

INSERTION LOSS VALUE DEPENDENCY OF THE LOW HEIGHT NOISE BARRIERS DISTANCE FROM RAILWAY TRACK

AJA TUMAVIČĖ, LAURA ŽALIMIENĖ*

*Road Research Institute, Vilnius Gediminas Technical University, Vilnius,
Lithuania*

Received on 8 August 2024; accepted 9 October 2024

Abstract. Railway noise can negatively affect both people's health and the value of their real estate. Various noise mitigation measures can be used on the railways. One of them is a noise barrier. Under certain conditions, low-noise barriers can be used to mitigate noise along the rails. Such barriers are installed closer to the railway track than regular noise barriers, which mitigate the noise generated by the wheel-rail interaction. In some cases, the gauge at which structures at railway tracks can be installed is limited; thus, this research was carried out to determine which parameters of low noise barriers were most effective dependent on the distance of the track. The aim of the research was to determine which parameters the low noise barrier would be effective at a longer distance from the railway track compared to existing practice. A railway track noise simulation (existing situation without a noise barrier and with a 3.5 m height noise barrier located 4.0 m from the railway track) was developed. The insertion loss of noise barriers was carried out using the Computer Aided Noise Abatement (CadnaA) software. Numerical noise level simulation was done at a distance of 7.5 m and 45 m from the axis of the railway tracks and various speeds of rolling stock from 50 to 250 km/h. The noise level and insertion loss were calculated at different heights from the top of the railway track (1.5 m,

* Corresponding author. E-mail: laura.zalimiene@vilniustech.lt

Aja TUMAVIČĖ (ORCID ID 0000-0002-2373-5427)
Laura ŽALIMIENĖ (ORCID ID 0000-0002-8429-7563)

Copyright © 2024 The Author(s). Published by RTU Press

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

3.5 m, and 5.5 m). It was established that the speed of the rolling stock had almost no influence on the insertion loss of the noise barrier. Therefore, all additional barriers were simulated at the same rolling stock speed of 250 km/h.

Keywords: insertion loss, low noise barrier, railway, traffic noise.

Introduction

Railways are a relatively environmentally friendly mode of transport (they emit relatively little CO₂, do not cause congestion, etc.), but they also have a negative impact on the environment. The biggest negative impact on the environment is the noise emitted by railways, especially by freight trains (Oertli & Hubner, 2010; Wiebe et al., 2011). The higher the level of rail noise, the higher the probability of awakening from sleep, from 6.5% at 35 dB(A) to 20.5% at 80 dB(A), especially if freight trains pass nearby (Elmenhorst et al., 2012). Severe sleep disturbances are more often recorded with increasing nighttime equivalent sound pressure level, peak sound pressure level, and increasing train traffic intensity (Schreckenberget al., 2018). The impact of nighttime noise on residents (awakening, sleep disturbances, and irritation) has short-term (fatigue and increased risk of accidents the next day) and long-term (causes illness) consequences (Muller et al., 2018). Yoon et al. (2018) found that the level of irritation was highly influenced by varying noise frequencies. Walker et al. (2016) found out that low-frequency noise was particularly dangerous, which could lead to long-term changes in heart rate. It was found that exposure to a railway noise of ≥ 60 dB increased the probability of hypertension by 8%, instead of when exposed to a noise of < 60 dB (Sorensen et al., 2011), and a 10 dB increase in noise level was associated with a 5.4% increase in hypertension diagnoses (Zeeb et al., 2017). Erdmann et al. (2022) found no strong association between railway noise and the risk of most childhood cancers; however, an association between noise and some cancers was found.

The costs of noise exposure to human health (1 euro per 1000 tkm) can be divided into irritation costs and healthcare costs (Siciliano et al., 2016). The negative effects of noise can also affect property prices (Cushing-Daniels & Murray, 2005). Land plots located in areas where nighttime noise levels exceed limit values have been found to have ~57% lower prices than land plots adjacent to these zones (Lowicki & Piotrowska, 2015). Chang & Kim (2012) found that an increase in noise level by 1 dBA reduced the value of private property by 0.534%, and Beimer & Maennig (2017) found that the same increase reduced the price of housing by ~1500 EUR.

It is obvious that it is very important to reduce the negative impact of noise generated by the railway track on the environment as much as possible. Rail 2050 vision (Mazzino et al., 2017) presents a general concept in which direction the railway system should be improved until 2050. Special attention is paid to the problems arising from noise and vibration, and thoughtful spatial planning policies are needed to reduce the resistance of residents of densely populated areas to the development of the transport network (Mazzino et al., 2017). In addition, the White Paper of the European Commission and the working document of European Union authorities (European Commission, 2011) predict that the external costs associated with noise are expected to decrease by 46% by 2050 compared to the case if no policy intervention would take place.

1. Insertion loss of low noise barriers

Unlike roads, there is a wide choice of noise mitigation measures for rails. In Lithuania, the most popular measure to mitigate rail noise is a regular (high) noise barrier. Such barriers are extremely effective in mitigating noise, but they also have disadvantages, for example, they limit visibility at crossings, are visually unattractive, and cost more for their installation and maintenance. Under certain conditions, low-noise barriers are also used around the world. They are installed closer to the railway track than regular noise barriers. Such barriers are designed to mitigate the noise generated by the wheel-rail interaction.

Nilsson et al. (2014) performed a numerical evaluation of different types of low noise barriers. The identified loss of insertion of noise barriers was 2 dBA to 16.7 dBA. Cizkova & Stulikova (2014) performed tests of the effectiveness of low noise barriers ($h = 0.73$ m) while taking measurements in the field. The identified insertion loss was 6.5 dB. The numerical simulation of equivalent barriers using *LimA* software showed that the insertion loss was 7.2 dB. Such a difference can be considered a measurement (calculation) allowance. Jolibois (2013) conducted field tests on the effectiveness of low-noise barriers installed on a tram line. Inverted L-shaped noise barriers ($h = 0.95$ m) were tested. The insertion loss was identified at 5–10 dBA. Cizkova (2016) performed tests of the effectiveness of low noise barriers ($h = 0.73$ m) while taking measurements in the field. The identified insertion loss was up to 7.6 dB. Vogiatzis & Vanhonacker (2016) performed field measurements of low noise barriers ($h = 1.10$ – 1.20 m). The insertion loss was identified at 4.1–5.8 dBA. Jones et al. (2001) tested the effectiveness of a noise mitigation measure consisting of an ultralow noise barrier installed very close

to the railway track ($h = 0.18$ m, 0.33 m from the track axis) and shields mounted on rolling stock, using boundary element methods and statistical energy analysis for mathematical (numerical) optimisation (calculation). The results of these tests were compared with the results of field measurements, and a good correlation was established. Both measures were found to have an insertion loss of up to ~ 6.0 dBA, and when using only ultralow noise barriers it was up to 1.6 dBA. Nieuwenhuizen & Yntema (2018) performed low noise barriers ($h = 0.76$ m) according to the Dutch Technical Regulations (2006). The results were compared with calculations made according to the Dutch calculation methodology for normal height barriers. The measurements results ($6\text{--}10$ dBA) correlate well with the calculations results. Margiocchi et al. (2009) performed mathematical (numerical) optimisation (calculation) of innovative noise barriers (low noise barriers and barriers with multi-element top) using the boundary element method. The identified insertion loss of low noise barriers was from 5 dBA to 12 dBA. Barrier-mounted top elements provide additional insertion loss of over 5 dBA. Lazaro et al. (2022) also performed calculations for the optimisation of the shape of low noise barriers ($h = 1.2$ m) and the integration of a part of the sound-absorbing porous concrete layer using the boundary element method. A loss of insertion of the curve barrier of up to 10.0 dBA was identified in all calculated frequency ranges. Torija & Flindell (2014) conducted tests of low noise barriers ($h = 1.0$ m) in the laboratory (by simulating sounds and conducting a survey of respondents) and in field conditions (in both cases, an insertion loss was 6 dBA). The test results were found to correlate well. Baulac et al. (2005) used a multi-criteria optimisation method to evaluate low noise barriers ($h = 1.0$ m). Also, mathematical (numerical) optimization (calculation) was performed using the method of boundary elements. Insertion loss was identified at 11 dBA.

The permitted driving speed on most railway lines and between stations in Lithuania is up to 160 km/h. When the driving speed of the rolling stock is between 50 km/h and $240\text{--}250$ km/h, rolling noise generated by wheel-rail interaction is predominant among other types of noise of a railway track (Hemsworth, 2008; Guiral et al., 2018). There are many single-level crossings in such sections in Lithuania; therefore, low noise barriers, which effectively suppress this type of noise and do not limit visibility, would be an extremely suitable measure for noise mitigation. However, a rather large gauge, i.e., distance from the railway tracks, is used in Lithuania. If a low noise barrier is installed at such a distance, its effectiveness will be low, the noise generated by the wheel-rail interaction will spread over its top. A study was carried out to adapt low noise barriers for countries with stricter restrictions on how far barriers can be installed.

The aim of the research is to determine which low noise barrier parameters will be effective at a greater distance from the railway track than they are normally installed. In addition, the research aims at determining which parameters have the greatest influence on the insertion loss value.

2. Methodology

In order to compare the insertion loss of noise barriers of different heights and to select the optimal technical parameters of the barrier, numerical simulation was carried out using the Computer Aided Noise Abatement (CadnaA) software. The Cnossos-EU methodology, which is intended for European countries, was used to calculate the noise of railway transport.

The simulation was carried out on the railway track Kyviškės-Valčiūnai, in the same place where the existing regular noise barrier was previously (in 2018) tested in field conditions, during which the noise level generated by the railway track was measured in the case of driving

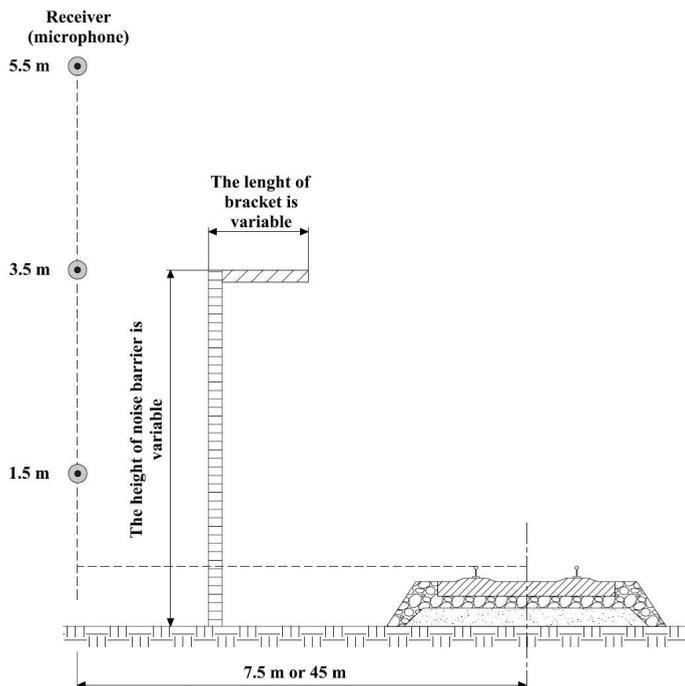


Figure 1. Schematic diagram of insertion loss simulation (made by authors)

rolling stock, and the noise level was measured using a loudspeaker, simulating railway track noise according to CEN/TS 16272-7 (2015). A railway track noise simulation (existing situation without a noise barrier and with a 3.5 m height noise barrier located 4.0 m from the railway track) was developed (Figure 1). It was calibrated according to the results of field tests. The noise level was determined to be 85.1–86.7 dBA. A simulation was created based on the rolling stock traffic schedule, taking into account the actual average number of rolling stocks with railcars on the Kyviškės–Valčiūnai rail track. During the night period, 37 rolling stock passes through the section, the average number of railcars in the train is 61 units. In the current situation, the rolling stock moves at a speed of 80 km/h. The noise level of the created noise simulation is 85.1 dBA, so it is accepted that the simulation is created correctly and correlates with the results of natural noise measurements.

The distances to railway tracks in Lithuania are limited by the document requirements of the Instruction for the Application of Construction Proximity Gauges 163/K (2001). The main requirements of this document are included in Annex H of the Commission Regulation No. 1299/2014 (2014), which regulates the proximity gauge of engineering structures of the 1520 mm gauge system. In sections of railway tracks located between stations, the minimum distance at which elements (signals, retaining walls, and barriers of other engineering structures of the railway ballast) can be installed is 2.45 m, the height of the elements from the level of the top of the rail head is 1.07 m. Engineering structures and facilities with a height of ≤ 3.20 m and located on the outer side of the side track can be installed at a distance of 3.1 m.

After analysing the experience of use of low noise barriers in foreign countries, it was found that such barriers were installed at a distance of 1.73–2.00 m from the axis of the railway tracks. According to the requirements of the legislation currently in force in Lithuania, it is not possible to install low noise barriers at such a distance, therefore, for the numerical comparison of noise barriers of different heights, the distances at which it is allowed to build certain structures and facilities in Lithuania were selected for simulation. Furthermore, to evaluate the effectiveness of the simulated barriers under the same conditions, an existing regular noise barrier and a low noise barrier were simulated away from the axis of the railway tracks at a distance at which they are installed in foreign countries. To find the most effective low noise barrier for Lithuanian conditions, a barrier of various heights was also simulated, at a distance of 2.45–3.10 m from the axis of the railway tracks, with brackets of different parameters.

Simulations were done for various speeds of rolling stock, i.e., 50 km/h (simulating the speed of rolling stock in the section of stations),

80 km/h (simulating the speed of rolling stock at the noise barrier chosen for the experiment), 120 km/h (simulating the maximum permissible speed for passenger rolling stock of categories I and II of the railway line), 160 km/h (simulating the maximum permissible speed for freight rolling stock on category I and II tracks of the railway line), 240 km/h and 250 km/h (the maximum limit at which rolling noise is present).

Noise level was simulated at a distance of 7.5 m and 45 m from the axis of the railway tracks (Figure 1). The distance of 7.5 m was chosen to determine the noise level immediately behind the barrier, where the acoustic shadow zone was and where the maximum insertion loss of the vertical noise barrier occurred. The distance of 45 m was chosen to determine the noise level at a greater distance, where there was no acoustic shadow of the barrier, and where there were buildings, in the environment of which the limit level of noise had not be exceeded according to the Lithuanian hygiene norm HN 33:2011 (2011), i.e., near the border of the land plot. The noise level and insertion loss were calculated at different heights from the top of the railway track (1.5 m, 3.5 m, and 5.5 m) to determine how noise levels changed with height.

3. Results of insertion loss analysis of low noise barriers

CadnaA program has no option to choose the material of the barrier, but it is possible to specify the sound absorption index $DL\alpha$ for the noise barrier to be simulated. This index expresses the ability of the material to absorb sound. There are no residential or public buildings on the side of Kyviškės–Valčiūnai railway track opposite to the side where the simulated noise barrier is, so it is not necessary to protect them from the negative impact of reflected noise. Taking this into account, the same sound absorption index $DL\alpha - 4$ dBA was chosen for all simulated barriers, i.e., A0 sound absorption category according to T TU 15 (2015), i.e., noise barriers that do not absorb sound were simulated.

The receiver (microphone) shown in the schematic diagram (Figure 1) represents the height of the noise level calculation from the top of the railway track.

Seven alternatives were simulated. The results of the calculation are presented in Table 1.

After the simulation of the noise barriers, it was found that if there was a need to protect the areas adjacent to the barrier, the most effective

was a regular noise barrier – the insertion loss of a 3.5 m height noise barrier located at a distance of 4.0 m from the axis of the railway track, detected at a height of 1.5 m from the top of the rails, at a distance of 7 m from the axis of the railway tracks, was even 8–9 times higher

Table 1. Simulated values of insertion loss of noise barrier options

| Distance from the track axis, m | Microphone height, m | Current situation | I opt. | II opt. | III opt. | IV opt. | V opt. | VI opt. |
|---------------------------------|----------------------|--|--|---|--|--|---|--|
| | | dBA | | | | | | |
| | | <i>H</i> – 3.5 m, <i>L</i> – 45 m, at a distance of 4 m | <i>H</i> – 0.76 m, <i>L</i> – 45 m, at a distance of 1.75 m | <i>H</i> – 1.2 m, <i>L</i> – 45 m, at a distance of 2.6 m | <i>H</i> – 1.0 m, <i>L</i> – 45 m, at a distance of 3.5 m. The length of the L-shaped bracket – 0.9 m | <i>H</i> – 1.10 m, <i>L</i> – 45 m, at a distance of 2.45 m | <i>H</i> – 1.3 m, <i>L</i> – 45 m, at a distance of 3.1 m. The length of the L-shaped bracket – 0.65 m | <i>H</i> – 1.3 m, <i>L</i> – 100 m, at a distance of 2.75 m. The length of the L-shaped bracket – 0.3 m |
| 50 km/h | | | | | | | | |
| 7.5 | 1.5 | 21.9 | 2.7 | 7.9 | 4.5 | 6.4 | 7.8 | 7.8 |
| | 3.5 | 13 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 1.5 | 5.5 | 3.4 | 4.7 | 4.2 | 4.4 | 4.6 | 8.8 |
| | 3.5 | 5.3 | 2.5 | 4.1 | 3.4 | 3.7 | 4 | 7 |
| | 5.5 | 4.5 | 1.5 | 3 | 2.3 | 2.7 | 3 | 4.9 |
| 80 km/h | | | | | | | | |
| 7.5 | 1.5 | 21.7 | 2.7 | 7.5 | 4.6 | 6.1 | 7.4 | 7.4 |
| | 3.5 | 12.4 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 1.5 | 5.4 | 3.3 | 4.5 | 4.1 | 4.2 | 4.5 | 8.4 |
| | 3.5 | 5.2 | 2.7 | 4 | 3.4 | 3.6 | 4 | 6.8 |
| | 5.5 | 4.5 | 1.5 | 3.1 | 2.5 | 2.8 | 3.1 | 4.9 |
| 120 km/h | | | | | | | | |
| 7.5 | 1.5 | 22 | 2.7 | 7.5 | 4.7 | 6.1 | 7.4 | 7.4 |
| | 3.5 | 12.5 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 1.5 | 5.5 | 3.4 | 4.6 | 4.2 | 4.3 | 4.6 | 8.6 |
| | 3.5 | 5.2 | 2.7 | 4 | 3.4 | 3.6 | 3.9 | 6.9 |
| | 5.5 | 4.5 | 1.4 | 3.1 | 2.5 | 2.8 | 3.1 | 5 |

| Distance from the track axis, m | Current situation | I opt. | II opt. | III opt. | IV opt. | V opt. | VI opt. | |
|---------------------------------|--|--|---|--|--|---|--|-----|
| | Microphone height, m <i>H</i> – 3.5 m, <i>L</i> – 45 m, at a distance of 4 m | <i>H</i> – 0.76 m, <i>L</i> – 45 m, at a distance of 1.75 m | <i>H</i> – 1.2 m, <i>L</i> – 45 m, at a distance of 2.6 m | <i>H</i> – 1.0 m, <i>L</i> – 45 m, at a distance of 3.5 m. The length of the L-shaped bracket – 0.9 m | <i>H</i> – 1.10 m, <i>L</i> – 45 m, at a distance of 2.45 m | <i>H</i> – 1.3 m, <i>L</i> – 45 m, at a distance of 3.1 m. The length of the L-shaped bracket – 0.65 m | <i>H</i> – 1.3 m, <i>L</i> – 100 m, at a distance of 2.75 m. The length of the L-shaped bracket – 0.3 m | |
| dBA | | | | | | | | |
| 160 km/h | | | | | | | | |
| 7.5 | 1.5 | 22.3 | 2.6 | 7.6 | 4.7 | 6.2 | 7.5 | 7.5 |
| | 3.5 | 12.8 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 1.5 | 5.5 | 3.4 | 4.6 | 4.2 | 4.4 | 4.6 | 8.8 |
| | 3.5 | 5.2 | 2.7 | 4 | 3.4 | 3.6 | 4 | 7 |
| | 5.5 | 4.5 | 1.4 | 3.1 | 2.5 | 2.9 | 3.1 | 5 |
| 200 km/h | | | | | | | | |
| 7.5 | 1.5 | 22.5 | 2.5 | 7.7 | 4.7 | 6.2 | 7.6 | 7.6 |
| | 3.5 | 13.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0.2 | 0 | 0 | 0 |
| 45 | 1.5 | 5.5 | 3.5 | 4.7 | 4.3 | 4.5 | 4.7 | 9.1 |
| | 3.5 | 5.3 | 2.7 | 4.1 | 3.5 | 3.7 | 4 | 7.1 |
| | 5.5 | 4.5 | 1.4 | 3.1 | 2.5 | 2.9 | 3.1 | 5 |
| 240 km/h | | | | | | | | |
| 7.5 | 1.5 | 22.4 | 2.6 | 7.3 | 4.5 | 6 | 7.2 | 7.2 |
| | 3.5 | 12 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 1.5 | 5.2 | 3.2 | 4.3 | 4 | 4.1 | 4.3 | 7.9 |
| | 3.5 | 4.9 | 2.5 | 3.8 | 3.2 | 3.4 | 3.8 | 6.4 |
| | 5.5 | 4.2 | 1.4 | 2.9 | 2.3 | 2.7 | 2.9 | 4.7 |
| 250 km/h | | | | | | | | |
| 7.5 | 1.5 | 22.3 | 2.5 | 7.2 | 4.4 | 5.9 | 7.1 | 7.1 |
| | 3.5 | 11.9 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 1.5 | 5.2 | 3.2 | 4.3 | 4 | 4.1 | 4.3 | 7.9 |
| | 3.5 | 4.9 | 2.5 | 3.8 | 3.2 | 3.4 | 3.8 | 6.4 |
| | 5.5 | 4.2 | 1.4 | 2.9 | 2.3 | 2.7 | 2.9 | 4.7 |

(depending on the speed of the rolling stock) than that of the ultra-low 0.76 m height noise barrier located at a distance of 1.75 m from the axis of the railway tracks. It was 2.7–3.1 times higher than the low 1.2 m height noise barrier located at a distance of 2.6 m from the axis of the railway tracks.

The highest insertion loss among the low noise barriers was found at a height of 1.5 m from the top of the tracks and at a distance of 7 m from the axis of the railway track. It was a 1.2 m height and 45 m long noise barrier located 2.6 m from the axis of the railway track (7.2–7.9 dBA). The lowest insertion loss was identified for the ultra-low, 0.76 m height noise barrier, located 1.75 m from the axis of the railway tracks, i.e., 2.5–2.7 dBA.

It was established that the insertion loss of all simulated low barriers at a height of 3.5 m and 5.5 m from the top of the rails, and at a distance of 7 m from the axis of the railway track, was 0. This type of barrier is not intended to protect noise-sensitive areas adjacent to rail tracks. They are used when it is necessary to mitigate noise in areas away from railway tracks.

It was established that the insertion loss of barriers of different heights and shapes, measured at a height of 1.5–5.5 m from the top of the rails, at a distance of 45 m from the axis of the railway track, differed less from each other than in the case when the insertion loss is measured closer to the axis of the railway track, for example, at a 50 km/h speed of the rolling stock at a height of 1.5 m, the lowest insertion loss identified was for a 0.76 m height noise barrier at a distance of 1.75 m from the axis of the railway track (3.4 dBA) and the highest insertion loss of a 1.3 m height noise barrier located at a distance of 2.75 m (barrier length – 100 m, L-shaped bracket length – 0.3 m) from the axis of the railway track (8.8 dBA), i.e., differed by ~2.6 times. Comparison of the effectiveness of the latter noise barrier with the effectiveness of the other tested barriers showed that the insertion loss was higher from ~1.6 times (height – 3.5 m, length – 45 m at a distance of 4 m) to ~ 2.1 times (height – 1.0 m, length – 45 m, at a distance of 3.75 m, L-shaped bracket length – 0.9 m) than the insertion loss of other barriers. Similar differences can be seen when measuring at different rolling stock speeds (as the speed increases, the insertion loss of all barriers generally decreases) and at different heights (when measured higher, a lower insertion loss is identified).

The identified insertion loss of a 0.76 m high noise barrier located at a distance of 1.75 m, measured at a distance of 45 m, was from 1.5 dBA to 3.5 dBA, depending on the location of the receiver (microphone) and the speed of the rolling stock. Nieuwenhuizen &

Yntema (2018) found a higher insertion loss (6–10 dBA) in a study of low noise barriers with the same parameters. It is likely that a higher insertion loss was obtained because a barrier with a sound-absorbing surface was tested.

In search of the most effective low-noise barrier, the noise barrier parameters were changed during the simulation of Alternative VI. A condition was established that the simulated noise mitigation barrier and its elements could be at a distance of 2.45–3.1 m from the axis of the railway tracks. Simulation determined that a low noise barrier would be most effective if extended in both directions to a total length of ~100 m. The 1.3 m high barrier should be at a distance of 2.75 m from the axis of the railway tracks, the length of the inverted L-shaped bracket was 0.30 m. It was determined that the effectiveness of the noise barrier with such technical parameters would be higher than the currently installed ~45 m long and 3.5 m high noise barrier.

To evaluate the effectiveness of the upper element of the barrier folded toward the railway track (inverted L-shaped bracket), an additional study was carried out by calculating the insertion loss of some straight and low noise barriers with a bracket. Taking into account the fact that the speed of the rolling stock has almost no influence on the insertion loss of the noise barrier, all additional barriers were simulated at the same speed of the rolling stock of 250 km/h. To determine how much the insertion loss of the noise barrier with the folded top element is affected by the folding angle of the top element, calculations were additionally performed for a 100 m long barrier with the top element folded at different angles (15°, 30°, 60°). Additional simulation results are presented in Table 2.

Additional numerical simulation of noise barriers demonstrated that low noise barriers with top elements folded towards the railway tracks were more effective than straight barriers without a top element, for example L-shaped (bracket length – 0.9 m) barrier with a height of 1.0 m and length of 45 m, installed at a distance of 3.75 m from the axis of the railway tracks, the insertion loss, identified at a height of 1.5 m from the top of the rails, was 1.2 times greater than the insertion loss of a straight barrier with the same parameters. The insertion loss identified in the same manner at a height of 3.5 m from the top of the rails was 1.28 times greater, and the insertion loss identified at a height of 5.5 m from the top of the rails was 1.92 times greater than the insertion loss of a straight barrier with the same parameters.

The simulated insertion loss values of all noise barriers modelled at a rolling stock speed of 250 km/h are presented in Figures 2 and 3.

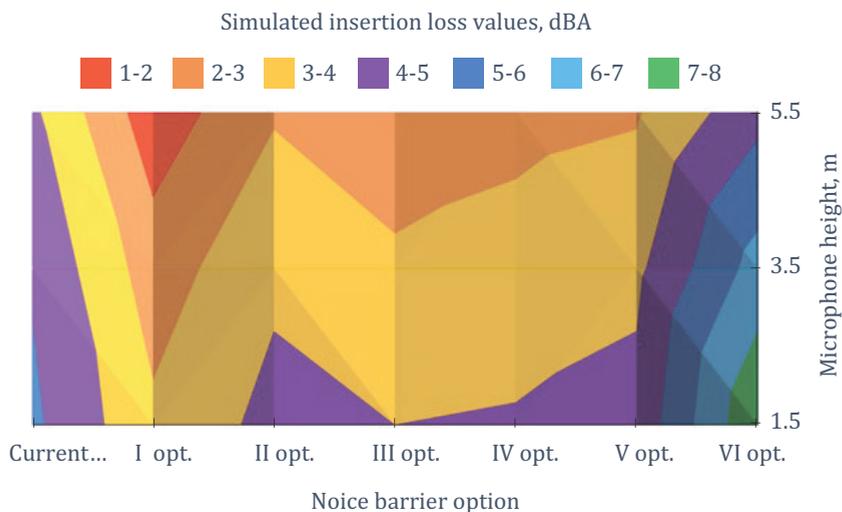


Figure 2. Simulated values of insertion loss of noise barrier options (at a speed of the rolling stock of 250 km/h)

Table 2. Additional simulated values of insertion loss of noise barrier options

| Distance from the track axis, m | Microphone height, m | Current situation | III A opt. | VA opt. | VI A opt. | VI B opt. | VI 15° opt. | VI 30° opt. | VI 60° opt. |
|---------------------------------|--|-------------------|---|---|--|--|--|--|--|
| | | dBA | | | | | | | |
| | <i>H</i> – 3.5 m, <i>L</i> – 45 m, at a distance of 4 m | | <i>H</i> – 1.0 m, <i>L</i> – 45 m, at a distance of 3.75 m | <i>H</i> – 1.3 m, <i>L</i> – 45 m, at a distance of 3.1 m | <i>H</i> – 1.3 m, <i>L</i> – 45 m, at a distance of 2.75 m | <i>H</i> – 1.3 m, <i>L</i> – 100 m, at a distance of 2.75 m | <i>H</i> – 1.3 m, <i>L</i> – 100 m, at a distance of 2.75 m. The leg is bent at an angle of 15° | <i>H</i> – 1.3 m, <i>L</i> – 100 m, at a distance of 2.75 m. The leg is bent at an angle of 30° | <i>H</i> – 1.3 m, <i>L</i> – 100 m, at a distance of 2.75 m. The leg is bent at an angle of 60° |
| | | 250 km/h | | | | | | | |
| 7.5 | 1.5 | 22.3 | 0.2 | 5.6 | 6.2 | 6.2 | 6.2 | 6.2 | 6.3 |
| | 3.5 | 11.9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 5.5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 45 | 1.5 | 5.2 | 3.3 | 4.1 | 4.2 | 7.3 | 7.3 | 7.3 | 7.4 |
| | 3.5 | 4.9 | 2.5 | 3.4 | 3.5 | 5.7 | 5.7 | 5.7 | 5.8 |
| | 5.5 | 4.2 | 1.2 | 2.6 | 2.8 | 4.4 | 4.4 | 4.4 | 4.5 |

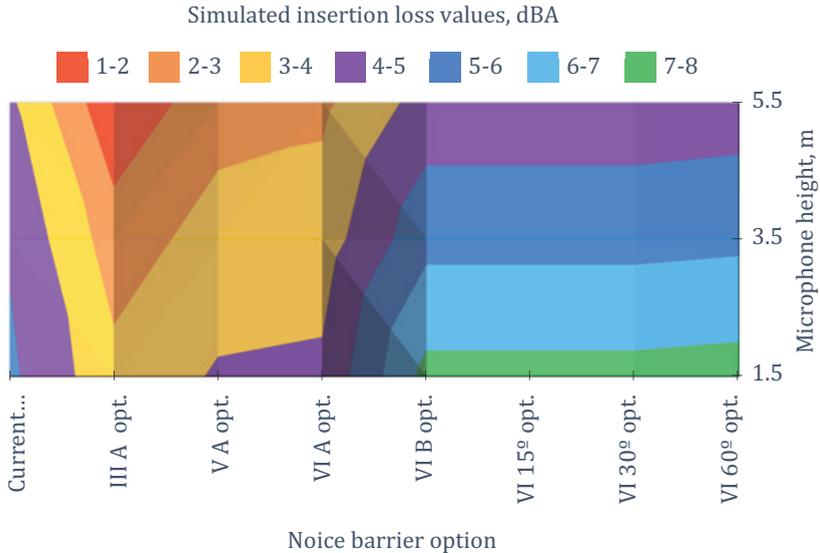


Figure 3. Additional simulated values of insertion loss of noise barrier options (at a speed of the rolling stock of 250 km/h)

4. Statistical evaluation of parameters of low noise barriers that affect values of insertion loss

To evaluate which parameters of the low noise barriers have a statistically significant influence on the insertion loss values, a statistical study was performed. The following noise barriers were used for the analysis: barrier height $H = \{0.76 \text{ m}, 1 \text{ m}, 1.1 \text{ m}, 1.2 \text{ m}, 1.3 \text{ m} \text{ and } 3.5 \text{ m}\}$, barrier length $L = \{45 \text{ m}, 100 \text{ m}\}$, shape (straight, bracket) $F = \{15^\circ, 30^\circ, 60^\circ, 90^\circ\}$, bracket length $GL = \{0.3 \text{ m}, 0.65 \text{ m}, 0.9 \text{ m}\}$, and distance from the axis of the railway track, where a barrier is installed, $A = \{4 \text{ m}, 3.75 \text{ m}, 3.1 \text{ m}, 2.75 \text{ m}, 2.6 \text{ m}, 2.45 \text{ m}, 1.75 \text{ m}\}$. For a certain barrier with a fixed set of parameters, the measurements were repeated three times at different rolling stock speeds (50 km/h, 80 km/h, 120 km/h, 160 km/h, 200 km/h, 240 km/h, and 250 km/h) and at two different distances from the track axis, i.e., at 7.5 m and at 45 m.

One-factor analysis of variance ANOVA, as well as T-test and Tukey test (Čekanavičius & Murauskas, 2001) were used for paired comparison of averages. The coefficient of correlation (ρ) was used to assess the strength of the linear dependence between quantitative characteristics. The results of statistical tests were interpreted using the p-value, the observed level of significance with which the correct hypothesis H_0

could be rejected for the available data. The analysis was performed using the R software package (The R Project for Statistical Computing).

After the statistical analysis, it was established that the standard deviation and average of the loss values were very similar at all speeds, i.e., no statistically significant differences were observed between the insertion loss obtained at different speeds ($p = 0.996$).

Using one-factor analysis of variance ANOVA, a comparison was performed to assess whether the insertion loss values were influenced by the height of the noise barrier, the angle of deflection of the bracket, and the distance from the axis of the railway tracks where the barrier was located.

Low noise barriers are effective at a greater distance, so a statistical comparison was made by taking noise level simulation values determined at a distance of 45 m from the axis of the railway tracks. After the statistical analysis was completed, it was established that the insertion loss was statistically significantly different depending on the height of the noise barrier and the distance at which the noise barrier was located (in both cases $p < 0.0001$), as well as the folding angle of the upper element of the noise barrier ($p < 0.001$).

To assess whether the length of the noise barrier affects the insertion loss values, a comparison was made using a two-sample T-test, since barriers of two lengths were simulated, i.e., the sample size was small. After statistical analysis, it was established that the average loss of insertion of the noise barrier of 100 m was higher than the average insertion loss of the noise barrier of 45 m long noise barrier, 4.37 ± 3.29 and 3.49 ± 4.07 , respectively. Thus, the difference can still be considered statistically significant, i.e., p is slightly above 0.05 ($p = 0.068$).

The main objective of the regression analysis was to evaluate low noise barriers that were effective at a greater distance from the track axis, therefore, the linear regression model evaluated only the simulation results at a distance of 45 m from the railway track axis, after eliminating the 3.5 m high from the data (Equation (1)).

$$IS = -1.39 + 2.52H_{(p < 0.0001)} + 0.04L_{(p < 0.0001)}, \quad (1)$$

where IS – insertion loss, H – height of the noise barrier, L – length of the noise barrier.

The multiple linear regression model was evaluated using the following barrier parameters (barrier height H and its length, shape (straight, bracket, and its length) and distance from the axis of the railway track), but only the length ($p < 0.0001$) and height ($p < 0.0001$) of the barrier remained significant in the simulation. If the height increases by 1 m, loss increases by 2.53 dBA on average (when other parameters remain the same). The level in a 100 m barrier is 2.47 dBA higher than in

a 45 m barrier. If the length increases by 1 m, loss increases by 0.045 dBA (when other parameters remain the same). After the performance of the statistical analysis, it was found that the coefficient of determination $R^2 = 0.67$, i.e., barrier height and length explain 67% of the scatter of loss values.

Conclusions

The noise caused by the railways has a negative impact on the environment, for example, on people's health (from irritation to serious health disorders). Such noise can cause fatigue, an increased risk of accidents on the next day, awakening, sleep disturbances, long-term changes in heart rate, hypertension, and even some cancers. In addition, the noise caused by railways has a negative effect on the market value of land plots and property prices.

Low noise barriers are installed at a shorter distance from the railway tracks than regular barriers in order to suppress rolling noise, i.e., the noise generated by the interaction between the wheel and the rail. Analysis of other studies shows that in some cases the insertion loss of low noise barriers is only 2.0–5.0 dBA. Although the insertion loss of these barriers is usually lower than that of regular noise barriers, they have advantages compared to regular noise barriers, e.g., they do not restrict visibility at crossings, they are visually attractive, and they have lower installation costs, so they are an extremely effective noise mitigation measure for certain conditions.

The study found that regular noise barriers were extremely effective in protecting adjacent noise sensitive areas – the loss of insertion of a 3.5 m height noise barrier located at a distance of 4.0 m from the axis of the railway track, detected at a height of 1.5 m from the top of the rails, at a distance of 7 m from the axis of the railway tracks, was even 8–9 times higher (depending on the speed of the rolling stock) than that of the ultra-low 0.76 m height noise barrier located at a distance of 1.75 m from the axis of the railway tracks. It was 2.7–3.1 times higher than the low 1.2 m height noise barrier located at a distance of 2.6 m from the axis of the railway tracks. Moving away from the railway tracks, the insertion loss decreased, and the calculated insertion loss levels were quite similar to the insertion loss levels of some analysed low noise barriers.

When comparing barriers of the same length of 45 m, installed at a height of 1.5 m from the top of the tracks, at a distance of 45 m from the axis of the railway track, the insertion loss of a 3.5 m height straight noise barrier (at a distance of 4.0 m from the axis of the railway track) was 20.93% higher than that of the 1.2 m height straight noise barrier

(at a distance of 2.6 m from the axis of the railway track) and the 1.3 m height inverted L-shaped noise barrier (at a distance of 3.1 m from the axis of the railway track, bracket length was 0.65 m); 26.83% higher than that of 1.0 m height straight noise barrier (at a distance of 2.45 m from the axis of the railway tracks). In comparison, the loss of insertion of a 45 m long 3.5 m height straight noise barrier (at a distance of 4.0 m from the axis of the railway track), identified at a height of 1.5 m from the top of the rails, at a distance of 45 m from the axis of the railway track was 34.17% lower than that of a 100 m long 1.3 m height inverted L-shaped noise barrier (at 2.75 m from the axis of the railway track, bracket length – 0.3 m).

After performing a statistical linear regression analysis, it was found that the insertion loss was statistically significantly dependent on two variables – the height ($p < 0.0001$) and length ($p < 0.0001$) of the noise barrier. Both parameters are positive, i.e., the longer and higher the barrier is, the higher the insertion loss. A 1 m increase in the height of the noise barrier results in an average increase of 2.53 dBA in insertion loss, all other parameters remain the same, and a 1 m increase in barrier length results in an average increase of 0.045 dBA in insertion loss, all other parameters remain the same.

Disclosure Statement

The authors declare no conflict of interest.

REFERENCES

- Baulac, M., Defrance, J., & Jean, P. (2005). Optimization of low height noise protections in urban areas. *Proceedings of the Conference: Forum Acusticum*, Budapest, Hungary, 1075–1080. https://www.researchgate.net/publication/253066431_Optimization_of_low_height_noise_protections_in_urban_areas
- Beimer, W., & Maennig, W. (2017). Noise effects and real estate prices: A simultaneous analysis of different noise sources. *Transportation Research Part D: Transport and Environment*, 54, 282–286. <https://doi.org/10.1016/j.trd.2017.05.010>
- Čekanavičius, V., & Murauskas, G. (2001). *Statistika ir jos taikymai 1* [Statistics and its applications 1]. Vilnius: TEV. https://www.spssanalize.lt/wp-content/uploads/2014/03/ius__Murauskas_-_Statistika_ir_jos_taikymai.pdf

- Chang, J. S., & Kim, D. (2012). Hedonic estimates of rail noise in Seoul. *Transportation Research Part D: Transport and Environment*, 19, 1–4. <https://doi.org/10.1016/j.trd.2012.11.002>
- Cizkova, P., & Stulikova, L. (2014). The effectiveness of a low height noise barrier. *14th International Multidisciplinary Scientific Geoconference (SGEM)*, Albena, Bulgaria, 711–718. https://www.researchgate.net/publication/293110440_The_effectiveness_of_a_low_height_noise_barrier
- Cizkova, P. (2016). The acoustic effectiveness of low height noise barrier. *Proceedings of the Conference INTER-NOISE and NOISE-CON Congress*, Hamburg, Germany, 3985–3992.
- Commission Regulation (EU). (2014). No. 1299/2014. Technical specifications for interoperability relating to the ‘infrastructure’ subsystem of the rail system in the European Union. <https://eur-lex.europa.eu/eli/reg/2014/1299/oj>
- Cushing-Daniels, B., & Murray, P. (2005). Welfare effects of increased train noise: A comparison of the costs and benefits of train whistle use at highway – railway crossings. *Transportation Research Part D: Transport and Environment*, 10(5), 357–364. <https://doi.org/10.1016/j.trd.2005.04.006>
- Dutch Technical Regulations. (2006). *Emissiemethoden Railverkeer* [Technische Regeling – Emissiemethoden Railverkeer].
- Elmenhorst, E.-M., Pennig, S., Rolny, V., Quehl, J., Mueller, U., Maass, H., & Basner, M. (2012). Examining nocturnal railway noise and aircraft noise in the field: sleep, psychomotor performance, and annoyance. *Science of the Total Environment*, 424, 48–56. <https://doi.org/10.1016/j.scitotenv.2012.02.024>
- Erdmann, F., Raaschou-Nielsen, O., Hvidtfeldt, U. A., Ketznel, M., Brandt, J., Khan, J., Schüz, J., & Sørensen, M. (2022). Residential road traffic and railway noise and risk of childhood cancer: A nationwide register-based case-control study in Denmark. *Environmental Research*, 212(A), Article 113180. <https://doi.org/10.1016/j.envres.2022.113180>
- European Commission. (2011). Accompanying document to the White paper. Roadmap to a single European transport area: Toward a competitive and resource efficient transport system (48453/EU XXIV.GP). Commission staff working paper. Impact assessment. https://www.parlament.gv.at/dokument/XXIV/EU/48453/imfname_10009805.pdf
- Guiral, A., Blanco, B., Iturritxa, E., & Alonso, A. (2018). CRoNoS railway rolling noise prediction tool: Wheelset model assessment. *Conference: Euronoise 2018*, Crete, Greece, 1471–1478. https://www.euronoise2018.eu/docs/papers/246_Euronoise2018.pdf
- Hemsworth, B. (2008). *Environmental noise directive development of action plans for railways*. International Union of Railways (UIC), 1–30. https://uic.org/IMG/pdf/action_planning_paper_final-2.pdf
- Jolibois, A. (2013). A study on the acoustic performance of tramway low-height noise barriers: gradient-based numerical optimization and experimental approaches [Doctoral dissertation, University of Paris-Est]. https://pastel.hal.science/pastel-00965168/file/TH2013PEST1116_complete.pdf
- Jones, C. J. C., Thompson, D. J., & Waters, T. P. (2001). Application of numerical models to a system of train- and track-mounted acoustic shields. *International Journal of Acoustics and Vibration*, 6(4), 185–192.

- Lazaro, J., Pereira, M., Costa, P. A., & Godinho, L. (2022). Performance of low-height railway noise barriers with porous materials. *Applied Sciences*, 12(6), Article 2960. <https://doi.org/10.3390/app12062960>
- Lithuanian Road Administration. (2015). T TU 15:2015: *Triukšmo užtvarų parinkimo, modeliavimo, projektavimo ir įrengimo taisyklės* [Rules for the selection, modeling, design and installation of noise barriers].
- Lithuanian Standards Board. (2015). CEN/TS 16272-7:2015: Geležinkelio taikmenys. Bėgių kelias. Triukšmo užtvaros ir susiję įtaisai, sulaukantys ore sklindantį garsą. Bandymo metodas akustinėms charakteristikoms nustatyti. 7 dalis. Papildomos charakteristikos. Vietoje nustatomos įneštinio silpninimo vertės [Railway applications – Track – Noise barriers and related devices acting on airborne sound propagation – Test method for determining the acoustic performance – Part 7: Extrinsic characteristics – In situ values of insertion loss].
- Lowicki, D., & Piotrowska, S. (2015). Monetary valuation of road noise. Residential property prices as an indicator of the acoustic climate quality. *Ecological Indicators*, 52, 472–479. <https://doi.org/10.1016/j.ecolind.2015.01.002>
- Margiocchi, F., Baulac, M., Poisson, F., Defrance, J., & Jean, P. (2009). Noise impact of innovative barriers dedicated to freight trains in urban areas. *16th International Congress on Sound and Vibration (ICSV16)*, Krakow, Poland. https://www.researchgate.net/publication/266384206_Noise_impact_of_innovative_barriers_dedicated_to_freight_trains_in_urban_areas
- Mazzino, N., Perez, X., Meuser, U., Santoro, R., Brennan, M., Schlaht, J., Chéron, C., Samson, H., Dauby, L., Furio, N., & Hernandez, C. (2017). *Rail 2050 vision. Rail – the backbone of Europe’s mobility*. The European Rail Research Advisory Council, 1–28. https://errac.org/wp-content/uploads/2019/03/122017_ERRAC-RAIL-2050.pdf
- Ministry of Health of the Republic of Lithuania. (2011). HN 33:2011: *Lietuvos higienos norma. Triukšmo ribiniai dydžiai gyvenamuosiuose ir visuomeninės paskirties pastatuose bei jų aplinkoje* [Lithuanian hygiene norm - Noise limits in residential and public buildings and their surroundings].
- Muller, U., Schreckenber, D., Möhler, U., & Liepert, M. (2018). Maximum-level as an additional criterion for the assessment of railway noise at night: Derivation of a wake-up protection criterion for standards and regulations. *Euronoise 2018*, Crete, Greece, 503–507. https://www.euronoise2018.eu/docs/papers/87_Euronoise2018.pdf
- Nieuwenhuizen, E., & Yntema, N. (2018). The effect of close proximity, low height barriers on railway noise. *Euronoise 2018*, Crete, Greece, 1375–1379. https://www.euronoise2018.eu/docs/papers/230_Euronoise2018.pdf
- Nilsson, M., Bengtsson, J. & Klæboe, R. (2014). *Environmental methods for transport noise reduction* (1st ed.). London: CRS Press. Taylor & Francis Group. <https://doi.org/10.1201/b17606>
- Oertli, J., & Hubner, P. (2010). *Railway noise in Europe. A 2010 report in the state of art*. International Union of Railways. Paris: ACINNOV, 1–31. https://uic.org/IMG/pdf/uic_railway_noise_the_state_of_the_art_2010.pdf

- Order of the General Director of the JSC Lithuanian Railways. (2001). 163/K: *Statinių artumo gabaritų taikymo instrukcija*, įsakymo Nr. 456 [Application of Construction Proximity Gauges, Order No.456].
- Schreckenber, D., Belke, C., Benz, S., Möhler, U., Müller, U., & Liepert, M. (2018). Maximum-level as an additional criterion for the assessment of railway noise at night: Definition of sleep quality and derivation of a protection criterion based on reported sleep disturbances for standards and regulations. *Euronoise 2018*, Crete, Greece, 509–513. https://www.euronoise2018.eu/docs/papers/88_Euronoise2018.pdf
- Siciliano, G., Barontini, F., Islam, D. M. Z., Zunder, T. H., Mahler, S., & Grossoni, I. (2016). Adapted cost-benefit analysis methodology for innovative railway services. *European Transport Research Review*, 8(4), Article 23. <https://doi.org/10.1007/s12544-016-0209-5>
- Sorensen, M., Hvidberg, M., Hoffmann, B., Andersen, Z. J., Nordsborg, R. B., Lillelund, K. G., Jakobsen, J., Tjønneland, A., Overvad, K., & Raaschou-Nielsen, O. (2011). Exposure to road traffic and railway noise and associations with blood pressure and self-reported hypertension: a cohort study. *Environmental Health*, 10, Article 92. <https://doi.org/10.1186/1476-069X-10-92>
- The R project for statistical computing*. <https://www.R-project.org/>
- Torija, A. J., & Flindell, I. H. (2014). Listening laboratory study of low height roadside noise barrier performance compared against in-situ field data. *Building and Environment*, 81, 216–225. <https://doi.org/10.1016/j.buildenv.2014.07.006>
- Vogiatzis, K., & Vanhonacker, P. (2016). Noise reduction in urban LRT networks by combining track based solutions. *Science of the Total Environment*, 568, 1344–1354. <https://doi.org/10.1016/j.scitotenv.2015.05.060>
- Walker, E. D., Brammer, A., Cherniack, M. G., Laden, F., & Cavallari, J. M. (2016). Cardiovascular and stress responses to short-term noise exposures – A panel study in healthy males. *Environmental Research*, 150, 391–397. <https://doi.org/10.1016/j.envres.2016.06.016>
- Wiebe, E., Sandor, J., Cheron, C., & Haas, S. (2011). ERRAC Roadmap. WP 01 – The greening of surface transport. “Towards 2030 – noise and vibrations roadmap for the European railway sector”. The European Rail Research Advisory Council (ERRAC), International Union of Railways (UIC) and the Association of the European Rail Industry (UNIFE), Paris and Brussels, 1–40. https://errac.org/wp-content/uploads/2013/07/ERRAC_WP01_Roadmap_Noise-and-Vibration_V06.pdf
- Yoon, K., Gwak, D. Y., Chun, C., Seong, Y., Hong, J., & Lee, S. (2018). Analysis of frequency dependence on short-term annoyance of conventional railway noise using sound quality metrics in a laboratory context. *Applied Acoustics*, 138, 121–132. <https://doi.org/10.1016/j.apacoust.2018.03.024>
- Zeeb, H., Hegewald, J., Schubert, M., Wagner, M., Dröge, P., Swart, E., & Seidler, A. (2017). Traffic noise and hypertension – results from a large case-control study. *Environmental Research*, 157, 110–117. <https://doi.org/10.1016/j.envres.2017.05.019>