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MODELLING OF NOISE BARRIER EFFICIENCY WITH INTEGRATED PHOTOVOLTAIC ELEMENTS

Andrew SALEEB*, Raimondas GRUBLIAUSKAS

Department of Environmental Protection and Water Engineering,
Vilnius Gediminas Technical University, Vilnius, Lithuania

**E-mail: andrew-safwat-ragheb.saleeb@stud.vilniustech.lt*

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Abstract. Railway noise pollution is a significant environmental concern, affecting urban and rural areas. Photovoltaic Noise Barriers (PVNBs) represent a multi-purpose solution that reduces noise pollution and generates renewable energy all at once. This study explores the effectiveness of various PVNB configurations in mitigating railway noise, considering factors such as barrier height, surface absorption, and tilt angle of the Photovoltaic segment. Special attention is given to the acoustic properties of bifacial PV modules, evaluating their impact on sound reflection and absorption. This research uses numerical simulations to assess the trade-offs between noise attenuation and solar energy efficiency. The results provide valuable insights for optimising PVNB designs to enhance noise reduction while maintaining energy harvesting performance, contributing to more sustainable urban infrastructure. This research clarifies that the crowning configuration of the PVNB has an impact on noise attenuation efficiency, for instance, the effect of the barrier crowning tilt angle on a point 50 meters away from the source for noise reduction was the highest for the horizontal configuration noise barrier crowning, ranging between −10.6 dB(A) neglecting the barrier effect, −30.2 dB(A) for the horizontal crowning barrier, and −28.3 dB(A) for the vertical configuration.

Keywords: CadnaA simulation, efficiency, photovoltaic noise barriers, tilt angle, railway noise mitigation.

1. Introduction

There is a significant need in urban innovation for the holistic integration of sustainable solutions with the environment and the existing infrastructure. The precise integration of railway noise barriers and renewable energy technology is a very distinctive aspect of this synergy. The increasing aspirations for a balanced city life in metropolitan areas worsen the fundamental problem of noise pollution. At the same time, there is a growing global demand to switch to renewable energy, considering that in the European Union, there is around 40 % of the population exposed to a noise level due to traffic and railways that exceed 55 dB(A) and around 20 % are exposed to noise levels above 65 dB(A) in the daytime. Greater than 30 % is exposed to levels exceeding 55 dB(A) at night. Combining conventional noise barriers with the unobtrusive potential of renewable energy not only provides a suitable way to reduce noise pollution but also marks a definitive leap towards a more environmentally friendly and energy-efficient urban setting. This study focuses mainly on the potential benefits of the connection between railway noise barriers and renewable energy sources, by exploring the hidden potential that exists at the nexus of sustainable energy production and noise reduction by looking at the installation of solar panels within large urban structures. In addition to improving the acoustics of urban areas, this integration strategy advances the larger global agenda of lowering carbon emissions and building resilient, environmentally friendly communities (Clark et al., 2020).

Noise barriers are widely used in railway applications; a study conducted by Sarpalius & Grubliauskas (2022) indicated the efficiency of short noise barriers in railway applications, where a one-meter sound barrier reached a 3 dB difference in noise levels. Still, this reduction is significant. Unlike the usual types, these barriers are less visible and more affordable. A two-meter noise barrier achieved an 8 dB decrease in noise level. Nevertheless, this comes at a much higher price, and it

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will be more conspicuous to stakeholders than if it were a one-meter noise barrier.

In another study (Redondo, 2022), the acoustic performance of the typical noise barriers was measured by the single-numbered insulation rating, for environmental noise barriers (e.g., highway or railway noise barriers), a common rating is the Insertion Loss (IL), which measures the reduction in noise levels before and after installing the barrier. Airborne sound insulation in noise barriers refers to the sound difference level (D_{LR}), which measures how effectively a barrier blocks airborne noise. It is defined as:

$$D_{LR} = L_1 - L_2, \quad (1)$$

where L_1 – is the sound level on the source side of the barrier in dB (A); L_2 – is the sound level on the receiver side of the barrier in dB (A).

A higher D_{LR} value indicates better airborne sound insulation. Typical D_{LR} values for noise barriers range from 15 dB to 40 dB, depending on the material and design. This research focuses primarily on the design of the PVNB.

Also, another basic study was conducted more than a decade ago to evaluate the performance of different configurations of noise barriers regarding the crowning of the barrier, which is the very top part of the barrier, by (Ishizuka & Fujiwara, 2004).This study offers suggestions for various crowning configurations of the typical noise barrier, as illustrated in the following figure.

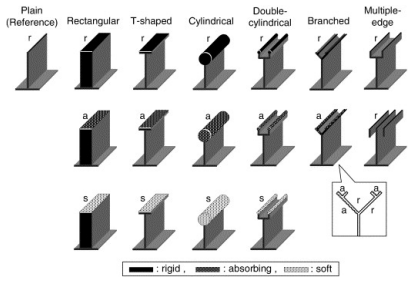


Figure 1. Noise barriers with different crowning configurations (Ishizuka & Fujiwara, 2004)

The need for noise barriers is expected to increase significantly in the upcoming decade, making it one of the most important fields of research and study. (Nayak & Mutreja, 2023). Figure 2 shows the most commonly used technologies for noise mitigation.

According to the previous figure, sound (noise) barrier walls rank fourth in terms of usage for noise mitigation. The need for this technology will almost double by 2031. It is also the most suitable technology for noise mitigation that can be used with railways, not to mention that it is the most convenient to integrate with photovoltaic solar cells.

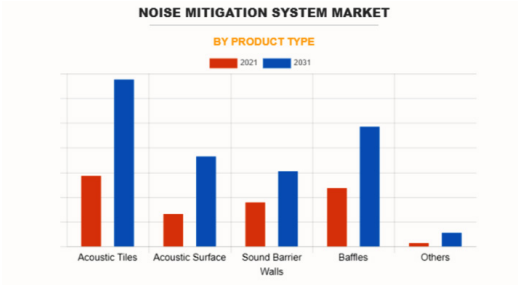


Figure 2. Noise mitigation systems market share per technology used, and the forecast for 2031 (Nayak & Mutreja, 2023)

Some angles related to the datum (horizon) and the sunbeam need to be understood clearly to proceed with this research, most notably the slope angle β, as illustrated in the following figure.

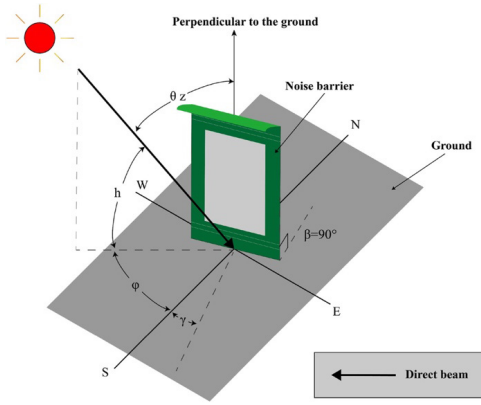


Figure 3. Various solar angles, studying a system of panels relative to the direction of the sunbeam (Zhong et al., 2021)

2. Methodology

In this study, different configurations for the PVNB were evaluated based on the acoustic performance for noise mitigation, the proposed configuration will be according to five distinct scenarios, depending on the tilt angle of the PV segment on the top of the railway noise barrier, measured from the side facing the railway to the vertical direction (Solitek, 2024). According to the following table, the PV segment will be identical for all scenarios with a sound absorption coefficient **α**, which is of constant values for the whole frequency spectrum of the sound according to Table 1 as well (Šarmavičienė, 2024).

Table 1. Tilt angle for various scenarios

Tilt angle for different scenarios β	
Scenario I	0° (Horizontal)
Scenario II	36°
Scenario III	45°
Scenario IV	75°
Scenario V	90° (Vertical)

Table 2. Sound absorption coefficient α for the used PVNB

Frequency (Hz)	Value of α for Bifacial glass PVNB
25 Hz	0.02
50 Hz	0.035
100 Hz	0.055
125 Hz	0.075
250 Hz	0.15
500 Hz	0.125
1000 Hz	0.2
2000 Hz	0.25
4000 Hz	0.3
8000 Hz	0.35

The chosen location for this study is the Juodšiliai area in the Vilnius district municipality, specifically the pilot project of the Kyviškės–Vaičiūnai railway line, as shown in the map below.



Figure 4. Juodšiliai map view (Google Earth, 2025), with a special resolution of (1 cm: 17.86 m)

The tool being used for noise modelling in this study is CadnaA, a tool developed by the German company DataKustik™, to map the studied area to simulate the noise emitted by the trains on the railways and to study the effect of installing the noise barrier with different configurations, the primary inputs – as shown in the following map – were:

A The buildings' height, knowing that the average height of a single floor is around 3 meters, the receiver height is set to be 4 meters, the ambient temperature is 10 °C, the relative humidity is 70%, and the wind speed is 3 meters per second.

B The foliage height: most common trees in the area are Scots Pine (*Pinus sylvestris*) and Norway Spruce (*Picea abies*), with an average height of 12 meters (Rivers et al., 2019).

C The railway train intensity, speed, and train types: according to the LTG Link website, after the year 2022, the number of trains going through the studied area was reduced to 1–2 per day due to restrictions on the Russian trains, freight trains dropped to 15–25 per day, and the locomotive models used are ChS4T, EP1M, 2TE10M for passenger trains and 2TE116, VL80, 2M62 for freight trains – in CadnaA presets these trains were not available, the alternative is to choose train models with the same rail gauge, engine type and weight capacity. The average train speed in the studied area is 50 Km/h and is regulated not to exceed 60 Km/h.



Figure 5. Studied the area modelled map on CadnaA with the exact spatial resolution of the previous map, showing the railway centred

The solar segment height is 1.1 meters, and the acoustic noise barrier height is 3.9 meters, resulting in a total PVNB height of 5 meters. It is also essential to have a total height of 5 meters for the PVNB with different tilt angles for the solar PV segment.

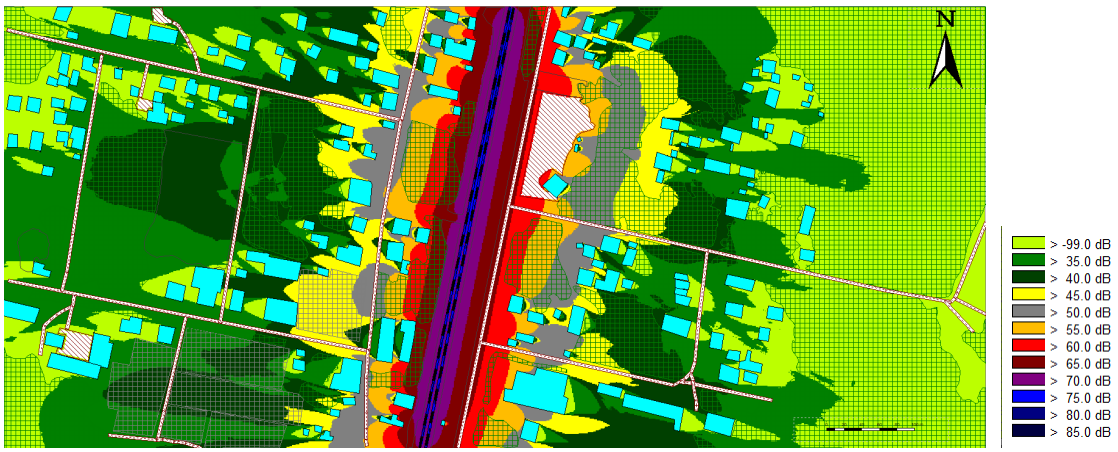


Figure 6. Railway noise spread without the barrier and colour scale

3. Results and discussion

The following results were obtained from the numerical simulation, measuring the noise level at fixed distances from the source in segments of 50 meters apart:

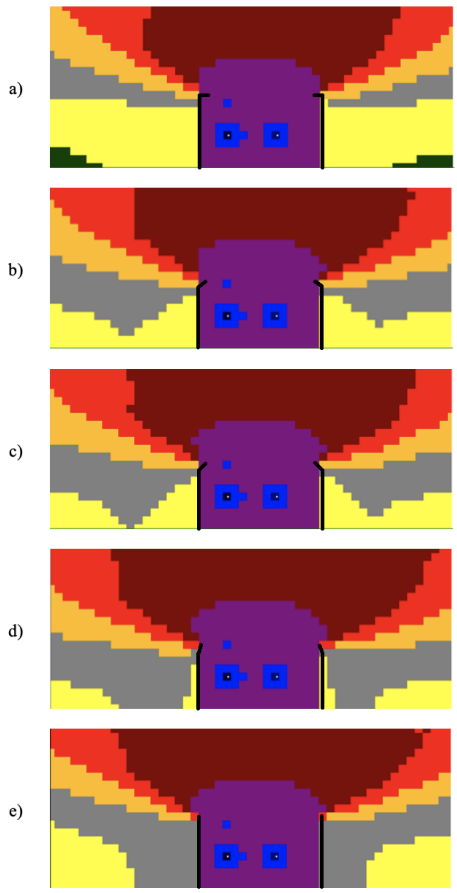


Figure 7. CadnaA simulation results for different configurations: a) Scenario I, b) Scenario II, c) Scenario III, d) Scenario IV, e) Scenario V, using the same colour scale as the previous figure, with a resolution of 1 × 1m^2

Table 3. Results of the numerical simulation for noise mitigation in dB(A) and the corresponding noise reduction percentages

Studied Scenario	Distance from the railroad			
	0 m	50 m	100 m	150 m
No barrier	74.6	64 (14.2%)	55 (26.2%)	46.7 (37.4%)
Scenario I	74.6	44.4 (40.4%)	39.4 (47.1%)	35 (53%)
Scenario II	74.6	47.6 (36.2%)	42.2 (43.4%)	36.6 (50.9%)
Scenario III	74.6	48 (35.6%)	42.6 (42.9%)	36.9 (50.5%)
Scenario IV	74.6	49 (34.3%)	43.4 (41.8%)	37.7 (49.4%)
Scenario V	74.6	46.3 (37.9%)	40.7 (45.4%)	35.6 (52.2%)

The effect of the PVNB is noticeable when it comes to noise mitigation (Table 3), with the most effective being the horizontal configuration (Scenario I) resulting from the scattering effect of the edge of the noise barrier crowning in the horizontal configuration resulting in the highest percentage of noise level reduction, the general performance of the noise barrier is not inversely proportioned with the tilt angle **β** this behaviour can be clarified even more by understanding the behaviour of the sound wave around the edges of the noise barrier for different configurations, resulting in lower D_{LR} as shown in the previous figure 7, which is showing a cross-sectional grid analysis throughout the railway (50 meters width section view).

The crowning (edge) effect of the PVNB, as shown in the previous figure, affects the behaviour of the sound wave emitted from the source (railway). The leading cause for this phenomenon is the scattering effect of the sharp edges and obstacles on the sound wave, resulting in a less intense wave once it reaches the edge of the PVNB. These findings are supported by a study that clarifies the tilt (inclination) angle of the PVNB crowning effect on noise mitigation, stating that the inclination angle has no impact on the reduction efficiency of the noise barrier but the highest efficiency for noise mitigation can be reached by adjusting the PVNB crowning inclination angle so that the sound wave direction is perpendicular to the surface of the top part (crowning) of the barrier. (Zaets, 2021). The soundwave direction is normal to the railway direction, according to (Thompson et al., 2024), which explains the behaviour of the noise (sound) wave about the different configurations of the PVNB crowning.

The effect of installing a noise barrier is significant, as shown in Table 3, lowering the noise levels below 55 dB(A) at a distance of 50 meters from the source. However, the pre-installation results indicate that even at a distance of 100 meters away from the source, the noise level remained above 55 dB(A). At the same time, the effect of changing the crowning configuration was less significant when it came to the final results.

The limitations of this study included its negligible effect on the results, assuming that weather conditions – specifically temperature, humidity and wind speed – varied minimally throughout the year. Also, the modelled barrier material structure was believed to be composed of a single material, the bifacial photovoltaic solar element, resulting in a constant value of the sound absorption coefficient.

4. Conclusions

Photovoltaic noise barriers hold the potential to reduce physical pollution levels in the form of noise while

producing clean energy simultaneously, leading to cleaner energy production. To maximise the noise reduction efficiency, it is crucial to minimise the crowning slope angle of the PVNB β, ranging between 0° and 90°, while considering the effect of slope angle changes on energy yields. The shape and configuration of the PV segment of the PVNB play a noticeable role when it comes to noise mitigation efficiency alongside solar energy harvesting efficiency, the scattering effect of the sharp edge of the PVNB on the sound wave is maximised at a 0° (horizontal) slope angle, while the energy yields – for bifacial PVNBs – are maximised at a 90° (vertical) slope angle (Zhang et al., 2024), making it a governing variable in optimising the performance of PVNBs. The difference in noise reduction between the horizontal and the vertical configuration for the exact source of noise and the same measurement point (receiver) is 1.9 dB(A) – at 50 meters distance to the east of the source; this significant difference emphasises the importance of considering the crowning tilt angle in the case of PVNB. For the same source that emits noise of 74.6 dB(A), after a distance of 150 meters without the use of any noise mitigation methodology, the reached noise level is 46.7 dB(A), however, installing a PVNB with a horizontal crowning configuration of 1.1-meter width causes the noise level at the same point to be 35 dB(A). The vertical configuration for the same PVNB at the same measurement point causes the noise level to be 35.6 dB(A), proving that PVNBs with a horizontal crowning configuration are the most effective setup for noise mitigation. The resulting values are significant considering the noise reduction of 40.4 % at a distance of 50 meters from the source, making the use of the railway noise barriers a dominant tool in noise mitigation.

Further studies can be conducted, taking into consideration the energy yields for different configurations of the PV segment and the overall environmental impact of photovoltaic noise barrier production in the form of a lifecycle assessment (LCA) for the studied unit, to gain a holistic view of the utilisation of the photovoltaic noise barriers (PVNBs).

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TRIUKŠMO UŽTVARŲ SU INTEGRUOTAIS FOTOVOLTINIAIS ELEMENTAIS EFEKTYVUMO MODELIAVIMAS

A. SALEEB, R. GRUBLIAUSKAS

Santrauka. Geležinkelio triukšmo tarša yra reikšminga aplinkosauginė problema, daranti įtaką tiek miesto, tiek užmiesčio vietovėms. Fotovoltinės triukšmo užtvaros (PVNB) yra daugiafunkcis sprendinys, leidžiantis vienu metu mažinti triukšmo taršą ir generuoti atsinaujinančią energiją. Šiame tyrime nagrinėjamas įvairių PVNB konfigūracijų efektyvumas mažinant geležinkelio triukšmą, atsižvelgiant į tokius veiksnius kaip užtvaros aukštis, paviršiaus garso sugertis ir fotovoltinės dalies posvyrio kampas. Ypatingas dėmesys skiriamas bifacialinių fotovoltinių modulių akustinėms savybėms. Tyrime naudojamas skaitinis garso sklaidos modeliavimas, o gauti rezultatai suteikia vertingų įžvalgų optimizuojant PVNB dizainą, siekiant maksimaliai sumažinti geležinkelio transporto sukeliamą triukšmą, taip prisidedant prie tvaresnės miestų infrastruktūros kūrimo. PVMB konfigūracija turi įtakos triukšmo slopinimo efektyvumui, pavyzdžiui, barjero efektyvumas 50 metrų atstumu nuo triukšmo šaltinio buvo didžiausias esant horizontaliai konfigūracijai ir siekė 28,3–30,2 dBA.

Reikšminiai žodžiai: efektyvumas, fotovoltinės triukšmo užtvaros, pasvirimo kampas, geležinkelio triukšmo mažinimas, CadnaA modeliavimas.