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Original Research Article

ASSESSMENT OF RAILWAY NOISE ON THE SECTION OF RAILWAY LINE NO. 3 PODSTOLICE – NEKLA

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Abstract

Railway noise influences the shaping of the acoustic climate in many regions. Although it is less bothersome than road and air traffic noise, it can still cause numerous negative effects, including discomfort, anger, depression, helplessness, and sleep disturbances. Currently, there are many methods available for estimating railway noise, including assessing its impact on humans, identifying sound sources, and modeling environmental noise. The aim of this article is to analyze the sound levels generated by passing trains depending on the topography around the railway line (tracks located at ground level, in a cutting, or on an embankment) and the type of traction vehicle pulling the train sets. The research was conducted on railway line No. 3 between Podstolice and Nekla in the Greater Poland Province. The measurements showed that the highest sound levels were generated when trains passed at ground level, while the lowest levels occurred when the tracks were located in a cutting.

Keywords: railway noise, topography around railway lines, sound exposure levels L_{AE}, railway noise environmental studies

1. INTRODUCTION

Railway noise is currently considered the second most significant source of noise shaping the acoustic climate in the environment. When comparing the three modes of transportation (i.e., road, rail, and air), railway noise is less disturbing at the same exposure level than road or aircraft noise. The reasons for this difference may include longer periods of silence between train passages, greater regularity and predictability of railway traffic, differences in frequency and acoustic characteristics, or people's attitudes toward the source. Recent studies indicate, however, that at night, this annoyance may become significant [1]. Noise maps created in 2017 showed that in the European Union, 22 million people are exposed to railway noise exceeding 55 dB during the day-evening-night period (L_{DEN}), with 11 million living in urban areas and 11 million in non-urban areas. At night (L_N), about 9 million people in urban

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areas and 8 million in non-urban areas are exposed to levels exceeding 50 dB. As a result, 4% of the European population is exposed to railway noise above acceptable thresholds during L_{DEN}, and 3% during L_N [2]. Moreover, at an L_{DEN} level of 55 dB, around 4% of the European population reports being highly annoyed by railway noise—lower than the rates reported for road traffic noise (6%) and aircraft noise (27%) [3]. At night, however, railway noise – especially from freight trains – can increase the frequency of nighttime awakenings more than aircraft noise [4]. Figure 1 presents the percentage of people living in urban areas in Europe exposed to railway noise exceeding 55 dB during the L_{DEN} period. This information was compiled based on acoustic map data collected by individual European countries in 2017.

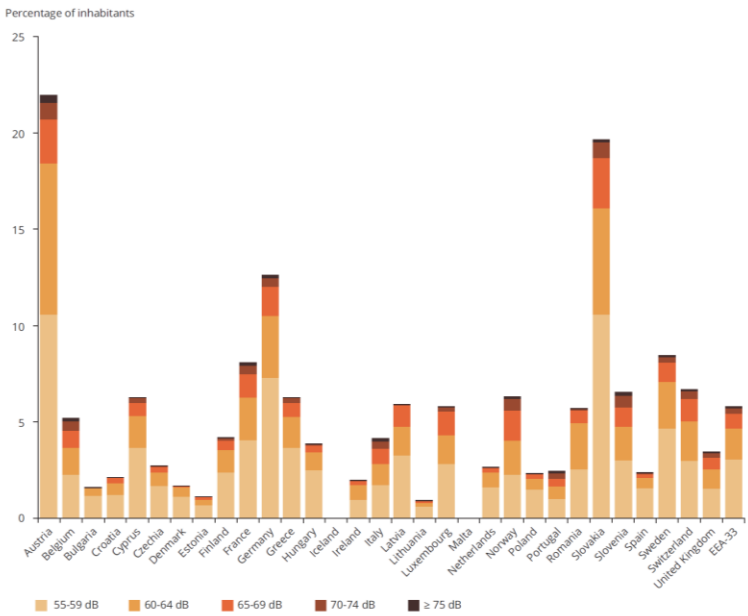

Fig. 1. Percentage of people exposed to railway noise in urban areas in Europe [2]

The number of people exposed to railway noise in urban areas is strongly correlated with the number of city inhabitants, the development level of tram and light rail systems, and varies between countries. It is estimated that, on average, 6% of people living in urban areas in Europe are exposed to railway noise L_{DEN} levels exceeding 55 dB. More than 10% of city residents in Austria, Germany, and Slovakia are exposed to L_{DEN} levels above 55 dB. Cities with high sound levels associated with rail vehicle operations include Bratislava, Paris, and Vienna—mainly due to their highly developed tram and metro networks. The share of the total population exposed to major sources of railway noise is highest in Central European countries, ranging from less than 0.5% in Croatia, Greece, Hungary, Ireland, Latvia, Lithuania, Norway, and Romania to 4–5% in Austria and Germany [2].

Many studies focus on the relationship between noise and its impact on human health and life [5, 6, 7, 8]. One significant non-auditory effect of noise is annoyance, an emotional state often accompanied by discomfort, anger, depression, and helplessness. Annoyance is one of the most important non-auditory effects of noise. The WHO recommends using the L_{DEN} index to assess annoyance. This index is the primary metric used in noise maps and enables assessment of average noise levels throughout the day and year in a given area [3, 9].

One of the most harmful effects of noise on humans is its impact on sleep, a crucial biological function. Noise can have health consequences and be linked to numerous diseases. Sleep deprivation caused by transport noise is recognized as a negative health effect (at L_N = 42 dB, sleep problems may occur). A 1 dB increase in railway noise can reduce deep sleep by 0.2%. Sleep disturbances are a key mechanism potentially leading to various health problems, including mental health issues. The risk of experiencing mental health problems is three times higher for people living near railway lines compared to those living further away. Additionally, higher noise levels are associated with poorer mental health test results [3, 4, 9, 10].

Although much attention is given to the health impacts of noise in the literature, vibrations – especially affecting residents near railways – are often overlooked. Studies [6, 10, 11, 12,] show that people exposed to both noise and vibrations report higher levels of annoyance than those exposed only to noise. Vibrations can also amplify the effects of noise, especially at night, causing sleep disturbances and increasing general discomfort. Ignoring vibration effects in acoustic assessments may result in underestimating the number of people severely affected and in less effective strategies for noise mitigation. Article [13] developed exposure-effect curves to assess the combined impact of railway noise and vibration on health and well-being. The authors used an energy summation method to convert vibrations into an equivalent noise level.

Another stream of research on railway noise focuses on identifying its main emission sources. These sources fall into three categories: rolling noise from wheel-rail contact, propulsion noise from engines, fans, and mechanical systems, and aerodynamic noise, which becomes significant at speeds over 200 km/h. Other rail noise sources that may have a significant impact on the environment include braking and infrastructure interactions (e.g., when passing over bridges, viaducts, tunnels), and station noise. To adopt effective strategies noise mitigation in the environment, it is essential to identify key components of railway noise and the mechanisms that generate it. This is often done using microphone arrays and advanced data processing. An example is the study [14] identifying noise sources around rail vehicle bogies. Based on the results and machine learning methods (ML), particularly neural networks (NN), a model was developed incorporating the Doppler effect to assess dominant noise sources in time and frequency domains and to identify individual bogies. Another study [15] used array techniques to determine the acoustic signature of the Alstom train type ETR610, series Ed250. Using collected data, a dynamic model was created for straight and curved track sections. At 200 km/h, rolling noise was confirmed as the dominant source, with sound levels primarily between 500 Hz and 3000 Hz. In addition to array-based studies, broadband and frequency-based studies are also conducted. Research on different track types [16] showed that tracks with wooden sleepers are on average 3 dB quieter than those with concrete sleepers. At a distance of 7.5 meters and a height of 1.2 meters, noise levels measured were 78 - 64 dB for concrete and 72 - 60 dB for wooden sleepers. Noise analysis showed that low-frequency noise between 31.5–400 Hz dominated, with peak levels reaching 78 dB. Latest studies have shown that pantograph design can also significantly affect external noise levels [17]. Pantograph aerodynamic noise increases with train speed, from 51 dB at 100 km/h to 67 dB at 160 km/h. Wind tunnel tests revealed that rectangular pantograph profiles generate 6–10 dB more noise than circular ones. During the analysis of the current state of knowledge regarding the impact of rail noise on the environment, no publications were found that addressed the influence of the rail track's location in relation to the terrain and its topography on the recorded sound levels.

Predictive models are also used for railway noise assessment and environmental modelling [18, 19, 20, 21, 22, 23]. In study [19], an economic analysis was conducted for selected noise mitigation strategies. In 2002, the European Union introduced a directive on environmental noise assessment and management [24]. Since its adoption, the directive has required member states to use noise indicators (L_{DEN} and L_{night}) for environmental noise assessment. The 2015 update of noise indicator assessment methods changed the strategic noise mapping process. Previously, EU member states could use own models to calculate noise maps. Since the update, all member states are required to use a unified method – CNOSSOS-EU [25]. However, comparing CNOSSOS-EU results with existing models presents challenges. In case of railway noise CNOSSOS-EU has been found to overestimate environmental noise levels by 5–10 dB. Publication [26] proposed supplementing CNOSSOS-EU with more detailed and reliable transfer functions for vehicles and tracks. These functions are derived using TWINS (Track-Wheel Interaction Noise Software) calculations for the components of wheels, rails, and sleepers. This approach is being tested by comparing how these refined transfer functions affect CNOSSOS-EU results versus the default ones, using TWINS results as a reference.

The aim of this article is to analyse the sound levels generated by passing trains depending on the surrounding terrain topography and the type of traction vehicle hauling the train sets. The research was conducted on a section of railway line No. 3 between Podstolice and Nekla.

2. MEASUREMENT METHODOLOGY

The subject of the acoustic study was trains operating on a section of the international railway line No. 3, connecting Warszawa Zachodnia and Kunowice, specifically on the Podstolice–Nekla segment located in the Greater Poland Province near Poznań. This route was selected due to the fact that the Podstolice–Nekla section is one of ten railway segments in Greater Poland with a traffic intensity exceeding 30,000 trains annually (approximately 83 trains per day) and features diverse terrain topography, which allowed for the designation of three measurement points (in a cutting, at ground level, and on an embankment). The entire length of the measurement section was modernized in 2005, and trains can operate on it at speeds of up to 160 km/h. The railway track bed was constructed using category B crushed stone ballast, INBK7 sleepers, prestressed concrete fastenings (SB), and 60E1 type rails [27]. Figure 2 shows the location of the noise measurement points.

Fig. 2. Location of the noise measurement points [27] 1 – point in a cutting, 2 – point at ground level, 3 – point on an embankment

The first measurement point (Point No. 1 in Figure 2) was located where the railway track runs in a cutting—the depth of the cutting at this location was 4 meters. The second measurement point (Point No. 2 in Figure 2) was situated at ground level, while the third measurement point (Point No. 3 in Figure 2) was located on an embankment with a height of 4 m [28].

There were no residential buildings or significant reflective or sound-absorbing structures in the vicinity of any of the three noise measurement locations. The nearest residential buildings were located approximately 1 kilometre away from the measurement points.

At the designated locations along the railway line, individual acoustic events (train passages) were measured. These included: first- and second-generation “Elf” Electric Multiple Units (EMUs), long-distance passenger trains hauled by EU46 “Vectron MS” and EU160 “Griffin” locomotives, and freight trains pulled by EU46 “Vectron MS” locomotives.

Based on the railway standard PN-EN ISO 3095 Railway applications – Acoustics – Measurement of noise emitted by rail vehicles and the Regulation of the Minister of the Environment of June 16, 2011 on the requirements for conducting measurements of substances or energy levels in the environment by managers of roads, railway lines, tram lines, airports, or ports, a research methodology was developed. The aim of the study was to analyse the sound levels generated by passing trains depending on the terrain profile surrounding the railway line and the type of traction vehicle hauling the trainsets. The study focused on noise emitted by rail vehicles during normal operational travel at a constant speed in both directions: westbound toward Poznań and eastbound toward Warsaw. Each measurement point was located 25 meters from the railway track and at a height of 1.5 meters above ground level. Table 1 presents the number of measurements taken for each terrain configuration, categorized by the type of traction vehicle operating on the selected measurement route.

Table 1. Summary of noise measurements sites and the number of trains for which the measurements were made

Type of traction vehicle	Track in a cutting	Track at ground level	Track on an embankment
1st generation 'Elf' EMUs	16	13	11
2nd generation 'Elf' EMUs	13	12	10
Passenger trains hauled by EU46 "Vectron MS" locomotives	10	12	12
Freight trains hauled by EU46 "Vectron MS" locomotives	11	10	13
Passenger trains hauled by EU160 "Griffin" locomotives	11	11	13

The trains for which sound levels were recorded can be described as follows:

The first-generation "Elf" EMUs, version 22WEa, were four-car trainsets with a total length of 75,250 mm. The second-generation "Elf" EMUs were five-car trainsets, with a total length of 90,530 mm. On the measurement route, these units reached a speed of approximately 80 km/h. The relatively low speed of these trainsets was due to the fact that they operated regional services, stopping at most stations along the route.

Trains hauled by EU160 "Griffin" locomotives consisted of seven passenger cars, including five 168A-type second-class coaches and two 156A-type first-class coaches. The total length of such a trainset was 195,200 mm.

Trains hauled by EU46 "Vectron MS" locomotives on the measurement route consisted of six cars: one 156A-type first-class coach, one 168A-type dining car, and four 168A-type second-class coaches. The total length of the trainset hauled by the EU46 "Vectron MS" locomotive was 169,700 mm. Passenger trains with EU160 Griffin and EU46 Vectron MS locomotives operating on the measurement section reached speeds of approximately 160 km/h. These were long-distance Intercity trains.

Freight trains hauled by EU46 Vectron MS locomotives had varying numbers of cars. For freight trains, the total mass hauled by the locomotive is an important factor. The EU46 Vectron MS locomotives have a power of 6.4 MW and typically haul trainsets with a total mass of 1,000–1,500 tons. The maximum speed for these locomotives in freight operation is 140 km/h.

All measurements were conducted in September 2021 during the daytime under similar atmospheric conditions: no precipitation, air temperature around 20°C, and wind speed of 5 m/s. The noise from passing trains was measured using single-event acoustic measurements, recording the sound exposure levels L_{AE} [27, 29, 30].

The sound exposure level L_{AE} is a quantity closely related to the equivalent continuous sound level and is used to describe individual acoustic events such as train pass passages. These events can be described using the following relationship:

$$E_A = \int_{t_{i-1}}^{t_i} p_A^2(t)dt \tag{2.1}$$

The integral contains the history of changes in sound pressure within the time interval (t_{i-1}, t_i) and represents the measure of the *i-th* individual acoustic event. The quantity E_A represents the sound exposure [$Pa^2 \cdot s$].

Sound exposure is proportional to the acoustic energy that passes through a unit surface area (containing the observation point) throughout the duration of the acoustic event. Sound exposure is associated with the sound exposure level, also known as the exposure sound level, expressed by the following relationship:

$$L_{AE} = 10log\left(\frac{E_A}{p_0^2 \cdot t_0}\right) \tag{2.2}$$

The sound exposure level corresponds to a constant sound over time t_0 = 1 s (reference time) that delivers to the observer (listener) the same amount of energy as the time-varying sound L_{pA} (t) during the interval ($t_i - t_{i-1}$) [31, 32]. During the measurements, the passing trains were classified into five types of acoustic events:

- long-distance passenger trains hauled by EU160 "Griffin" locomotives,
- long-distance passenger trains hauled by EU46 "Vectron MS" locomotives EU46,
- regional passenger trains operated by 1st generation "Elf" EMUs,
- regional passenger trains operated by 2nd generation "Elf" EMUs,
- freight trains hauled by EU46 "Vectron MS" locomotives.

All measurements were carried out using a Brüel & Kjær Type 2250 integrating sound level meter. During each individual measurement session, the following were recorded: the sound exposure level L_{AE}, the maximum sound level L_{Amax}, and the minimum sound level L_{Amin}.

3. RESEARCH RESULTS

All noise measurements were performed along the Podstolice – Nekla section of railway line No. 3. The study was conducted for three types of terrain surrounding the tracks: the track laid in a 4-meter-deep cutting, at ground level, and on a 4-meter-high embankment. Measurement points were located 25 meters from the railway track at a height of 1.5 meters above ground level. In total, 178 train passages were recorded across all terrain configurations. For each group of traction vehicles (individual acoustic events), the average sound exposure levels $L_{AEśr}$ were calculated using the following formula [30]:

$$L_{AEsr} = 10log\left(\frac{1}{n} \cdot \sum_{i=1}^{n} 10^{0,1 \cdot L_{AEki}}\right) \tag{3.1}$$

where:

L_{AEsr} – average sound exposure level determined for individual acoustic events belonging to class k [dB],
n – number of individual acoustic events belonging to class k,
L_{AEki} – exposure level value for individual acoustic events classified as class k [dB].

Table 2 presents a summary of measurement results for the track located in a cutting.

Table 2. L_{AE} [dB] measurement results for the track located in a cutting

Lp.	Traction vehicles				
	1st gen. “Elf” EMUs	**2nd gen. “Elf” EMUs**	**EU46 “Vectron MS” locomotives (passenger)**	**EU160 “Griffin” locomotives (passenger)**	**EU46 “Vectron MS” locomotives (freight)**
1.	73	75	75	75	84
2.	74	76	82	78	80
3.	73	77	91	86	84
4.	79	79	81	83	82
5.	75	77	85	88	84
6.	74	77	82	85	84
7.	71	78	83	82	85
8.	76	76	78	86	85
9.	75	76	79	89	82
10.	70	80	82	84	84
11.	83	76	–	83	81
12.	83	79	–	–	–
13.	81	85	–	–	–
14.	80	–	–	–	–
15.	83	–	–	–	–
16.	79	–	–	–	–

The recorded exposure sound levels for regional trains (“Elf” EMUs of the first and second generation) ranged between 70 – 85 dB. In the case of long-distance passenger trains hauled by EU46 Vectron MS locomotives, the levels reached 75 – 91 dB, while for trains hauled by EU160 “Griffin” locomotives, the range was 75 – 89 dB. The passage of freight trains hauled by EU46 “Vectron MS” locomotives resulted in recorded exposure sound levels ranging between 80 – 85 dB. Figure 3 presents the averaged values of exposure sound levels for the measurement point located in a cutting.

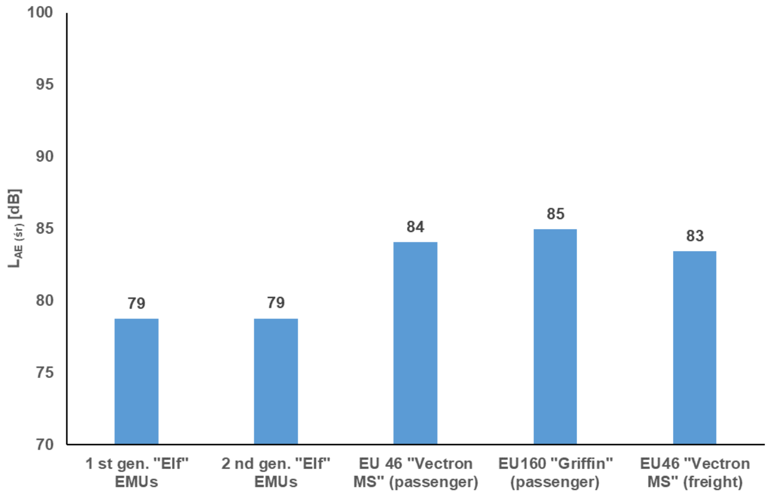

Fig. 3. Average $L_{AE,śr}$ levels for train passages with the track located in a 4m cutting

In the case where the railway track was located in a cutting, the highest sound exposure levels were recorded for passenger trains hauled by the following locomotives: EU160 “Griffin MS” at 85 dB and EU46 “Vectron MS” at 84 dB. For freight trains hauled by EU46 “Vectron MS” locomotives, the average sound exposure levels were 1 dB lower than for passenger trains hauled by EU46 “Vectron MS” and 2 dB lower than those hauled by EU160 “Griffin MS.” The average exposure level for freight trains was 83 dB. For the first- and second-generation “Elf” EMUs, the average sound exposure levels were the lowest among all tested trains, measured at 79 dB. These average levels were 6 dB lower than those of the passenger trains and 4 dB lower than those of the freight trains.

The second terrain configuration used for measurements was the track located at ground level. Table 3 presents the noise measurement results for the railway track at ground level.

Table 3. L_{AE} [dB] measurement results for the track located at ground level

Lp.	**Traction vehicles**				
	1st gen. “Elf” EMUs	**2nd gen. “Elf” EMUs**	**EU46 “Vectron MS” Locomotives (passenger)**	**EU160 “Griffin” locomotives (passenger)**	**EU46 “Vectron MS” locomotives (freight)**
1.	85	80	84	84	94
2.	80	80	86	99	95
3.	85	84	88	92	94
4.	84	77	86	92	86
5.	82	82	87	97	85
6.	81	77	87	92	90
7.	85	80	87	91	90
8.	85	81	82	84	88
9.	80	79	85	96	86
10.	84	79	91	91	89
11.	83	78	88	98	–
12.	83	75	84	–	–
13.	83	–	–	–	–

In the case where the railway track was located at ground level, the recorded sound exposure levels were as follows: “Elf” EMUs of the first and second generations ranged from 75 to 85 dB; passenger trains hauled by EU46 “Vectron MS” locomotives ranged from 82 to 91 dB; and those hauled by EU160 “Griffin MS” locomotives ranged from 84 to 99 dB. For freight trains hauled by EU46 “Vectron MS” locomotives, the sound exposure levels ranged from 85 to 95 dB. Figure 4 presents the average sound exposure levels for train passages at ground level.

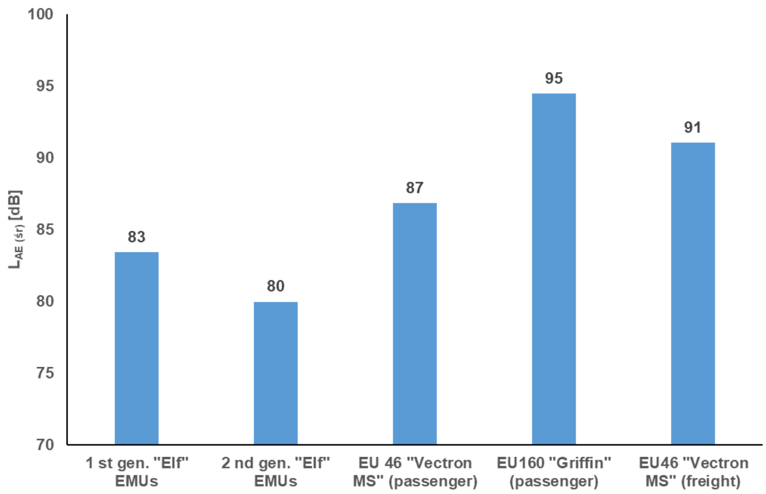

Fig. 4 Average $L_{AE,śr}$ levels for train passages at ground level

In this measurement point location—where the railway track was situated at ground level—the average sound exposure level values were more varied. 1st-generation “Elf” EMUs reached an average of 83 dB, which was 3 dB higher than the 2nd-generation “Elf” units. For passenger trains hauled by EU46 “Vectron MS” and EU160 “Griffin MS” locomotives, the highest average sound exposure level was 95 dB, recorded for those hauled by the EU160 “Griffin MS”. These values were 12 dB and 15 dB higher, respectively, than those of the first- and second-generation “Elf” units, 8 dB higher than passenger trains hauled by the EU46 “Vectron MS”, and 4 dB higher than freight trains pulled by the EU46 “Vectron MS”.

Trains hauled by the EU46 “Vectron MS” locomotives registered average sound exposure levels of 87 dB for passenger trains and 91 dB for freight trains. These average values were 4 dB and 7 dB higher than those of the first- and second-generation “Elf” units, respectively, and 8 dB lower than those of the passenger trains hauled by the EU160 “Griffin MS”.

For freight trains hauled by the EU46 “Vectron MS”, the average levels were 11 dB and 8 dB higher than those of the first- and second-generation “Elf” EMUs, 4 dB higher than the passenger trains hauled by the same EU46 locomotive, and 4 dB lower than passenger trains hauled by the EU160 “Griffin MS”.

The third configuration in which measurements were taken was for the railway track located on a 4-meter embankment. Table 4 presents a summary of the measurement results for the track situated on the embankment.

Table 4. L_{AE} [dB] measurement results for the track situated on an embankment

Lp.	Traction vehicles				
	1st gen. “Elf” EMUs	**2nd gen. “Elf” EMUs**	**EU46 “Vectron MS” Locomotives (passenger)**	**EU160 “Griffin” locomotives (passenger)**	**EU46 “Vectron MS” locomotives (freight)**
1.	83	81	88	88	81
2.	83	80	88	81	87
3.	84	81	86	93	85
4.	86	81	86	86	86
5.	83	79	87	94	90
6.	86	79	91	90	80
7.	83	79	90	92	88
8.	85	81	90	88	80
9.	86	81	88	88	78
10.	87	80	88	85	78
11.	90	–	90	84	81
12.	–	–	92	89	82
13.	–	–	–	89	79

For the third measurement point location – a track situated on a 4-meter embankment – the following values of exposure sound levels were recorded: for the first and second generation "Elf" Electric Multiple Units, 79–90 dB; for passenger trains hauled by EU46 "Vectron MS" locomotives, 86–92 dB; for passenger trains hauled by EU160 "Griffin MS" locomotives, 81–94 dB; and for freight trains hauled by the EU46 "Vectron MS" locomotive, 78–90 dB. Figure 5 presents the averaged results of the exposure sound level measurements for train passages when the track is located on an embankment.

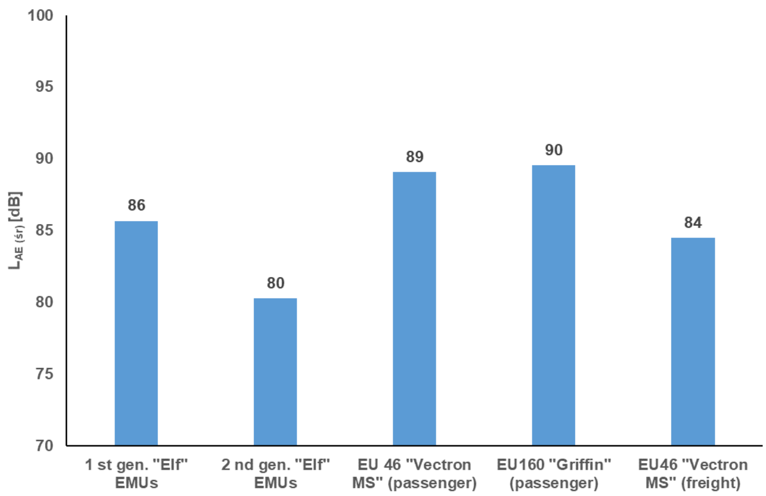

Fig. 5. Averaged $L_{AE,śr}$ levels for train passages when the track is located on an embankment

In the case where the railway track is located on an embankment, the average values of exposure sound levels for the various types of trains can be characterized as follows. Freight trains hauled by EU46 "Vectron MS" locomotives recorded the lowest exposure sound level – 84 dB – compared to passenger trains: 2 dB lower than first-generation "Elf" EMUs, 5 dB lower than passenger trains hauled by EU46 "Vectron MS" locomotives, and 6 dB lower than passenger trains hauled by EU160 "Griffin MS" locomotives. Only in comparison to the second-generation "Elf" EMUs were the average exposure sound levels of freight trains 4 dB higher.

Among passenger trains, the highest average exposure sound level was recorded for those hauled by EU160 "Griffin MS" locomotives – 90 dB. These values were 1 dB lower for passenger trains hauled by EU46 "Vectron MS" locomotives, 4 dB lower for first-generation "Elf" EMUs, 6 dB lower for freight trains hauled by EU46 "Vectron MS" locomotives, and 10 dB lower for second-generation "Elf" Electric Multiple Units. The exposure sound levels of the first-generation "Elf" EMUs were 8 dB higher than those of the second-generation units.

Figure 6 presents a summary of the noise measurements for all trains and terrain configurations included in the study.

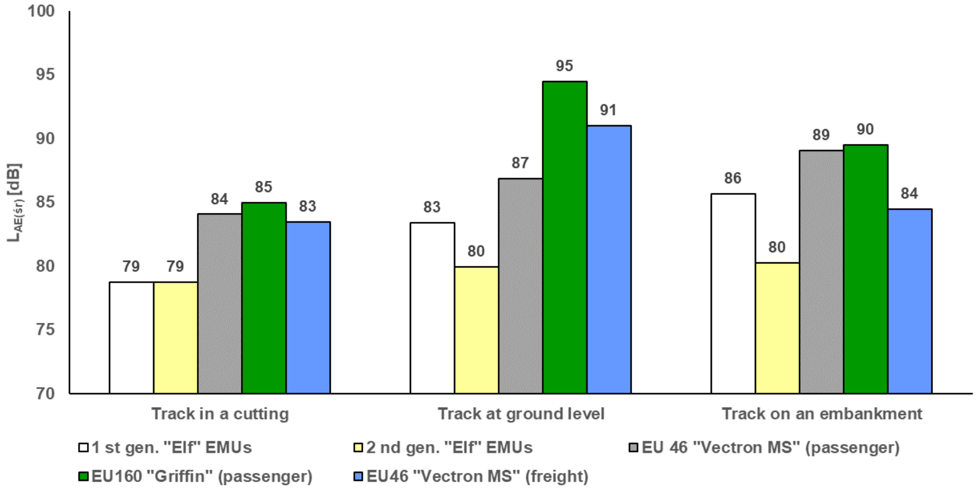

Fig. 6. Averaged exposure sound levels for train and track types

The conducted study showed that the highest exposure sound levels were recorded when trains passed at ground level. The highest average exposure sound level – 95 dB – was recorded for passenger trains hauled by EU160 "Griffin" locomotives, and 91 dB for freight trains hauled by EU46 "Vectron MS" locomotives. In the case of passenger trains hauled by EU46 "Vectron MS", the exposure sound level was 87 dB. First- and second-generation "Elf" Electric Multiple Units, in the scenario where the track runs at ground level, achieved 80–83 dB. These values were the lowest among all tested trains.

When the railway track is situated on an embankment, the highest exposure sound levels, approximately 90 dB, were recorded for passenger trains hauled by EU46 "Vectron MS" and EU160 "Griffin" locomotives. First- and second-generation "Elf" EMUs reached levels of 80–86 dB. For freight trains hauled by EU46 "Vectron MS", the exposure sound level was 84 dB.

The lowest exposure sound levels were recorded when the railway track was located in a cutting. In this case, first- and second-generation "Elf" EMUs reached 79 dB, while passenger trains hauled by EU46 "Vectron MS" and EU160 "Griffin" locomotives reached 83–85 dB. Freight trains were 1 dB quieter than passenger trains.

Knowing the number of acoustic events (train passages by category), and the average exposure sound levels for different train types running on three types of terrain configurations (track in a cutting, at ground level, and on an embankment), the equivalent continuous sound level was determined using the following equation [30]:

$$L_{Aeq,16h} = 10 \cdot log\left[\frac{1}{T} \cdot \sum_{k=1}^{m} N_k \cdot 10^{0,1 \cdot L_{AEk}}\right] \tag{3.2}$$

where:

T – reference time period = 16 hours (from 6:00 a.m. to 10:00 p.m.) [s],

N_k – number of single acoustic events of class “k”occurring during the reference period within one day of measurements,

L_{AEk} – average exposure level for single acoustic events of class“k”, in decibels [dB],

m – number of classes of single acoustic events.

The resulting equivalent continuous sound levels (L_{Aeq}) were: 53 dB for the track in a cutting, 60 dB for the track at ground level and 57 dB for the track on an embankment.

4. SUMMARY

Based on the conducted noise measurements, the following conclusions can be drawn:

- The highest values of the exposure sound level, 90 dB, were recorded for trains running at ground level. The lowest values, 83 dB, were obtained for trains running in a cutting. A railway cutting functions as a barrier that limits the propagation of acoustic waves. The walls of the cutting reflect, scatter and partially absorb sound, which leads to a reduction in noise levels in the surroundings compared to ground-level conditions. The degree of sound attenuation fur such a track location depends on the depth and width of the cutting, the type of track the train runs on, and the meteorological conditions. For this track configuration, the exposure sound levels obtained in the study were 7 dB lower than those measured at ground level. Therefore, noise attenuation by the cutting can be considered more favourable from the perspective of acoustic protection of areas adjacent to the railway line
- In contrast to a cutting, an embankment raises the track above the surrounding terrain. In this configuration, the acoustic wave can propagate more freely without natural terrain obstacles that would limit its propagation. For this measurement location, a value of 85 dB was obtained. These values were 2 dB higher than those obtained for the cutting and 5 dB lower than those measured at ground level.
- The observed differences in exposure sound levels result from the varying propagation conditions of acoustic waves for different railway line configurations, as well as the lack of a shielding effect in the embankment and ground-level setups.
- The first- and second-generation "Elf" EMUs showed the lowest exposure sound levels across all terrain configurations around the railway line.
- The first-generation "Elf" EMUs had more variation in sound exposure depending on terrain: 86 dB on the embankment (highest), 83 dB at ground level, 79 dB in a cutting (lowest). These trains were 75,250 mm long.
- For second-generation "Elf" EMUs, average exposure sound levels ranged from 79–80 dB. The lowest values were recorded in a cutting, and the highest – 80 dB – both at ground level and on

the embankment. These trains were 15,280 mm longer than the first-generation Electric Multiple Units. Moreover, second-generation Elf units were the quietest among all tested trains across all three measurement locations.

- For trains hauled by EU46 "Vectron MS" locomotives, average exposure sound levels were: 87 dB for passenger trains, 86 dB for freight trains. Passenger trains hauled by this locomotive generated higher exposure levels in the cutting and on the embankment compared to freight trains. Only at ground level did freight trains hauled by EU46 "Vectron MS" reach 91 dB, which was 4 dB higher than passenger trains with the same locomotive.
- The highest exposure sound levels among all tested trains were recorded for passenger trains hauled by EU160 "Griffin" locomotives: 85 dB in a cutting, 95 dB at ground level, 90 dB on an embankment. These trains were also the longest, with a total length (locomotive + 7 coaches) of 195,200 mm.

ADDITIONAL INFORMATION

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