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Environmental Impacts of High-Speed Rail. Part 1: Acoustic Impacts

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Summary
The article discusses issues related to acoustic impacts generated by high-speed railways. It indicates the most important legal regulations concerning noise in railway transport and characterises the main sources of noise generated by high-speed railway lines. It attempts to determine the negative acoustic impact on various elements of the environment during the construction, operation and decommissioning of a high-speed railways. Furthermore, it also outlines the most frequently applied solutions to minimise this impact.

Keywords: noise, acoustic impact, high-speed railway, environmental impact of high-speed railway

1. Introduction

A major challenge in the process of increasing urbanisation is to provide adequate conditions for the rapid movement (Latin: *mobility*) of the population. For this reason, the promotion of the construction or expansion of high-speed railway systems has been noticeable for many years. Maintaining economic growth while taking environmental protection into account is one of the main "obstacles" affecting the further development of the global economy. The increased environmental awareness of society mandates the consideration of the environment in the development of all sectors of the economy, including rail transport. As a result, individual sectors have started to implement environmentally friendly solutions or reduce their negative impact on the environment [1–5].

Rail transport is considered to be one of the most environmentally friendly modes of transport. Emissions of pollutants emitted by means of rail transport to the environment are definitely lower than in the case of road or air transport [6, 7]. Therefore, the further development of the railway system, including high-speed lines, taking into account the principle of sustainable development, is a very important aspect. This principle involves such a socio-economic development, which integrates political, economic, and social activities while maintaining natural balance and permanence of basic natural processes in order to guarantee the possibility of satisfying the basic needs of individual social groups and citizens, both today and for future generations [8].

The implementation of the construction/modernisation of the railway line and its subsequent operation must comply with environmental protection requirements. Consideration of environmental principles will significantly enable the reduction of the negative impact of the investment on the surroundings. A major challenge lies in identifying all the factors that can affect the environment and its processes, not only the obvious ones that are easily measurable (such as noise or air pollution) but also those that are difficult to identify (landscape). Defining all the sensitive elements of the environment, their sensitivity and the most important features and processes will make it possible to identify the threats that may have an adverse impact on its condition and will enable the identification of possible solutions, actions, or safeguards to protect them from negative impacts. The main threats connected with the construction, modernisation, and operation of a high-speed railway line include:

- noise emissions,
- vibration emissions,
- land occupation, change of terrain, impact on the landscape,
- impact on valuable natural areas, including protected areas,
- impact on biodiversity, including protected habitats. plant and animal species,

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- emissions of pollutants into the atmospheric air,
- impact on climate,
- impact on surface and groundwater,
- other impacts (e.g. impacts on historic monuments, cumulative and transboundary impacts) [9].

The first part of the article presents issues related to the acoustic impact generated by high-speed railway vehicles. It discusses the legal aspects regulating noise in high-speed rail transport, characterises its sources, determines the influence of acoustic impacts on the environment and presents the most important noise-reducing solutions.

A report by the European Environment Agency [10] shows that rail transport is the second largest source of noise in Europe. It affects approximately 4% of the population during the day-evening-night period and 3% of the population during the night period, making it one of the more troublesome sources of environmental pollution [11]. Adequate recognition of the impacts generated by high-speed railway vehicles will enable effective selection and implementation of solutions to reduce the impact of noise on the environment and its elements.

2. Assessment of noise nuisance in normative acts

The main legislation laying down rules on protection against rail noise is Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise [12], which aims to define Community measures to reduce noise from major sources, including but not limited to rail transport. Member States are obliged to determine the level of exposure to environmental noise by drawing up noise maps (at least every 5 years) for, inter alia, railway lines on which more than 30,000 train sets pass annually. Common methodologies and assessment indicators make it possible to obtain comparable results from all EU Member States, on the basis of which preventive and mitigating measures are defined for the prevention and protection of acoustic climate quality in areas with no exceedances [13, 14].

When discussing the legal acts that define the framework for rail transport at the European level, it is important to mention the technical specification for interoperability relating to the subsystem 'rolling stock – noise' (hereinafter TSI Noise) [15]. This document defines permissible sound levels for stationary, starting and pass-by noise for railway vehicles, including high-speed vehicles.

Stationary noise is the noise generated by a railway vehicle when stationary in the normal state of engagement of engines and auxiliary equipment, including, but not limited to, cooling systems and air conditioning (compressors). For stationary noise, limit values under normal conditions have been defined for:

- the equivalent continuous sound level A of the unit ($L_{pAeq,T[unit]}$),
- the A-weighted equivalent continuous sound level at the nearest measurement position "i", including the main air compressor ($L^{i}_{pAeq,T}$).

Limits for stationary noise levels for electric multiple units (including, but not limited to, high-speed railway vehicles), are presented in Table 1.

Table 1

Limits for stationary noise levels [15]

Type of rolling stock	$L_{pAeq,T[unit]}$ [dB]	$L^{i}_{pAeq,T}$ [dB]
Electric multiple units	65	68

Starting noise limits for high-speed vehicles for the maximum sound level with A correction and FAST time constant ($L_{pAF,max}$) were set at 80 dB for electric multiple units travelling at speeds of less than 250 km/h. For vehicles with higher speeds, the limit value was set at 83 dB.

For noise from the passage of high-speed vehicles (electric multiple units), the maximum limit values for the equivalent continuous sound level A are defined in Table 2.

Table 2

Limits for pass-by noise [15]

Type of rolling stock	$L_{pAeq,Tp[80\ km/h]}$ [dB]	$L_{pAeq,Tp[250\ km/h]}$ [dB]
Electric multiple units	80	95

For high-speed railway vehicles with a maximum speed of 250 km/h, the pass-by noise must be determined at 80 km/h and at the maximum speed of the unit. If the maximum operating speed v max of the unit is greater than 80 km/h and less than 250 km/h, the pass-by noise must be measured at 80 km/h and at the maximum speed of the unit. Both measured values of the pass-by noise must be normalised to a reference speed of 80 km/h $L_{pAeq,Tp(80\ km/h)}$ based on the following relation [15]:

$$L_{pAeq,Tp(80\ km/h)} = L_{pAeq,Tp(Vtest)} - 30\log\frac{V_{test}}{80\ km/h} \quad (1)$$

where: V_{test} – speed recorded during the measurement.

The normalised value must not exceed the limit value $L_{pAeq,Tp(80\ km/h)}$ set out in Table 2.

For vehicles with an operating speed of 250 km/h or more, the pass-by noise must be measured at 80 km/h and at the maximum speed of the unit, but no more than 320 km/h. The pass-by noise measured at 80 km/h must be normalised, using the relation (1), to a reference speed of 80 km/h $L_{pAeq,Tp(80\ km/h)}$. The pass-by noise values for the maximum speed of the unit must be normalised to a reference speed of 250 km/h $L_{pAeq,Tp(250\ km/h)}$ according to the following relation [15]:

$$L_{pAeq,Tp(250\ km/h)} = L_{pAeq,Tp(Vtest)} - 50 \log \frac{V_{test}}{250\ \text{km/h}} \quad (2)$$

where: V_{test} – speed recorded during the measurement.

The normalised value must not exceed the limit value set for the reference speed of 80 km/h, i.e. 80 dB and 95 dB for a reference speed of 250 km/h.

Environmental protection against noise is regulated by the Environmental Protection Act (EPA) [8] together with implementing acts, which ensure that noise is kept below or at the very least at the permissible level, and where this level is exceeded, that noise is reduced to at least the permissible level. The basic tool defined by the EPA for limiting excessive noise in the environment is the assessment of the acoustic climate of the environment, which implements the provisions of Directive 2002/49/EC [12], as described at the beginning of this chapter.

An important tool for protecting the environment against noise is the determination, by way of a regulation [16], of permissible noise levels caused by individual groups of noise sources, including railways. The regulation divides noise-protected areas according to their function and type of development, establishing different noise limit values for the daytime (6:00 a.m. to 10:00 p.m.) and the nighttime (10:00 p.m. to 6:00 a.m.). Noise limit values for railways, covering the different groups of areas, are presented below (Table 3).

Standards are vital in shaping European and national legislation on environmental noise protection. The most important documents relating directly or indirectly to the acoustic impact of rail transport are standards covering the measurement of noise emitted by rail vehicles [17], the calculation of aerodynamic impacts caused by passing trains [18], requirements for noise protection devices [19–24] and sound attenuation during propagation in open space [25, 26].

3. Noise sources in railway vehicles

Noise generated by passing high-speed rail vehicles depends on many factors ranging from the technical condition of the rolling stock and the railway line to traffic density to terrain and speed [27–29]. Noise sources in rail transport can be divided into 5 groups: rolling noise, impact noise, squealing noise, starting and braking noise and aerodynamic noise. For high-speed rail, the dominant noise sources are rolling noise and aerodynamic noise. With this in mind, for the purposes of this article, the author only characterised these two noise sources.

The sound created at the wheel-rail interface and transmitted to the vehicle structure and track components is known as rolling noise. The main factor generating such noise is wheel and rail vibrations, even

Table 3

Permissible values of noise for railway lines [16]

No.	Intended use of the area	Permissible noise level [dB]	
		L_{AeqD} daytime t = 16 h	L_{AeqN} night-time t = 8 h
1.	a) spa protection areas A, b) hospital premises outside urban areas.	50	45
2.	a) single-family housing development areas, b) developed areas associated with a permanent or temporary stay of children and youth, c) social care homes, d) hospital premises in urban areas	61	56
3.	a) multi-family and collective housing development areas, b) homestead areas, c) recreation and leisure areas, d) residential and service areas.	65	56
4.	Areas in the inner-city zone of cities with more than 100 thousand inhabitants	68	60

though their contact area is only about 1.5 cm^2. The unevenness of the rail and wheel running surfaces leads to vibrations in both components. By spreading, these vibrations condition the generation of the sound radiation of the individual parts, which are the components of rolling noise [27, 30].

The noise at the wheel-rail interface is generated by the roughness of their surfaces (macro roughness), which causes these components to move against each other (vibrate). Vibrations are transmitted to both in-contact structures equally, i.e. regardless of which element has the greater roughness [31]. If a wavelength λ [m] is applied to either part and the vehicle is moving at a speed v [m/s], a sinusoidal vibration will be generated at a frequency f [Hz], according to the following relation [32–34]:

$$f = \frac{v}{\lambda} \tag{3}$$

where:
f – frequency [Hz],
v – vehicle speed [m/s],
λ – wavelength [m].

Rolling noise on high-speed trains is most significant at speeds up to about 200–250 km/h. The rolling noise level is strongly dependent on the vehicle speed and increases by about 9 dB as the speed doubles. The frequency range is between 50 Hz and 5,000 Hz, with higher frequencies characterised by wheel vibrations, medium rail vibrations and lower frequencies corresponding to sleeper vibrations [27, 35–38].

Aerodynamic noise is generated by the movement of particles in an elastic medium (air) and not by vibrations in solids. With this in mind, the higher the vehicle speed, the greater the aerodynamic interactions [39]. While a railway vehicle moves, its various components – primarily the pantograph, the running gear (bogie) and the body – cause non-uniform flows of air layers [40, 41]. Due to the different technical designs of railway vehicles, aerodynamic noise can dominate at different speeds for specific high-speed vehicles. Nevertheless, studies to date have confirmed that this type of noise occurs at speeds above 250 km/h [33, 42, 43].

Around a railway vehicle travelling at high speed, the elastic medium (air) is put into motion, in the form of a flow of layers ranging from free to zero movement (at the surface of the vehicle body). Parallel layers of air move at different speeds, creating disturbances (turbulence) in the movement of the air near the vehicle's surfaces. The thickness of the layer affected by airflow disturbance (the so-called boundary layer) is about 2 m behind the front of the train, increasing significantly along the train's vertical axis and becoming the widest at the track surface [27, 33, 44, 45]. A schematic of the airflow boundary layer is shown in Figure 1.

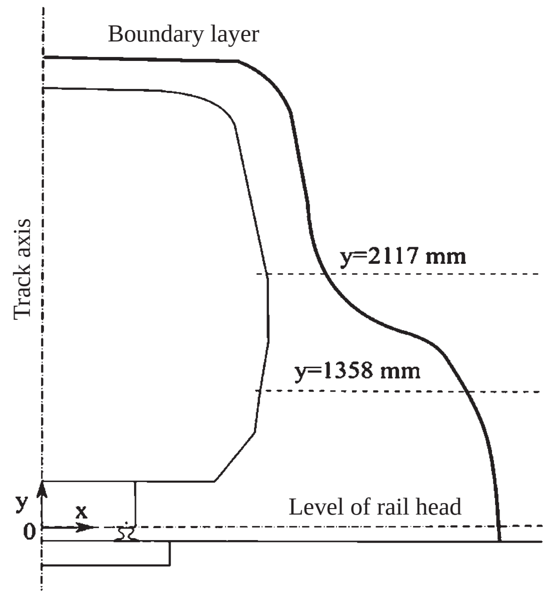

Fig. 1. Airflow boundary layer schematic [40]

The aerodynamic noise spectrum for high-speed trains is considered to be broadband noise, with a frequency range between 800 Hz and 4–5 kHz [46, 47].

4. Impact of high-speed rail on the acoustic environment

Noise is one of the most diffuse pollutants in the environment and is one of the main concerns regarding the environmental impact of high-speed rail projects. Acoustic events on a railway line can be heard as many as several hundred metres away [48]. Noise nuisance depends on many factors, such as the volume of traffic, the type of railway vehicles, the technical condition of the unit and the railway line, and the terrain. Considering the subjective perception of each individual (whether human or animal), acoustic impacts can vary considerably for different sections of a high-speed railway line. Determining the impact of noise on the environment requires knowledge of the local population structures, the state of the natural environment, as well as the land use in the vicinity of the railway line.

When carrying out an impact analysis for the reconstruction or expansion of a high-speed railway line, the impact condition of the existing line should be taken as a reference. The analysis should include an assessment of the impact during the project's construction, operation and decommissioning phases.

During the construction phase, negative acoustic impacts will be related primarily to the operation of heavy equipment and other construction machinery and the need to transport construction materials and raw materials. The level of noise nuisance along the railway line will vary greatly and be more noticeable near the interchange (station), engineering structure and other construction sites, as well as near construction site camps and machine operation areas. Construction work may cause discomfort among nearby residents; however, any such nuisance would be temporary, effectively ceasing once the project is completed. In the case of construction work, we are dealing with short- to medium-term noise. Since the parameters influencing noise emissions, i.e. vehicle types and the technical condition and number of equipment and machines used for construction work and the duration of their operation, are largely unknown, detailed noise predictions for the construction phase are impossible. Based on the list of basic construction machinery used during specific work and a simple relationship defining noise decrease with distance [40], the author believes that no significant risks from noise emissions should be present at 50–70 m from the project site.

Wildlife may be adversely affected during the construction phase as it will be driven away from the settlement areas and forced to change its migration routes or periodically abandon its feeding or breeding grounds. However, as in the case of human impacts, this will be a temporary impact, limited to a certain area, which will cease once all construction work is completed.

During the operational phase, acoustic nuisance will be associated with high-speed vehicle traffic. Information on the types of vehicles, traffic volumes and land use near the high-speed railway line is required to accurately determine the spatial distribution of noise levels. The input data used to develop the noise propagation model would enable the detailed representation of the environmental noise level distribution in the form of isolines. An example map with the noise level isolines from the railway line is shown in Figure 2.

The railway line may cause a nuisance in the neighbouring noise-protected areas like single- and multi-family housing development areas, developed areas associated with a permanent or temporary stay of children and youth, hospital premises, social care homes and spa protection areas. Excessive and prolonged exposure to noise can lead to mental and physical health problems in addition to discomfort.

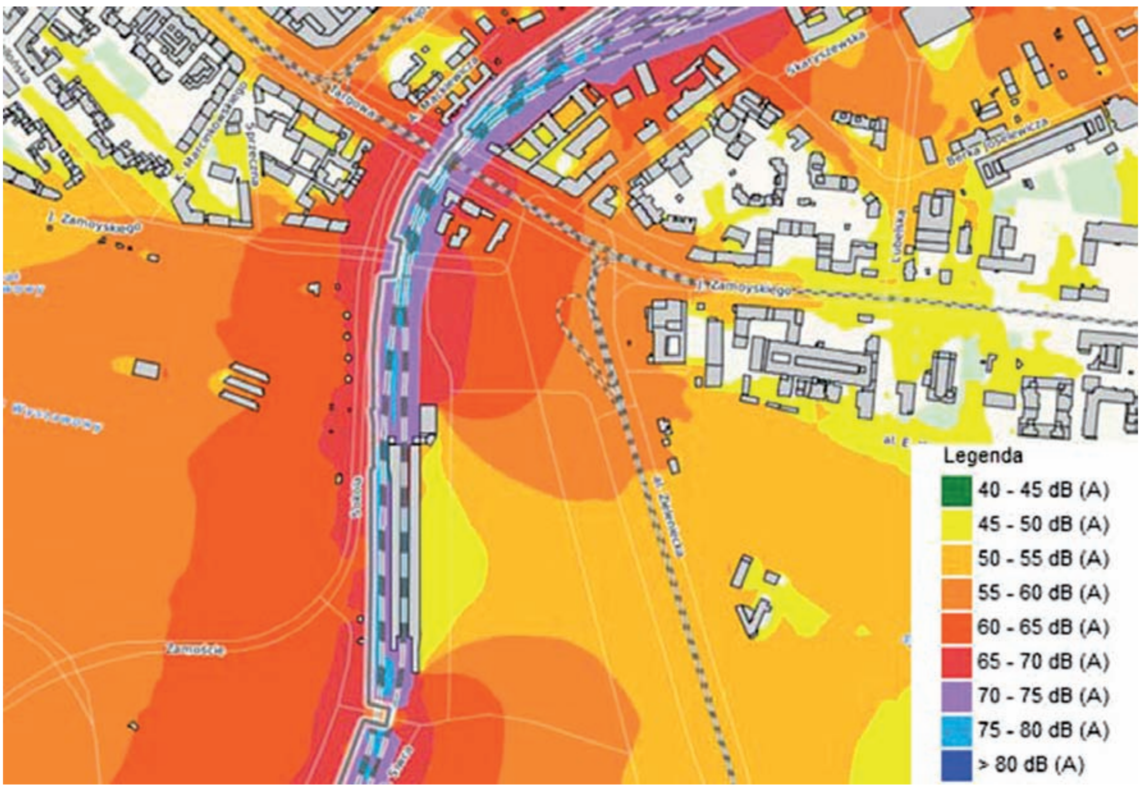

Fig. 2. Example map of a railway line with noise level distribution (isolines) [49]

According to a World Health Organisation (WHO) report [50], noise exposure can cause slow but permanent hearing deterioration by damaging internal hearing system structures. Prolonged or excessive noise results in health problems such as cardiovascular disease, cognitive impairment in children, tinnitus and hearing loss. Noise can also cause poor concentration, increased stress levels, lower productivity at work, as well as irritability, problems communicating with people, chronic fatigue and, in the long term, even immunity problems [51].

Wildlife can also be adversely affected by noise during the operation of a high-speed railway line. Acoustic impacts can have many behavioural and physical effects on wildlife. Excessive noise can scare animals away, causing a barrier effect, i.e. disrupting the cohesion and continuity of migration corridors and preventing animals from accessing feeding and breeding grounds. Long-term noise can also generate stress, limiting the wildlife's ability to reproduce or causing it to abandon existing habitats.

The decommissioning phase of the high-speed rail lines is bound to be associated with similar acoustic impacts as the construction phase. This is because such work will be carried out using similar construction machinery as in the construction phase.

5. Solutions to Minimise Acoustic Impacts

Choosing solutions and measures to protect against railway noise is one of the most important decisions while constructing or modernising railway infrastructure. Proper identification of noise sources is vital, as it enables a more effective selection of actions and measures to reduce acoustic impacts from high-speed rail. The issue of limiting the negative effects of railway noise is frequently addressed in the literature [29, 52–54]. Rail noise mitigation solutions can be broken down into three phases: construction, operation and decommissioning.

During the project implementation/decommissioning phase, the reduction of negative impacts in terms of noise emissions is effected through:

- restricting construction work in the vicinity of noise-protected areas to daytime,
- setting up construction camps and access roads in areas where they will be less of a nuisance to people and animals,
- using modern and efficient construction equipment in good working order,
- regularly inspecting and maintaining construction machinery,
- optimising the use of construction equipment and means of transport (minimising unnecessary trips, limiting idling of machinery, etc.).

At the operational stage, solutions to minimise negative acoustic impacts can be broken down into two groups: those under the responsibility of the high-speed railway line manager and those under the responsibility of the rail carriers (vehicle manufacturers). For noise reduction, high-speed railway line managers typically apply such solutions as:

- line upgrading/refurbishment,
- rail grinding
- installing noise barriers (earth embankments, trenches, noise barriers),
- noise insulation of buildings (replacing windows and doors, installing noise barriers) [9, 40, 55, 56].

In the case of high-speed rail, the widest range of measures to reduce the negative impact of noise on the environment are available to the carriers. The most common solutions include:

- replacing vehicles with modern rolling stock,
- modernising rolling stock (installing modern wheels, slip control systems, replacing cooling systems),
- using aerodynamic pantographs,
- reducing the number of pantographs,
- installing pantograph covers,
- installing bogie covers [57–60].

6. Conclusions

Today's society spends a significant amount of time either travelling or hauling goods so transport is becoming an increasingly important part of everyday life. This trend is forcing the creation of new travel solutions, such as high-speed rail. Increasing train speeds is not an end in itself but merely a means of meeting the demands of the modern world, which include faster rail transport. Nonetheless, accommodations introduced for some (passengers) must not be at the expense of the living conditions of others (people living near high-speed rail lines). Environmental protection must be also taken into account when building/upgrading the high-speed rail system (rolling stock, infrastructure).

This article aims to provide an overview of the acoustic impact of high-speed railway lines. It discusses the most important legal regulations concerning noise in railway transport and characterises the main sources of noise generated by high-speed railway lines. The article attempts to identify the negative acoustic impact on various elements of the environment, together with the most commonly used solutions to minimise this impact.

A detailed knowledge and, above all, understanding of the individual elements of the environment and the processes that take place in it, will enable its effective protection. In turn, state-of-the-art solutions will make it possible to reconcile the desire to increase railway speeds with the need to reduce the acoustic impact on the environment.

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