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Effectiveness analysis of railway noise mitigation measures

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Subject review

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Effectiveness analysis of railway noise mitigation measures

The paper presents an overview of noise propagation mechanisms, wheel–rail interaction models, and the European legislation regulating noise emitted by railway traffic. Acoustic and non-acoustic methods for noise mitigation are described, and their effectiveness is evaluated. Recommendations are given about criteria that can be used for their evaluation so as to ensure the greatest possible level of their compliance with local conditions. The design documentation of Lithuanian international lines is analysed in order to determine noise mitigation measures applied in that region, and to assess their effectiveness.

Key words:
wheel-rail interaction, model, rolling noise, noise mitigation measure, effectiveness

Pregledni rad

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Analiza učinkovitosti mjera za smanjenje razina buke od željezničkog prometa

U radu je dan pregled mehanizama širenja buke, modela interakcije kotača i tračnica te europski propisi koji se odnose na buku od željezničkog prometa. Opisane su akustične i neakustične mjere za smanjenje razina buke te je procijenjena njihova učinkovitost. Dane su preporuke za definiranje kriterija za njihovo vrednovanje kako bi se u najvećoj mogućoj mjeri prilagodile lokalnim uvjetima. Analizirana je projektna dokumentacija litvanskih i međunarodnih željeznica kako bi se prikazalo koje su mjere zaštite primijenjene na toj lokaciji i kako bi se ocijenila njihova učinkovitost.

Ključne riječi:
interakcija kotača i tračnica, model, buka od kotrljanja, mjere smanjenja razina buke, učinkovitost

Übersichtsarbeit

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Analyse der Wirksamkeit von Maßnahmen zur Reduktion von Schienenlärm

In dieser Arbeit wird eine Übersicht von Mechanismen der Lärmausbreitung, Modellen der Räder-Schienen-Interaktion sowie europäischer Vorschriften bezüglich Schienenlärm gegeben. Akustische und nichtakustische Maßnahmen zur Lärmreduktion werden beschrieben und im Hinblick auf ihre Wirksamkeit beurteilt. Empfehlungen zur Definition von Kriterien für ihre Beurteilung werden gegeben, um sie so gut wie möglich den lokalen Bedingungen anzupassen. Die Projektdokumentation litauischer und internationaler Eisenbahnen wird analysiert und entsprechende lokale Schutzmaßnahmen werden aufgezeigt sowie hinsichtlich ihrer Wirksamkeit beurteilt.

Schlüsselwörter:
Räder-Schienen-Interaktion, Model, Schienenlärm, Maßnahmen zur Lärmpegelreduktion, Wirksamkeit

1. Introduction

As the standard of living rises and the quality of life improves and as, at the same time, the territories are becoming more and more urbanized and the need for transport increases, the effect of noise made by transport is increasingly becoming an important issue, especially in densely populated areas. Even though the majority of population is affected by the road transport noise (~ 90 % of the population is affected by the noise levels of > 65 dBA), the railway noise also has a negative effect (1.7 % of the population is affected by the noise levels > 65 dBA) [1]. This is especially important in densely populated zones crossed by railways. For instance, the study conducted at Paneriai railway station (Lithuania) reveals excessive noise limits (> ~ 8 dBA) [2]. In such places, appropriate measures must be taken to protect the surrounding areas from the impact of noise caused by railway traffic.

The problem is that proper noise mitigation measures are not always chosen on the basis of specific local conditions.

The aim of this study is to recommend criteria for choosing optimum noise mitigation measures to abate railway noise, by evaluating local conditions.

In order to suggest an effective solution, the paper looks at the origin mechanism and model of noise caused by wheel–rail interaction. The European legislation that regulates noise emitted by railways is also analysed. Applicable noise mitigation measures are categorized into acoustic and non-acoustic methods, and their expected effectiveness is evaluated.

Sections of RAIL BALTICA, which belongs to the Pan-European Corridor I (line "Warszawa–Kaunas–Riga–Tallinn–Helsinki"), are currently under construction in Lithuania. This kind of development is necessary in order to improve access to European countries. In some locations, these sections pass through densely populated areas where noise mitigation measures (such as noise barriers, window replacement, etc.) must be applied. Construction of other RAIL BALTICA sectors is also planned. It is therefore extremely important to assess noise mitigation measures already designed according to various criteria in order to make an optimum choice for other railway lines. The main problem is that noise reduction measures are not always appropriately chosen and applied. For example, noise barriers are often applied and, although effective, they are not always appropriate for specific local conditions. In addition, they are not always adequately designed and installed.

In order to assess whether the noise mitigation measures presented in the corresponding design documentation are also effective in other circumstances, the paper includes recommendations on criteria that could be applied to evaluate various noise mitigation measures. These criteria were most often used in the design of the Lithuanian railways. The dependence of the average declared (design) effectiveness of different materials used in noise barriers designed for RAIL BALTICA on the distance to rail axis was also evaluated.

2. Wheel–rail noise mechanism and models

Railway-related noise is most often caused by the wheel–rail interaction, which may be divided into three groups [3]:

- Rolling noise. The roughness of the wheel and rail surface is the basis for rolling noise occurring on straight tracks. This is the reason why relative vertical vibration occurs. Rolling noise is basically a linear process.
- Impact noise. This is a more severe case of rolling noise. However, it is not a linear process. The impact noise occurs due to cracks (defects) on the surface of the wheel or rail.
- Squeal noise. This kind of noise occurs in small-radius curves. It is usually due to lateral wheel to rail interaction.

Townes et al. [4] provide a slightly different categorization of the noise due to wheel–rail interaction:

- Noise at tangent track
- Noise at curve
- Impact noise occurring because of the joints, special trackwork, etc.

Rolling noise with a typical frequency range between 100 and 5,000 Hz occurs more often compared to other types of noise, such as the squeal or impact noise [5]. The following are four mechanisms of a simple rolling noise [4]:

- Roughness of wheels and rails
- Variation in parameters or moduli heterogeneity
- Creep
- Aerodynamic noise.

The rolling noise is the primary origin of noise caused by a railway, and will be discussed later on in the paper.

When the wheel interacts with the rail, the rolling noise is produced at the point of their contact. Significant noise emission is caused by both the rail and the wheel [1]. A (relative) vertical displacement between the rail and the wheel is produced by the wheel–rail roughness [1, 6].

High-frequency vertical vibrations occur at the contact area and are transferred to both structures. The structures vibrate and spread noise to the surrounding air [1].

The standard linear model of wheel/rail rolling noise generation is a parallel impedance model. This model is suitable for a normal rolling noise when wheels and rails are in good condition. However, this model does not cover many situations: nonlinear processes caused by large roughness, lateral forces, etc. [4].

The wheel–rail system consists of two dynamic systems that interact at a point and affect each other when relative displacement occurs. In parallel with these systems, there is a contact spring, which is another system [4].

There are two main models of noise caused by wheel–rail interaction: frequency domain model and time domain model.

The most comprehensive and the most widely used frequency domain model was established 40 years ago by P. Remington. Later on his model was improved by D. J. Thompson. The frequency domain is a linear model that does not depend on time [7]. This model is based on the assumption that the interaction between the roughness of the rail surface and that of the wheel surface creates vibration. This leads to rolling noise. Based on this model, the TWINS (Track–Wheel Interaction Noise Software) model was created 25 years ago [5]. The noise of different wheels or tracks (rails and sleepers), generated during train passage, may be evaluated with the TWINS model. Various theoretical models may be involved in the TWINS model in order to evaluate roughness, wheel–rail interaction, wheel dynamics, track dynamics, and sound radiation [6].

Many tests were conducted with the purpose of checking reliability of the TWINS predictions. The following results were obtained: overall differences between the measured noise and predicted noise are relatively small [8-10]. The difference between the measured noise and predicted noise is about 2 dB, while the standard deviation is about 2.0 dB [8, 9].

Later on, several model modifications were made, such as the possibility to model the slab track, bogie-mounted shields, and low-noise barriers [11]. In addition, the calculation procedure of the TWINS model was improved by creating the RRNPS (Railway Rolling Noise Prediction Software) model, which also features a graphical user interface. After comparing the RRNPS model with the TWINS model, it was found that noise predictions results obtained with the RRNPS model were also reliable in European conditions. This model may also be used to evaluate dynamic properties of rail pads, etc. [12].

Although the frequency domain model is suitable for rolling noise predictions, the time domain model may be needed in order to predict the squeal noise or the impact noise, when there is a stronger roughness or uneven epure of a railway, etc. [13]. With each model, it is possible to either include or exclude a certain property, e.g., discrete supports, parametric excitation, and nonlinear contact spring [7]. With the frequency domain model, the noise is calculated relatively simply and quickly. On the other hand, this model does not involve nonlinear processes. The time domain model, which also involves nonlinear processes, was developed over 20 years ago by M. Heckl.

The time domain model is based on the modelling with finite elements [14]. This model may involve nonlinear processes of all types. The main cases in which these processes are formed are severe roughness and/or low static preload [15]. Nonlinear Hertzian contact mechanics can be used, but is less realistic than a discretized contact region allowing for rough surfaces. The wheel is a rigid mass [7].

The RRNPS can be utilized as a predictive tool to investigate new strategies aimed at controlling and mitigating railway rolling noise growth due to corrugation and rail roughness growth [16]. The TWINS model is frequently and widely used when creating new elements making low sound, e.g. wheels, rail and wheel dampers. It is also used to evaluate effectiveness of these elements. TWINS and models similar to it may be used in the future to change actual tests into virtual ones. The TWINS model also served as a basis for creating new legislation regulating noise made by railways, e.g. Commission Regulation (EU) No. 1304/2014 [5].

3. Railway noise regulation

Appropriate regulations have been passed (non-acoustic noise mitigation measures) in an attempt to reduce noise generated by railways, or its effect on the environment.

Directive 2008/57/EC [17] determines basic environmental requirements: rail system impact on the environment must be assessed at the design stage. In addition, railways must meet all regulatory requirements that are related to noise emission.

The Directive 2002/49/EC [18] establishing that European member countries must *inter alia* prepare strategic noise maps was passed in 2002. The Commission Decision 2006/66/EC of 23 December 2005 [19], which concerns technical specification for interoperability relating to the subsystem "rolling stock – noise" of the trans-European conventional rail system, was issued in 2005. The technical specification for interoperability is applied for measuring or regulating noise made by freight wagons, locomotives, rolling stocks coupled in a row, and passenger coaches. The 2008 Communication from the Commission to the European Parliament and the Council – "Rail noise abatement measures addressing the existing fleet" [20] establishes that the best solution to modernise all European freight wagons is the combination of differentiated charge based on the noise made for using the railway, highest noise limits, and voluntary obligations.

The "Railway rolling stock – noise" subsystem TSI [21] applies to all rolling stock. The highest limit values for different types of noise are given in this TSI. In addition, the Control-command and signalling subsystem TSI [22] and the Control, management and signal subsystem TSS [23], indicate that the control-command equipment must meet all regulatory requirements that are related to noise emission.

Usually, every EU country regulates separately the limit values of noise affecting the environment (see Table 1).

Valid limit values for some European countries show that different European countries use different noise indicators to evaluate noise. Also, different countries have different limit values for the same indicators. In some countries requirements differ depending on the type of transport. Other countries apply the same requirements for noise made by cars and railways. In some countries, limit value requirements also depend on the territory and buildings that need to be protected.

According to hygiene standard HN33:2011 [26], noise limit values are assessed by measurements and (or) modelling. Noise measurement results are compared with limit values (see Table 1).

The regulations are a bit of an embarrassment – according to hygiene standard HN33:2011 [26], non-steady noise is assessed at the design stage by the equivalent sound pressure level in reference time interval, or by annual noise indicators L_{den}, L_{day}, $L_{evening}$ and L_{night}. However, according to hygiene standard HN33:2011 [26], the non-steady noise after installation is

Table 1. Noise limit values used in some EU countries [24-28]

Country	Field of application	L_{den} [dB(A)]	L_{day} [dB(A)]	$L_{evening}$ [dB(A)]	L_{night} [dB(A)]	L_{AeqT} [dB(A)]	L_{Amax} [dB(A)]
Austria[1]	Rail-traffic noise	–	70	–	60	65-70 $L_{Aeq(day)}$ 55-60 $L_{Aeq(night)}$	–
Belgium (Flemish Region	Rail-traffic noise (outdoor)	–	–	–	–	40-60 $L_{Aeq(7-19)}$ 35-55 $L_{Aeq(19-22)}$ 30-55 $L_{Aeq(22-7)}$	–
Belgium (Wallonia Region)	Rail-traffic noise (outdoor)	–	–	–	–	50-60 $L_{Aeq(7-19)}$ 45-55 $L_{Aeq(6-7\&19-22)}$ 40-50 $L_{Aeq(22-6)}$	–
Belgium (Brussels Capital Region)	Rail-traffic noise (outdoor)	–	–	–	–	65 (70)[2] $L_{Aeq(7-22)}$ 60 (65)[2] $L_{Aeq(22-7)}$	–
Denmark[1]	Rail-traffic noise	–	–	–	–	63 $L_{Aeq(24h)}$[3]	85[3]
Estonia[4]		–	–	–	–	–	–
Finland	Rail-traffic noise	–	–	–	–	58 $L_{Aeq(day)}$ 53 $L_{Aeq(night)}$	–
	Residential areas, etc.	63	–	–	52	–	–
	New residential areas, etc.	63	–	–	47	–	–
	Holiday settlements, etc.	53	–	–	42	–	–
France	Rail-traffic noise	73	–	–	65	63 (60)[5] $L_{Aeq(day)}$ 58 (55)[5] $L_{Aeq(night)}$	–
Germany[1]	Rail-traffic noise	–	–	–	–	67 $L_{Aeq(day)}$ 57 $L_{Aeq(night)}$	–
Greece		–	–	–	–	–	–
Hungary	Rail-traffic noise	63	–	–	55	–	–
Latvia	Rail-traffic noise: Residential areas (with detached houses), etc.	–	50	45	40	–	–
	For residential areas, etc.	–	55	50	45	–	–
	For areas with multifunctional buildings	–	60	55	45	–	–
	For business areas, public areas, etc.	–	60	55	50	–	–
Lithuania	Residential buildings (houses) and public service function buildings (except the catering and cultural buildings) environment, affected by transport noise	65	65	60	55	65 $L_{Aeq\ (6-18)}$ 60 $L_{Aeq\ (18-22)}$ 55 $L_{Aeq\ (22-6)}$	70 $L_{Aeq\ (6-18)}$ 65 $L_{Aeq\ (18-22)}$ 60 $L_{Aeq\ (22-6)}$
Poland	Rail-traffic noise: Health centres, hospitals located outside cities	–	50 L_{DWN}	–	45 LN	50 $L_{Aeq\ D}$ 45 $L_{Aeq\ N}$	–
	One-family houses, hospitals located in cities, etc.	–	64 L_{DWN}	–	59 LN	61 $L_{Aeq\ D}$ 56 $L_{Aeq\ N}$	–
	Multifamily houses, recreation areas outside cities, etc.	–	68 L_{DWN}	–	59 LN	65 $L_{Aeq\ D}$ 56 $L_{Aeq\ N}$	–
	City centres (city > 100 000 inhabitants)	–	70 L_{DWN}	–	65 LN	68 $L_{Aeq\ D}$ 60 $L_{Aeq\ N}$	–

Tablica 1. Dopuštene vrijednosti razina buke u nekim državama Europske unije [24-28] - nastavak

Country	Field of application	L_{den} [dB(A)]	L_{day} [dB(A)]	$L_{evening}$ [dB(A)]	L_{night} [dB(A)]	L_{AeqT} [dB(A)]	L_{Amax} [dB(A)]
Portugal	Rail-traffic noise: Noise-sensitive zone (residential, hospitals, schools)	55	–	–	45	–	–
	Mixed zone, etc.	65	–	–	55	–	–
	Areas not yet classified by municipality	63	–	–	53	–	–
	Line projected when approving noise-sensitive zone	60	–	–	50	–	–
Slovakia	Rail-traffic noise	60	–	–	50	–	–
Slovenia	Rail-traffic noise: For noise-sensitive areas (hospitals, etc.)	–	54 (57)[2]	–	44 (47)[2]	–	–
	For less noise-sensitive areas (solely residential areas, etc.)	–	59 (63)[2]	–	49 (53)[2]	–	–
	For less noise-sensitive areas (agricultural areas, etc.)	–	64 (69)[2]	–	54 (59)[2]	–	–
	For noise-insensitive areas (industrial areas, etc.)	–	69 (80)[2]	–	59 (70)[2]	–	–
Sweden	Rail-traffic noise	–	–	–	–	58 $L_{Aeq(24h)}$	45 L_{Amax} (indoors)
The Netherlands[1]	Rail-traffic noise	–	–	–	57	63 $L_{Aeq(day)}$ 58 $L_{Aeq(evening)}$ 53 $L_{Aeq(night)}$	–

[1] For rail + 5 dBA if compared with the noise limit value for road.
[2] New noise sources (Current noise sources).
[3] New railway line.
[4] Individual noise levels that depend on local conditions.
[5] Bracketed values are for TGV lines.
– data not available.

assessed by the equivalent sound pressure level (L_{AeqT}) and maximum sound pressure level (L_{AFmax}) only. The assessor is not sure how to check effectiveness if during the design stage the effectiveness of noise mitigation measures is assessed using annual noise indicators L_{den}, L_{day}, $L_{evening}$ and L_{night}.
In addition, there is a specific case in Lithuania for "Railway rolling stock – noise" subsystem TSI [21] when the gauge is 1520 mm. National regulations can be used for the rolling stock that uses this type of gauge.

4. Classification of railway noise mitigation measures

4.1. Acoustic classification of railway noise mitigation measures

A number of noise mitigation measures are applied across the world with regard to the source of noise, noise propagation path, and effect on neighbouring buildings. For example, one of the methods to reduce the noise emitted by wheel–rail interaction is to increase the size of the contact area between them or to decrease the contact stiffness (5–10 dB reduction) [29]. Noise mitigation measures may also be used together, e.g. overlapping screens (bogie-mounted shields together with low noise barriers). Studies were conducted to determine efficiency of very low noise barriers mounted next to the railway together with the bogie-mounted shields. The highest efficiency was achieved when these two elements were used together [30].
Table 2 presents noise mitigation measures categorized as acoustic and non-acoustic. In addition, their expected effectiveness is provided in accordance with international practice.
It can be seen that the range of noise mitigation measures is quite broad. They may be chosen depending on the type of noise that needs to be reduced. Damped wheels are not very effective on straight track sections. On the other hand, they are quite effective as a means to reduce squeal noise at sharp curves. Rail grinding or wheel truing is not necessary on straight tracks if the rails or wheels are in good condition [4].

Table 2. Noise mitigation measures for railways

Method	Group	Element	Noise mitigation measure	Expected effectiveness
Acoustic methods	at the source	rolling stock	change brake blocks	8-10 dB(A) [31]
			design of a wheel (shape of a wheel, diameter of a wheel, etc.)	0-6 dB(A) [32]
			material of a wheel (elastic, multiple materials, etc.)	up to 5-10 dB(A) [33]
			wheel absorbers	1-3 dB(A)[1] [31]
			vehicle-mounted friction modifiers [30]	–
			effective muffling of diesel locomotive exhaust noise, cooling systems that emit low noise, air gap noise control (mufflers, active control systems)	up to 13 dB(A) [32]
			hoods	0-10 dB(A) [32]
			low-noise pantograph (in high speed electric lines) pantograph head shape optimization, special materials like porous coating of pantographs, shielding, etc.)	up to 4 dB(A)[8] [32]
			regular maintenance (wheel truing, supervision of wheels	up to 20 dB(A) [32]
		track and substructure[2]	design of a track (different track forms, etc.)	–
			rail absorbers	1-3 dB(A)[1] [31]
			track-side lubricators and friction modifiers [32]	–
			resilient track (resilient base plates, special rail dampers, etc.) [34]	–
			avoiding sharp shift in substructure or track geometry [34]	–
			railway embankment sound absorption with positive retention system	0-5 dB(A) [32]
			track with concrete sleepers instead of wooden sleepers	1-3 dB(A) [35]
			ballast-and-sleepers track instead of concrete slab	4-5 dB(A)[3] [4]
			jointless track	0-5 dB(A)[4] [32]
			change installation places of signals in noise-sensitive areas, etc. [25]	–
			regular maintenance (rail grinding, etc.)	up to 20 dB(A) [31]
	on the propagation path	–	noise barriers (walls, embankments, edge-modified noise barriers, natural gabions noise barriers, greenery, trenches, cuttings, etc.)[5]	0-15 dB(A) [31]
			enclosures	10-30 dB(A)[6] [31,36]
	at the neighbouring buildings	–	noise-insulated windows	10-30 dB(A)[7] [31]
			facade insulation (green wall, double facade, etc.)	–
			door sound insulation	0-10 dB(A) [32]
Non-acoustic methods	–	regulation	noise-related directives, limit values, action control, etc. [32]	–
	–	socio-economic means	social means (public education, staff education, etc.)	–
			economic means (rail infrastructure charges of high noise polluters, financial support means, compensation, etc.)	–
	–	spatial planning and management	buildings placed away from the source, building design, building (rooms) layout, shape and arrangement of building walls, orientation of building, parks and green spaces design, spatial zoning, buildings that are not sensitive to noise (e.g. noise barriers), etc.	up to 20 dB(A) [32]
	at source	controlling rail traffic	limiting train speed, traffic planning, traffic routing	up to 20 dB(A) [32]
	at source	track design	using alternative track (far from noise-sensitive areas) [25]	–

[1] 4 to 8 dB(A) [37].
[2] Specific rail systems technology can be applied, for example, the magnetic levitation principle. Also, the electrification of a railway line;
[3] Specific ballastless track type can be applied, e. g. embedded rail structure; elastic base plate; covered sleepers like Sedefmolded sleepers, eg. "Rheda"; floating plate like "Shinkansen", etc [32].
[4] 2 to 10 dB(A) [33].
[5] a set of measures can be applied, e.g. bogie - mounted shields with low noise barriers – up to 10 dBA [34,37].
[6] in some cases noise can be eliminated completely.
[7] 0 to 40 dB(A) [33].
[8] Shielding of pantographs – 5 to 10 dBA [34].

4.2. Noise mitigation measures in Lithuanian railway design documentation

During the planning/design of noise mitigation measures, non-steady noise was assessed according to the equivalent sound pressure level in the reference time interval L_{AeqT} (in railway corridor IX B Vilnius bypass Kyviškės-Valčiūnų section and railway sections Kyviškės-Vaičiūmai and Vaidotai (Pušynas)-Paneriai). However, in other design documentations, non-steady noise was assessed according to L_{den}, L_{day}, $L_{evening}$ and L_{night} (railway section Naujoji Vilnia-Kaišiadorys and RAIL BALTICA (railway section Marijampolė-Šeštokai)).

Table 3 shows noise mitigation measures and their declared (design) effectiveness in Lithuanian railway design documentation (railway corridor IX B Vilnius bypass Kyviškės-Valčiūnų section and railway sections Kyviškės-Vaičiūnai and Vaidotai (Pušynas)-Paneriai), railway section Naujoji Vilnia-Kaišiadorys and RAIL BALTICA (railway section Marijampolė-Šeštokai)).

The design documentation of RAIL BALTICA (railway section Marijampolė-Šeštokai) was analysed with respect

Table 3. Noise mitigation measures in Lithuanian railway design documentation

Designed noise mitigation measure	Features of noise mitigation measure[1]	Declared (design) effectiveness of noise mitigation measure
RAIL BALTICA (RAILWAY SECTION MARIJAMPOLĖ-ŠEŠTOKAI)[2]		
Noise barrier made of non-transparent aluminium sound-absorbing panels	H = 2.0 m; L = 3.1[3]-4.5 m	10-15 dB(A)
Noise barrier made of transparent sound-absorbing panels	H = 2.0-4.0 m; L = 4.2-9.6 m	2-20 dB(A)
Noise barrier made of "Durisol" type blocks	H = 2.0-3.5 m; L = 3.8-15 m	2-15 dB(A)
RAILWAY CORRIDOR IX B VILNIUS BYPASS KYVIŠKĖS-VALČIŪNŲ SECTION		
Noise barrier made of aluminium (1) or noise barrier made of aluminium (up to 1 m in height) and transparent plastic (2)	(1) H = 3.0-3.5 m; L = 4.0 m (2) H = 2.8 m; L = 4.0 m	25 dB(A)
Noise barrier made of aluminium (1) or noise barrier made of aluminium (up to 1 m in height) and transparent plastic (2)	(1) H = 3.5 m; L = 3.8 m (2) H = 2.8 m; L = 3.8 m	30 dB(A)
Embankment, planted with hawthorn, rowan and thorns	H = 5 m. width-26/6	> 20 dB(A)
Stripe of thuja	Height of thuja H=1.8 m planted in a chess order 1 m from each other	5 dB(A)
Noise-insulated windows with acoustic vent		30 dB(A)
RAILWAY SECTION NAUJOJI VILNIA-KAIŠIADORYS		
Noise barrier	H = 1.5-4.0 m	5-15
Sectors with rail dampers (absorbers)	-	3 dB for passengers trains and 4 dB freight trains
Exchange of brake blocks		8-10[4]
RAILWAY SECTIONS KYVIŠKĖS-VAIČIŪNAI IR VAIDOTAI (PUŠYNAS)-PANERIAI		
Noise barrier	H = 2.5-3.5 m; L = 3.8 m; on the one hand absorption – 0.6.	5-10 dB
Rail grinding		For freight trains, 4–7 dB; for passenger trains, 6–12 dB; and for intermodal rail, 7–8 dB
Window replacement / additional glazing		All buildings: open windows –10 dBA Frame buildings: single glazing (closed) – 20 dBA Masonry buildings: single glazing (closed) – 25 dBA Double glazing (closed) – 35 dBA

[1] H – height of noise mitigation measure [m]. L – distance of noise mitigation measure from rail axis [m].
[2] design documentation also includes sections with jointless track that are also considered a noise mitigation measure, but it was not evaluated upon planning noise mitigation measures.
[3] on viaducts and bridges. [4] international practice.

to implementation of noise barriers. Three types of noise barriers, each made of a different material, were modelled at this section: aluminium sound-absorbing panels, transparent sound-absorbing panels, and "Durisol" type blocks. Further modifications can be made after analysis of technical segments of railway design. When modelling noise pollution near residential buildings and public buildings, the analysis point is set 1 m away from the nearest building wall and no less than 1.5 m above the ground level. While modelling at the second and higher floors, 3 m was added for each level.

The following was established during analysis of the design documentation: declared (design) effectiveness and average distance from the track axis of noise barriers made of different materials in RAIL BALTICA (Railway section "Marijampolė-Šeštokai") are given in Figure 1, Figure 2, and Figure 3.

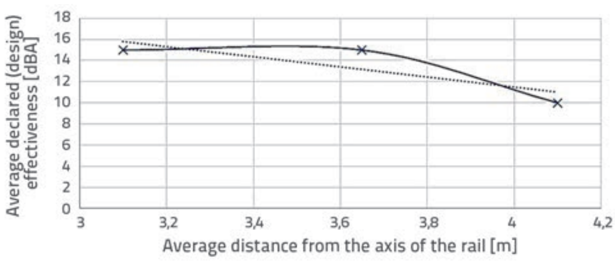

Figure 1. Average declared (design) effectiveness and average distance from track axis of non-transparent noise barrier (made of aluminium sound-absorbing panels)

It could be stated that the declared (design) effectiveness of the non-transparent noise barrier (made of aluminium sound-absorbing panels) depends partly on the distance from rail axis, i.e. the mounting place of the barrier itself, because the noise barrier installed at the greatest distance is acoustically the least effective. On the other hand, in this RAIL BALTICA section there are only 3 noise barriers of this type, and it could be argued that the effectiveness may have been affected not only by the distance from rail axis, but also by other parameters, such as height of the noise barrier and terrain.

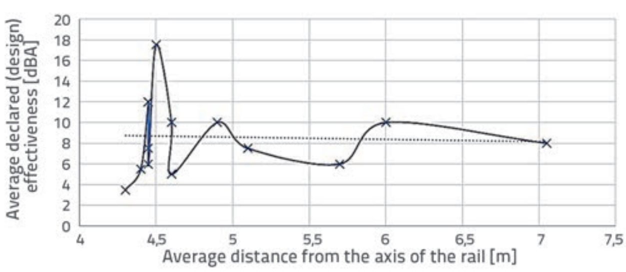

Figure 2. Average declared (design) effectiveness and average distance from track axis of transparent noise barrier (made of sound-absorbing panels)

After evaluation of declared (design) effectiveness of the transparent noise barrier (made of sound-absorbing panels), it can be said that it does not exclusively depend on the distance from rail axis. That is because the barrier of the highest effectiveness (~ 17 dBA) and the barrier of the lowest effectiveness (~ 3 dBA) are almost at the same distance from rail axis, i.e. – 4.5 m and 4.3 m, respectively. Hence, even though the distance is almost the same and the noise absorbing material is also basically the same, the effectiveness differs by more than 5 times. Moreover, it can be observed that the noise barrier at a relatively long distance from rail axis (~ 7 m) has a relatively higher effectiveness of – 8 dBA.

Therefore, the following factors should be taken into account during the modelling: topographical conditions, type of ground surface, type of building (residential building or public building), and communication structures (roads, railways, etc.) location and measurements, greenery, pools, local atmospheric conditions, etc.

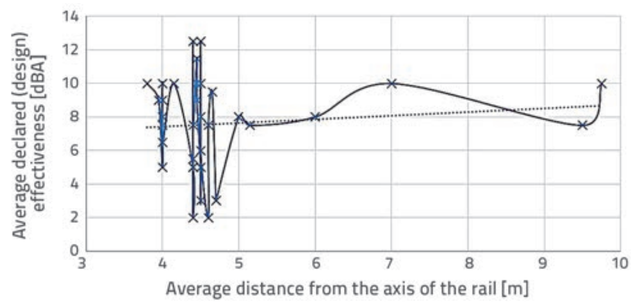

Figure 3. Average declared (design) effectiveness and average distance from track axis of non-transparent noise barrier (made of "Durisol" type blocks)

The declared (design) effectiveness of the non-transparent noise barrier (made of "Durisol" type blocks) may also be evaluated in the same manner, i.e. it does not actually depend on the distance from rail axis. For instance, eighteen noise barriers are mounted at a distance of 4.4 to 4.6 m from track axis, with the effectiveness ranging from 2 dBA to ~ 12 dBA. Moreover, one noise barrier is also mounted at 9.8 m from the axis, but its effectiveness is relatively high – 10 dBA.

It can therefore be stated that the effectiveness of a noise barrier does not necessarily depend on its distance from rail axis, i.e. a high effectiveness may be achieved after mounting a noise barrier at a rather long distance from the source of sound. However, a high effectiveness may also be achieved after mounting a noise barrier at a short distance from the source of noise. On the other hand, there may be cases when a small effectiveness is reached after mounting the barrier at a short distance. It is believed that this effectiveness is determined by other conditions as well (terrain, neighbouring buildings, etc.).

Nevertheless, it can be claimed that the effectiveness is closely related to the type of material the noise barrier is made of. After analysing the noise barrier established by RAIL BALTICA (railway section Marijampolė–Šeštokai), it was found that the lowest average effectiveness is obtained for non-transparent noise barriers (made of "Durisol" type blocks) – 7.6 dBA. A slightly higher average effectiveness is obtained for transparent noise barriers (made of sound-absorbing panels) – 8.6 dBA. The highest average effectiveness is obtained for non-transparent noise barriers (made of aluminium sound-absorbing panels) – 13.3 dBA. It should however be noted that even though the effectiveness of transparent noise barriers (made of sound-absorbing panels) is not very high, such noise barriers do have their advantages: they ensure better visibility (e.g. at a crossing), and are more acceptable to the residents staying in a residential area because they do not create a blind wall view, etc.

5. Recommendations for selection of railway noise mitigation measures

Following evaluation of a relatively wide range of noise mitigation measures, and taking into account the fact that sources of noise and, accordingly, their mitigation measures may differ, it is very important to select an optimal noise mitigation measure after evaluation of local conditions. In practice, noise mitigation measures are very often chosen on the basis of the effectiveness criterion, i.e. depending on the extent to which such measures are expected to reduce noise. However, it was noticed that not all noise mitigation measures may be evaluated according to their effectiveness criterion. For instance, this makes it complicated to evaluate prolonged non-acoustic noise mitigation measures (socio-economic means, spatial planning and management, etc.). Hence, upon choosing a noise mitigation measure, it is very important to evaluate other criteria as well, such as traffic safety and economic criteria.

We suggest that evaluation of noise mitigation measures be done on the basis of the guidance scheme provided in Table 4, which also includes noise mitigation measures that are most often used in the design of Lithuanian railways.

Noise barriers are the most popular noise mitigation measure in Lithuanian railway design documentation (see Table 3). This measure is quite effective acoustically (0–15 dBA). On the other hand, it has some negative aspects, when evaluation is made according to other criteria. For instance, as illustrated in Table 4, it is rather expensive to mount and maintain noise barriers; this measure may limit the visibility at crossings, especially if it is a non-transparent noise barrier. On the other hand, even a transparent noise barrier may limit visibility under certain local conditions, e.g. dew, snow or mud. Moreover, these noise mitigation measures may not always match the environment, especially if road engineers are not consulted by architects during their design, etc.

Other noise mitigation measures (e.g. sectors with rail dampers (absorbers), rail grinding, etc.) are rarely designed, prepared and used in Lithuania. Some noise mitigation measures are seldom used for railways, e.g. territory planning measures, and economic measures (rail infrastructure charges for high noise polluters, financial support, etc.). Thus, the need and possibilities

Table 4. Assessment of noise mitigation measures in Lithuanian railway design documentation depending on various criteria

Criteria	Noise mitigation measure							
	window replacement / additional glazing	noise barrier	planted embankment	stripe of thuja	sectors with rail dampers (absorbers)	exchange of brake blocks (eg. LL- brake blocks)	rail grinding	jointless track
Effectiveness (design or world practice), dBA	0-30 (40) [1]	0-15	0-15	5 [2]	0-6	8-10	1-3	0-10
Traffic safety	0	- [3]	- [4]	- [4]	0	0 [5)]	0	0
Costs (mounting and maintenance)	Average	Significant	Average	Average	Significant	Significant	Average	Significant
Acceptance by the society	+	- [7]	+	+	0	0	0	0
Applicability	+ [8]	+ [9]	- [10]	- [11]	+	+	+	+
Impact on the environment	0 [12]	- [13]	+	+	0	0	0	0

[1] Effective only after closing windows or using special ventilation vents. [2] To achieve effectiveness, the vegetation belt must be wide, very high and thick. [3] The visibility at crossings may be limited if the noise barrier is high. In case of partially or completely transparent noise barriers, the visibility may also be limited, especially if glass is misty. [4] Visibility at crossings may be restricted.
[5] Brake systems must be tested in order to ensure safety. [6] Relatively not high if, for example, there is primer from spoil. [7] May limit the pedestrian crossing over the railway. May create visual pollution and obstruct the view. Partially or completely transparent are more acceptable to the society. [8] Protects the building only if it is sufficiently sound-proof. [9] Protects the surroundings of the building as well, e.g. yard. [10] Takes up a lot of space. [11] In order to increase effectiveness, the vegetation belt must be broadened.
[12] May even be positive – greater resistance windows may be installed that way, ensuring a lower heat output.
[13] May create a visual pollution, especially if they are not designed by architects; may block air flows (air quality will deteriorate).
Legend: + positive impact; - negative impact; 0 no impact.

for using other noise mitigation measures (means) should be analysed in the future, based on appropriate evaluation criteria. After identification of rolling noise emanating from the wheel–rail interaction as the primary source of noise caused by railways, and in addition to elimination of the roughness itself (by changing the front brake systems of rolling stock, by applying a constant maintenance of rails and wheels (wheel truing, rail grinding)), it should be considered whether low noise barriers should be used instead of standardly applied high barriers. The low barriers would be installed by the rail because the rolling noise basically originates at the ground level, i.e. at the track. The best effectiveness can be ensured by using these barriers together with the mounted wagon hoods.

6. Conclusions

The wheel–rail interaction is the main source of noise generation in railway transport. Therefore, it is very important to take this factor into consideration when designing noise mitigation measures. A proper evaluation of noise level and selection of right measures is strictly required in cities or other populated areas traversed by or close to a rail line.
Railway noise evaluation indicators and/or limits vary from country to country. In some countries limit values vary with the transport mode and in others such values are the same for roads and railways. In Lithuania, the main mismatch is that design noise limit values and noise limit values for constructed infrastructure and mitigation measure' effectiveness are not the same. There is a problem in evaluating measures that were designed by annual noise indicators L_{den}, L_{day}, $L_{evening}$ and L_{night}.
In general, two main noise mitigation methods could be applied in railways: acoustic (changing of brake blocks, applying less noisy rolling stock, jointless track, rail absorbers, carrying out regular maintenance, noise barriers, etc.) and non-acoustic (regulation, socio-economic measures, territory planning, etc.). It could be stated that there are plenty of noise mitigation measures to be applied for rails, and hence the need for their proper selection.

Noise walls are the most popular railway noise mitigation measure in Lithuania. The analysis of technical documentation for the RAIL BALTICA section (railway section "Marijampolė-Šeštokai") led to the conclusion that the type of barrier and material are more significant for noise reduction than the distance of the barrier from rail axis. The analysis of RAIL BALTICA (railway section Marijampolė-Šeštokai) showed that the average effectiveness of non-transparent noise barriers (made of "Durisol" type blocks) is up to 7.6 dBA; transparent noise barriers (made of sound-absorbing panels) are more effective – up to 8.6 dBA; and the highest effectiveness is obtained by using non-transparent noise barriers (made of aluminium sound-absorbing panels) – up to 13.3 dBA.
During design or modelling processes, noise barriers are most often selected solely on the basis of their effectiveness. After a detailed best practice analysis, some additional measure-selection criteria were proposed (traffic safety, applicability, etc.). The efficiency of the use of the most popular measure, noise barriers, was evaluated according to these criteria. It was noted that noise barriers are an expensive measure and that in some cases they limit visibility at crossings, while in other cases they are not properly integrated in the surrounding landscape. Furthermore, we need to analyse the need for making assessment based on additional criteria, e.g., competitiveness, demand of territory, and relative effectiveness of assessing non-acoustics methods, etc.
Only a limited number of different railway noise mitigation measures are currently used in Lithuania. Even common rail dampers (absorbers) or rail grinding are quite rare. To reduce negative impact on environment, we also recommend using an even wider range of means, such as acoustic measures (wheel design, wheel absorbers, special track forms, rail fasteners, etc.) or non-acoustic measures (socio-economic measures, spatial planning and management, track design, etc.). Since the main source of noise is the wheel to rail contact, the need for low noise barrier installation close to the rail area should also be evaluated, as well as the wheel shields, which could significantly increase the efficiency of such barriers.

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