

Article

Mapping Noise from Motorised Transport in the Context of Infrastructure Management

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Abstract: Noise pollution presents significant challenges for urban infrastructure management, highlighting the need for practical assessment tools such as noise maps. These maps enable the visualization and geo-referencing of noise levels, identifying areas requiring immediate intervention and long-term strategic responses. Road sections with traffic exceeding 3 million vehicles per year were selected for measurement. The findings are presented in detail, revealing that the Long-term Day-Night Average Noise Level (L_{den}) exceeds acceptable limits, affecting approximately 1.899 km² and impacting around 1200 residents within the exceedance zone. Similarly, the equivalent noise level (L_{Aeq}) surpasses acceptable thresholds over an area of 1.220 km², affecting an additional 700 residents. Notably, there were no exceedances of the key noise impact indicators, including high annoyance (HA), high sleep disturbance (HSD), and ischemic heart disease (IHD). Changes in traffic organisation were implemented to address areas that exceed the applicable noise standards, including a ban on trucks and the introduction of local speed limits. The measures have successfully mitigated the noise problem in Grodzisk County (Poland). Further anti-noise initiatives are planned, including planting vegetation along the roadways.

Keywords: noise; noise map; road management

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1. Introduction

Studies indicate that approximately 40% of Europeans are exposed to daytime noise levels exceeding the World Health Organisation (WHO)'s recommended threshold of 55 dB [1,2]. The European Environment Agency reports that road noise affects around 125 million people, making it a significant social and environmental issue [3,4]. Noise is estimated to contribute to the loss of approximately 1.6 million disability-adjusted life years (DALYs) annually in Europe alone [5,6]. The ongoing urbanisation and increasing demand for transport services, coupled with the rise in the number of motor vehicles, significantly impact the magnitude of the adverse effects of noise on both people and the environment [7]. According to the Polish Central Statistical Office, road transport accounts for over 80% of all freight transport in Poland [8], exacerbating the problem of noise emissions. Car transport is a primary contributor to urban noise pollution, responsible for approximately 80% of the overall noise levels in many cities [9,10]. Numerous research papers have examined the relationship between traffic congestion and noise levels, highlighting the co-occurrence of public health issues as a result of increased noise exposure based on the models developed [3,8,11,12]. The primary organ affected by excessive noise impact is

hearing; however, indirect effects, such as heightened stress levels and diminished quality of life, associated with increased dB values have also been noted [13,14].

The World Health Organisation (WHO) has established guidelines indicating that noise levels exceeding 55 dB can lead to significant annoyance and health disorders. In contrast, levels above 70 dB can result in permanent hearing loss and increased mortality from cardiovascular causes [15]. Studies also indicate that noise exposure can trigger physiological stress responses, manifesting as elevated blood pressure, heart disease, and other cardiovascular conditions [16,17]. A meta-analysis by Babish highlights that road noise is a risk factor for coronary heart disease and may also influence an increased risk of stroke [18]. Similarly, research has shown that people living near heavily trafficked roads experience more sleep disturbances and various health issues. Estimates suggest that the indirect impact of road noise contributes to approximately 2000 premature deaths per year in Japan alone [19]. The effect of noise on sleep disturbance is associated with a potential increased risk of cognitive impairment and mental health issues, for example, increasing the risk of ischemic heart disease (IHD) [16], attention deficit disorder (HA) [20], sleep disturbances (HSD) [21,22], and depression [23,24]. The relationship between noise exposure and annoyance is also significant: studies demonstrate that even at similar decibel levels, different types of noise (e.g., road vs. aeroplane) can induce varying degrees of annoyance and health impacts [25,26]. This suggests that noise characteristics, including frequency and duration, are crucial in determining health effects [25]. Researchers indicate that prolonged exposure to high noise levels can lead to increased irritability, anxiety, and depression [13,27].

In addition to direct health impacts, noise from motorised transport has broader implications for urban planning and community well-being. Metropolitan areas with high traffic noise often experience reduced physical activity among residents, as noise discomfort can discourage outdoor activities [28,29]. This decline in physical activity can contribute to various health problems, including obesity and related chronic diseases [30,31]. Furthermore, green spaces have been shown to mitigate some of the adverse effects of noise pollution by promoting physical activity and enhancing mental well-being [32].

The accumulation of noise pollution in urban areas can diminish the quality of life, disrupt local ecosystems [33,34], and contribute to biodiversity loss [35,36]. Animals exposed to high anthropogenic noise levels may alter their behaviour, leading to habitat fragmentation and decreased reproductive success [35,36]. Noise pollution can modify animal behaviour, resulting in broader ecological impacts [9]. As urban areas continue developing, effective noise management strategies are becoming increasingly critical.

Effective noise mapping and mitigation strategies are essential for identifying high-exposure areas and implementing measures to reduce noise pollution, thereby protecting public health and improving environmental quality [37–39]. This article presents an example of conducting road noise impact measurements by developing maps that indicate the area exposed to negative impacts [40,41].

The study aimed to verify noise levels for areas near major roads in Grodzisk County. The selected study sections are characterised by an average annual vehicle traffic of more than 3 million trips/year, giving rise to the hypothesis of a problem of harmful effects resulting from transit traffic. According to data from the Polish Central Statistical Office, car transport in the context of freight transport accounted for 81.7% of all freight transport carried out in Poland, which increases the risk of exceeding acceptable noise standards. This article was produced in cooperation with the County Road Administration, for which post-measurements were carried out and conclusions drawn. An important issue is the inclusion and use of noise maps in road management by road managers as a tool to make decisions

and changes to the road environment that will compensate for possible exceedances of noise standards.

2. Materials and Methods

2.1. Related Studies and Guidelines

Urban development requires effective noise management strategies [42–44]. While the implementation of noise regulations is a key element of a comprehensive noise management approach [3,14], there is currently insufficient control [45].

The simplest solution applied to multi-lane roads is the introduction of noise barriers [46,47], while for single-lane roads, applying the indicated solution is economically and visually unfeasible. Therefore, research and application of road noise-mitigation pavements are essential [48,49]. Transport development is also related to using quieter engines and implementing tyres that reduce noise emissions from motor vehicles [14,50]. The electrification of transport is also an essential aspect of combating noise emissions [51–53], as electric motors operate much quieter than traditional internal combustion engines [14,50].

An interesting conclusion of the study is that traffic control should be considered to reduce road noise emissions. Traffic reduction measures like priority for public transport, development of cycling infrastructure [54], the concept of the 15-minute city, and promotion of walking [52,55] are crucial. Educating residents about the health impacts of noise and encouraging community involvement in local planning decisions can foster a collective approach to noise reduction [54]. In addition, policies that promote public transport and non-motorised modes can help shift social norms towards quieter, more sustainable transport options [14,54]. Awareness campaigns can also educate communities about the health impacts of noise pollution and encourage them to engage in noise reduction initiatives [56].

Measuring and mapping road transport noise is essential for establishing areas of harmful exposure and is key to verifying noise standards [7,57]. One of the primary methods for mapping road noise involves using statistical models that correlate noise levels with various urban parameters, such as traffic volume, road geometry, and environmental conditions. For example, Hanigan et al. [58] used a statistical approach to generate high-resolution health risk maps related to road noise. In contrast, Adza et al. [59] employed Geographic Information System (GIS) techniques to investigate the combined effects of road noise and air quality according to the UK Road Noise Calculation Method (CRTN). This research highlights the importance of integrating statistical analysis with spatial data to improve the accuracy of noise mapping. Suyunov emphasises the necessity of using noise data to update noise maps and produce mapping work that reflects the changing urban landscape [60]. The systematic collection of noise data is essential for accurately representing noise exposure in urban environments based on actual measurement data [61,62].

By the regulations in force, the assessment was carried out for one-hour indicators. The basis of the evaluation is the Regulation of the Minister of Environment of 14 June 2007 on permissible noise levels in the environment and the requirements contained therein [63].

According to the Environmental Protection Law, the basis for categorising areas subject to noise protection is the provisions of local spatial development plans. Article 114 (1) of the Act states that when drawing up a local spatial development plan, when differentiating between areas with different functions or development principles, it shall be indicated which of them belong to the particular types of areas referred to in Article 113 (2) para. 1 (i.e., the areas specified in the Decree of 14 June 2007 [63]). The applicable values of permissible sound levels in the environment are presented in Tables 1 and 2.

Table 1. Permissible levels of environmental noise caused by specific groups of noise sources, excluding noise caused by aircraft take-offs, landings and overflights, and power lines expressed in terms of L_{Aeq} and L_{Aeq} [64].

No.	Type of Terrain	The Permissible Noise Level in (dB)			
		Roads or Railway Lines		Other Facilities and Noise-Generating Activities	
		L_{Aeq} Time Reference Interval Equal to 16 h	L_{Aeq} 8 h Post-Elevation Time Interval	L_{Aeq} Reference Time Interval Equal to the 8 Least Favourable Hours of the Day Consecutively	L_{Aeq} Time Reference Interval Equal to 1 Least Favourable Hour of the Night
1	(a) Spa protection zone 'A' (b) Hospital areas outside the city	50	45	45	40
2	(a) Areas of single-family residential development (b) Areas of buildings connected with permanent or long-term residence of children and young people (c) Social housing areas (d) Hospital areas in cities	61	56	50	40
3	(a) Areas of multi-family residential development and collective housing (b) Areas of homestead development (c) Recreation and leisure areas (d) Residential and service areas	65	56	55	45
4	Areas in the inner city zone of cities with more than 100,000 inhabitants	68	60	55	45

Table 2. Permissible environmental noise levels caused by specific groups of noise sources, excluding noise caused by aircraft take-offs, landings and overflights, and power lines, expressed in terms of L_{den} and L_{Aeq} [64].

No.	Type of Terrain	The Permissible Noise Level in [dB]			
		Roads or Railway Lines		Other Facilities and Noise-Generating Activities	
		L_{den} Reference Time Interval Equal to All Days of the Year	L_{Aeq} Reference Time Interval Equal to All Times of the Night	L_{den} Reference Time Interval Equal to All Days of the Year	L_{Aeq} Reference Time Interval Equal to All Times of the Night
1	(a) Spa protection zone 'A' (b) Hospital areas outside the city	50	45	45	40
2	(a) Areas of single-family residential development (b) Areas of buildings connected with permanent or long-term residence of children and young people (c) Social housing areas (d) Hospital areas in cities	64	59	50	40
3	(a) Areas of multi-family residential development and collective housing (b) Areas of homestead development (c) Recreation and leisure areas (d) Residential and service areas	68	59	55	45
4	Areas in the inner city zone of cities with more than 100,000 inhabitants	70	65	55	45

2.2. Methods and Data Used to Perform Acoustic Calculations

The measurements and development of the noise map were conducted according to the requirements of the Minister of Climate and Environment Regulation of 1 July 2021 on the detailed scope of data included in strategic noise maps, as well as the manner of their presentation and the form of their transmission [65]. For the calculations, CadnaA software was used (developer: DataKustik GmbH (Gilching, Germany), Version 2021) [66], which incorporates the CNOSSOS-EU methodology [67], as mandated by the provisions of Directive 2002/49/EC of the European Parliament [68].

The reference methodology for measuring road noise levels emitted into the environment is established in the Decree of the Minister of the Environment dated 16 June 2011. This decree specifies the requirements for conducting measurements of the levels of substances or energy in the environment by the manager of roads, railway lines, tramway lines, airports, and ports [69]. The method of determining the long-term L_{den} indicator is detailed in the Regulation of the Minister of the Environment dated 10 November 2010 on determining the value of the L_{den} noise indicator [70]. According to this regulation, the L_{den} noise indicator is calculated using the following formula:

$$L_{den} = 10 \cdot \log \left[\frac{12}{24} \cdot 10^{0.1L_D} + \frac{4}{24} \cdot 10^{0.1(L_W+5)} + \frac{8}{24} \cdot 10^{0.1(L_N+10)} \right] \quad (1)$$

where

L_D —long-term average A sound level expressed in dB, determined during all daytime periods of the year, including the time of day (understood as the interval from 06:00 to 18:00 h);

L_W —long-term average sound level A expressed in dB, determined over all the evening periods of a year, including the daytime (defined as the interval from 18:00 to 22:00);

L_N —long-term average sound level A expressed in dB, determined during all the night periods of the year (understood as the time interval from 22:00 to 06:00).

Description of the methodology used to calculate the number of dwellings in residential buildings and the population attributed to residential buildings.

A key aspect of strategic noise mapping is analysing potential exposure to noise among inhabitants and its associated harmful effects. According to point 2.8 of Annex II of Directive 2002/49/EC, the analysis involves calculating noise emissions at the façades of residential buildings [68]. Subsequently, based on estimating the number of dwellings in a given area, we can approximate the number of inhabitants exposed to noise. For this purpose, we utilised data published by the Central Statistical Office [71] for the municipality where the measurements were carried out.

2.3. Testing Ground

Central to noise mapping is the accurate characterisation of the area being assessed. It is essential to identify potential noise sources and their impact on the designated regulatory regions. In the adopted methodology, communication routes (roads) are treated as linear noise sources within the computational model, the generated noise level of which depends on many factors, such as the following:

- Geometrical parameters of the noise source (road): type and technical condition of the road surface, cross-section of the road (width of the carriageway, number of lanes, width of the separation lane), location of the road about the ground level (on an embankment, in a trench, at ground level), and location of engineering structures limiting noise emissions (acoustic screens);

- Traffic parameters: traffic volume and structure (number of light and heavy vehicles), average traffic speed, type of traffic (smooth, interrupted, accelerated, and decelerating);
- Independent parameters: topography and land cover between the noise source and the receptor point, and meteorological conditions;
- Meteorological conditions (configured in CadnaA): temperature, air humidity, wind speed, and direction.

Basic information about the testbed under consideration is presented in Tables 3 and 4.

Table 3. Geographical coordinates of the analysed sections.

Road Number	Street Name	Vehicles/Year	Length (m)	GPS Coordinates in the 1992 System	
				Start of Road Section X/Y	End of Road Section X/Y
1503	Grodzisk Mazowiecki—Siestrzeń Ojrzeń	3,901,120	8060	472,176.28/ 611,955.16	467,138.46/617,626.89
1505	Grodzisk Mazowiecki—Józefina	4,113,915	2870	472,031.80/ 611,317.31	469,229.06/611,540.84
1511	Milanówek—Fałęcin—Kotowice	5,114,380	620	474,633.94/ 613,882.26	474,284.26/614,061.16
1526	Grodzisk Mazowiecki—Milanówek	3,935,795	1200	472,789.29/ 611,620.36	473,320.31/612,598.64

Table 4. Characteristics of the central county roads (width of road lane).

Road	Road Class	Width of Right-of-Way (m)	Surface Width (m)	Width of Roadway (m)	Number of Roadways	Number of Lanes	Type of Surface
Droga 1503W: Grodzisk Maz.—Siestrzeń—Ojrzeń, ul. Nadarzyńska	Main road (G)	up to 25	6–7	8–9	1	2 (1 in each direction)	Bituminous mass
Droga 1505W: Grodzisk Maz.—Józefina	Collective (Z)	20	6.5–7.5	8–9	1	2 (1 in each direction)	Bituminous mass
Droga 1526W: Grodzisk Mazowiecki ul. 3-go Maja, Milanówek ul. Dębowa	Collective (Z)	20	6.7–7.2	8–9	1	2 (1 in each direction)	Bituminous mass
Droga 1511W: Milanówek—Fałęcin—Kotowice, ul. Kazimierzowska, ul. Nowowiejska, ul. Piłsudskiego, ul. Dębowa, ul. Smoleńskiego, ul. Kościelna, ul. Kościuszki	Collective (Z)	20	5.9–6.2	6.5–7.5	1	2 (1 in each direction)	Bituminous mass

The following assumptions were made for the measurements:

- Traffic intensity: The traffic volume values on the individual road sections included in the scope of this study were estimated based on the traffic volume measurements carried out on the separate segments of the analysed roads. The 24-h average traffic volumes used in the calculations, categorised into daily and annual numbers of vehicles, are shown in the table below.
- Traffic speed: For these calculations, the average speed of vehicle traffic was assumed to be equal to the maximum permissible speed of vehicles at a given time of day.

The permissible traffic speeds were determined according to the list of vertical signs provided by the Contracting Authority.

- Type and condition of the road surface: The type and condition of the pavement in the calculation model were adopted by the actual condition observed during site visits conducted for noise level field measurements.
- Landforms and screening objects: For this study, a Numerical Terrain Model (NMT) layer and a Topographic Database (BDOT) were obtained from the resources of the Head Office of Geodesy and Cartography (GUGiK) [72]. The data received enabled the appropriate modelling of the nullification of individual road sections in relation to neighbouring areas, the landform in the immediate vicinity, and objects of a reflective and screening nature.

2.4. Description of the Calculation Model Calibration Methodology

For the verification and calibration of the computational model, measurements were carried out using the sampling method by point G (a height of $4.0 \text{ m} \pm 0.1 \text{ m}$) of the reference methodology, recording the value of the equivalent continuous A-weighted Sound Pressure Level at representative noise emission intervals. The number of measurements in each representative measurement interval taken of not less than three and with a duration of at least 10 min depended on the gap between the extreme results of these measurements. If the difference between the results of the individual measurements is greater than 7 dB, the duration of a single measurement is increased to a minimum of 15 min. The value of the acoustic background level was determined as far as possible when the source noise was not emitted, and if this was not possible, using the L95 index.

Calibration of the computational model was carried out concerning the results of noise measurements and vehicle traffic recorded during the study. The calibration process sought to minimise the error resulting from the difference between the measured sound level value and the value derived from the calculation model. During the calibration process, corrections were made to parameters determined with the most significant uncertainty, e.g., parameters relating to the type of road surface and ground absorption coefficient, G.

The calibration started once all complete data had been entered into the computer model, including the following:

- Complete geometry of the individual road sections,
- Traffic volume and vehicle speeds observed during the noise measurements,
- Type of pavement—based on visual inspection,
- Geometry of shielding, attenuating and reflecting objects,
- Elevation model of the area.

Irrespective of the measured sound level, either a single measurement result, L_{zm} , or a set of n values is available for comparison with the calculation results. In the second case, the average value used in the calibration procedure is determined from Formula (2):

$$L_{zm} = 10 \cdot \log \left[\frac{1}{n} \sum_{i=1}^n 10^{\frac{L_{zm,i}}{10}} \right] \quad (2)$$

Validation is a process designed to address the degree of agreement between model predictions and the actual value. Specifically, validation refers to the methodology used to evaluate the accuracy of the calculation method, where accuracy is measured by the error (the difference) between the calculated and measured sound levels. The outcome of the validation procedure is the determination of a so-called calibration correction for the computational model (a value-added or subtracted to the result of the calculation or the emission level of the noise source, depending on the software used), introduced to increase its accuracy. If the calibration correction falls within the acceptable range (meets

the established criteria), then the model and its predictions can be considered valid. The minimum value of the calibration correction is determined in a procedure referred to as calibration or adjustment of the acoustic model parameters to obtain the best agreement with the measurement result. Table 5 compares the measured results with the results obtained by calculation.

Table 5. Summary of results of calibration of the computational model.

Street	Measured Value (dB)		Calculated Value (dB)		Difference (dB)	
	L _{Aeq D}	L _{Aeq N}	L _{Aeq D}	L _{Aeq N}	L _{Aeq D}	L _{Aeq N}
ul. Nadarzyńska	67.2	61.4	66.9	60.9	0.3	0.5
3 Maja	67.4	61.1	66.2	60.3	1.2	0.8
ul. Smoleńskiego	65.1	60.2	64.8	59.6	0.3	0.6

Based on the calculations performed, it is concluded that the prerequisite for calibration has been met.

3. Results and Discussion

3.1. Results of the Strategic Noise Map Development

Description and location of areas where permissible noise levels expressed by the L_{den} indicator are exceeded.

The permissible value of the L_{den} indicator = 50 dB applies to development areas:

- Protective zone 'A' of the spa,
- Hospital areas outside the city.

The permissible L_{den} = 64 dB applies to the following development areas:

- Areas of single-family residential development,
- Areas of buildings connected with permanent or temporary residence of children and young people,
- Areas of social housing,
- Urban hospital areas.

The limit value of L_{den} = 68 dB applies to the following areas:

- Areas of multi-family residential development and collective residence,
- Areas of farm buildings,
- Recreation and leisure areas,
- Residential and service areas.

Here, we offer the description and location of areas where permissible noise levels expressed by the L_{Aeq} indicator are exceeded.

The permissible value of the indicator L_{Aeq} = 45 dB applies to the following development areas:

- Protective zone 'A' of the spa,
- Areas of hospitals outside the city.

The permissible value of indicator L_{Aeq} = 59 dB applies to the following development areas:

- Areas of single-family housing development,
- Areas of buildings connected with permanent or long-term residence of children and young people,
- Areas of social housing,
- Urban hospital areas,
- Areas of multi-family residential development and collective residence,

- Areas of farm buildings,
- Recreation and leisure areas,
- Residential and service areas.

3.2. Population Figures Exposed to Noise

The following subsections summarise statistics regarding the estimated number of dwellings, residents, facilities for the permanent or temporary residence of children and young people, hospitals, and social care homes exposed to road noise expressed by L_{den} and L_{Aeq} indicators.

The data concerning the number of residents and dwellings exposed to noise expressed by L_{den} and L_{Aeq} indicators follow the guidelines outlined in Appendix No. 2 of the Regulation of the Minister of Climate and Environment of 1 July 2021. This regulation details the scope of data included in strategic noise maps, as well as their presentation and transmission formats [65]. The figures have been rounded to the nearest 100, i.e., according to the explanations in Annex VI of the Directive 2002/49/EC of the European Parliament and the Council on standard methods of noise assessment, ‘the numbers are rounded to the nearest hundred’ (i.e., 5200 = between 5150 and 5249; 100 = between 50 and 149; 0 = less than 50).

Statistics on the occurrence of acceptable noise levels are shown in Tables 6 and 7.

Table 6. Statistics on the occurrence of exceedances of noise limits for county roads.

Grodzisk County	L_{den}				L_{Aeq}			
	1–5 dB	5.1–10 dB	10.1–15 dB	>15 dB	1–5 dB	5.1–10 dB	10.1–15 dB	>15 dB
Area (km ²)	0.114	0.012	0.000	0.000	0.022	0.000	0.000	0.000
Number of residential units	0	0	0	0	0	0	0	0
Number of residents	0	0	0	0	0	0	0	0
Facilities for the permanent or temporary stay of children and young persons	0	0	0	0	0	0	0	0
Healthcare facilities	0	0	0	0	0	0	0	0
Social welfare facilities	0	0	0	0	0	0	0	0

Table 7. Noise-exposure statistics for county roads.

Grodzisk County	L_{den}						L_{Aeq}					
	55–59 dB	60–64 dB	65–69 dB	70–74 dB	75–79 dB	+80 dB	50–54 dB	55–59 dB	60–64 dB	65–69 dB	70–74 dB	+75 dB
Area (km ²)	0.836	0.527	0.367	0.169	0.000	0.000	0.572	0.410	0.230	0.008	0.000	0.000
Number of residential units	372	301	232	0	0	0	252	312	11	0	0	0
Number of residents	600	500	100	0	0	0	500	200	0	0	0	0
Facilities for the permanent or temporary stay of children and young persons	1	3	4	0	0	0	0	0	0	0	0	0
Healthcare facilities	0	0	0	0	0	0	0	0	0	0	0	0
Social welfare facilities	0	0	0	0	0	0	0	0	0	0	0	0

Based on the data obtained, values were calculated for indicators to assess the harmful effects of environmental noise:

- Significant annoyance (HA, from high annoyance),
- High sleep disturbance (HSD),
- Ischaemic heart disease (IHD).

The results of the analyses are presented in Table 8.

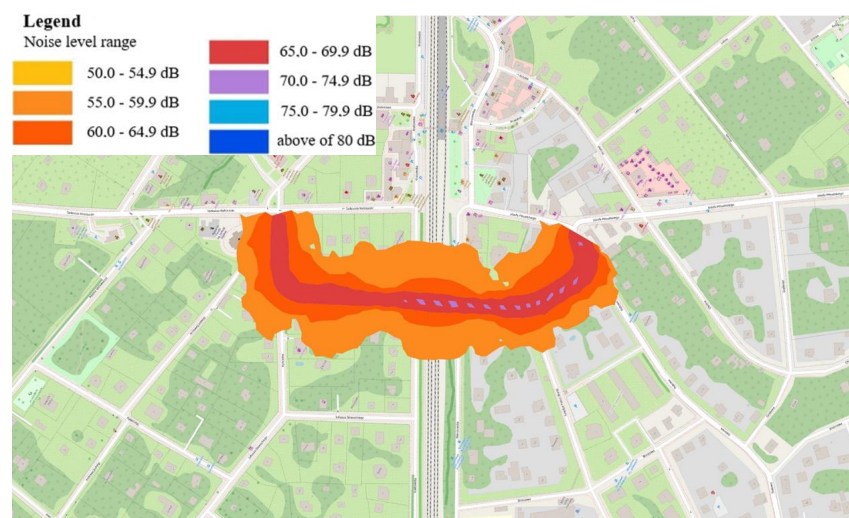
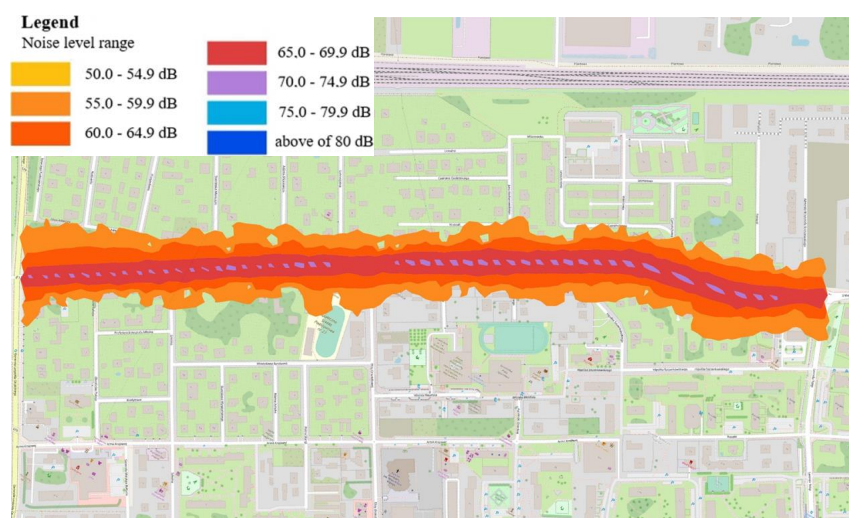
Table 8. Analysis of the number of residents affected by the harmful effects of noise.

County	The Number of People Affected by the Harmful Effects of Noise, as Expressed by the Indicator		
	HA	HSD	IHD
Grodzisk	0	0	0

3.3. Strategic Noise Map for County Roads

Noise maps have been produced for all road routes, as indicated in Table 3. Three sections are presented below for visualisation (using CadnaA software [71]):

- Noise emission map showing noise expressed by L_{den} (Figures 1–3).
- Emission map showing noise expressed as L_{Aeq} (Figures 4–6).
- Map of acoustically protected areas with permissible noise levels expressed in L_{den} and L_{Aeq} indicators (Figures 7–9).
- Map of noise-prone areas where the permissible noise levels, expressed in L_{den} , are exceeded (Figures 10–12).

**Figure 1.** Noise emission map showing noise expressed by L_{den} .**Figure 2.** Noise emission map showing noise expressed by L_{den} .

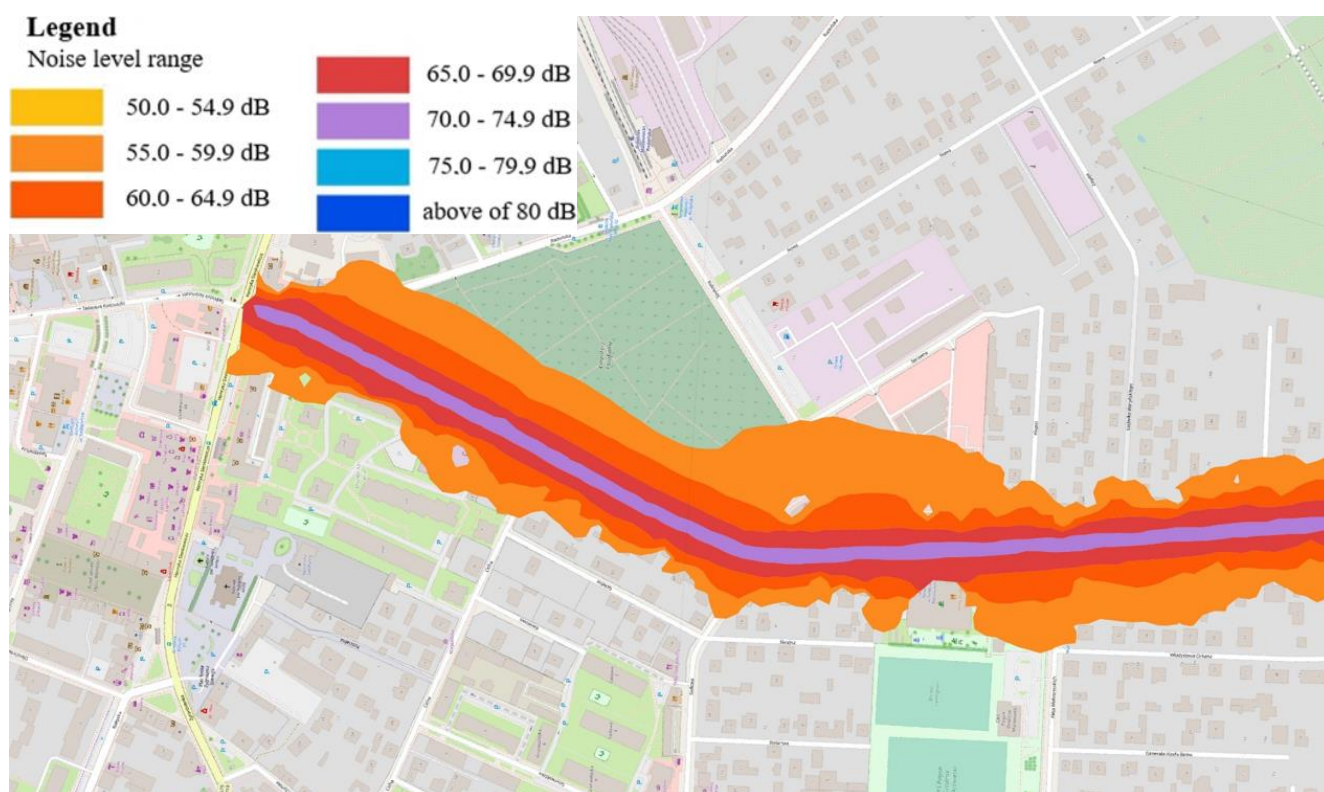


Figure 3. Noise emission map showing noise expressed by L_{den} .

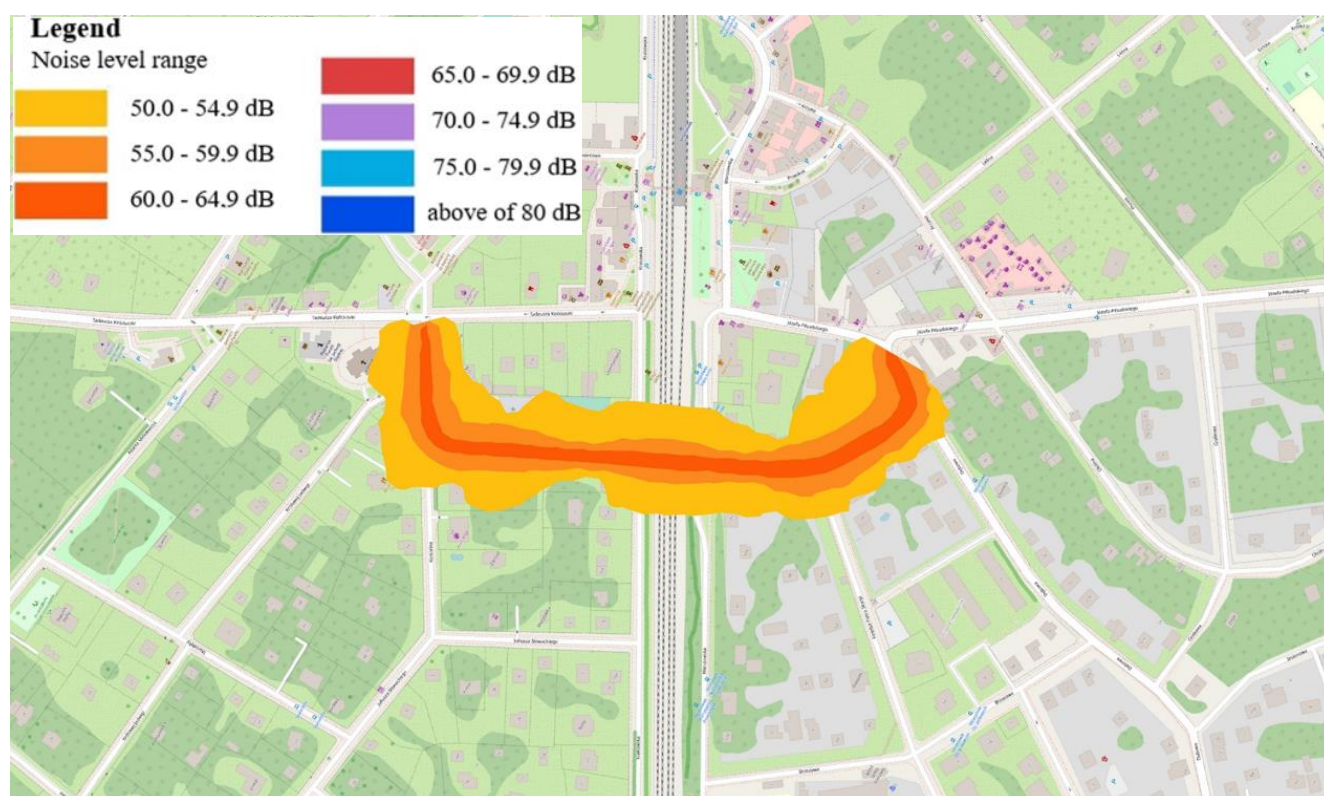


Figure 4. Emission map showing noise expressed as L_{Aeq} .

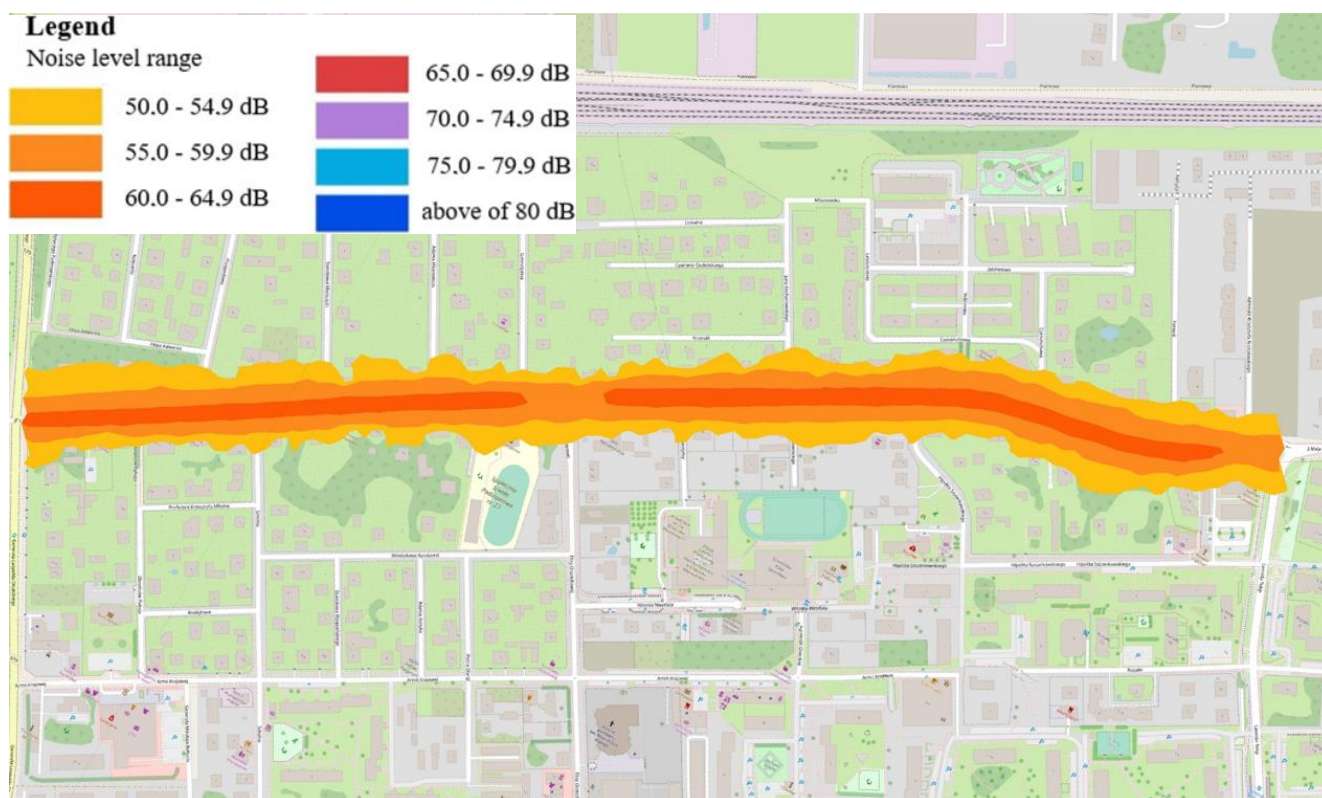


Figure 5. Emission map showing noise expressed as L_{Aeq} .

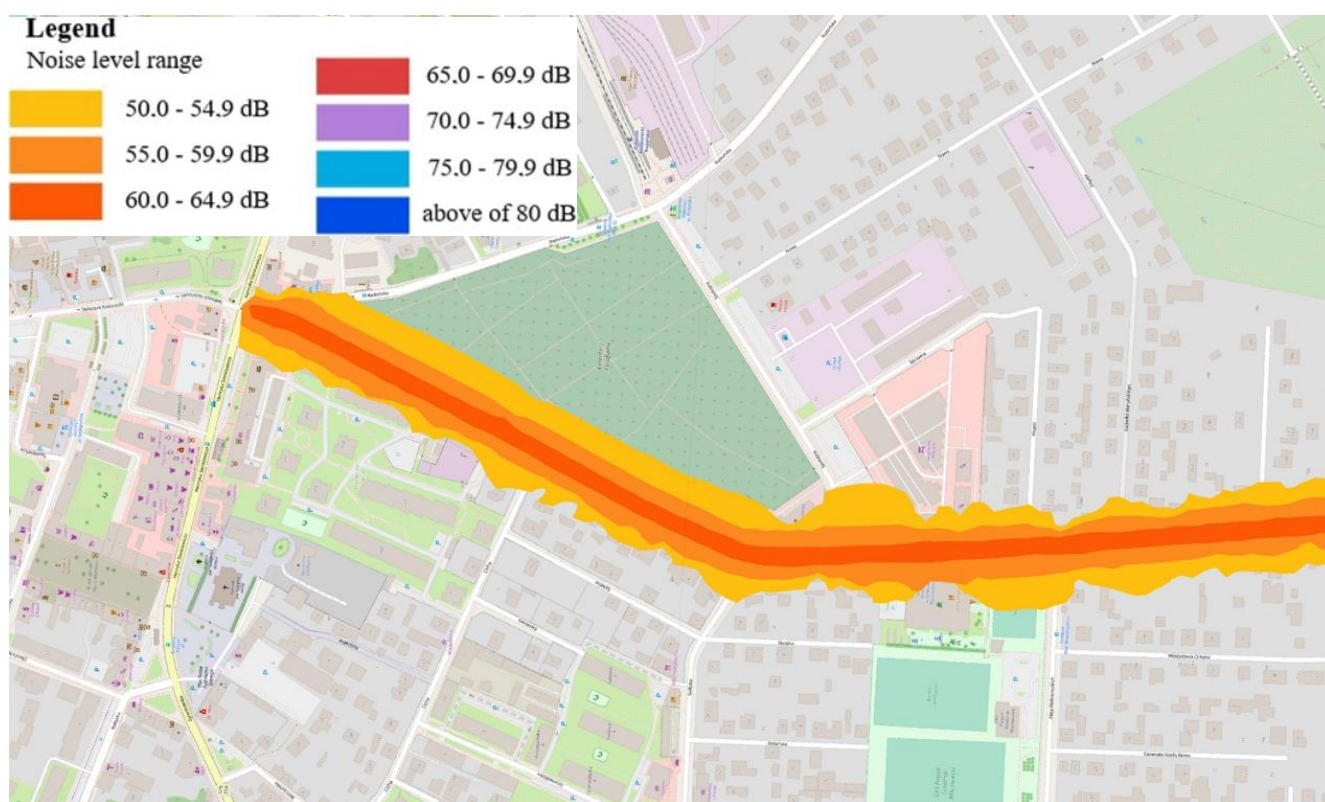


Figure 6. Emission map showing noise expressed as L_{Aeq} .

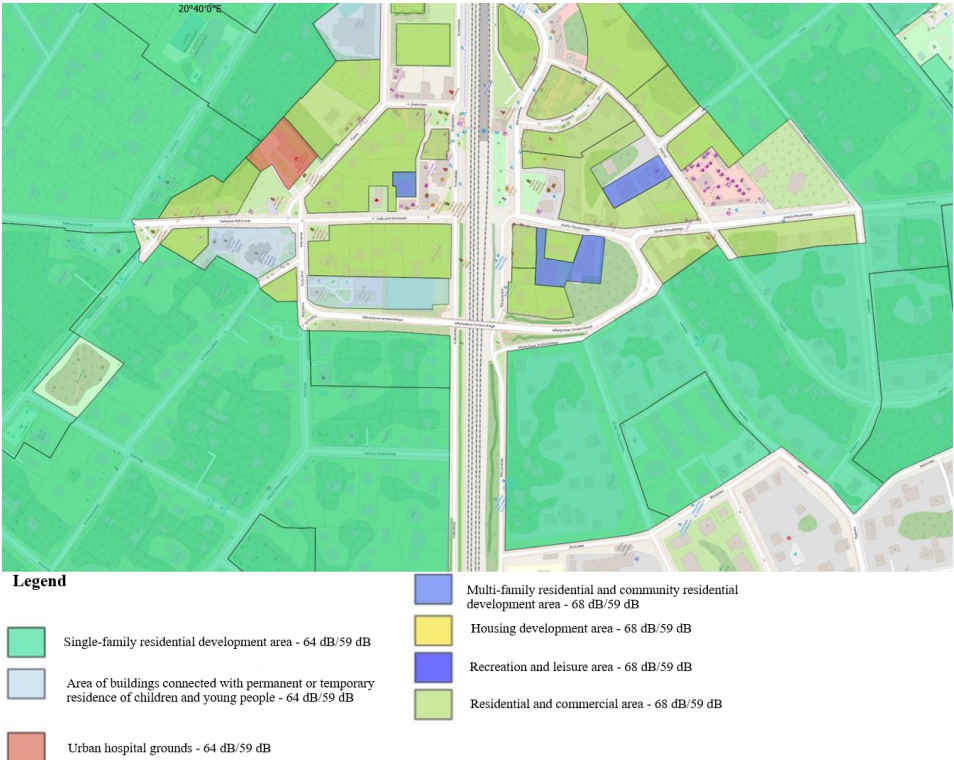


Figure 7. Map of acoustically protected areas with permissible noise levels expressed in L_{den} and L_{Aeq} indicators.

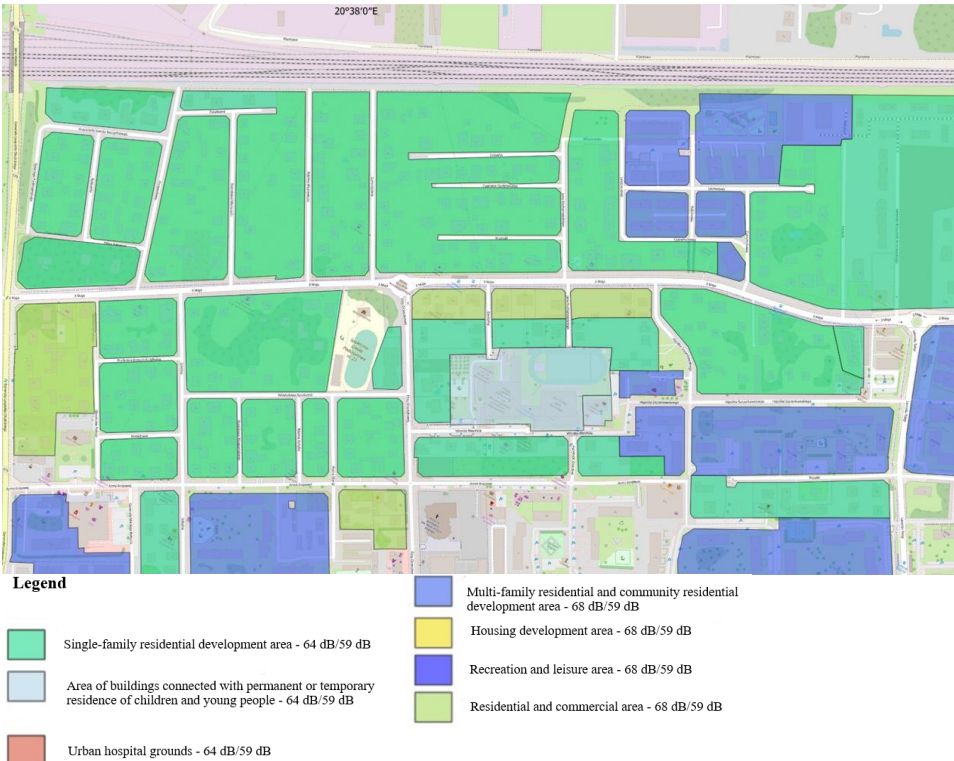


Figure 8. Map of acoustically protected areas with permissible noise levels expressed in L_{den} and L_{Aeq} indicators.

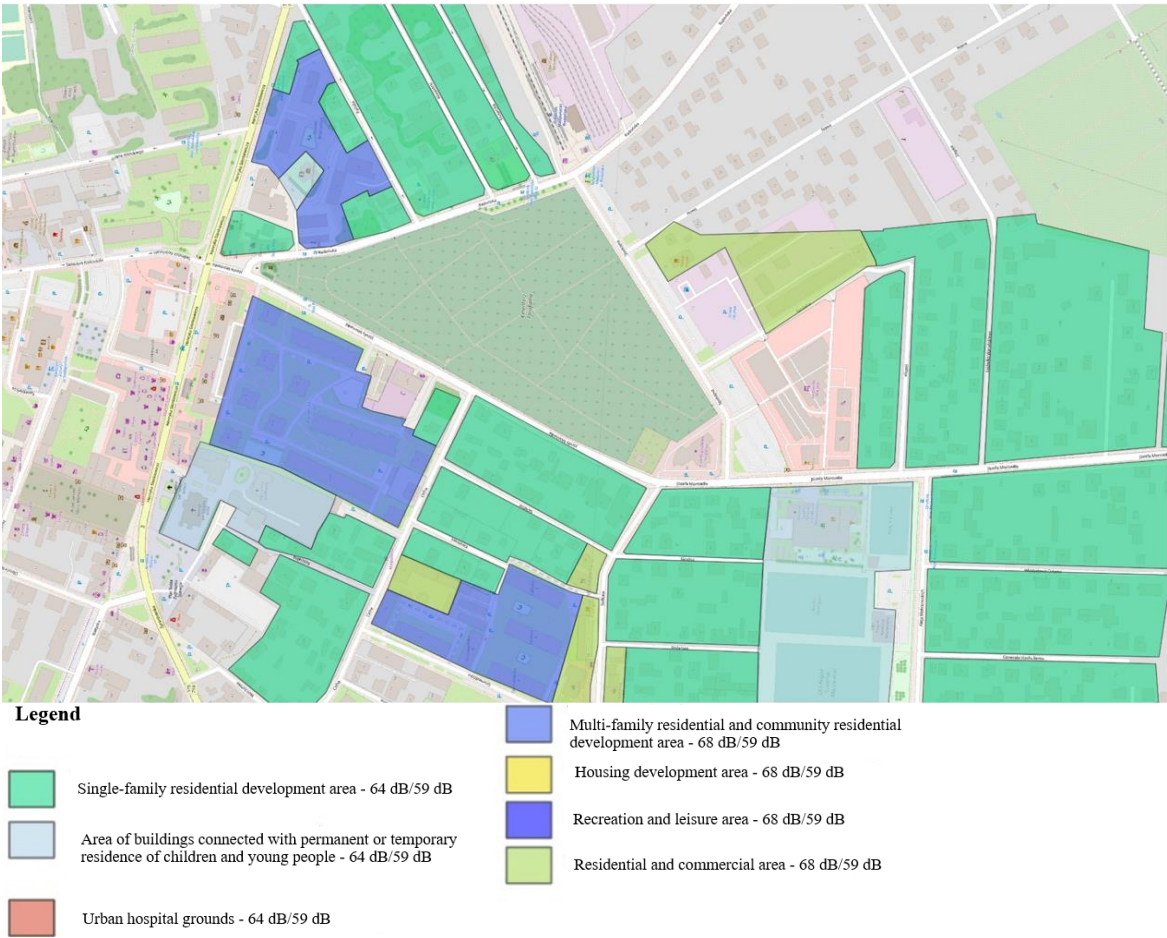


Figure 9. Map of acoustically protected areas with permissible noise levels expressed in L_{den} and L_{Aeq} indicators.

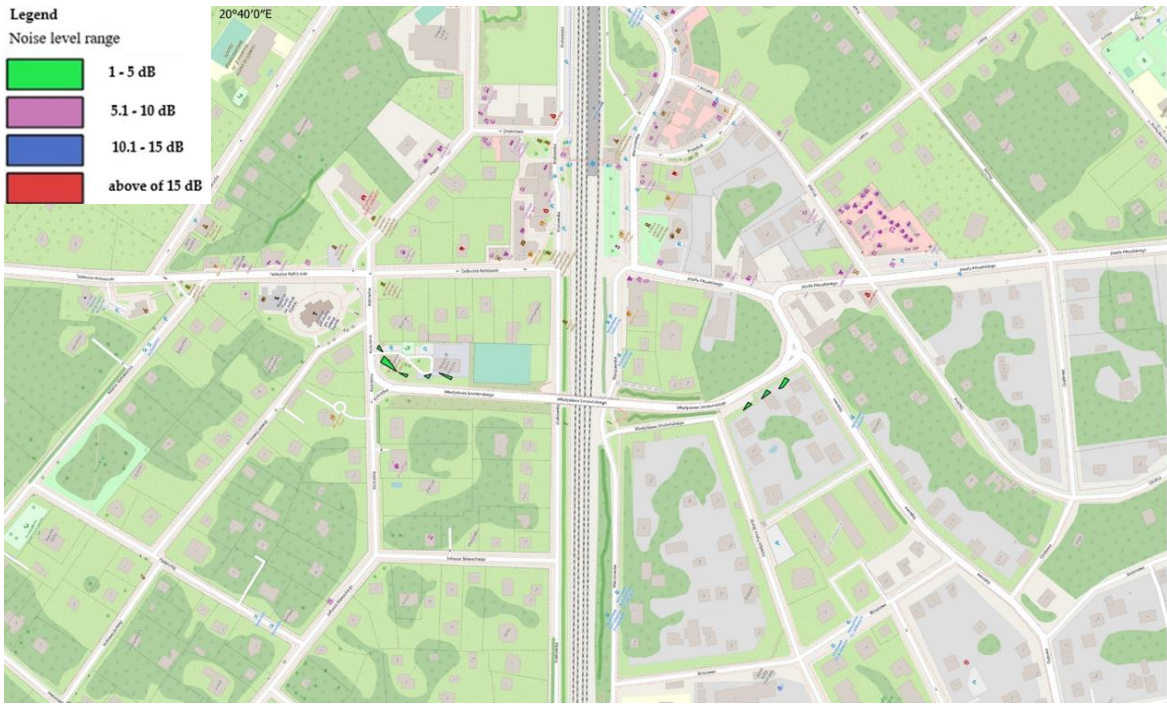


Figure 10. Map of noise-prone areas in which the permissible noise levels expressed in L_{den} are exceeded.

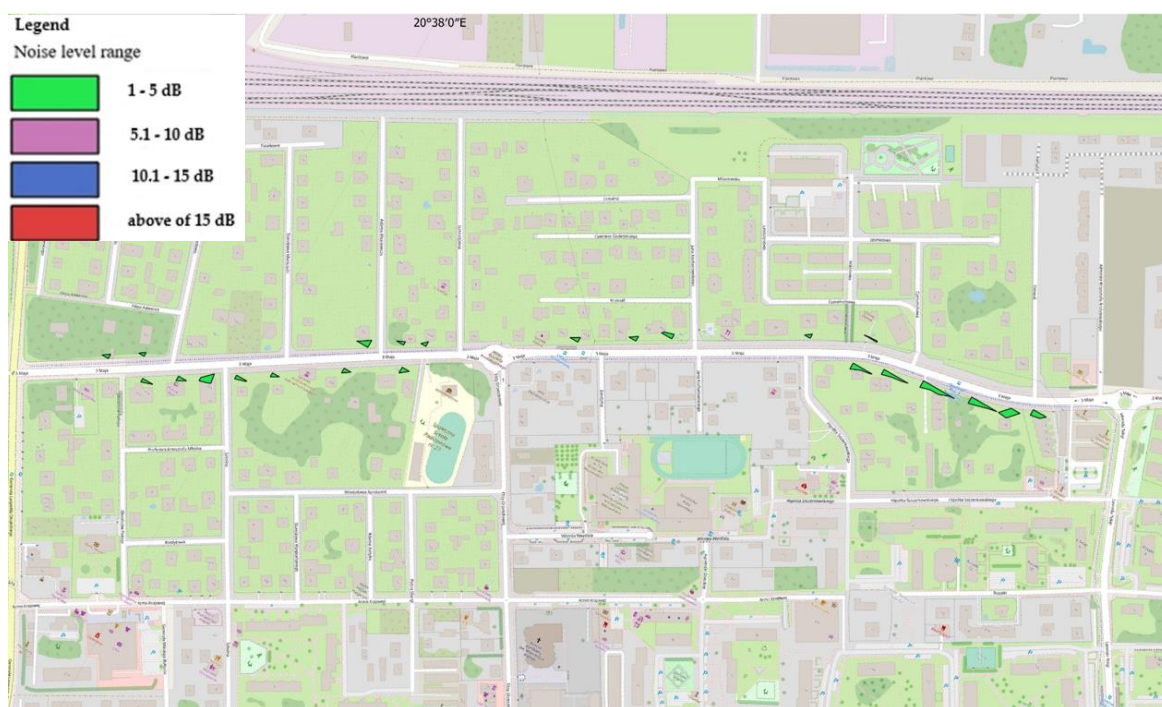


Figure 11. Map of noise-prone areas in which the permissible noise levels expressed in L_{den} are exceeded.

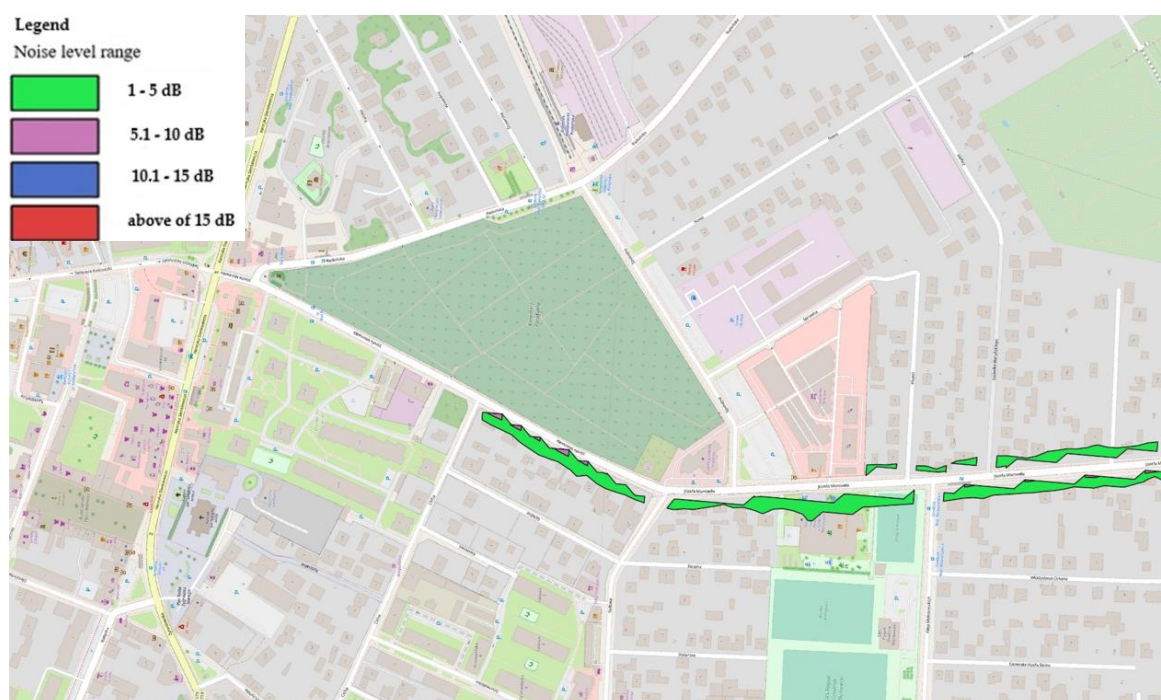


Figure 12. Map of noise-prone areas in which the permissible noise levels expressed in L_{den} are exceeded.

Noise maps are valuable tools for assessing the scale of the noise problem for infrastructure managers [73–75]. The visualisation of noise levels on a map, together with the geo-referencing of data, makes it possible to identify sites which require intervention or which will require a response in the long term. The issue of noise pollution in the context of building approvals should be integrated into the local spatial development plan. According to the measurements taken, noise impact according to L_{den} was found on 1.899 km². This

translates into an impact on approximately 1200 residents living in the exceedance zone of the indicated indicator. In contrast, for the L_{Aeq} metric, the exceedance occurs over an area of 1.220 km², impacting around 700 residents. It is important to note, that none of the key indicators was referenced for the study area, i.e., L_{Aeq} : significant annoyance (HA, from high annoyance), high sleep disturbance (HSD), and ischaemic heart disease (IHD).

One of the most common strategies for reducing traffic noise is the installation of noise barriers [76–78]. However, this approach is often ineffective due to challenging urban conditions and limited space for their installation [79]. Minor noise exceedances can be mitigated by incorporating greenery along the road lane [80–82]. The main elements in the fight against traffic noise in cities are the use of noise protection measures consisting of proper traffic organisation [83,84] or the introduction of new solutions, such as noise-reducing pavements [48].

Noise maps are an important tool for road managers in the process of road operation. The analysis of noise maps allows for unambiguous indication of locations where the noise value is exceeded and taking appropriate action. In the process of road operation and management, this makes it possible to plan intervention works and investments taking into account the current or future needs of the road.

As part of the results, the infrastructure manager has decided to reduce noise levels by applying speed limits and increasing enforcement of existing speed limits [15,85]. For the short section of road with the highest exceedances, it was decided to ban heavy goods vehicle traffic [86,87]. In the next stages, it is planned to plant greenery in the road lane. Applying the indicated solutions has made it possible to reduce noise levels and eliminate the problem for the surveyed road sections. The assumed effect of the introduced and planned works is the complete elimination of exceeded noise standards.

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