Environmental Research 269 (2025) 120879

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

Exposure-response relationships between road traffic, railway, and aircraft noise and annoyance in Bulgarian cities

Angel M. Dzhambov [a,b,*], Angel Burov [a,b,c], Julian Hagenauer [d], Marco Helbich [a,b,d], Donka Dimitrova [a,b,e], Iana Markevych [a,b,f], Mark J. Nieuwenhuijsen [g,h,i]

[a] Health and Quality of Life in a Green and Sustainable Environment Research Group, Strategic Research and Innovation Program for the Development of MU – Plovdiv, Medical University of Plovdiv, Plovdiv, Bulgaria
[b] Environmental Health Division, Research Institute at Medical University of Plovdiv, Medical University of Plovdiv, Plovdiv, Bulgaria
[c] Department of Urban Planning, Faculty of Architecture, University of Architecture, Civil Engineering and Geodesy, Sofia, Bulgaria
[d] Department of Human Geography and Spatial Planning, Faculty of Geosciences, Utrecht University, Utrecht, the Netherlands
[e] Department of Health Management and Health Economics, Faculty of Public Health, Medical University of Plovdiv, Plovdiv, Bulgaria
[f] Institute of Psychology, Jagiellonian University, Krakow, Poland
[g] Barcelona Institute for Global Health, Barcelona, Spain
[h] Universitat Pompeu Fabra, Barcelona, Spain
[i] CIBERESP, Madrid, Spain

ARTICLE INFO

Keywords:
Transport noise exposure
Noise perception
Noise sensitivity
Noise survey
Eastern Europe

ABSTRACT

This study aimed to develop exposure-response relationships (ERRs) between road, rail, and air traffic noise and high noise annoyance (HNA) and to assess the HNA disease burden. In 2023, 4640 adults were cross-sectionally sampled from the five largest cities in Bulgaria. Participants' road, rail/tram, and air traffic HNA was defined as the top two categories (60% cut-off point) of a 5-point scale. A 72% cut-off approximation was also used. European Noise Directive maps were used to assign day-evening-night equivalent sound levels (L_{den}) to residences. ERRs were derived and used, together with the new WHO disability weight for HNA, to calculate disability-adjusted life years (DALYs). DALYs were monetised based on Bulgaria's gross domestic product (GDP) per capita and the value of a life year (VOLY). In fully adjusted models, L_{den} was non-linearly associated with HNA. Road traffic L_{den} [range 42.5–77.5 dB] was positively associated with HNA only above 62.5 dB, whereas the upward trend for rail [range 37.5–72.5 dB] and air traffic L_{den} [range 37.5–57.5 dB] started at 40–45 dB. Using this study's ERRs, the burden among people exposed to ≥40 dB was 3476 (1896–5056) DALYs, $ 39 138 953 (21 348 520–56 929 386) based on GDP, and € 243 310 984 (94 796 487–505 581 266) based on VOLY. Using the WHO's curves, the burden was 4312 (2352–6273) DALYs, $ 48 559 330 (26 486 907–70 631 753), and € 301 873 648 (117 613 110–627 269 918). In conclusion, we could only derive a plausible ERR for railway noise annoyance. Until better ERRs are derived for the Bulgarian population, we recommend using the WHO curves for road traffic and aircraft noise annoyance.

1. Introduction

Traffic noise is one of the most prevalent environmental risk factors among urban populations (WHO, 2018). At least 20% of the European population is exposed to traffic noise levels above the European Noise Directive (END, Directive 2002/49/EC) threshold for mapping and reporting environmental noise of 55 dB (dB) (EEA, 2020b), which is considered harmful to human health (WHO, 2018). Long-term exposure to traffic noise is associated with health in several ways, primarily acting as a stressor to the body and resulting in mental, neurocognitive, cardiovascular, metabolic, and pregnancy-related impairments (Welch et al., 2023; Chen et al., 2023a). However, a large proportion of the population experiences severe annoyance from traffic noise long before other noise effects become clinically manifest (Guski et al., 2017). Noise annoyance is an indicator of the psychophysiological stress response to noise; it undermines quality of life and is a precursor to more serious

* Corresponding author. Environmental Health Division, Research Institute at Medical University of Plovdiv, Medical University of Plovdiv, 15A Vassil Aprilov Blvd., 4002, Plovdiv, Bulgaria.
E-mail addresses: angelleloti@gmail.com, angel.dzhambov@mu-plovdiv.bg (A.M. Dzhambov).

https://doi.org/10.1016/j.envres.2025.120879
Received 8 November 2024; Received in revised form 15 January 2025; Accepted 16 January 2025
Available online 16 January 2025

complications, such as sleep disturbance (Smith et al., 2022), mental (Gong et al., 2022) and physical health problems (Eze et al., 2018; Hahad et al., 2024).

A World Health Organization (WHO) synthesis of studies from different countries provided exposure-response relationships between traffic noise sources and annoyance (Guski et al., 2017). Estimates of the relationships between traffic noise and annoyance are essential for quantifying the burden of disease from environmental noise. The distribution of this burden is uneven across Europe. Therefore, understanding the causes of such inequalities requires knowledge of the local exposure-response relationships used for burden of disease calculations (cf. Khomenko et al., 2022). Such exposure-response relationship data are scarce and the evidence of noise annoyance needs to be stronger, especially in middle-income countries like Bulgaria (Chen et al., 2023b). In a recent European assessment of noise-induced health effects, Sofia, Bulgaria, had the highest percentage of the population highly noise-annoyed (Khomenko et al., 2022). These calculations were based on the application of the WHO exposure-response curves to official noise data reported by the national administration under the END (Khomenko et al., 2022). Known limitations of these data are that they are based on noise mapping of variable quality across Europe, and that the population exposed to day-evening-night equivalent sound levels (L_{den}) below 55 dB is not reported to the European Environment Agency (EEA). Furthermore, in 2024 the WHO recommended the use of a new disability weight for environmental noise annoyance across the WHO European Region (WHO, 2024), which is markedly different from the one previously used. It is, therefore, unknown whether these methodological issues have resulted in some degree of under or overestimation of the actual impact on noise annoyance, which is essential given the potential for heterogeneity between local exposure-response relationships (cf. Guski et al., 2017).

Some of the major setbacks hindering scientific progress in Bulgaria on the relationship between noise and annoyance were the lack of large-scale socio-acoustic surveys (Dzhambov and Dimitrova, 2015) and the limited quality of noise data (i.e., the unavailability of continuously modelled road traffic noise) (Dzhambov et al., 2023). Some Bulgarian studies leveraged available END maps to assess the health effects of noise, but their samples were small and unrepresentative. Therefore, the results could not be generalised to the population (Dzhambov and Dimitrova, 2015). Furthermore, the few existing Bulgarian noise health impact studies focused mainly on road traffic noise (Chen et al., 2023b), while railway and aircraft noise are characterised by different exposure patterns, spatial distributions, and effects on annoyance (Guski et al., 2017).

Here, we analysed a sample of the general population of the five largest cities in Bulgaria, to respond to the methodological issues outlined and to develop population-based exposure-response relationships between road, rail/tram, and air traffic noise and high noise annoyance (HNA). We also aimed to calculate the health burden of high noise annoyance and the corresponding monetary costs.

2. Materials and methods

2.1. Study design and data collection

Between August and October 2023, a survey on environmental conditions, perceptions, and health was conducted in the five largest Bulgarian cities, namely the capital of Sofia, Plovdiv, Varna, Burgas, and Ruse (Supplementary Fig. S1, Supplementary File 1). The cities of Sofia, Varna, and Burgas have an airport on their outskirts. In the case of Plovdiv, the airport is in a nearby settlement and is likely to have little impact on residents' noise exposure. All five cities have a railway network, and Sofia also has a well-developed tram public transportation system.

We pre-tested the survey questionnaire in a small convenience sample and had a focus group discussion with a professional survey company. This company was contracted to conduct the fieldwork using interviewers who underwent prior training by the research team to harmonise data collection procedures. This training involved a mock interview, followed by a discussion. Printed maps of the areas to visit with a list of all addresses within the sampling areas and a designated starting address were provided. The interviewers were also assigned sociodemographic quotas they were required to meet.

Potential participants were approached at home by calling at their door or in case they were encountered in front of the building and confirmed that they lived there. Only one person per household was interviewed. To be eligible to take part in the survey, respondents had to be at least 18 years old, able to read and write, and capable of forming a mental intent. We only included people who had lived in their current dwelling for at least one year prior to enrolment in the survey. We applied a quota sampling approach to obtain a representative sample of the adult population in terms of age, sex, education, and ethnicity for each city. Respondents were interviewed face-to-face with an average interview duration of 22 ± 9.5 min.

Out of 10 914 eligible respondents, 6032 refused participation, and 242 did not complete the survey. This resulted in a sample size of 4640 participants – 1512 from Sofia, 1012 from Plovdiv, 1001 from Varna, 655 from Burgas, and 460 from Ruse. The overall response rate was 43%, ranging from 31% in Sofia to 58% in Plovdiv (Supplementary Fig. S2, Supplementary File 1). Given the diversity of research hypotheses generated for the project, power calculations did not inform the target sample size. Instead, we aimed to maximise the number of participants relative to the city population and ensure sufficient variability in the data. To increase the possibility of disentangling the health effects of different physical exposures by ensuring sufficient variability in exposure, participants' address locations were sampled from eight spatial typologies based on harmonised spatial data obtained from OpenStreetMap (OpenStreetMap contributors, 2023), Bulgarian cadastre (Geodesy, Cartography and Cadastre Agency, 2023), and European Union Land Copernicus Urban Atlas (Copernicus Land Monitoring Service, 2021). The criteria were: within ≥/<50 m of a major road; within ≥/<100 m Euclidean distance to ≥10 households associated as groups using fossil fuel for heating; and within ≥/< 300 m of a green urban area. Addresses from which the interviewers were to start the sampling were randomly selected within each spatial type, and individually for each city. A similar strategy was previously used by Dzhambov et al. (2023).

Participants were first given detailed information about the study (of which they kept a printed copy) and were allowed to ask questions, then they were asked to give verbal informed consent to take part in the survey and a separate consent for their personal data to be processed. Their consent was marked on the tablet device, before the survey itself could be loaded. Relevant European Union data protection legislation was followed. The study was approved by the Scientific Ethics Committee of the Medical University of Plovdiv (Protocol № 4/04.05.2023 and Opinion № P-1253/17.05.2023).

2.2. Noise annoyance

Participants were asked about their annoyance over the past 12 months from road traffic, rail/tram, and air traffic. The wording of these questions was consistent with the verbal scale recommended by the International Commission on Biological Effects of Noise (ICBEN): "*Think about the last* 12 months*, when you were at home, and tell me how much did … road traffic noise, railway/tram noise, aircraft noise … bother or disturb you?*". The annoyance caused by each noise source was rated separately on a 5-point response scale with the verbal marks "not at all", "slightly", "moderately", "very", and "extremely". The "very" and "extremely" categories were combined into "high noise annoyance" (HNA) (Fields et al., 2001). Therefore, for the main analysis we used the previously recommended ICBEN cut-off point of 60% to define HNA, but also report adjusted percentages of HNA according to ISO/TS 15666:2021

(ISO/IEC, 2021) to allow comparison with other studies (Brink et al., 2021).

2.3. Traffic noise exposure

A Global Positioning System-based device was used to link survey responses to objective noise exposure data. Where a visual inspection of the geocoded addresses revealed significant displacement, we manually adjusted the coordinates in QGIS 3.28.2 using cadastral data and a text record of the respondent address.

We linked participant's address to L_{den} data from the Bulgarian strategic noise maps delivered under the END (EEA, 2020a). The linkage was based on the L_{den} value associated with the polygon the address point intersected with. END maps were modelled by an acoustic engineering company using the CNOSSOS-EU framework, at a spatial resolution of 10 m × 10 m and 4 m height, and then calibrated and validated against short-term measurements (SPECTRI, 2016, 2017a, 2017b, 2017c, 2017d) (see Dzhambov et al. (2023) for more details). The most recent END maps available for the study areas were from 2017 and included 5-dB noise bands. As done elsewhere (Jarup et al., 2008; Floud et al., 2013; Dzhambov et al., 2023), we generated a pseudo-continuous L_{den} variable for each traffic source by assigning to the 5-dB noise classes their respective midpoint value (e.g., the 50–55 dB band was assigned a value of 52.5 dB). Although rail/tram and aircraft L_{den} were modelled to a minimum of 10 dB, we assigned all exposure levels below 40 dB a value of 37.5 dB L_{den} (Romero Starke et al., 2023). Addresses outside the contours of the noise maps, for which we had no noise data and which were effectively considered unexposed to the respective source, were not included in the analysis. The distribution of residential addresses over noise contours is shown in Supplementary Figs. S3–S7, Supplementary File 1.

2.4. Other variables

This study used the disjunctive cause criterion to control for confounding (VanderWeele, 2019). The following theoretically plausible predictors of either traffic noise exposure or noise annoyance were selected: Participants reported their age (in years), sex, education (primary school not completed, primary school completed, secondary school completed, higher school completed), and ethnicity (Bulgarian, other). Perceived income was assessed with a question about the ability to make ends meet financially in the household ("very difficult", "difficult", "with some difficulty", "mostly easy", "easy", "very easy"). Noise sensitivity was measured with a single item: "*Please tell me how sensitive you are to the following things in general, compared to most people you know …. Noise*". Answers were given on a 5-point scale ("not at all", "slightly", "moderately", "very", "extremely"). Dwelling characteristics included the type of the building (single-family house, multi-family house, apartment in a building, dormitory/hostel) and floor.

2.5. Statistical analysis

Data were summarised using descriptive statistics and distribution plots. Bivariate associations were analysed using Spearman correlation coefficients. All analyses were performed with complete cases owing to the low percentage of missing data (<5% for any given variable).

Associations between L_{den} of each traffic source and HNA were tested for non-linearity using generalised additive models (Hastie and Tibshirani, 1986; Royston and Ambler, 1998) implemented in the "gamplot" package for Stata. To prevent overfitting, these models were fitted with 3 degrees of freedom for the estimated smooth functions. The presence of non-linearity was inferred from visual inspection of the relationships and a significant Gain statistic, which quantifies the deterioration in fit when a linear term is used instead of the smooth term. Models were incrementally adjusted for city, then further adjusted for age, sex, education, ethnicity, and perceived income, and further adjusted for noise sensitivity, dwelling type, floor, and month of data collection. Multicollinearity was not found (variance inflation factors <5, tolerance values > 0.2). Collinearity was tested using the "collin" package for Stata.

We then used logistic regression models to compare the predicted probability of HNA derived from an unadjusted model (with only L_{den} as an independent variable) with the WHO curve for the respective noise source (Romero Starke et al., 2023). WHO curves were constructed following Guski et al. (2017):

$$\text{Predicted road traffic \%HNA} = 78.9270 - 3.1162 \times L_{den} + 0.0342 \times L_{den}^2;$$

$$\text{Predicted railway traffic \%HNA} = 38.1596 - 2.05538 \times L_{den} + 0.0285 \times L_{den}^2;$$

$$\text{Predicted aircraft noise \%HNA} = -50.9693 + 1.0168 \times L_{den} + 0.0072 \times L_{den}^2.$$

Effect estimates were considered statistically significant at the $p < 0.05$ level (two-tailed). Statistical data processing was performed using Stata MP v. 18 (StataCorp, 2023).

2.6. Calculation of burden of high noise annoyance

The quantification of the burden of disease from HNA followed the methodology proposed by the WHO (WHO Regional Office for Europe, 2011). Disability-adjusted life years (DALYs) were used as a summary measure of population health, where one DALY represents fatal and non-fatal losses equivalent of one year of full health (Salomon, 2014). DALYs for each noise source were calculated as the "number of people highly annoyed" multiplied by a disability weight multiplied by the duration of exposure (i.e., 1 year), effectively capturing years lived with disability. A disability weight, which takes on a value between 0 (for full health) and 1 (equivalent to dead), indicated the percentage of time spent in less than full health with a condition (Salomon et al., 2012). We used two types of disability weights. For our main analysis, we used the new disability weight proposed by a WHO expert group, which is derived from the judgments of members of the general public (WHO, 2024). This disability weight has a value of 0.011 for severe (i.e., high) annoyance and an uncertainty interval (UI) of 0.006–0.016 (WHO, 2024). As a sensitivity analysis, we used the previously recommended disability weight of 0.02 (95% UI: 0.01–0.12) based on the judgments of medical experts (WHO Regional Office for Europe, 2011). To estimate the number of highly annoyed people, we applied our exposure-response relationships to the number of people exposed to each noise level. As the number of people exposed (taking into account the most exposed building façade) is reported by Member States to the European Environment Agency for 5-dB noise bands starting at 55 dB L_{den}, we used the more granular results from Bulgarian END noise mapping (i.e., at 1 dB resolution, except for Burgas) obtained by SPECTRI (SPECTRI, 2016, 2017a, 2017b, 2017c, 2017d).

The calculated DALYs were monetised by multiplying them by Bulgaria's gross domestic product (GDP) per capita in 2021 (Brown, 2008). Following others (Kirigia and Kubai, 2023), we used non-health GDP per capita in US dollars ($ 11 260) by subtracting current health expenditure per capita ($ 1040) from the GDP per capita in current prices ($ 12 300). Data were obtained from the International Monetary Fund World Economic Outlook database (https://www.imf.org/en/Publications/WEO/weo-database/2024/April) and the WHO Global Health Expenditure database (https://apps.who.int/nha/database). As a sensitivity analysis, we used the value of a life year (VOLY) as an alternative monetary cost per DALY (Engelmann et al., 2023). The VOLY is a measure of the economic value of extending life, that is the value of an additional life year gained. A VOLY of € 70 000 (UI: 50 000–100 000) per

DALY (for 2016) was proposed for health risk assessment using data reported under the END to analyse noise-attributed health costs at European Union level (Engelmann et al., 2023). Calculations were made in Microsoft Excel (see Supplementary File 3).

3. Results

3.1. Sample characteristics and data patterns

The study sample consisted of 4640 participants. A summary of the characteristics of the participants is given in Table 1. The majority lived in the cities of Sofia, Plovdiv, and Varna. Most participants were female (54%), ethnic Bulgarian (96%), had secondary education (57%), and reported some difficulties with their financial situation (44%). The sample was largely representative of the target population in terms of age, sex, education, and ethnicity (see Supplementary Table S1, Supplementary File 1).

The traffic noise levels from the different sources had a relatively wide range. L_{den} distributions varied between cities (Supplementary Fig. S8, Supplementary File 1). For example, participants were exposed to the highest levels of aircraft noise in Varna, and in Plovdiv to the lowest. In contrast, Plovdiv had the highest levels of railway noise. We also observed city-specific patterns in annoyance responses, especially for railway and aircraft noise annoyance (Supplementary File 2).

Table 1
Participant characteristics (N = 4640).

Characteristics	Descriptive statistics
Age [years] (mean, SD)	50.4 (17.5)
Male (N, %)	2117 (45.6)
Bulgarian ethnicity (N, %)	4437 (95.8)
Education (N, %)	
Primary not completed	17 (0.4)
Primary	217 (4.7)
Secondary	2622 (57.0)
Higher	1746 (38.0)
Perceived income adequacy (N, %)	
Very difficult	257 (5.8)
Difficult	730 (16.5)
With some difficulty	1949 (44.0)
Mostly easy	1090 (24.6)
Easy	320 (7.2)
Very easy	81 (1.8)
High noise annoyance (road) (N, %)	688 (14.9)
High noise annoyance (railway) (N, %)[a]	102 (2.2)
High noise annoyance (aircraft) (N, %)[a]	226 (4.9)
Noise sensitivity (median, IQR)	1.00 (2.0)
L_{den} (road) [dB] (mean, SD)	63.66 (5.8)
L_{den} (railway) [dB] (median, IQR)[b]	32.50 (15.0)
L_{den} (aircraft) [dB] (median, IQR)[b]	27.50 (20.0)
Month (N, %)	
August	583 (12.6)
September	2478 (53.4)
October	1579 (34.0)
Floor of dwelling (median, IQR)	3 (2)
Dwelling type (N, %)	
Single-family house	415 (9.0)
Multi-family house	351 (7.6)
Apartment in a building	3757 (81.1)
Dormitory/hostel	5 (0.1)
Other	106 (2.3)
City (N, %)	
Sofia	1512 (32.6)
Plovdiv	1012 (21.8)
Varna	1001 (21.6)
Burgas	655 (14.1)
Ruse	460 (9.9)

Note. Abbreviations: L_{den} – day-evening-night equivalent sound level. Missing cases for these variables do not exceed 5%.

[a] The frequency of high noise annoyance is given for all participants, including those not exposed to the source in question.

[b] The distributions are given before assigning 37.5 dB to L_{den} below 40 dB.

In bivariate analyses, road and rail HNA were positively correlated with L_{den} (Supplementary Fig. S9, Supplementary File 1). Aircraft L_{den} was also associated with road traffic HNA, but the association between aircraft L_{den} and HNA was almost null. Lower perceived income was associated with higher aircraft HNA (rho = −0.12). Noise sensitivity was the strongest correlate of road traffic HNA (rho = 0.30), but not of aircraft and railway HNA. Other correlations were negligible.

3.2. Exposure-response relationships between traffic noise and annoyance

There was little change in the effect size between unadjusted and fully adjusted models for road traffic HNA, but a notable increase in the strength of the associations for railway and aircraft noise (data not shown). Fig. 1 shows the non-linear associations from the fully adjusted model. It is noteworthy that road traffic L_{den} was positively associated with HNA only above 62.5 dB, while the upward trend for railway and aircraft L_{den} started already at 40–45 dB.

Fig. 2 shows the predicted probability of HNA from logistic regression models. The curve for railway railway L_{den} ran on a higher level followed by the one for aircraft L_{den}. Conversely, the exposure-response relationship for road traffic L_{den} was relatively flat.

Fig. 3 compares our exposure-response relationship curves, derived from unadjusted logistic regressions, with the WHO curves. Our curves for road traffic (above 60 dB) and aircraft noise were lower than the WHO reference curves, while the railway curve was very close, although slightly steeper.

The polynomial approximations of the Bulgarian curves shown in Fig. 3 are as follows:

$$\text{Predicted road traffic \%HNA} = 15.713 - 0.6905 \times L_{den} + 0.0106 \times L_{den}^2;$$

$$\text{Predicted railway traffic \%HNA} = 64.271 - 3.058 \times L_{den} + 0.0387 \times L_{den}^2;$$

$$\text{Predicted aircraft \%HNA} = 16.798 - 0.8504 \times L_{den} + 0.0138 \times L_{den}^2.$$

In Fig. 3, the percentage of HNA in this survey is defined according to a cut-off point of 60% (the top 2 categories) on the 5-point verbal scale for noise annoyance. The percentages observed in this survey that are adjusted to be comparable to those predicted by the WHO curves using a 72% cut-off point are shown in Table 2. The percentage of highly annoyed residents did not monotonically increase with higher L_{den} levels and was lower than the estimated percentage with the WHO curves. Moreover, our survey provided sparse data in some L_{den} categories, flattening the observed relationships.

3.3. Health burden of high noise annoyance

Using the WHO's curves starting at 40 dB and the new WHO disability weight yielded 4312 (2352–6273) DALYs for all traffic sources across all five cities. The corresponding monetary costs were $ 48 559 330 (26 486 907–70 631 753) using the GDP per capita cost per DALY, and € 301 873 648 (117 613 110–627 269 918) using VOLY (Supplementary File 3). With the Bulgarian exposure-response relationships, the estimated burden was 3476 (1896–5056) DALYs, $ 39 138 953 (21 348 520–56 929 386), and € 243 310 984 (94 796 487–505 581 266). Table 3 shows source- and city-specific estimates with the Bulgarian exposure-response relationships. Considering the population size, Plovdiv had the highest road and rail traffic noise DALY rate per 100 000 residents. In a sensitivity analysis using the old disability weight, the burden was 2–3 times higher (Supplementary File 3).

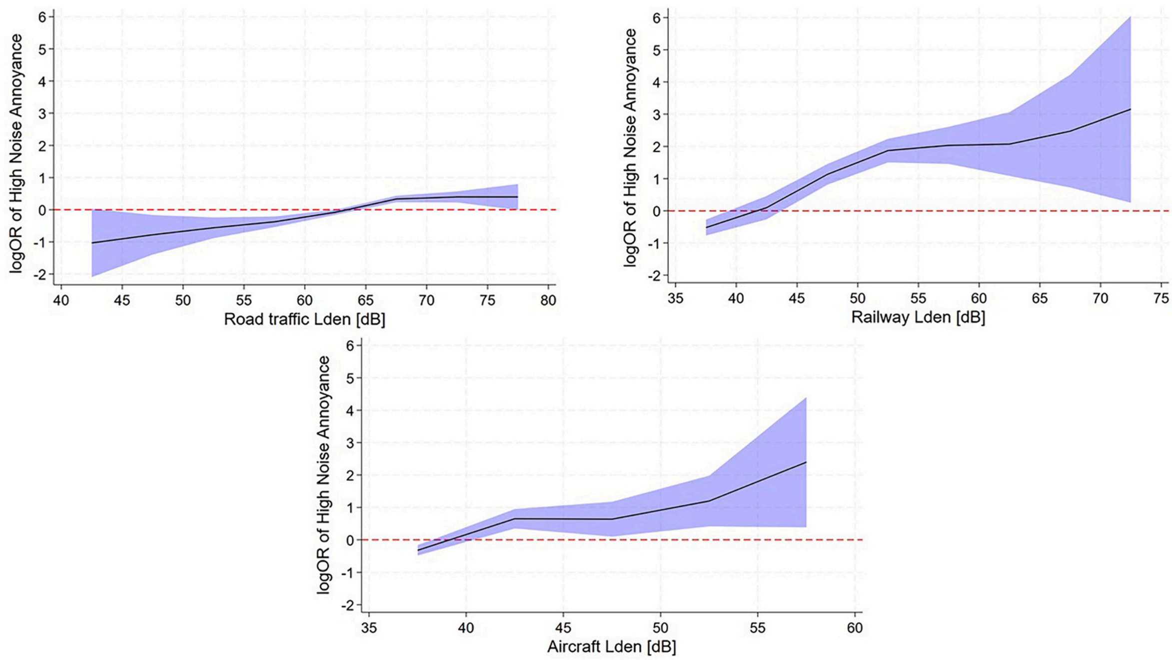

Fig. 1. Generalised additive models of the association between day-evening-night equivalent sound level (L_{den}) and the prevalence of high noise annoyance from different traffic sources. Abbreviations: L_{den} – day-evening-night equivalent sound level, logOR – natural logarithm of the odds ratio coefficient. Models are adjusted for city, age, sex, education, ethnicity, perceived income, noise sensitivity, dwelling type, dwelling floor, and month of data collection. The aircraft noise model does not include respondents from the city of Ruse. High noise annoyance is defined as the top two categories on a 5-point verbal scale (60% cut-off point). The black solid line corresponds to the log odds ratio of HNA and the purple shaded area around it to its 95% confidence interval. The red horizontal dashed line corresponds to a null effect threshold at the $p < 0.05$ level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

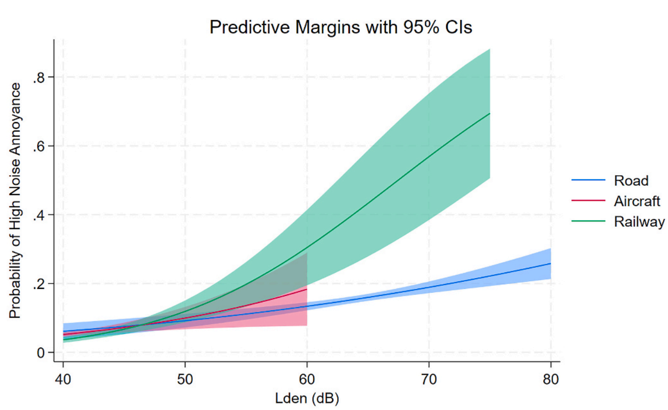

Fig. 2. Logistic regression model of the association between day-evening-night equivalent sound level (L_{den}) and the probability of being highly annoyed by noise from different traffic sources. Abbreviations: L_{den} – day-evening-night equivalent sound level. Models are adjusted for city, age, sex, education, ethnicity, perceived income, noise sensitivity, dwelling type, dwelling floor, and month of data collection. High noise annoyance is defined as the top two categories on a 5-point verbal scale (60% cut-off point).

4. Discussion

4.1. General findings

This is the first study in Bulgaria to investigate population-level associations between traffic noise sources and HNA. The exposure-response relationships derived in this study differed from the WHO curves. Road traffic noise was estimated to be less annoying, and we could only see an increased prevalence of HNA above 62.5 dB, which contradicts the established effect of road traffic noise on annoyance at much lower levels (Guski et al., 2017). The curve for railway noise in our study was well aligned with the WHO curve. Thus, we did not find support for the so-called "railway bonus"; that is, we observed that railway noise was not less annoying than road traffic noise at the same noise level. The observed aircraft noise levels in our data were below 60 dB, so there was little overlap with the WHO curve, which starts at 40 dB and goes up to 80 dB. This may explain the relatively flat exposure-response relationships we observed.

Based on our exposure-response relationships, we estimated annual losses of about 3500 DALYs and $ 40 million, which were lower than estimates derived using the WHO curves and the old disability weight. A previous small study in Plovdiv also reported the burden of road traffic HNA (Dzhambov and Dimitrova, 2015), which was higher than what we have found for Plovdiv here. The EEA estimated the total number of people in Bulgaria exposed to >55 dB to be 302 327 for road traffic, 5723 for rail and 1345 for aircraft noise, but did not include people exposed to lower noise levels (EEA, 2022). More recently, an expert group proposed a methodology for assessing noise exposure below the END thresholds when such data was unavailable (Engelmann et al., 2023). However, we had access to data on the population exposed to noise levels below the 55 dB L_{den} threshold used by the EEA. We used alternative approaches for the monetisation of DALYs, first, by multiplying DALYs by the non-health GDP per capita in Bulgaria, and second, by multiplying by a VOLY of € 70 000. An Estonian study also used this VOLY (Veber et al., 2022), although this value was initially proposed for quantifying economic costs of health risks at the European Union level (Engelmann et al., 2023), and may lead to an overestimation of the costs in Eastern European countries. On the other hand, the GDP-based monetisation approach was purposely conservative in order to provide a lower bound for a wide uncertainty range for the estimated monetary costs. Alternatively, we could have used three times GDP per capita as the cost of a DALY, since this is a typically used cost-effectiveness threshold in assessment of health-related interventions (Robinson et al., 2017).

Given the concerns we had about the weak associations between

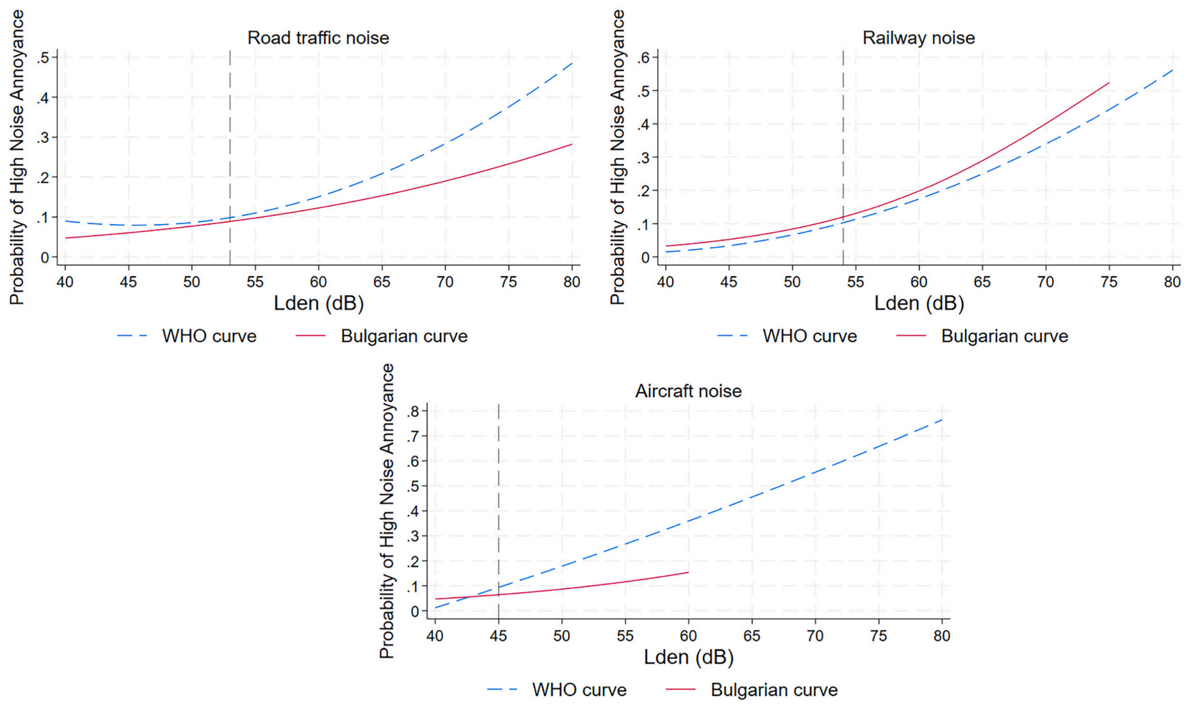

Fig. 3. Comparison of probabilities of being highly noise annoyed according to exposure-response curves developed by the World Health Organization and the current study. Abbreviations: L_{den} – day-evening-night equivalent sound level, WHO – World Health Organization. The Bulgarian curves are derived from unadjusted logistic regression with only L_{den} as the independent variable and high noise annoyance defined as the top two categories on a 5-point verbal scale (60% cut-off point). See Supplementary File 2 for data underlying these plots. Vertical dashed lines indicate WHO L_{den} guideline values.

Table 2
Comparison of the observed percentage of high noise annoyed people in this survey and the predicted percentage derived from the exposure-response curves developed by the World Health Organization.

L_{den} [dB]	%HNA Road		%HNA Railway		%HNA Aircraft	
	This survey[a]	WHO curve	This survey[a]	WHO curve	This survey[a]	WHO curve
42.5	0.00	8.26	0.45	2.28	1.62	5.25
47.5	2.45	8.07	4.81	4.83	7.19	13.57
52.5	5.79	9.59	7.19	8.81	1.65	22.26
57.5	5.55	12.82	6.00	14.20	2.07	31.30
62.5	6.88	17.76	0.00	21.03	25.00	40.71
67.5	13.81	24.41	0.00	29.27	–	50.47
72.5	10.98	32.77	40.00	38.95	–	60.59
77.5	9.80	42.84	–	50.05	–	71.08

Note. HNA- High noise annoyance, L_{den} – day-evening-night equivalent sound level, WHO – World Health Organization.
[a] The definition of HNA in this survey is adjusted according to ISO/TS 15666:2021 (ISO/IEC, 2021) to approximate the 72% cut-off point used by the WHO.

road traffic and aircraft L_{den} and HNA in our survey, it is likely that the burden from these sources, particularly road traffic noise, has been significantly underestimated. Therefore, we recommend the continued use of the Guski et al. (2017) exposure-response relationships for road traffic and aircraft noise until more plausible exposure-response relationships can be derived for the Bulgarian population. Ongoing are efforts to develop more fine-grained and accessible noise maps for urban areas in Bulgaria (Helbich et al., 2024).

4.2. Strengths and limitations

This was the first study to generate exposure-response relationships between traffic noise and annoyance based on a large representative sample of the Bulgarian population. We modelled associations with all

Table 3
High noise annoyance-attributed burden of disease in Bulgaria.

Noise source	DALYs (95% UI)	GDP-based value [in USD] (95% UI)
All cities		
Road traffic	3039 (1657–4420)	34 216 459 (18 663 523–49 769 395)
Railway traffic	271 (148–395)	3 055 440 (1 666 604–4 444 277)
Aircraft traffic	166 (90–241)	1 867 054 (1 018 393–2 715 715)
Sofia (Population 1 196 806)		
Road traffic	1543 (842–2244)	17 372 275 (9 475 786–25 268 763)
Railway traffic	135 (74–197)	1 522 522 (830 467–2 6214 578)
Aircraft traffic	40 (22–58)	452 697 (246 926–658 469)
Plovdiv (Population 325 485)		
Road traffic	592 (323–862)	6 670 500 (3 638 455–9 702 546)
Railway traffic	121 (66–176)	1 365 329 (744 725–1 985 933)
Aircraft traffic	–	–
Varna (Population 314 607)		
Road traffic	455 (248–662)	5 125 127 (2 795 524–7 454 731)
Railway traffic	4 (2–6)	45 704 (24 929–66 478)
Aircraft traffic	126 (69–183)	1 414 356 (771 467–2 057 245)
Burgas (Population 188 114)		
Road traffic	269 (147–391)	3 026 104 (1 650 602–4 401 605)
Railway traffic	0.46 (0.25–0.67)	5190 (2831–7548)
Aircraft traffic	–	–
Ruse (Population 122 116)		
Road traffic	180 (98–261)	2 022 452 (1 103 156–2 941 749)
Railway traffic	10 (6–15)	116 696 (63 653–169 740)
Aircraft traffic	–	–

Abbreviations: DALYs – disability-adjusted life years for 2017, GDP – Gross domestic product, USD – United States dollars for 2021. The reference year for monetisation of DALYs is 2021. An uncertainty interval in brackets is constructed using the uncertainty interval for the disability weight to calculate DALYs. The exposure-response relationships for high noise annoyance used in these calculations use high annoyance defined as the top two categories on a 5-point vernal scale (60% cut-off point). The data underlying these calculations are presented in Supplementary File 3.

three major sources of traffic noise, measured noise annoyance with standard items that allow comparison with previous research by reporting the underlying data, and controlled for several individual and contextual variables. In addition, our study is among the first to use the disability weight for HNA recently published by the WHO (WHO, 2024). We also adopted alternative monetisation approaches, including the recommended VOLY per DALY by Engelmann et al. (2023).

However, we are mindful of the limitations of this work. First, like any burden of disease analysis, ours relies on several assumptions about the chosen exposure-response relationship, disability weight, population exposure data, and the valuation approach used. We believe that the DALYs and their monetary value reported here are more precise than previously calculated estimates for Bulgaria using local exposure-response relationships, but this is still a simplistic approach to quantifying the societal costs of noise exposure, and our calculations are likely to have underestimated the actual burden due to the limited quality of the available noise data. These estimates should only be taken at the population level to inform the investment of resources in noise mitigation rather than as an accurate measure of the actual costs incurred by individuals or the economy.

Furthermore, this was a cross-sectional study. While this design is typically used in this line of research (Guski et al., 2017), we could not explore changes in noise annoyance over time or ascertain the stability of the annoyance ratings. Our findings cannot be extrapolated to rural areas and small towns. They may also be biased since we could not explore the differences between residents included in our sample and those who could not be reached during the field survey (e.g., who did not answer the door or were not found at home). In this sense, while the sample's sociodemographic characteristics resembled those of the general population of each city, the sample may not have been truly representative of noise exposure and the related prevalence of annoyance. This was suggested by the relatively low frequency of people highly annoyed from road traffic noise in some cities.

Exposure misclassification played a role, as noise levels were only pseudo-continuous and were assigned based on the address point coordinates rather than estimated at specific building facades. This likely reduced the magnitude of the observed association with HNA. Another issue with the exposure assessment is that we relied on 2017 END data, as the latest noise maps for 2022 were yet to be available through the EEA. However, we are not too concerned about this because noise levels at the same location are highly correlated over multiple time points, even if absolute levels decrease (SPECTRI, 2016, 2017a, 2017b, 2017c, 2017d). Valorisation of DALYs was based on population exposure data from 2017 and GDP data from 2021.

Although we had modelled noise data down to 10 dB, we did not use it in the analyses because of concerns about the error bandwidth in noise calculations at low levels. However, the burden of disease estimates would be much larger if exposure levels down to around 10 dB were taken into account for aircraft and rail L_{den}. Both approaches introduce bias by either ignoring a large proportion of the population exposed to <40 dB or by allowing a larger error in noise calculation below 40 dB.

The END mapping approach differs between European Union Member States and in some countries, such as Bulgaria, the data are reported at low resolution and are not continuous (Khomenko et al., 2022). Moreover, END maps are primarily produced to identify highly exposed areas and to support the development of action plans to reduce noise exposure above the European Union threshold of 55 dB L_{den}. Like others (Eriksson et al., 2013; Romero Starke et al., 2023), we expected that meaningful Bulgarian exposure-response curves, consistent with the proposed WHO curves, would support their use for burden of disease calculations. One of the main concerns we had about the use of END noise map data was the 5 dB bands, which masked small scale variations that are essential for assigning individual noise exposure at home addresses. We were less concerned about this for aircraft and railway noise, as these noise sources are not as widely integrated into the urban fabric as the road network is. Even data reported in 5-dB bands could provide sufficient railway and aircraft noise exposure gradients depending on the distance from the respective source. However, despite our efforts to ensure adequate exposure variation, our sample did not include enough people exposed to high levels of aircraft noise, which is likely to have attenuated the association with HNA and underestimated the annoyance burden. In a study by Preisendörfer et al. (2022), aircraft noise levels were also restricted to about the same range as in our study. The authors observed a very low prevalence of aircraft noise annoyance and flatter ERR in Zurich as opposed to Mainz, which they ascribed to the stronger public salience of aircraft noise in Mainz (Preisendörfer et al., 2022). We were unable to control for attitudes towards noise and environmental concerns, but this is an intriguing possibly.

Summing the DALYs from all transport noise sources may lead to some overestimation because a certain percentage of people are exposed to more than one noise source. This could lead to some double counting of HNA persons. On the other hand, simultaneous traffic sources could lead to an inhibitory effect with one type of annoyance dominating the other (Brink and Lercher, 2007; Lercher et al., 2007). In this vein, while annoyance was asked about specific sources, in practice, noise annoyance from different sources can overlap, and one noise source can contribute to annoyance even when another source has been referenced in the wording of the annoyance question (Michaud et al., 2022). However, we did not collect information on annoyance from non-traffic sources like industrial, recreational, or construction activities.

The 5-point verbal scale for noise annoyance was translated *ad hoc* into Bulgarian and did not follow the full procedure recommended by ICBEN for constructing the scale (Fields et al., 2001). We also chose to dichotomize the annoyance scale at 60% to define HNA, as suggested by ICBEN (Fields et al., 2001; Brink et al., 2021) and done by Romero Starke et al. (2023). Nevertheless, to facilitate the comparison and pooling of our results with studies using a 72% cut-off (Brink et al., 2021), we also report the distributions of the individual annoyance scores as well as the weighted HNA with the frequency of the "very" and "extremely" categories of the 5-point verbal scale counted as recommended in ISO/TS 15666:2021 (ISO/IEC, 2021). Finally, we assessed the burden of only HNA because we did not have a standardised question on sleep disturbance. Future burden of disease studies should consider this additional outcome, as it also contributes significantly to the public health impacts of traffic noise (Smith et al., 2022).

4.3. Public health and urban planning implications

The results of this study can serve as a basis for promoting applied noise and health research, defining more appropriate regulations, and proactively developing key noise policies in South Eastern European cities, although the HNA burden estimated with our exposure-response relationships is lower than what can be calculated with the WHO curves. It is crucial to raise public awareness of the health and economic impacts of traffic noise pollution, given the considerable number of people affected in Bulgarian cities. While efforts to reduce traffic are often ineffective because of resistance from some groups of the population or businesses, increasing the resilience of both individuals and communities can ultimately support public health outcomes. Thousands of annual deaths in Bulgaria could be prevented if the country's noise levels met WHO guidelines (Khomenko et al., 2022). Concerns about air pollution have dominated public discourse on the environmental health field, while noise pollution is rarely perceived as more than an everyday nuisance. Local evidence of its impact will be more relatable to concerned citizens or responsible decision-makers. It can be a stronger argument to gain public support for improving the acoustic situation. Improvements could be sought through better scoping and prioritisation of intervention areas in strategic urban plans for structural and operational investment, stronger enforcement of noise protection through urban design regulations, and more appropriate siting of architectural, structural, and transport engineering solutions. Noise levels at public buildings like hospitals and schools, which should be shielded from traffic noise, often exceed legal standards. Modelling scenarios involving modified land use planning and targeted interventions, such as the construction of noise barriers, better sound insulation, and community education campaigns, could benefit from the exposure-response relationships generated in our study.

The EEA has developed an interactive viewer showing the health impacts of road traffic noise for 156 cities in Europe, but Bulgarian cities were not included (Peris et al., 2023; EEA, 2024). In addition, the EEA did not visualise the impacts of aircraft and railway noise, the calculations were restricted to noise bands >55 dB L_{den}, and the visualisation was rendered at a resolution of 1 km × 1 km (Peris et al., 2023; EEA, 2024). When our results are refined, they could be used to produce more detailed maps of the health impacts of road, railway, and aircraft noise in major Bulgarian cities. Visualisation of the spatial distribution of DALYs can raise public awareness and help local authorities and citizens identify areas with the highest burden of long-term high annoyance to support the development of policies and mitigation measures.

5. Conclusions

Traffic noise annoyance has a considerable disease burden on adults in Bulgaria, but we could only produce plausible exposure-response relationships for railway noise annoyance. Until exposure-response relationships better than the ones we derived here can be determined for the Bulgarian population, we recommend the continued use of the WHO curves to calculate the high annoyance burden from road traffic and aircraft noise.

CRediT authorship contribution statement

Angel M. Dzhambov: Writing – original draft, Visualization, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Angel Burov:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Julian Hagenauer:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Marco Helbich:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Donka Dimitrova:** Writing – review & editing, Supervision, Methodology, Investigation. **Iana Markevych:** Writing – review & editing, Supervision, Investigation. **Mark J. Nieuwenhuijsen:** Writing – review & editing, Supervision, Methodology, Investigation.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used DeepL in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Funding

This study was supported by the "Strategic Research and Innovation Program for the Development of Medical University – Plovdiv", Contract No. BG-RRP-2.004-0007-C01, Establishment of a network of research higher schools, National Plan for Recovery and Resilience, financed by the European Union – NextGenerationEU. All authors except Julian Hagenauer are affiliated with project No. BG-RRP-2.004-0007-C01. The funders have not been involved in any aspect of the study design or reporting.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.120879.

Data availability

Input data for the burden of disease calculations are available in the Supplement. Other participant microdata generated and/or analysed during the current study are not publicly available.

References

Brink, M., Giorgis-Allemand, L., Schreckenberg, D., Evrard, A.S., 2021. Pooling and comparing noise annoyance scores and "high annoyance" (HA) responses on the 5-point and 11-point scales: principles and practical advice. Int. J. Environ. Res. Publ. Health 18 (14), 7339. https://doi.org/10.3390/ijerph18147339.

Brink, M., Lercher, P., 2007. The effects of noise from combined traffic sources on annoyance: the interaction between aircraft and road traffic noise. In: Proceeding of Inter Noise 2007, p. 8. Istanbul, Turkey.

Brown, D.W., 2008. Economic value of disability-adjusted life years lost to violence: estimates for WHO Member States. Pan Am. J. Public Health 24, 203–209.

Chen, X., Liu, M., Zuo, L., Wu, X., Chen, M., Li, X., et al., 2023a. Environmental noise exposure and health outcomes: an umbrella review of systematic reviews and meta-analysis. European Jounral of Public Health 33 (4), 725–731.

Chen, Y., Hansell, A.L., Clark, S.N., Cai, Y.S., 2023b. Environmental noise and health in low-middle-income-countries: a systematic review of epidemiological evidence. Environ. Pollut. 316 (Pt 2), 120605.

Copernicus Land Monitoring Service, 2021. Urban Atlas Urban Atlas Land Cover/Land Use 2018. European Environment Agency.

Dzhambov, A., Dimitrova, D., 2015. Road traffic noise and annoyance: exposure-response relationship and burden of disease calculations in Bulgaria. Scripta Sci. Med. 47 (2), 22–30.

Dzhambov, A.M., Dimitrova, V., Germanova, N., Burov, A., Brezov, D., Hlebarov, I., et al., 2023. Joint associations and pathways from greenspace, traffic-related air pollution, and noise to poor self-rated general health: a population-based study in Sofia, Bulgaria. Environ. Res. 231 (Pt 1), 116087.

EEA, 2020a. EIONET - central data repository. https://cdr.eionet.europa.eu/bg/eu/noise/df8/2017/. (Accessed 19 November 2023).

EEA, 2020b. Environmental Noise in Europe — 2020. https://doi.org/10.2800/686249. ISBN 978-92-9480-209-5.

EEA. Health impacts of exposure to noise from transport. Published 18 Jul 2022. https://www.eea.europa.eu/en/analysis/indicators/health-impacts-of-exposure-to-1. (Accessed 18 May 2024).

EEA, 2024. Viewer on combined health impacts from road traffic noise and air pollution in urban areas. Available at: https://www.eea.europa.eu/themes/human/noise/viewer-on-combined-health-impacts. (Accessed 25 May 2024).

Engelmann, N., Blanes Guàrdia, N., Fons Esteve, J., Vienneau, D., Röösli, M., 2023. Environmental noise health risk assessment: methodology for assessing health risks using data reported under the Environmental Noise Directive (Eionet Report – ETC HE 2023/11). European Topic Centre on Human Health and the Environment. Available at: https://www.eionet.europa.eu/etcs/etc-he/products/etc-he-products/etc-he-reports/etc-he-report-2023-11-environmental-noise-health-risk-assessment-methodology-for-assessing-health-risks-using-data-reported-under-the-environmental-noise-directive. (Accessed 14 December 2024).

Eriksson, C., Nilsson, M.E., Stenkvist, D., Bellander, T., Pershagen, G., 2013. Residential traffic noise exposure assessment: application and evaluation of European Environmental Noise Directive maps. J. Expo. Sci. Environ. Epidemiol. 23 (5), 531–538.

Eze, I.C., Foraster, M., Schaffner, E., Vienneau, D., Héritier, H., Pieren, R., et al., 2018. Transportation noise exposure, noise annoyance and respiratory health in adults: a repeated-measures study. Environ. Int. 121 (Pt 1), 741–750.

Fields, J.M., De Jong, R.G., Gjestland, T., Flindell, I.H., Job, R.F.S., Kurra, S., et al., 2001. Standardized general-purpose noise reaction questions for community noise surveys: research and a recommendation. J. Sound Vib. 242, 641–679.

Floud, S., Blangiardo, M., Clark, C., de Hoogh, K., Babisch, W., Houthuijs, D., et al., 2013. Exposure to aircraft and road traffic noise and associations with heart disease and stroke in six European countries: a cross-sectional study. Environ. Health 12, 89.

Geodesy, Cartography and Cadastre Agency, 2023. Buildings from Cadastral Map of Bulgaria. Ministry of Regional Development and Public Works.

Gong, X., Fenech, B., Blackmore, C., Chen, Y., Rodgers, G., Gulliver, J., et al., 2022. Association between noise annoyance and mental health outcomes: a systematic review and meta-analysis. Int. J. Environ. Res. Publ. Health 19 (5), 2696.

Guski, R., Schreckenberg, D., Schuemer, R., 2017. WHO environmental noise guidelines for the European region: a systematic review on environmental noise and annoyance. Int. J. Environ. Res. Publ. Health 14 (12), 1539.

Hahad, O., Gilan, D., Michal, M., Tüscher, O., Chalabi, J., Schuster, A.K., et al., 2024. Noise annoyance and cardiovascular disease risk: results from a 10-year follow-up study. Sci. Rep. 14 (1), 5619.

Hastie, T., Tibshirani, R., 1986. Generalized additive models. Stat. Sci. 1 (3), 297–310.

Helbich, M., Hagenauer, J., Burov, A., Dzhambov, A., 2024. Replication Data: traffic noise assessment in urban Bulgaria using explainable machine learning. https://doi.org/10.24416/UU01-HNHGVC. (Accessed 14 December 2024).

ISO/IEC, ISO/TS 15666:2021, 2021. Acoustics—assessment of noise annoyance by means of social and socio-acoustic surveys. https://www.iso.org/obp/ui#iso:std:iso:ts:15666:ed-2:v1.

Jarup, L., Babisch, W., Houthuijs, D., Pershagen, G., Katsouyanni, K., Cadum, E., et al., 2008. Hypertension and exposure to noise near airports: the HYENA study. Environ. Health Perspect. 116 (3), 329–333.

Khomenko, S., Cirach, M., Barrera-Gómez, J., Pereira-Barboza, E., Iungman, T., Mueller, N., et al., 2022. Impact of road traffic noise on annoyance and preventable mortality in European cities: a health impact assessment. Environ. Int. 162, 107160.

Kirigia, J.M., Kubai, P.K., 2023. Monetary value of disability-adjusted life years and potential productivity losses associated with neglected tropical diseases in the East African community. Res. Rep. Trop. Med. 14, 35–47.

Lercher, P., Botteldooren, D., De Greve, B., Dekoninck, L., Rüdisser, J., 2007. The effects of noise from combined traffic sources on annoyance: the case of interactions between rail and road noise. Proceeding of Inter Noise 2007. Istanbul, Turkey.

Michaud, D.S., Marro, L., Denning, A., Shackleton, Sy, Toutant, N., McNamee, J.P., 2022. Annoyance toward transportation and construction noise in rural suburban and urban regions across Canada. Environ. Impact Assess. Rev. 97, 106881. https://doi.org/10.1016/j.eiar.2022.106881.

OpenStreetMap contributors, 2023. OpenStreetMap. OpenStreetMap Foundation [Data set].

Peris, E., Blanes, N., Domingues, F., Sáinz del la Maza, M., Soares, J., Gsella, A., et al., 2023. Viewer on combined health impacts from road traffic noise and air pollution in urban areas. Proceedings of the 14th ICBEN Congress on Noise as a Public Health Problem, pp. 18–22. Belgrade.

Preisendörfer, P., Liebe, U., Bruderer Enzler, H., Diekmann, A., 2022. Annoyance due to residential road traffic and aircraft noise: empirical evidence from two European cities. Environ. Res. 206, 112269. https://doi.org/10.1016/j.envres.2021.112269.

Robinson, L.A., Hammitt, J.K., Chang, A.Y., Resch, S., 2017. Understanding and improving the one and three times GDP per capita cost-effectiveness thresholds. Health Pol. Plann. 32 (1), 141–145. https://doi.org/10.1093/heapol/czw096.

Romero Starke, K., Schubert, M., Kaboth, P., Gerlach, J., Hegewald, J., Reusche, M., Friedemann, D., Zülke, A., Riedel-Heller, S.G., Zeeb, H., Seidler, A., 2023. Traffic noise annoyance in the LIFE-adult study in Germany: exposure-response relationships and a comparison to the WHO curves. Environ. Res. 228, 115815. https://doi.org/10.1016/j.envres.2023.115815.

Royston, P., Ambler, G., 1998. sg79: generalized additive models. Stata Tech. Bull. 42, 38–43.

Salomon, J.A., Vos, T., Hogan, D.R., Gagnon, M., Naghavi, M., Mokdad, A., Begum, N., Shah, R., Karyana, M., Kosen, S., Farje, M.R., Moncada, G., Dutta, A., Sazawal, S., Dyer, A., Seiler, J., Aboyans, V., Baker, L., Baxter, A., Benjamin, E.J., Bhalla, K., Bin Abdulhak, A., Blyth, F., Bourne, R., Braithwaite, T., Brooks, P., Brugha, T.S., Bryan-Hancock, C., Buchbinder, R., Burney, P., Calabria, B., Chen, H., Chugh, S.S., Cooley, R., Criqui, M.H., Cross, M., Dabhadkar, K.C., Dahodwala, N., Davis, A., Degenhardt, L., Díaz-Torné, C., Dorsey, E.R., Driscoll, T., Edmond, K., Elbaz, A., Ezzati, M., Feigin, V., Ferri, C.P., Flaxman, A.D., Flood, L., Fransen, M., Fuse, K., Gabbe, B.J., Gillum, R.F., Haagsma, J., Harrison, J.E., Havmoeller, R., Hay, R.J., Hel-Baqui, A., Hoek, H.W., Hoffman, H., Hogeland, E., Hoy, D., Jarvis, D., Karthikeyan, G., Knowlton, L.M., Lathlean, T., Leasher, J.L., Lim, S.S., Lipshultz, S.E., Lopez, A.D., Lozano, R., Lyons, R., Malekzadeh, R., Marcenes, W., March, L., Margolis, D.J., McGill, N., McGrath, J., Mensah, G.A., Meyer, A.C., Michaud, C., Moran, A., Mori, R., Murdoch, M.E., Naldi, L., Newton, C.R., Norman, R., Omer, S.B., Osborne, R., Pearce, N., Perez-Ruiz, F., Perico, N., Pesudovs, K., Phillips, D., Pourmalek, F., Prince, M., Rehm, J.T., Remuzzi, G., Richardson, K., Room, R., Saha, S., Sampson, U., Sanchez-Riera, L., Segui-Gomez, M., Shahraz, S., Shibuya, K., Singh, D., Sliwa, K., Smith, E., Soerjomataram, I., Steiner, T., Stolk, W.A., Stovner, L. J., Sudfeld, C., Taylor, H.R., Tleyjeh, I.M., van der Werf, M.J., Watson, W.L., Weatherall, D.J., Weintraub, R., Weisskopf, M.G., Whiteford, H., Wilkinson, J.D., Woolf, A.D., Zheng, Z.J., Murray, C.J., Jonas, J.B., 2012. Common values in assessing health outcomes from disease and injury: disability weights measurement study for the Global Burden of Disease Study 2010. Lancet 380 (9859), 2129–2143. https://doi.org/10.1016/S0140-6736(12)61680-8.

Salomon, J.A., 2014. Disability-adjusted life years. In: Culyer, A.J. (Ed.), Encyclopedia of Health Economics. Elsevier, pp. 200–203. https://doi.org/10.1016/B978-0-12-375678-7.00511-3. ISBN 9780123756794.

Smith, M.G., Cordoza, M., Basner, M., 2022. Environmental noise and effects on sleep: an update to the WHO systematic review and meta-analysis. Environ. Health Perspect. 130 (7), 76001. https://doi.org/10.1289/EHP10197.

SPECTRI, 2017a. Development of an Updated Strategic Map of Environmental Noise in Sofia Agglomeration.

SPECTRI, 2017b. Development of an Updated Strategic Noise Map of Environmental Noise in Varna Agglomeration.

SPECTRI, 2017c. Development of an Updated Strategic Noise Map of Environmental Noise in Burgas Agglomeration.

SPECTRI, 2016. Development of Updated Strategic Noise Maps for Plovdiv Agglomeration.

SPECTRI, 2017d. Development of Updated Strategic Noise Maps for Ruse Agglomeration.

StataCorp, 2023. Stata Statistical Software: Release 18. StataCorp LLC, College Station, TX.

VanderWeele, T.J., 2019. Principles of confounder selection. Eur. J. Epidemiol. https://doi.org/10.1007/s10654-019-00494-6.

Veber, T., Tamm, T., Ründva, M., Kriit, H.K., Pyko, A., Orru, H., 2022. Health impact assessment of transportation noise in two Estonian cities. Environ. Res. 204 (Pt C), 112319. https://doi.org/10.1016/j.envres.2021.112319.

Welch, D., Shepherd, D., Dirks, K.N., Reddy, R., 2023. Health effects of transport noise. Transport Rev. 43 (6), 1190–1210.

WHO Regional Office for Europe, 2011. Burden of disease from environmental noise. Quantification of Healthy Life Years Lost in Europe. Copenhagen.

WHO, 2024. Disability weights for noise-related health states in the WHO European Region. WHO/EURO:2024-9196-48968-72969. https://www.who.int/europe/publications/i/item/WHO-EURO-2024-9196-48968-72969.

WHO, 2018. Environmental Noise Guidelines for the European Region. ISBN 978 92 890 5356 3.