periodicity, the time domain approach was preferred for non-periodic and localized defects. A fairly accurate description of the interaction between the track and the vehicle was modelled. The main contributions were to model the wheel/rail contact using a nonlinear contact algorithm and to use a detailed 2D vehicle model in the presence of wheel/rail discontinuities. In [22], the potential vibration effect of a flat spot located on a single wheel of a tram is demonstrated. By changing the vehicle and the studied speed range [21], very small levels of vibration are observed for the wheel flat. It was also shown that the type of defect has

a significant influence on the levels of vibration. Clearly, the difference between the studied vehicles was revealed and provided a clear requirement for further work on more comprehensive models of the vehicle. Another studied example [23] showed the drawback of using models that were limited to the prediction of only the vertical wheel/rail forces and their interaction with the track and the surrounding ground. The effect of horizontal vibrations due to the presence of rail joints was numerically underestimated, indicating that the dynamic behaviour in the longitudinal direction of the track should also be considered.

2.5. Source of vibration

As aforementioned, the source of vibration arises from the contact between the wheels and the rail. Any imperfection in the rolling surface creates a dynamic effect amplified by the vehicle dynamics and the track/soil response. The presence of local defects induces elevated localized vibrations. In urban area, these local defects are the main contribution of ground vibration because the quasi-static effect is often negligible due to the low speed of the vehicle. The key challenge is to limit the impact of these defects by redesigning the surface shape (e.g. rail joints need to be smoothed by adapting or creating transition zones to avoid abrupt changes in the rolling surface).

Regarding the railway ground vibration models, a linear contact law is often assumed for the vehicle/track coupling by considering small variation around the nomination penetration between the wheel and the rail. This hypothesis is available when the surface imperfection is non-existent or very small. However, when important variations in the contact point are present, the complete Hertz's theory is necessary to accurately predict the interaction forces at wheel/rail contact points [21].

2.6. Evaluation and vibration control

Human perception and building damages due to vibrations are the two main issues needed to be analysed in typical vibration studies [20]. Inhabitant health and comfort may be affected by vibrations that can also affect the structural integrity of buildings due to imposing important dynamic loads. Therefore, engineers need to evaluate all possible damages ensuring that the level of vibrations in building does not cause negative effects on people's comfort. Several vibration standards and recommendations exist, with the most important ones presenting hereafter. The most important ones are the following:

- As the main reference for comfort evaluation, the international standards ISO [24] are often retained. A root-mean-squared (*rms*) value $\check{a}_w$ is calculated and describes the smoothed vibration amplitude by supposing that the human body responds to an average vibration amplitude during a recorded time $0 \leq t \leq T$

$$\check{a}_w = \sqrt{\frac{1}{T} \int_0^T a_w^2(t) dt} \quad (3)$$

where a_w is the weighted acceleration derived from the time history of the acceleration at the studied location. Guidelines are given for the effect of vibrations on comfort and perception with valuable limits defining grades of various magnitudes of reaction to vibrations. The associated standard [24] less describes the effects on health by giving only two bounds (probable risk if above the upper limit, improbable risk below the lower limit). No additional information is provided for the case when the calculated value lies within the intermediate region.

- The recommendations [25] of the United States Department of Transportation (USDOT) on the assessment of potential vibration impacts resulting from high-speed train lines use a decibel scale

$$V_{dB} = 20 \log_{10} \frac{v_{rms}}{5 \cdot 10^{-8}} \quad (4)$$

where v_{rms} is the root-mean-square amplitude of the velocity time history. Both comfort and structural damages are estimated with this single indicator.

- The German standards DIN4150-2 [26] is used in Germany, in Belgium and some other European countries. A weighted time-averaged signal is defined by

$$KB_F(t) = \sqrt{\frac{1}{\tau} \int_0^T KB^2(\xi) e^{-\frac{t-\xi}{\tau}} d\xi} \quad (5)$$

where the weighted velocity signal $KB(t)$ is obtained by flowing the original velocity signal through a high-pass filter. The integration time τ to run the averaging is equal to 0.125 s, which allows taking into account transient phenomena such as impacts or shocks that would otherwise be masked if a simple *rms* operation was performed.

- The Swiss and German standards SN640 312a [27] and DIN4150-3 [28] are based on the peak particle velocity *PPV*, defined as the maximum of absolute velocity, to assess the building damages.

All these baselines represent the most used assessment guidelines for measurement and interpretational methodologies.

3. Airborne and ground-borne noise in the vicinity of urban rail networks

The field of railway noise is too large to be presented in a detailed way. Nowadays, noise in urban area is usually managed by national and regional stakeholders. In Europe, the Environmental Noise Directive (END) 2002/49/EC requires European Union Member States to

determine the exposure to environmental noise through strategic noise mapping and to elaborate action plans in order to reduce noise pollution, where necessary. The END [29] has aims to

- define a common homogeneous approach in order to prevent, reduce or avoid the harmful effects due to exposure on environmental noise, including annoyance, on a prioritized basis and
- to provide a basis for developing mitigation measures on all major 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 noise such as high-speed railways, or metropolitan underground and superficial tram and metro networks, in order to quantify the impact of additional factors such as technical characteristics of the 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). There is need to establish valid dose-response curves for cardiovascular response during sleep and noise taking into account the source characteristics and especially vehicle speed. In urban conditions, railway vehicle passes with a relatively low speed, so traction and rolling noise mainly affect the sound pressure level (SPL) (Figure 7).

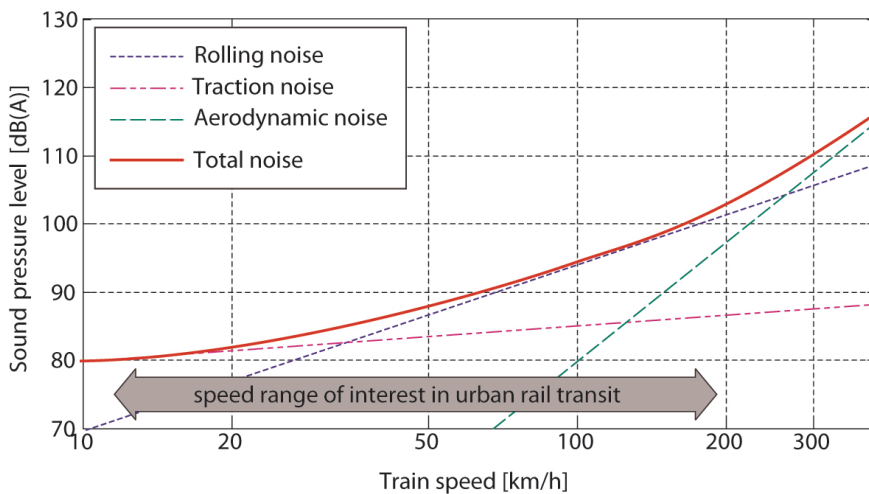


Figure 7. Speed relation for the three noise sources: sound pressure level as a function of train speed.

According to the Directive 2002/49/EC (annex II), the assessment methods and noise indicators for environmental train noise referred in Article 6 [29] are presented hereafter. The day-evening-night level L_{den} in decibels (dB) is defined by the following formula:

$$L_{\text{den}} = 10 \log_{10} \frac{12 \cdot 10^{\frac{L_{\text{day}}}{10}} + 4 \cdot 10^{\frac{L_{\text{evening}} + 5}{10}} + 8 \cdot 10^{\frac{L_{\text{night}} + 10}{10}}}{24} \quad (6)$$

introducing

- the A-weighted long-term average sound level L_{day} determined over all the day periods of a year,
- the A-weighted long-term average sound level L_{evening} determined over all the evening periods of a year and
- the A-weighted long-term average sound level L_{night} determined over all the night periods of a year,

as defined in the international standards ISO 1996-2:1987 [30]. The night-time period is 8 h for the noise indicator L_{night} . A year is a relevant year as regards the emission of sound and an average year as regards the meteorological circumstances and an assessment point is the same as for L_{den} . The L_{den} assessment point is located on a specific height according to the recommendations. In the case of strategic noise mapping, the assessment points must be at 4.0 ± 0.2 m (3.8–4.2 m) above the ground and at the most exposed façade. In such case, the external wall facing onto and nearest to the specific noise source is retained although other choices may be made for other purposes. According to this directive for Member States that have no national computation methods or Member States that wish to change the computation method, the Netherlands national computation method ('Reken-en Meetvoorschrift Railverkeerslawaaai 96', or RMR) is recommended. This method provides two different calculation schemes, SRM I (simplified scheme) and SRM II (detailed scheme). The conditions under which each of the schemes can be used are finely described by the method, in order to determine which method to use for the purpose of strategic noise mapping following the Directive 2002/49/EC [31].

In practice, the obligations which Directive 2002/49/EC imposes on the Member States and the European Commission address noise from road, rail and air traffic and industrial installations in agglomerations. Legislation on sources is complementary to the END as reducing the contribution to noise at source obviously reduces the exposure at the receiver. Recently, the European Commission in cooperation with the European Union Member States 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 a new European Union Commission Directive (based on a revised Annex II of the END) and will be mandatory for all European Union Member States after 31 December 2018 [31]. 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 CNOSSOS-EU becoming fully operational in the European Union Member States.

The aforementioned Dutch railway noise computation method RMR has its own emission model; however, the emission model remains as the original. Prior to the calculation of an ‘equivalent continuous sound pressure level’ generated by all vehicles that use a specified section of railway line and follow the appropriate service, guidelines should be either placed in the 10 railway vehicles categories provided in the Dutch emission database (**Table 1**).

Category	Train description
1	Block-braked passenger trains
2	Disc-braked and block-braked passenger trains
3	Disc-braked passenger trains
4	Block-braked freight trains
5	Block-braked diesel trains
6	Diesel trains with disc brakes
7	Disc-braked urban subway and rapid tram trains
8	Disc-braked InterCity and slow trains
9	Disc-braked and block-braked high-speed trains
10	Provisionally reserved for high-speed trains of the ICE-3 (M) type

Table 1. Railway vehicle categories provided by the Dutch emission RMR database.

According to SRM I, emission values in dB(A) are determined as follows:

$$E = 10 \log \left(\sum_c y 10^{E_{nr,c}/10} + \sum_c y 10^{E_{r,c}/10} \right) \quad (7)$$

where $E_{nr,c}$ is the emission term per rail vehicle category for nonbraking trains, $E_{r,c}$ the emission term for braking trains, c the train category and y the total number of categories present. The emission values per rail vehicle category are determined from

$$E_{nr,c} = a_c + b_c \log v_c + 10 \log Q_c + C_{b,c} \quad (8)$$

$$E_{r,c} = a_{r,c} + b_{r,c} \log v_c + 10 \log Q_{br,c} + C_{b,c} \quad (9)$$

where the standard emission values a_c , b_c , $a_{r,c}$ and $b_{r,c}$ are provided in RMR. Q_c and $Q_{br,c}$ are the mean number of non-braking and braking units of the railway vehicle category

concerned, respectively, v_c is the mean speed of passing railway vehicles (making the distinction between braking and non-braking units) and $C_{b,c}$ is a correction factor. SRM II suggests that the emission values per octave band are determined for each train category and for different sound source heights (up to five heights). The emission of the specified section of railway line is calculated taking into account the passage of different train categories with the emission factor in octave band i to be calculated as follows:

$$L_{E,i}^h = 10 \log \left(\sum_c n 10^{E_{nb,i,c}^h/10} + \sum_c n 10^{E_{br,i,c}^h/10} \right) \quad (10)$$

where

$$E_{br,i,c}^h = a_{br,i,c}^h + b_{br,i,c}^h \log v_c + 10 \log Q_{br,c} + C_{bb,i,m,c} \quad (11)$$

$$E_{nb,i,c}^h = a_{i,c}^h + b_{i,c}^h \log v_c + 10 \log Q_{br,c} + C_{bb,i,m,c} \quad (12)$$

Additional parameters are introduced: $a_{br,i,c}^h$, $b_{br,i,c}^h$, $a_{i,c}^h$ and $b_{i,c}^h$ are emission terms for train category in braking and nonbraking conditions, for octave band i at height h . $C_{bb,i,m,c}$ is also a correction factor, including the presence of the track disconnection, the track discontinuity and the rail roughness.

The new common framework for noise assessment methods (CNOSSOS-EU) recently developed by the European Commission in co-operation with the EU Member States is to be applied for strategic noise mapping, represents a harmonized and coherent approach to address and assess noise levels from the main sources of noise—including railway traffic—based on state-of-the-art knowledge and resulted from an intensive collaboration, exchange of data and evaluation procedure via a formal process at both policy and scientific/technical levels [32]. In the new environmental noise calculation method, a vehicle is defined as any single railway sub-unit of a train moving independently. All sub-units are grouped into a single vehicle. The existing tracks may also differ due to different acoustic properties. The overall track properties are defined by two acoustically essential parameters, for example, the railhead roughness and the track decay rate, according to ISO 3095:2013 [33], as well as the radius of curvature of the track.

The different equivalent rail airborne noise line sources are placed at different heights and at the centre of the track. The equivalent sources include various categories of physical sources as follows:

- the rolling noise (including rail- and track-base vibration wheel vibration as well as superstructure noise of the freight vehicles),

- the traction noise,
- the aerodynamic noise,
- the impact noise (from crossings, switches and junctions),
- the squeal noise and
- the noise due to bridges and viaducts.

In the new methodology [31, 32], the sound power emission assessment for railway traffic noise is analogue to road traffic noise. The noise sound power emission of a specific track type to fulfil a series of requirements is described in the vehicle and track classification, in terms of a set of sound power per each vehicle $L_{w,0}$. Furthermore, the noise emission of a traffic flow on each track is represented by a set of two source lines with relative directional sound power per metre and per frequency band. This corresponds to the sum of the sound emissions due to the individual vehicles passing by taking into account the time spent by the vehicles in the railway section (for stationary vehicles). The directional sound power per metre and per frequency band, due to all the vehicles passing by each track section on the track type (j), is defined as follows:

- for each frequency band (i);
- for each given source height (h) (for sources at (1) $h = 0.5$ m and (2) $h = 4.0$ m) and is the energy sum of all contributions from all vehicles running on the specific j -th track from:
 - the vehicle types (t),
 - the speeds (s),
 - the running conditions (constant speed) (c) and
 - the source types (as presented above, e.g., rolling, impact, squeal, traction, aerodynamic and bridge noise) (p).

To calculate the directional sound power per metre (input to the propagation part) due to the average mix of traffic on the j th track section, the following formula is used:

$$L_{W',eq,T,dir,i} = 10 \log \left(\sum_{x=1}^X 10^{L_{W',eq,line,x}/10} \right) \quad (13)$$

where T is the reference time period for which the average traffic is considered and X is the total number of existing combinations of i, t, s, c, p for each j -th track section. $L_{W',eq,line,x}$ is the x th directional sound power per metre for a source line of one combination of t, s, c, p on each j th track section. It takes into account the index t for vehicle types on the j th track section, the index s for train speed, the index c for running conditions: 1 (for constant speed) or 2 (idling), the index p for physical source types: 1 (for rolling and impact noise), 2 (curve squeal), 3 (traction noise), 4 (aerodynamic noise) or 5 (additional effects).

If a steady flow of vehicles Q /hour is assumed, with an average speed v , there will be an equivalent number of Q/v vehicles per unit length of the examined railway section, on average, at each moment in time. The noise emission of the vehicle flow in terms of directional sound power per metre $L_{W',eq,line}$ (expressed in dB/m (ref. 10^{-12} W)) is integrated by

$$L_{W',eq,line,i}(\psi, \phi) = L_{W,0,dir,i}(\psi, \phi) + 10 \log \left(\frac{Q}{1000 v} \right) \quad (\text{for } c = 1) \quad (14)$$

where Q is the average number of vehicles per hour on the j -th track section and $L_{W,0,dir,i}$ the directional sound power level of the specific noise (rolling, impact, squeal, braking, traction, aerodynamic, other effects) of a single vehicle in the angular directions (ψ, ϕ) defined with respect to the vehicle's direction of movement.

The vehicle contribution and the track contribution to rolling noise are separated into four essential elements: wheel roughness, rail roughness, vehicle transfer function to the wheels and to the superstructure (vessels) and track transfer function. Not including one of these four parameters would prevent the decoupling of the classification of tracks and trains [38].

4. Examples

Three examples are retained in this chapter to illustrate the complexity of ground vibration in urban areas.

4.1. T2000 circulating in Brussels: the effect of vehicle design

The first case is related to Belgian urban public transport company who replaced the old PCC7000 trams by the new T2000 LRV in Brussels Capital Region (Belgium). The T2000 LRV tram was developed by Bombardier Transport and is defined as a multicar tramway characterized by a low-floor design. This imposes that bogies involve independent rotating wheels and the motors are mounted directly inside the wheels. This example is based on experimental studies, after having observed important vibratory nuisances in the neighbourhood of this new tram. Among all the studies initiated by national projects to alleviate the vibratory level in the surrounding buildings, the research work [34] focused the effect of the roughness or local unevenness such as a rail defect on the soil vibration level.

Experiments have been performed by measuring the vibrations induced by the passing on an artificial local defect. Simulations completed the study showing the surprising results that a decrease vehicle speed from 20 to 30 km/h reveals a reduction of the vibratory level. The developed model allowed verifying this trend by simulating other cases considering a larger velocity range. **Figure 8** illustrates this statement and plots the vertical *PPV* as a function of the distance from the track and the tram speed. It turns out that the *PPV* regularly decreases not only with the distance but also with the speed.

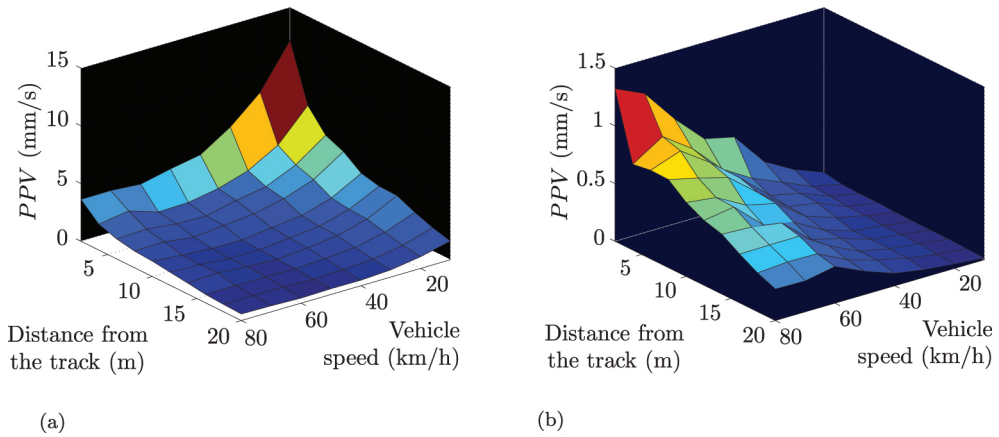


Figure 8. Vertical peak particle velocity PPV calculated from T2000 LRV passing as a function of the distance from the track and of the tram speed [34]. (a) During the passing on the local defect and (b) during the passing on a rough rail (without local defect).

4.2. Vibration and ground-borne noise generated by the passing of vehicles over turnouts —the case of Athens Metro

The second example illustrates the challenge in old and dense urban centres as the municipality of Athens (Greece) and the associated ground vibration problems of underground networks with respect to the protection of the cultural heritage in the case of archaeological area and museum. Intensive measurement campaigns were performed over the last decade, combined with predictive calculation in order to evaluate the efficiency of floating slabs as mitigation measures. Light-rapid-transit underground and surface networks in urban conditions represent a substantial reduction of air pollutants emissions. Indeed, this sustainable means of transportation offers a way to decrease the number of cars and heavy vehicles (i.e. buses) circulating in a road network. However, as aforementioned, an increased level of vibration transmitted to buildings in close proximity is often observed. This example illustrates this important adverse effect of Athens metro operation. It was observed that ground-borne noise and vibration in buildings was the result of the dynamic impact forces generated at the wheel-rail interface coupled to wheel and rail irregularities. A direct transmission of ground-borne vibration induced by metro traffic was clearly identified: ground-borne vibrations excite the foundation walls of nearby buildings, beneath the ground.

Figure 9 shows the results regarding the evaluation of anti-vibration performance of the floating slabs at several crossover locations [35, 36]. Additional measurements were recorded in order to verify that the vibration level at the closest buildings to the crossover locations was also below the fixed limit. To quantify the gain brought by the mitigation measure, the insertion loss factor IL is usually used. The ratio of the vibration level between the unisolated and the isolated track is defined:

$$IL = 20 \log_{10} \frac{v_{unisolated}}{v_{isolated}} \quad (15)$$

where $v_{unisolated}$ and $v_{isolated}$ are the corresponding vibration velocity amplitudes. **Figure 9** shows in which frequencies the response decreased due to the insertion of a floating. This example demonstrates how mitigation measures can be tuned to efficiently reduce the generated ground vibration levels in a specified frequency range.

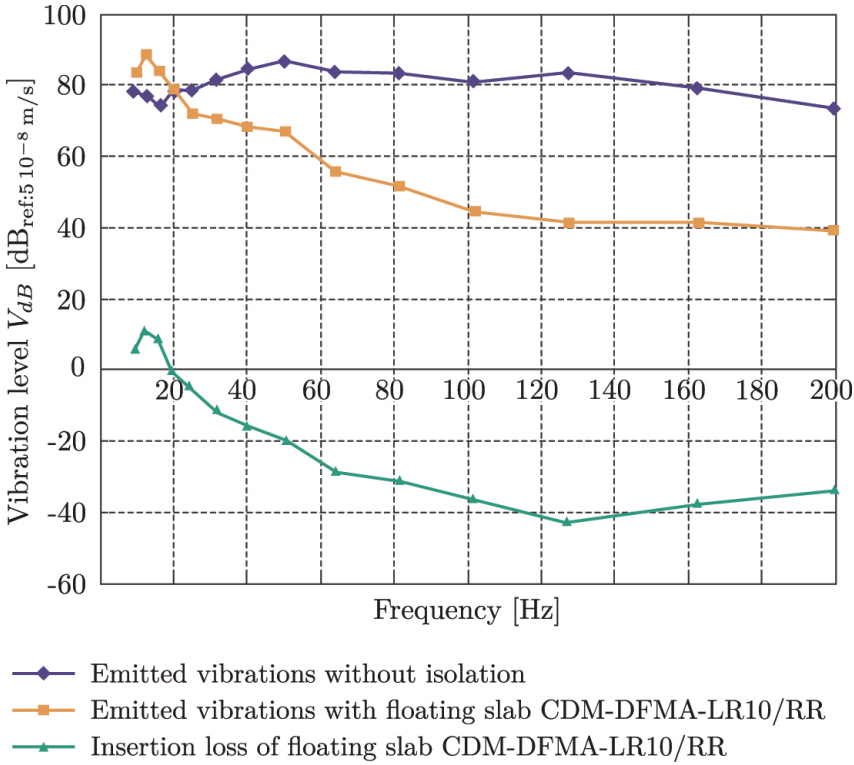


Figure 9. Comparison of 1/3 frequency analysis of vibration velocity with and without floating slabs at Athens metro extensions crossover locations [35].

4.3. Airborne noise in the vicinity of urban rail networks—the Quiet-Track Project in Athens Metro line 1

The overall objective of the Quiet-Track project [37] is to provide efficient solutions by including track-based noise-mitigation systems and maintenance schemes. The project focused on the

development and validation of performance solutions for reduction of track-related noise and on providing track noise management tools. Existing solutions were combined to yield an overall attenuation of at least 6 dB(A). This was done by simulation: the simulation of the combined effect of these solutions was completed by the implementation and the validation of the results in the network of Attiko Metro line 1, in Athens. The track was composed by twin-block concrete sleepers rigidly embedded in a concrete slab track. An existing outside concrete slab—ballastless system—track revealed high airborne noise and a combination of existing solutions was evaluated for noise reduction. Three distinct actions regarding possible mitigation measures were investigated, both on individual and on combined bases [38]:

- *Action 1:* Absorbing panels placed on the track, close to the source, between the rails aiming to mitigate contributions of both the wheels and the rails by influencing sound waves that are normally reflected.
- *Action 2:* Noise-reflective barrier was considered next to the track along the protective fence, preventing sound propagation by directly reflecting the sound waves, achieving an important level of noise reduction.
- *Action 3:* Rail dampers were also considered. Their application was confined to the track itself, influencing only the contribution of the rail. This action is to be considered only in cases where the rail contribution dominates or it is equally important as the wheel contribution.

Numerical simulations were also implemented combining different software tools for noise prediction [39]. The procedure was validated in the network of Attiko Metro line 1 where the selected noise-mitigation measures were installed. The expected attenuation of sound pressure level *SPL* (before and after mitigation measures) using the insertion loss factor *IL* in dB described by

$$IL = SPL_{after} - SPL_{before}, \quad (16)$$

was therefore determined and afterwards compared to the measured noise reduction. A full program of acoustic ‘initial situation’ noise measurements, of train normal conditions operation, was ALSO executed in order to establish the acoustic performance of the installed RHEDA system before any noise-mitigation measure implementation. The International Standards ISO 3095:2013 [33] specifies the conditions for obtaining reproducible and comparable measurement results of levels and spectra of noise for vehicles operating on rails or other types of fixed track. It was implemented using a class 1 multi-channel noise analyser [39]. **Figure 10** shows the sound pressure level in dB(A) computed by the software IMMI. The overall noise level before installation was 78.1 dB(A), meanwhile after installation of all three mitigation measures was reduced to 68.9 dB(A), resulting in an overall gain of 9.2 dB(A). The measured sound pressure levels for all cases are also presented, suggesting an overall good correlation between both calculated/simulated and measured values. **Table 2** summarizes the results for all cases.

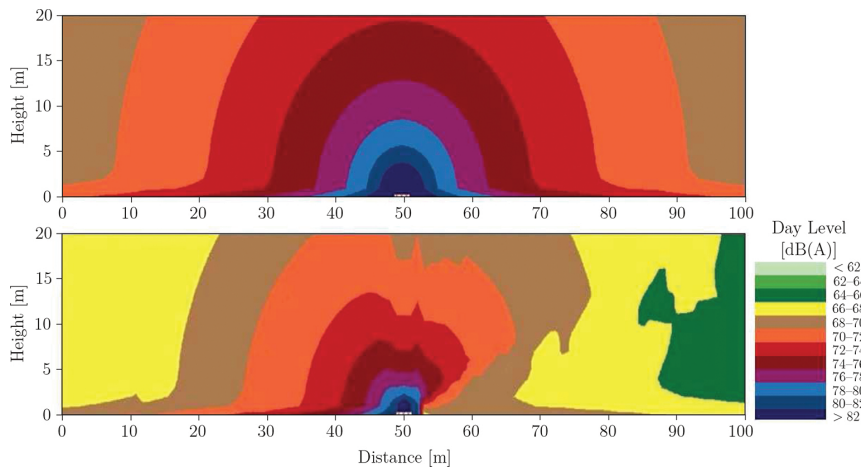


Figure 10. Sound pressure level *SPL* in dB(A) before (reference) and after all mitigation measures were in place [39].

The Quiet-Track Project in Athens Metro NOISE-MITIGATION MEASURES ACTIONS	Overall SPL [dB(A)]	
	Measured	Simulated
Reference	78.1	78.1
Absorbing panels	76.1	76.0
Absorbing panels + noise barrier	69.5	70.7
Absorbing panels + noise barrier + rail dampers	68.0	68.9

Table 2. Comparison of measured and simulated overall sound pressure levels [39].

5. Concluding remarks

As suggested in [1], as vibration prediction models become more complex, they achieve higher accuracy at the expense of an increase in software computational requirements. Four cornerstones of a vibration prediction model are usually interlinked, as shown in **Figure 11**. For instance, a simple empirical model presents a negligible execution time with a high usability. Extensive training is thus not required and the parameter requirements are low. This results in few input parameters which require investigation prior to execution. However, these advantages balance with a poor accuracy of such simplified model.

The most challenging aspect in the study is to develop models for urban cases. The nature of wheel/rail contact must be analysed in-depth in order to develop a comprehensive vehicle/track model. This offers a way to treat complex problems encountered in practice where the train interacts with important local defects and to quantify the effect of these defects according to their size and shape for any possible situation.

Compared to vibration assessment, noise evaluation benefits to a certain degree of maturity. CNOSSOS-EU framework will 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 comparing solutions such as absorbing panels on the track, noise barriers next to the track and rail dampers, considerable positive results may be achieved, ensuring also a very good correlation between predicted and measured noise levels. The developed technology can, therefore, be used without restrictions by all concerned such as engineering companies working in the field, consultants, contractors, operators and infrastructure managers and cities. Therefore, a dissemination strategy for a wide-spread information transfer was also set up, to ensure that the above results need to be integrated into existing standards, informing the relevant stakeholders who will implement the results, maximizing therefore the market uptake by external dissemination activities towards other nonparticipating bodies to monitor and implement specific national needs of the light-rapid-transit operators.

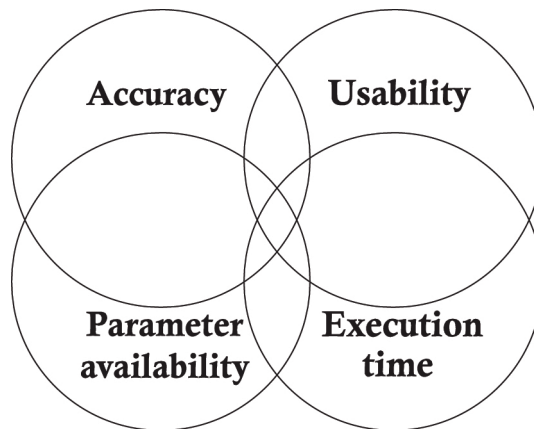


Figure 11. The four desirable characteristics of a vibration prediction model [1].

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