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Impact of road traffic noise on annoyance and preventable mortality in European cities: A health impact assessment

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ABSTRACT

Background: Road traffic is the main source of environmental noise in European cities and one of the main environmental risks to health and wellbeing. In this study we aimed to provide an in-depth assessment of available road traffic noise data and to estimate population exposure and health impacts for cities in Europe.

Methods: We conducted the analysis for 724 cities and 25 greater cities in 25 European countries. We retrieved road traffic strategic noise maps delivered under the Environmental Noise Directive (END) or available from local sources. We assessed noise exposure using the 24 h day-evening-night noise level indicator (L_{den}) starting at exposure levels of 55 dB L_{den} – based on data availability – for the adult population aged 20 and over ($n = 123{,}966{,}346$). For the adults exposed to noise levels above 55 dB L_{den} we estimated the health impacts of compliance with the World Health Organization (WHO) recommendation of 53 dB L_{den}. Two primary health outcomes were assessed: high noise annoyance and Ischemic Heart Disease (IHD), using mortality from IHD causes as indicator. Exposure Response Functions (ERFs) relating road traffic noise exposure to annoyance and IHD mortality were retrieved from the literature. Uncertainties in input parameters were propagated using Monte Carlo simulations to obtain point estimates and empirical 95% Confidence Intervals (CIs). Lastly, the noise maps were categorized as high, moderate and low quality following a qualitative approach.

Results: Strategic noise map data was delivered in three distinct formats (i.e. raster, polygon or polyline) and had distinct noise ranges and levels of categorization. The majority of noise maps (i.e. 83.2%) were considered of moderate or low quality. Based on the data provided, almost 60 million adults were exposed to road traffic noise levels above 55 dB L_{den}, equating to a median of 42% (Interquartile Range (IQR): 31.8–64.8) of the adult population across the analysed cities. We estimated that approximately 11 million adults were highly annoyed by road traffic noise and that 3608 deaths from IHD (95% CI: 843–6266) could be prevented annually with compliance of the WHO recommendation. The proportion of highly annoyed adults by city had a median value of 7.6% (IQR: 5.6–11.8) across the analysed cities, while the number preventable deaths had a median of 2.2 deaths per 100,000 population (IQR: 1.4–3.1).

Abbreviations: CNOSSOS, Common noise assessment methods; CI, Confidence Interval; CVD, cardiovascular disease; END, Environmental Noise Directive; EC, European Commission; EEA, European Environment Agency; ESM, European Settlement Map; ERF, Exposure Response Function; GHSL, Global Human Settlement Layer; HIA, Health Impact Assessment; IQR, Interquartile Range; IHD, Ischemic Heart Disease; L_{den}, 24h day-evening-night noise level indicator; NUTS, Nomenclature of Territorial Units for Statistics; OECD, Organization for Economic Cooperation and Development; PAF, Population Attributable Fraction; RMSE, Root Mean Square Error; UTOPHIA, Urban and Transport Planning Health Impact Assessment; WHO, World Health Organization; YLD, Years Lived with Disability; YLL, Years of Life Lost.

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Conclusions: Based on the provided strategic noise maps a considerable number of adults in European cities are exposed to road traffic noise levels harmful for health. Efforts to standardize the strategic noise maps and to increase noise and disease data availability at the city level are needed. These would allow for a more accurate and comprehensive assessment of the health impacts and further help local governments to address the adverse health effects of road traffic noise.

1. Introduction

Environmental noise is considered one of the main environmental risks to health and wellbeing (EEA, 2020b; WHO, 2018). Environmental noise can be defined as all unwanted and harmful outdoor sound from human activities, such as transportation (i.e. road, rail and air traffic) and industry (EEA, 2020b). Notably, the main source of environmental noise is transport, and transportation noise is considered the second major environmental cause of adverse health outcomes in western Europe, after particulate matter (Hänninen et al., 2014; WHO & JRC, 2011).

Environmental noise has been related to many non-auditory adverse health outcomes, including sleep disturbance, annoyance, cardiovascular and metabolic disease, adverse birth outcomes, cognitive impairment and poor mental health and wellbeing (Basner & McGuire, 2018; Clark & Paunovic, 2018; Eriksson et al., 2018; Guski et al., 2017; van Kempen et al., 2018; WHO, 2018). The strongest evidence so far has been found for environmental noise exposure, particularly road traffic noise, and the development of cardiovascular disease (CVD) (van Kempen et al., 2018). Long-term exposure to environmental noise may cause a sustained stress reaction which leads to the activation of the sympathetic nervous system and endocrine system, resulting in the release of stress hormones, increases in the heart rate, blood pressure and vasoconstriction, eventually leading to chronic diseases such as CVD (Eriksson et al., 2018). In addition, a prolonged activation of the stress response can result in the development of depression and anxiety disorders (Clark & Paunovic, 2018). Annoyance is also one of the main effects of noise exposure related to the stress response (EEA, 2020b; Guski et al., 2017). Generally, noise annoyance results from a repeated disturbance of daily activities (e.g. communicating, reading, working, sleeping, etc.), anger, negative evaluation of the noise source and distress (Guski et al., 2017). Finally, sleep disturbance caused by noise impairs a proper sleep restoration, being a precursor for many diseases such as obesity, diabetes, high blood pressure and dementia (Basner & McGuire, 2018). Thus, environmental noise has multiple adverse health effects. Previous research has shown an increase in the proportion of highly annoyed and highly sleep disturbed individuals associated with an increased exposure to environmental noise (Basner & McGuire, 2018; Guski et al., 2017; Miedema & Oudshoorn, 2001; Miedema & Vos, 2007). Given the projections of rapid urban growth (United Nations, 2018) and related increases in transport demand (EEA, 2013), an increase in population noise exposure and noise-related adverse health outcomes can be expected.

In the European context, the Environmental Noise Directive (END, Directive 2002/49/EC) is the main legislative framework for environmental noise control (EEA, 2020b; European Commission, 2002). Under the END the member states are required to: 1) produce strategic noise maps every 5 years for all major roads (with>3 million vehicle passages per year), railways (with>30,000 train passages per year), airports (with>50,000 movements per year) and urban agglomerations (with >100,000 residents); 2) calculate the number of people exposed to each noise source (i.e. road, rail and air traffic) inside and outside urban areas and 3) develop action plans to prevent and reduce environmental noise exposure, particularly in areas where it can produce adverse effects on human health (EEA, 2020b; European Commission, 2002). In this way, the END is an instrument that promotes the identification of the main environmental noise sources and allows to develop adequate measures to address the adverse effects of environmental noise. The last round of environmental noise mapping under the END was conducted for the year 2017 (EEA, 2020b).

In this study, we focused on road traffic as the main source of environmental noise in European cities (EEA, 2020b). We retrieved strategic noise maps for urban agglomerations delivered under the END and estimated the impact of road traffic noise on two primary health outcomes: high noise annoyance and Ischemic Heart Disease (IHD), using mortality from IHD causes as indicator. Our main objectives were: 1) to provide an in-depth assessment of the road traffic noise data delivered as strategic noise maps under the END and 2) to provide city-level estimates of road traffic noise exposure and associated health impacts. To our knowledge, this is the first large city-scale study to estimate road traffic noise exposure and related health impacts for a large number of European cities simultaneously. We expect that the findings from this study will place focus and help local governments to address the adverse health effects of road traffic noise, will improve the next rounds of noise mapping in terms of data availability, methodology and data quality, and will promote targeted and health preserving urban and transport planning policies in European cities.

2. Methods

2.1. Definition of European cities

We retrieved boundaries of European cities from the Urban Audit 2018 dataset (Eurostat, 2018). In this dataset, the European cities are defined according to the city definition provided by the Organization for Economic Cooperation and Development (OECD) and the European Commission (EC) (Dijkstra & Poelman, 2012). Overall, this dataset contained data on 980 cities and 49 greater cities in 31 European countries. The 49 greater cities covered 161 cities either by representing a city of larger area than the defined city or by constituting a combination of several cities. We excluded Saint Denis (Réunion) and Fort-de-France (Martinique) because of their location out of the European study area. The analysis was performed for 724 cities and 25 greater cities in 25 European countries (**appendix 1 p 4**). The remaining cities and greater cities were excluded due to lack of road traffic strategic noise maps and the inability to estimate road traffic noise exposure.

2.2. Baseline road traffic noise exposure

Baseline road traffic noise exposure was estimated using the strategic noise maps delivered by the European countries under the END (EEA, 2020a) or available from local sources using the 24 h day-evening-night noise level indicator (L_{den}) (Fig. 1, **appendix 1 pp 5–7**). The L_{den} indicator was employed because it accounts for long-term noise exposure, based on noise levels over a whole day with a penalty of 10 dB(A) for night time noise (i.e. 23.00–7.00) and an additional penalty of 5 dB(A) for evening noise (i.e. 19.00–23.00) (EEA, 2020b; WHO, 2018). The baseline data ranged between the years 2012–2018.

There is not a defined protocol for the countries to deliver strategic noise map data, thus, many differences exist in the underlying noise mapping methods, data formats, noise band categories, spatial coverage and geographical projections between cities and countries. Accordingly, to consider these differences, the baseline road traffic noise exposure was estimated country by country (**appendix 1 pp 9–162**). For each city, we calculated the population distribution in 5-dB noise bands: < 55 dB, 55–59 dB, 60–64 dB, 65–69 dB, 70–74 dB and ≥ 75 dB L_{den}. The lowest noise category was set at < 55 dB L_{den} because the majority of the strategic noise maps did not include road traffic noise exposure at levels below 55 dB L_{den}. To estimate the population distribution in 5-dB noise bands we combined 3 datasets: 1) the Global Human Settlement Layer (GHSL) containing city-level population data at 250 m grid cell level for 2015 (European Commission, 2019b); 2) the European Settlement Map (ESM) building type layer providing data on residential built-up area at 10 m resolution (Copernicus, 2017; European Commission, 2019a) and 3) the strategic noise maps. We distributed the population data from the GHSL among the building units from the ESM weighting for the building unit area. Road traffic noise exposure was calculated at the building unit level by intersecting the building layer with the strategic noise maps (Fig. 2, **appendix 1 pp 5–7**). Subsequently, data were aggregated at the grid cell level to estimate the population distribution in 5-dB noise bands for each 250 m grid cell. Overall, data were available for 421 cities and 25 greater cities.

For the remaining 303 cities included in the study and for which the strategic noise maps were not available, the baseline road traffic noise exposure was estimated employing a previously described gap filling procedure (Houthuijs et al., 2018). We constructed prediction models at the 250 m grid cell level based on the data available from strategic noise maps using ordered logistic regression for aggregated data (**appendix 1 p 8**). We constructed one model per country due to country-specific differences in strategic noise maps. The following predictor variables were included in the models based on previous research and available data (Houthuijs et al., 2018): population density, highway length, primary road length, secondary road length, tertiary road length, city area and city population. The outcome variable was the population probability distribution in 5-dB noise bands. The prediction models were validated using the leave group-out cross-validation with 100 repetitions. The following parameters were calculated for model validation: the percentage of population classified in the same 5-dB noise band, the Pearson correlation between the estimates from the strategic noise maps and those predicted by the models and the Root Mean Square Error (RMSE). Estimates from prediction models were considered valid and used for gap filling when >80% population was classified in the same 5-dB noise band and the Pearson correlation was higher than 0.8 for at least half of the cities of each country. The estimated road traffic noise exposure levels from the strategic noise maps and the gap filling procedure at 250 m grid cell level were aggregated to city level for the Health Impact Assessment (HIA) analysis.

2.3. *Population data and age distributions*

Total population counts for each city and greater city were available from the GHSL for the year 2015 (European Commission, 2019b). The population age distributions for 2015 were retrieved from Eurostat at the Nomenclature of Territorial Units for Statistics (NUTS) 3 level (Eurostat, 2019c). NUTS is a geographical definition in the European Union (EU) which divides the territory into three levels: NUTS1, NUTS2 and NUTS3, moving from larger to smaller territorial units, respectively (Eurostat, 2021). We calculated the proportion of population in each 5-year age group by NUTS3 (i.e. 20–24, 25–29, 30–34, 35–39, 40–44, 45–49, 50–54, 55–59, 60–64, 65–69, 70–74, 75–79, 80–84 and 85 years and older). These proportions were applied to the corresponding city-level total population counts to estimate the population distribution by age group and the adult (aged 20 and over) population count for each city and greater city (**appendix 1 p 163**).

2.4. *Mortality data*

City-specific total all-cause mortality counts for 2015 were available from Eurostat (Eurostat, 2019a). Overall, 95 cities and 8 greater cities had missing mortality counts. In these cases, all-cause mortality counts

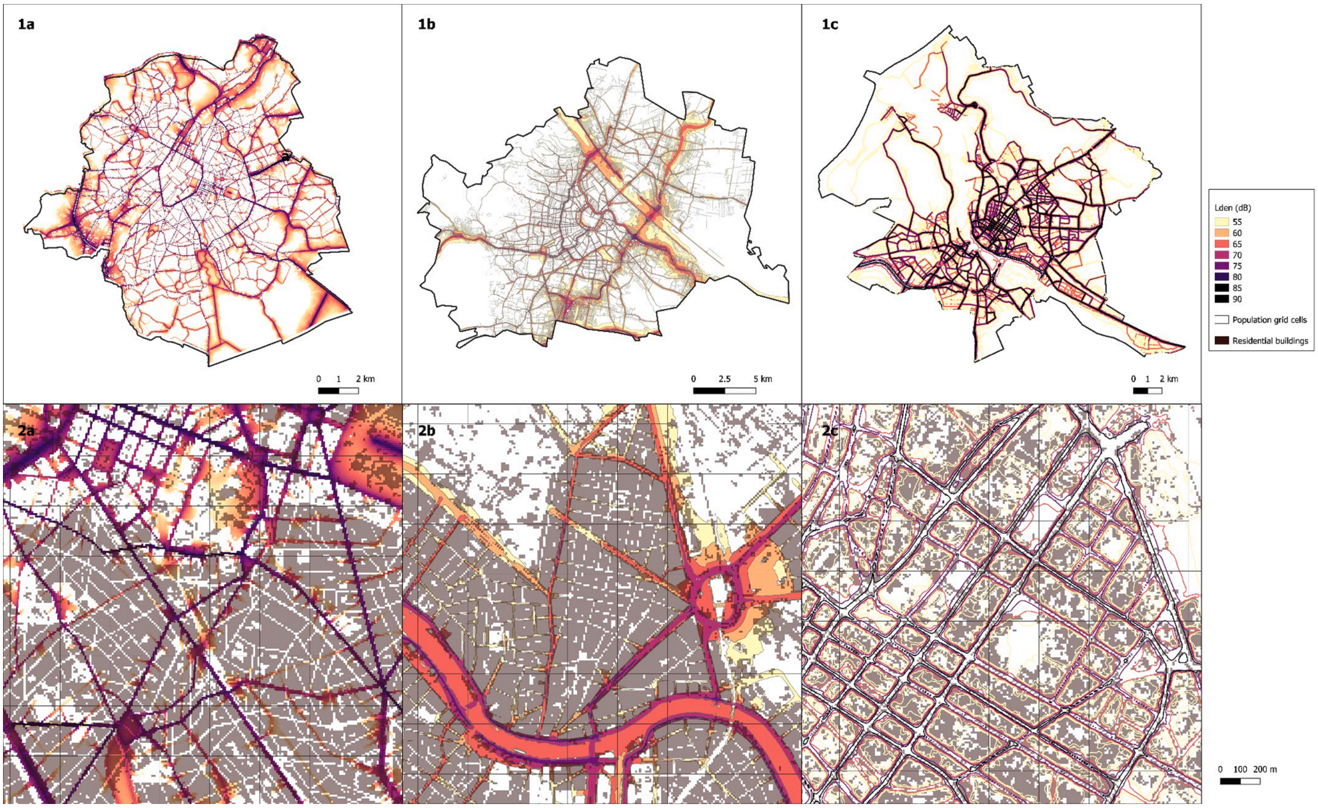

Fig. 1. Examples of the road traffic strategic noise maps delivered under the END for Brussels (1a, 2a), Vienna (1b, 2b) and Riga (1c, 2c). Each city delivered the strategic noise map in a distinct format: raster for Brussels, polygon for Vienna and polyline for Riga. A zoom in into each city is shown to provide a better visualization of the road traffic noise values depicted in each map, the population grid cell layer and the residential buildings layer (2a, 2b and 2c).

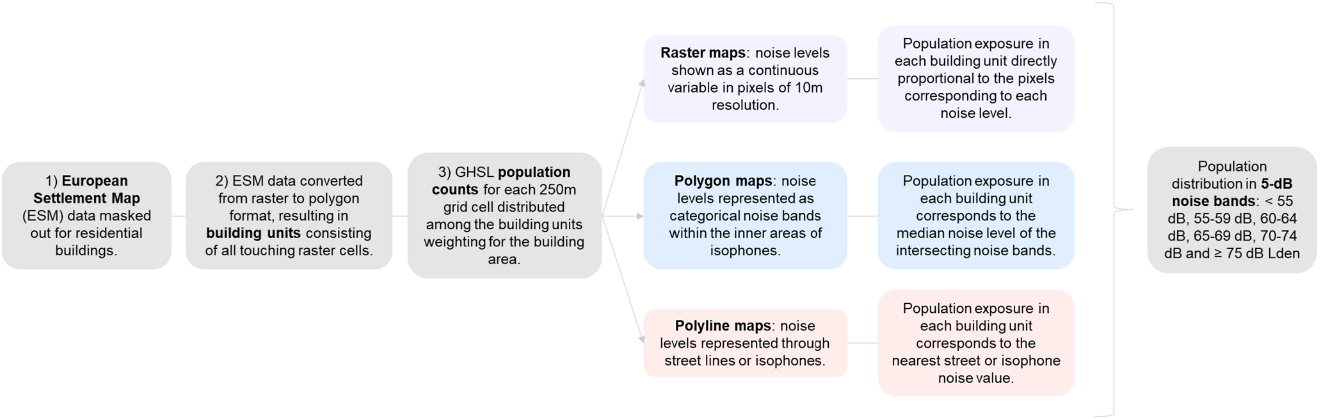

Fig. 2. General procedure to estimate population exposure to road traffic noise from the strategic noise maps.

were estimated using the corresponding NUTS3 ($n = 102$) or NUTS2 ($n = 1$) all-cause age-specific mortality rates. We retrieved NUTS3 level mortality counts by age group and NUTS2 and country level mortality counts by age and cause of death (Eurostat, 2019c, 2019b). We calculated the IHD (defined by the International Classification of Diseases 10 (ICD10) mortality codes I20-I25), CVD (defined by the ICD10 mortality codes I00-I99) and external (defined by the ICD10 mortality codes V01–Y89) death fractions by age group and estimated the proportion of deaths due to IHD, CVD and natural causes by age group at the NUTS3-level. We applied these proportions to the corresponding city-level total all-cause mortality counts to estimate the number of IHD (for the main analysis), CVD and natural-cause mortality counts (for the sensitivity analyses) for each city and greater city (**appendix 1 p 163**).

2.5. Evaluation of impact on annoyance

For each city and greater city, we estimated the number of adults highly annoyed by road traffic noise. We employed the updated exposure–response relation between road traffic noise levels and the percentage of highly annoyed residents (**appendix 1 p 164**) (Guski et al., 2017). Highly annoyed are those respondents that choose a high position on the annoyance response scale, as evaluated in the studies included in the *meta*-analysis by Guski and colleagues (Guski et al., 2017). We calculated the number of highly annoyed individuals in each 5-year age group by multiplying the number of individuals in each 5-dB noise band above 55 dB L_{den} by the expected percentage of highly annoyed individuals at the corresponding noise exposure level. We aggregated the number of highly annoyed individuals for all age groups. In addition, we calculated the Years Lived with Disability (YLD) due to noise annoyance, assuming a constant 1-year noise exposure (Hänninen & Knol, 2011) (**appendix 1 p 164**).

2.6. Evaluation of impact on mortality.

For each city and greater city, we estimated the number of deaths from IHD due to road traffic noise among the adult population. We followed the Urban and Transport Planning Health Impact Assessment (UTOPHIA) framework, based on the comparative risk assessment approach (Ezzati et al., 2006; Iungman et al., 2021; Khomenko et al., 2020, 2021; Mueller et al., 2017b, 2018; Nieuwenhuijsen et al., 2022; Pereira-Barboza et al., 2021). We obtained Exposure Response Functions (ERFs) from the literature quantifying the strength of association between road traffic noise exposure and mortality from IHD (**appendix 1 p 165**) (Cai et al., 2021; Héritier et al., 2017; van Kempen et al., 2018). We established as the counterfactual scenario the World Health Organization (WHO) recommendation to not exceed an exposure of 53 dB L_{den} (WHO, 2018). In our main analysis a risk estimate of 1.05 (95% Confidence Interval (CI): 0.97–1.13) per 10 dB L_{den} increase in exposure was employed, based on the HIA methodology outlined in the European Environment Agency (EEA) noise report (EEA, 2020b). Although the most robust associations have been reported between road traffic noise and incidence of IHD (van Kempen et al., 2018), we could not evaluate this health outcome due to lack of city-level disease incidence data. The steps for the analysis were as follows: 1) we estimated the baseline population distribution in 5-dB noise bands; 2) for the population in noise bands above 55 dB L_{den}, we calculated the difference between the average noise exposure in the 5-dB noise band and the counterfactual level; 3) we employed the ERFs to compute the relative risk for mortality associated to the exposure difference and 4) we calculated the Population Attributable Fraction (PAF) for each exposure difference. The analysis was performed for each 5-year age group. We aggregated the results for all age groups to estimate 1) the number of preventable deaths from IHD; 2) the preventable age-standardized mortality rates per 100,000 population based on the European standard population (Eurostat, 2013) and 3) the percentage of annual preventable deaths. In addition, to complement the mortality estimates, we calculated the Years of Life Lost (YLL) due to the preventable deaths (**appendix 1 p 166**).

2.7. Impact calculation procedure.

We obtained the point estimates and empirical 95% CIs for annoyance and mortality by propagating the uncertainties in four input parameters for which the uncertainty distributions were known: 1) the ERFs, 2) the average noise exposure levels in each 5-dB band, 3) the prediction models employed for gap filling and 4) the average age of death (needed to compute the YLL due to road traffic noise exposure). Uncertainties were propagated employing Monte Carlo simulations (Harrison, 2010; Khomenko et al., 2021; Pereira-Barboza et al., 2021). Briefly, given that ERF estimates were reported as relative risks, ERF values were simulated from a log-normal distribution using the reported ERF point estimate and 95% CIs (**appendix 1 pp 167–168**). We could not consider the uncertainty in the exposure–response relation for annoyance as the CIs for this exposure–response relation could not be estimated (Guski et al., 2017). To propagate the uncertainty in the average noise exposure levels in each 5-dB band, we downscaled the exposure to a 1-dB resolution using a multinomial distribution (**appendix 1 pp 168–170**) (EEA, 2020b; Houthuijs et al., 2019). For the population in each 5-dB noise band, we calculated the population probability distribution in 1-dB noise bands, sampled the 1-dB noise exposure and calculated the sample mean to estimate the average noise exposure in the 5-dB noise band. To consider the uncertainty in the prediction models for gap filling, we simulated the population distribution in 5-dB noise bands using the multinomial distribution estimated by the ordered logistic models described above (**appendix 1 pp 170–171**). For each 250 m grid cell we sampled the population probability distribution for each 5-dB noise band and multiplied it by the total population count in the grid cell. Finally, to propagate the uncertainty in the average age of death within each 5-year age group, we assumed a uniform distribution in the age of death in each 5-year age group, sampled the age of deaths values and calculated the sample mean (**appendix 1 pp 171–172**). The sampling procedure was replicated 500 times, which allowed us to obtain 500 sampling impact estimates that provided point estimates (by calculating the sample mean) and empirical 95% CIs (by calculating the sample 2.5th and 97.5th percentiles). The number of sampling replications was chosen as a balance between computational cost and robust results. As a sensitivity analysis, the calculation procedure was tested with 100 replications without substantial variation in the estimated impact. The analysis was conducted in R (version 4.0.3).

Table 1
Baseline road traffic noise exposure data in 25 European capitals.

City	Data source and year	Data format	Noise exposure assessment	Total city population (n)	Population exposed > 55 dB L_{den} (n)	Adults exposed > 55 dB L_{den} (n)	% population exposed > 55 dB L_{den}	Noise map quality category
Amsterdam, the Netherlands	RIVM, 2017	Raster	Continuous range between 5 and 87 dB L_{den}	924,203	437,495	343,809	47.3%	High
Berlin, Germany	END, 2017	Polygon	Categorized > 55 dB L_{den}	3,341,974	996,570	825,454	29.8%	Moderate
Brussels, Belgium	END, 2017	Raster	Continuous range between 1 and 92 dB L_{den}	1,181,531	358,237	268,533	30.3%	High
Budapest, Hungary	END, 2017	Polygon	Categorized > 35 dB L_{den}	1,795,482	685,734	566,670	38.2%	Moderate
Copenhagen, Denmark	END, 2017	Polygon	Categorized > 55 dB L_{den}	570,642	265,286	212,977	46.5%	Moderate
Dublin (greater city), Ireland	END, 2017	Polygon	Categorized > 55 dB L_{den}	1,288,711	452,538	338,280	35.1%	Moderate
Helsinki, Finland	END, 2017	Polygon	Categorized > 50 dB L_{den}	614,030	276,868	215,033	45.1%	Moderate
Lisbon, Portugal	END, 2017	Polygon	Categorized > 30 dB L_{den}	533,715	216,782	171,613	40.6%	Moderate
Ljubljana, Slovenia	END, 2017	Polygon	Categorized > 50 dB L_{den}	289,402	141,211	112,338	48.8%	Moderate
London (greater city), UK	CNOSSOS-EU, 2017	Thiessen polygons around postcode address	Continuous range between 49 and 112 dB L_{den}	8,542,705	2,883,760	2,110,064	33.8%	Low
Luxembourg city, Luxembourg	END, 2017	Polygon	Categorized > 60 dB L_{den}	103,567	96,637	74,950	93.3%	Low
Madrid, Spain	Madrid City Council, 2016	Raster	Continuous range between 5 and 90 dB L_{den}	3,173,038	1,388,915	1,105,767	43.8%	High
Oslo, Norway	END, 2017	Polygon	Categorized > 50 dB L_{den}	637,432	398,290	312,064	62.5%	Moderate
Paris (greater city), France	Bruitparif, 2017	Polygon	Categorized > 55 dB L_{den}	6,845,310	4,576,987	3,677,486	66.9%	Moderate
Prague, Czech Republic	END, 2017	Polygon	Categorized > 50 dB L_{den}	1,305,785	922,009	755,803	70.6%	Moderate
Riga, Latvia	END, 2017	Polyline	Categorized > 50 dB L_{den}	620,649	506,339	415,102	81.6%	Moderate
Rome, Italy	END, 2017	Polygon	Categorized > 55 dB L_{den}	2,613,183	1,580,625	1,288,186	60.5%	Moderate
Sofia, Bulgaria	END, 2017	Polygon	Categorized between 15 and 80 dB L_{den}, continuous > 80 dB L_{den}	996,211	994,493	820,357	99.8%	Low
Stockholm, Sweden	Stockholm City Council, 2017	Raster	Continuous range between 10 and 95 dB L_{den}	915,966	402,952	306,953	44.0%	High
Tallinn, Estonia	END, 2017	Polygon	Categorized > 50 dB L_{den}	390,958	136,427	107,574	34.9%	Moderate
Valletta, Malta	END, 2017	Raster	Continuous range between 0 and 75 dB L_{den}	186,809	76,469	61,222	40.9%	High
Vienna, Austria	END, 2017	Polygon	Categorized > 55 dB L_{den}	1,773,176	1,533,604	1,240,349	86.5%	Moderate
Vilnius, Lithuania	END, 2017	Polygon	Categorized > 45 dB L_{den}	528,977	375,368	298,769	71.0%	Moderate
Warsaw, Poland	END, 2017	Polygon	Categorized > 55 dB L_{den}	1,712,584	1,106,758	909,953	64.6%	Moderate
Zurich (greater city), Switzerland	END, 2017	Raster	Continuous range between 1 and 90 dB L_{den}	618,300	277,461	223,071	44.9%	High

* CNOSSOS: Common noise assessment methods; END: Environmental Noise Directive; RIVM: National Institute for Public Health and the Environment. ** For London, the Thiessen polygons were constructed from population-weighted residential postcode address centroids, with road traffic noise modelled in accordance to CNOSSOS-EU guidelines. *** For Luxembourg, the strategic noise map only included exposure levels > 60 dB Lden.

2.8. Sensitivity analyses

We conducted sensitivity analyses to evaluate the impact of 1) changes in the exposure–response relation for annoyance; 2) changes in the ERFs for mortality and 3) changes in the baseline road traffic noise exposure data. In addition, we conducted a sensitivity analysis to evaluate the impact of the potential uncertainty in exposure levels shown in the strategic noise maps on our point estimates and 95% CIs. For the first sensitivity analysis, we retrieved an alternative exposure–response relation provided by the updated review on noise annoyance which did not consider studies conducted in Asia and the Alpine valleys (Guski et al., 2017) (**appendix 1 pp 173–174**). For the second sensitivity analysis, we retrieved alternative ERFs for IHD, CVD and natural-cause mortality (Cai et al., 2021; Héritier et al., 2017) (**appendix 1 pp 175–181**). For the third sensitivity analysis, we used the tabular data on population distribution in 5-dB noise bands estimated by each country and delivered under the END for 460 cities (EEA, 2020b; European Commission, 2002) (**appendix 1 pp 182–206**). Finally, for the last sensitivity analysis we repeated the calculation procedure four times assuming each time that up to 10%, 25%, 50% and 75% of the population in each grid cell and 5-dB noise band could be misclassified into an adjacent noise category (**appendix 1 pp 207–211**).

2.9. Noise map quality

Lastly, we assessed the quality of the strategic noise maps following a qualitative approach (**appendix 1 pp 212–213**). The following parameters were considered: the range of noise exposure levels, the level of exposure categorization, noise map format (i.e. raster, polygon or polyline), the plausibility of exposure levels (based on the lack of quiet areas) and noise propagation. Each strategic noise map was evaluated independently based on these parameters by two researchers (SK and MC) and assigned a score (**appendix 1 p 212**). Higher scores were given to strategic noise maps showing continuous noise exposures below 55 dB L_{den} in polygon or raster formats. Penalties were given to strategic noise maps without quiet areas and not displaying noise propagation from the street level. Based on the assigned scores, the strategic noise maps were categorized into low, moderate and high quality (**appendix 1 p 213**).

2.10. City comparisons

Given the country-specific differences in strategic noise maps and the distinct methodologies for baseline road traffic noise estimation (i.e. assignment from strategic noise maps or gap filling), we considered that the obtained estimates for the analysed cities could not be directly compared. We present estimates for 25 European capitals (Tables 1-3, Figs. 3-4) and discuss potential causes of variability in road traffic noise exposure between cities and countries.

3. Results

Overall, 123,966,346 adults resided in the 724 cities and 25 greater cities in 2015. Adult population counts ranged from 6314 (in Suwalki, Poland) to 6,250,746 (in London, UK) with a median of 98,373 adult residents. A total of 179,585 deaths from IHD, 519,588 deaths from CVD and 1,399,473 deaths from natural causes were estimated in 2015 among the adult population of the analysed cities. Mortality rates per 100,000 population ranged between 22 and 686 deaths for IHD, 80–1173 deaths for CVD and 298–1879 deaths for natural-cause mortality (**appendix 2 p 1**).

We found several differences in the baseline strategic noise maps (Table 1**,** Fig. 1, **appendix 1 pp 9–162**). The primary differences were in data formats (i.e. raster, polygon or polyline) and noise exposure assessment (i.e. with distinct noise ranges and levels of categorization). Most of the strategic noise maps were delivered as polygons (i.e. 72.0%), followed by rasters (i.e. 17.0%) and polylines (i.e. 11.0%). All raster maps presented continuous exposure levels, however, with distinct noise exposure ranges. The majority of the polygon and polyline maps (i.e. 55.6% and 71.4%, respectively) categorized noise levels in 5-dB categories above 55 dB L_{den}. We found that the exposures estimated from raster and polygons maps were more comparable to each other than those from polyline maps, which were generally higher (i.e. we estimated a median of 39.0% and 45.0% of population exposed above 55 dB L_{den} for raster and polygon maps, respectively, compared to a median of 84.1% for polyline maps) (**appendix 1 p 7**). Most of the noise maps were considered of moderate or low quality, i.e. 42.6% and 40.6%, respectively (**appendix 2 pp 2–3**). The prediction models for gap filling

Table 2
Road traffic noise impact on noise annoyance in 25 European capitals.

City	Adults annoyed by noise (n) (95% CI)	% adults annoyed by noise (95% CI)	YLD due to noise annoyance (95% CI)	YLD per 100,000 population (95% CI)
Amsterdam, the Netherlands	57,003 (56,999–57,007)	7.8% (7.8–7.8)	1140 (1140–1140)	157 (157–157)
Berlin, Germany	132,781 (132,775–132,789)	4.8% (4.8–4.8)	2656 (2656–2656)	96 (96–96)
Brussels, Belgium	57,157 (57,152–57,162)	6.5% (6.5–6.5)	1143 (1143–1143)	129 (129–129)
Budapest, Hungary	109,281 (109,275–109,288)	7.4% (7.4–7.4)	2186 (2185–2186)	147 (147–147)
Copenhagen, Denmark	37,681 (37,677–37,685)	8.2% (8.2–8.2)	754 (754–754)	165 (164–165)
Dublin (greater city), Ireland	49,495 (49,491–49,498)	5.1% (5.1–5.1)	990 (990–990)	103 (103–103)
Helsinki, Finland	38,530 (38,526–38,533)	8.1% (8.1–8.1)	771 (771–771)	162 (162–162)
Lisbon, Portugal	35,150 (35,147–35,154)	8.3% (8.3–8.3)	703 (703–703)	166 (166–166)
Ljubljana, Slovenia	20,271 (20,269–20,274)	8.8% (8.8–8.8)	405 (405–405)	176 (176–176)
London (greater city), UK	383,158 (383,146–383,170)	6.1% (6.1–6.1)	7663 (7663–7663)	123 (123–123)
Luxembourg city, Luxembourg	16,359 (16,357–16,362)	20.4% (20.4–20.4)	327 (327–327)	407 (407–407)
Madrid, Spain	200,300 (200,292–200,308)	7.9% (7.9–7.9)	4006 (4006–4006)	159 (159–159)
Oslo, Norway	60,497 (60,492–60,502)	12.1% (12.1–12.1)	1210 (1210–1210)	242 (242–242)
Paris (greater city), France	708,040 (708,023–708,056)	12.9% (12.9–12.9)	14,161 (14160–14161)	257 (257–257)
Prague, Czech Republic	136,009 (136,002–136,015)	12.7% (12.7–12.7)	2720 (2720–2720)	254 (254–254)
Riga, Latvia	88,932 (88,926–88,938)	17.5% (17.5–17.5)	1779 (1779–1779)	350 (350–350)
Rome, Italy	245,298 (245,288–245,307)	11.5% (11.5–11.5)	4906 (4906–4906)	230 (230–230)
Sofia, Bulgaria	207,538 (207,527–207,546)	25.3% (25.3–25.3)	4151 (4151–4151)	505 (505–505)
Stockholm, Sweden	57,473 (57,468–57,477)	8.2% (8.2–8.2)	1149 (1149–1150)	165 (165–165)
Tallinn, Estonia	20,846 (20,843–20,849)	6.8% (6.8–6.8)	417 (417–417)	135 (135–135)
Valletta, Malta	12,658 (12,656–12,660)	8.5% (8.5–8.5)	253 (253–253)	169 (169–169)
Vienna, Austria	178,807 (178,800–178,814)	12.5% (12.5–12.5)	3576 (3576–3576)	249 (249–249)
Vilnius, Lithuania	64,690 (64,685–64,696)	15.4% (15.4–15.4)	1294 (1294–1294)	307 (307–307)
Warsaw, Poland	193,164 (193,156–193,174)	13.7% (13.7–13.7)	3863 (3863–3863)	274 (274–274)
Zurich (greater city), Switzerland	39,703 (39,700–39,706)	8.0% (8.0–8.0)	794 (794–794)	160 (160–160)

Table 3
Road traffic noise impact on mortality in 25 European capitals.

City	Preventable deaths (n)(95% CI)	% of natural-cause mortality (95% CI)	% of IHD mortality (95% CI)	Preventable deaths per 100,000 population (95% CI)	YLL due to preventable mortality (95% CI)	YLL per 100,000 population (95% CI)
Amsterdam, the Netherlands	7 (2–12)	0.12% (0.04–0.20)	1.74% (0.58–2.91)	1.3 (0.4–2.2)	92 (41–143)	15 (7–24)
Berlin, Germany	42 (11–72)	0.13% (0.04–0.23)	0.95% (0.25–1.62)	1.5 (0.4–2.6)	488 (202–758)	18 (7–28)
Brussels, Belgium	11 (2–18)	0.12% (0.02–0.21)	1.51% (0.27–2.60)	1.3 (0.3–2.3)	123 (49–193)	17 (7–26)
Budapest, Hungary	86 (24–149)	0.41% (0.11–0.70)	1.61% (0.46–2.79)	5.7 (1.6–9.9)	803 (337–1304)	54 (23–87)
Copenhagen, Denmark	5 (1–9)	0.13% (0.02–0.24)	1.82% (0.33–3.24)	1.7 (0.3–3.0)	61 (29–95)	20 (9–31)
Dublin (greater city), Ireland	11 (4–18)	0.14% (0.05–0.25)	0.98% (0.33–1.67)	1.6 (0.4–2.8)	133 (66–207)	19 (9–29)
Helsinki, Finland	15 (3–26)	0.32% (0.07–0.56)	1.78% (0.38–3.09)	3.8 (0.6–6.7)	182 (78–280)	43 (18–67)
Lisbon, Portugal	13 (3–22)	0.19% (0.05–0.32)	1.96% (0.46–3.25)	2.8 (0.6–4.6)	154 (71–234)	34 (15–51)
Ljubljana, Slovenia	5 (1–8)	0.23% (0.07–0.37)	2.00% (0.63–3.26)	2.1 (0.7–3.5)	59 (26–89)	27 (12–40)
London (greater city), UK	74 (26–125)	0.15% (0.05–0.26)	1.38% (0.49–2.34)	1.4 (0.5–2.4)	927 (476–1420)	18 (8–27)
Luxembourg city, Luxembourg	3 (1–5)	0.50% (0.17–0.80)	5.24% (1.77–8.29)	5.0 (1.7–7.8)	46 (23–68)	65 (32–97)
Madrid, Spain	39 (8–70)	0.14% (0.03–0.25)	1.83% (0.40–3.30)	1.5 (0.5–2.5)	484 (225–744)	19 (9–29)
Oslo, Norway	16 (4–28)	0.33% (0.08–0.57)	2.91% (0.68–5.09)	4.4 (1.3–7.6)	187 (84–291)	51 (23–80)
Paris (greater city), France	70 (12–126)	0.18% (0.03–0.32)	3.14% (0.52–5.68)	1.3 (0.3–2.2)	903 (367–1464)	18 (8–28)
Prague, Czech Republic	93 (13–167)	0.76% (0.11–1.38)	2.88% (0.40–5.21)	9.3 (1.4–16.8)	860 (305–1389)	85 (30–138)
Riga, Latvia	109 (39–183)	1.38% (0.49–2.31)	4.44% (1.57–7.42)	20.2 (6.9–33.7)	1158 (564–1766)	218 (106–332)
Rome, Italy	96 (6–176)	0.39% (0.03–0.71)	2.79% (0.18–5.14)	3.8 (0.5–6.8)	1011 (339–1630)	42 (15–67)
Sofia, Bulgaria	77 (24–125)	0.67% (0.21–1.10)	6.66% (2.06–10.89)	10.9 (2.9–18.1)	839 (401–1284)	115 (54–176)
Stockholm, Sweden	14 (4–25)	0.23% (0.07–0.41)	1.87% (0.58–3.26)	2.3 (0.7–3.9)	167 (73–257)	26 (12–41)
Tallinn, Estonia	15 (4–25)	0.38% (0.11–0.65)	1.59% (0.45–2.72)	5.0 (1.3–8.8)	157 (64–250)	54 (22–87)
Valletta, Malta	7 (2–12)	0.45% (0.11–0.80)	1.99% (0.48–3.49)	5.3 (1.1–9.8)	87 (37–134)	62 (26–98)
Vienna, Austria	86 (15–154)	0.56% (0.09–1.00)	2.40% (0.41–4.31)	6.3 (1.4–11.1)	884 (344–1406)	66 (26–106)
Vilnius, Lithuania	71 (25–118)	1.36% (0.49–2.26)	3.83% (1.37–6.34)	18.7 (6.1–31.2)	710 (342–1061)	184 (87–278)
Warsaw, Poland	82 (21–146)	0.47% (0.12–0.84)	3.33% (0.86–5.97)	5.4 (1.6–9.5)	904 (430–1468)	62 (31–100)
Zurich (greater city), Switzerland	11 (1–20)	0.24% (0.02–0.45)	1.83% (0.13–3.38)	2.2 (0.2–4.0)	114 (42–186)	24 (9–38)

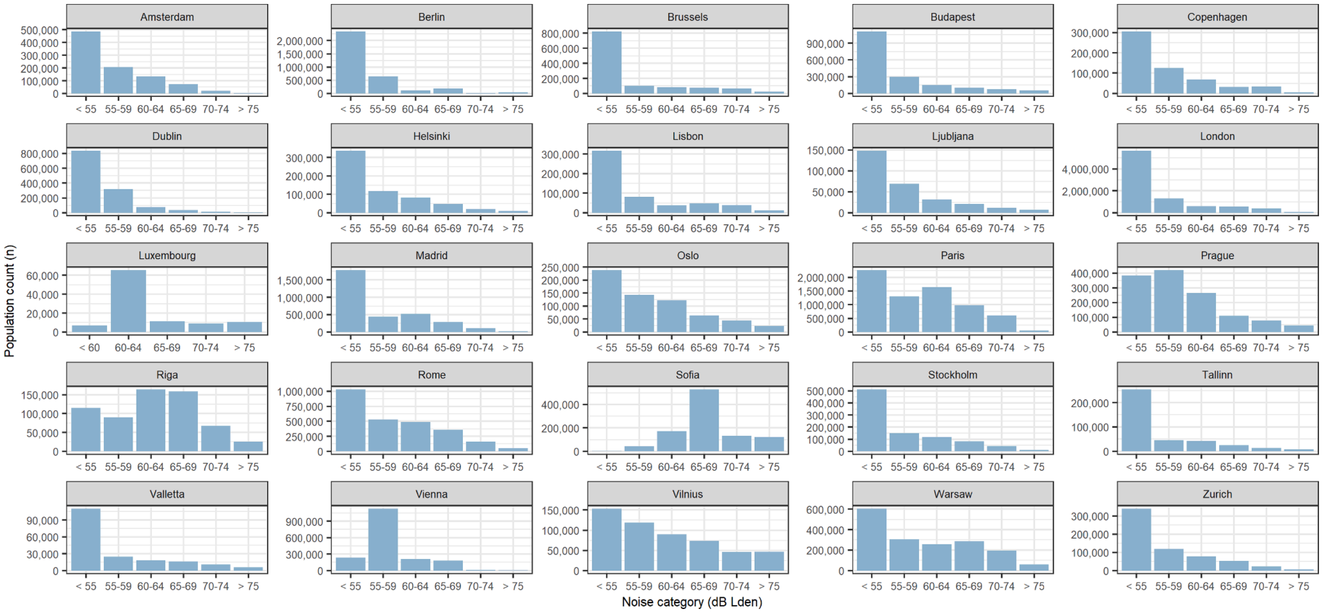

Fig. 3. Baseline road traffic noise exposure in 25 European capitals. Population distribution in 5-dB noise bands is shown for each capital. For Luxembourg, the strategic noise map only included exposure levels > 60 dB Lden.

delivered acceptable results (**appendix 1 pp 9–162**). A median of 88.5% of population was classified in the same 5-dB noise band as in the data from the strategic noise maps (Interquartile Range (IQR): 82.6–92.5%) and the median Pearson correlation was 0.975 (IQR: 0.918–0.994). The RMSE had a median of 1549 (IQR: 805–2778).

Combining the data from the strategic noise maps and the gap filling procedure we estimated that 59,869,395 adults (95% CI: 59,852,109 – 59,886,798) were exposed to road traffic noise levels above 55 dB L_{den} in the 724 cities and 25 greater cities, equating to a median value of 42.1% (IQR: 31.8–64.8) of the adult population (**appendix 1 pp 9–162**).

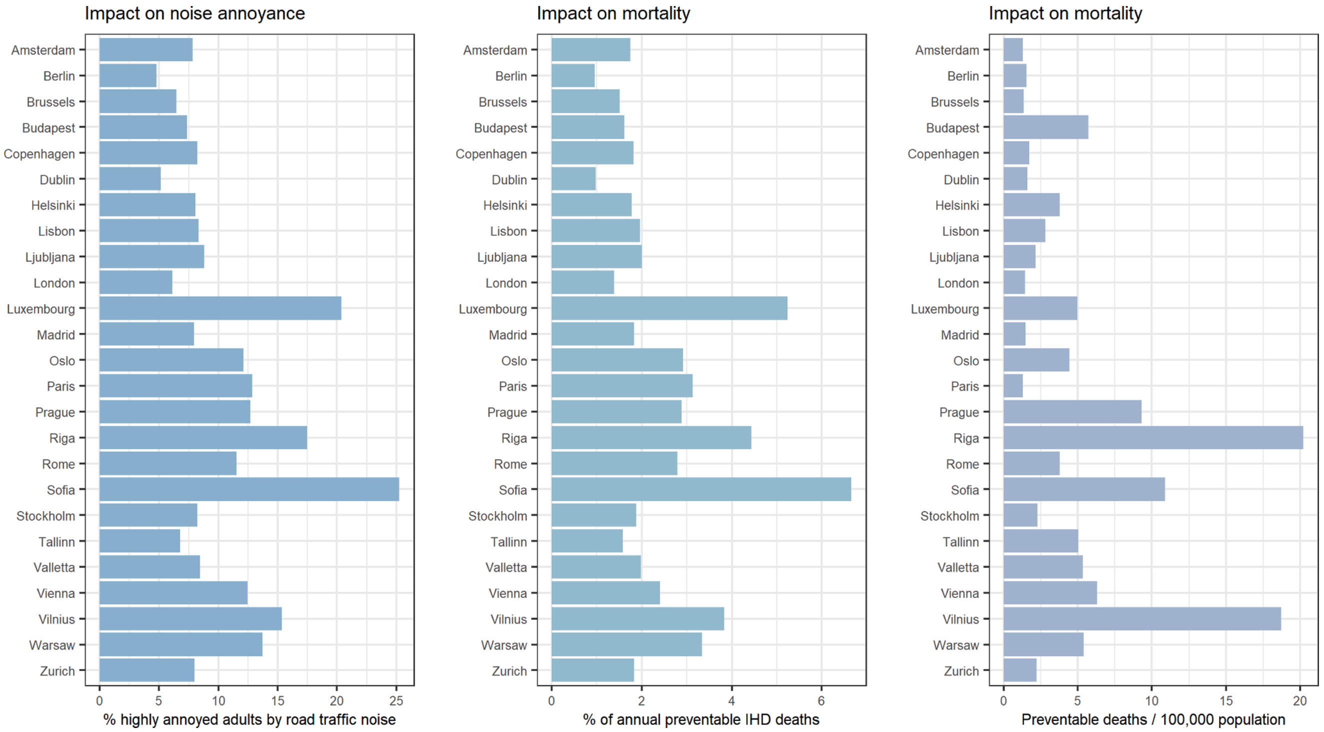

Fig. 4. Road traffic noise impact on noise annoyance and mortality in 25 European capitals.

Among the 25 European capitals, the percentage of population exposed to road traffic noise above 55 dB L_{den} varied between 29.8% (in Berlin, Germany) and 99.8% (in Sofia, Bulgaria), with a median value of 46.5% (Table 1).

3.1. *Impact on noise annoyance*

We estimated that 11,091,131 adults (95% CI: 11,086,519–11,095,771) were highly annoyed by road traffic noise in all analysed cities, corresponding to a median value of 7.6% (IQR: 5.6–11.8) of the adult population (**appendix 2 p 4**). In the 25 European capitals, the proportion of adults highly annoyed by road traffic noise ranged between 4.8% (in Berlin, Germany) to 25.3% (in Sofia, Bulgaria), with a median value of 8.3% (Table 2). Overall, noise annoyance accounted for 221,823 YLD (95% CI: 221,730–221,915) (**appendix 2 p 4**).

3.2. *Impact on mortality*

We estimated that 3608 deaths from IHD (95% CI: 843–6266) could be prevented each year among all analysed cities if road traffic noise levels were lowered to WHO recommendations, which equated to a median value of 2.2 deaths per 100,000 population (IQR: 1.4–3.1) (**appendix 2 p 5**). We estimated that between 3 and 109 deaths from IHD could be prevented each year in the 25 European capitals (Table 3). Among these cities, the number of preventable deaths ranged between 1.3 (in Paris, France) and 20.2 (in Riga, Latvia) deaths per 100,000 population, with a median value of 3.8 deaths (Table 3). Overall, preventable mortality due to road traffic noise resulted in 40,658 YLL (95% CI: 17,107–63,717) (**appendix 2 p 5**).

3.3. *Sensitivity analyses*

The sensitivity analyses showed the greatest changes in the estimated impact due to changes in the ERFs for mortality (**appendix 1 pp 175–181**). In the sensitivity analyses, the number of preventable deaths ranged from 1741 to 6069, i.e. equating to a change of −52% to +76%. The use of the alternative exposure–response relation for noise annoyance resulted in a general decrease in the estimated impact of −16% (**appendix 1 pp 173–174**). We also found differences between our estimates and those resulting from the tabular data delivered under the END (**appendix 1 pp 182–206**). The correlation between our and the delivered estimates on the % of population exposed above 55 dB L_{den} was r = 0.631 and varied depending on the data format of the strategic noise maps (r = 0.569 for raster, r = 0.721 for polygon and r = 0.286 for polyline) and the country (median r = 0.524, IQR: 0.193–0.926) (**appendix 1 pp 183–185**). We obtained comparable but slightly decreased estimates on population exposure, high annoyance and mortality of −17% to −6%, however, with high variability between cities (**appendix 1 pp 204–206**). Finally, our last sensitivity analysis showed that considering the uncertainty in the strategic noise maps has a bigger impact on the point estimates and 95% CIs of population exposure and high annoyance than those of mortality (**appendix 1 pp 207–211**).

4. Discussion

To our knowledge, this is the first study to estimate road traffic noise exposure and the associated health impacts for a large number of cities in Europe. We provide a detailed assessment of the road traffic noise data represented in the strategic noise maps delivered under the END and we highlight the variability that exists between these in terms of data formats and noise exposure assessment. Based on the available data we estimate that a considerable number of adults (i.e. almost 60 million and a median of 42% of the adult population) across the analysed cities are exposed to road traffic noise levels harmful for health and we show that road traffic noise reductions to WHO recommended levels can lead to positive health outcomes in terms of reduced number of people highly annoyed and mortality. Nevertheless, we are still missing a large part of the burden due to the lack of noise data for many European cities and the unavailability of city-level disease incidence data. Efforts to standardize the strategic noise maps and to increase noise and disease data availability at the city level are still needed. These would allow for a more accurate and comprehensive assessment of the health impacts and further help local governments to address the adverse health effects of road traffic noise.

4.1. Data on road traffic noise exposure in Europe

We found great variability among the strategic noise maps delivered under the END (**appendix 1 pp 9–162**). Up to date, a standardized protocol to deliver strategic noise map data does not exist (European Commission, 2002). In accordance, we found many differences in the strategic noise maps due to the distinct noise mapping methods employed by each country, the data formats (i.e. raster, polygon or polyline) and noise exposure assessment (i.e. noise exposure range and level of categorization). Notably, the majority of the noise maps were categorized as moderate or low quality, highlighting the need to improve the quality of the delivered data. Based on our criteria, we believe data quality can be improved by mapping continuous data with wider noise exposure ranges (i.e. also covering exposures below 55 dB L_{den}) and delivering the noise maps in raster format, which allows for a more accurate evaluation of population exposure to road traffic noise (**appendix 1 pp 5–7, 212–213**).

In the last round of noise mapping (i.e. in 2017) a common noise mapping method for all countries was not available (EEA, 2020b). Each country was allowed to employ its own national methods, e.g. in the choice of road typologies covered by the noise mapping or by using distinct assumptions in the predictive models for noise levels estimations, which can lead to substantial differences in noise exposure between countries and cities (EEA, 2020b; Hegewald et al., 2021). In this way, the baseline strategic noise maps employed in this study were expected to carry many inconsistencies and uncertainties related to the underlying noise mapping method, which was expected to affect the quality of the reported data and to impair direct comparability between countries and cities. For instance, the strategic noise maps for some of the studied countries, such as Bulgaria or Luxembourg, showed very high road traffic noise exposure levels, which led us to estimate that almost the whole population (i.e. >90%) was exposed to road traffic noise levels harmful for health (**appendix 1 pp 18–22, 115–116**). Given these inconsistencies, we have calculated the exposures country by country. Nevertheless, inconsistencies in noise mapping methods within countries are still possible and, therefore, we believe that the presented estimates should be interpreted with caution and comparisons between cities (even within the same country) should not be conducted.

Furthermore, the different data formats and noise exposure assessment of the delivered strategic noise maps were expected to impact the estimated road traffic noise exposures in this study. The noise assignment method differed for raster, polygon and polyline maps (Fig. 2, **appendix 1 pp 5–7**) and the resulting road traffic noise exposures were more comparable for raster and polygon maps than for polyline maps, for which the estimated exposure was generally higher (**appendix p 7**). We had a higher degree of confidence in the strategic noise maps delivered in raster format as the data represented in the maps was highly resolved and had a continuous and wide noise exposure range (i.e. also including noise levels below 55 dB L_{den}), thus, providing a higher degree of precision. Contrastingly, the polyline maps represented noise exposure either using street lines or isophones. In these cases, the noise assignment method that delivered the best results was to assign the nearest street or isophone noise value to each building unit. Nevertheless, this method was prone to overestimations by assuming that the noise value from the nearest street or isophone was the same as at the building façade. We did not attempt to adjust the polyline maps to consider noise propagation to the buildings from the street level as this would require many assumptions on noise propagation and absorption characteristics of the building materials, thus, introducing even more uncertainties in the baseline road traffic noise exposures. For the polygon maps, we had an intermediate degree of confidence. These maps generally provided good quality data, however, categorizing noise exposure levels in 5-dB categories, which is a wide range of exposure, and in many occasions only including exposures above 55 dB L_{den}, which is above the recommended levels to protect health.

Given all the above, the variability in the estimated road traffic noise exposure between European cities could be due to real differences in road traffic noise levels (e.g. due to higher motorized traffic levels or urban design) but also due to the underlying noise mapping method and the noise exposure assignment procedure. Despite this, the delivered strategic noise maps represent the best available data on road traffic noise exposure in Europe. In the near future, further harmonization in noise mapping methods and protocols to deliver strategic noise maps (i.e. having the same data format and noise exposure assessment) should be implemented. In the last years, a common method for noise mapping (i.e. CNOSSOS-EU) has been developed and must be followed by the member states for the preparation of strategic noise maps since January 2019 (EEA, 2020b). Thus, it is plausible that future rounds of noise mapping will deliver more harmonized and comparable data. This would allow for more quality control and to provide more accurate estimates on road traffic noise exposure and the related health impacts for European cities.

4.2. Road traffic noise health effects

Recent research has linked road traffic noise to many non-auditory health effects (Basner & McGuire, 2018; Clark & Paunovic, 2018; Eriksson et al., 2018; Guski et al., 2017; van Kempen et al., 2018; WHO, 2018). A recent review on the effects of environmental noise on cardiovascular and metabolic disease has found the strongest evidence for road traffic noise exposure and the incidence of IHD (van Kempen et al., 2018). Similarly, robust associations have been found for the relation between an increased road traffic noise exposure and the proportion of highly annoyed and highly sleep disturbed individuals (Basner & McGuire, 2018; Guski et al., 2017). Accordingly, the incidence of IHD, annoyance and sleep disturbance are the three main health outcomes recommended by the WHO to be included in a HIA for road traffic noise (Basner & McGuire, 2018; EEA, 2020b; Guski et al., 2017; van Kempen et al., 2018; WHO, 2018). Nonetheless, additional health outcomes could also be assessed, including the incidence of stroke and diabetes, and mental health outcomes such as depression and anxiety, for which evidence is becoming stronger (Clark & Paunovic, 2018; Dzhambov & Lercher, 2019; EEA, 2020b; Lan et al., 2020; Roswall et al., 2021; Thacher et al., 2021; van Kempen et al., 2018; WHO, 2018). In this study, we could only focus on two primary health effects of road traffic noise: high annoyance and IHD, using mortality from IHD causes as indicator. We could not assess additional health outcomes such as the incidence of IHD, stroke, diabetes, depression and/or anxiety due to the lack of city-level disease incidence data. In the same way, we could not evaluate the impact on sleep disturbance – an important contributor to the total health burden of road traffic noise (Eriksson et al., 2017; Mueller et al., 2017a; Veber et al., 2022) – due to the limited availability of strategic noise maps containing information on the average night noise exposure (i.e. in dB L_{night}) (EEA, 2020a; European Commission, 2002). In addition, noise exposure levels below 55 dB L_{den} can also contribute to adverse health effects due to road traffic noise (Hegewald et al., 2021; Veber et al., 2022). Thus, it is very likely that the health impacts of road traffic noise presented in this study are underestimated. Given that we estimate that almost 60 million adults (i.e. a median of 42% of the adult population) across the analysed cities are exposed to road traffic noise levels above 55 dB L_{den} and that we were not able to evaluate population exposure below this level, it is reasonable to expect wider adverse health impacts in terms of incidence of cardiovascular and metabolic diseases, annoyance, sleep disturbance and poor mental health and quality of life. Further research on the health effects of road traffic noise and the availability of more detailed noise and health data at the city level will likely improve future assessments of the health impacts of road traffic noise exposure, providing a more comprehensive picture of the adverse health effects of this environmental pollutant.

4.3. Comparison to previous studies

Up to date, HIA studies on road traffic noise at the city level are generally scarce. A few studies have estimated the health impacts of road traffic noise for specific cities in Europe including Athens, Barcelona, Bradford, London, Madrid, Tallinn, Tartu, Turin, Vienna and Warsaw (Iungman et al., 2021; Khomenko et al., 2020; Mitsakou et al., 2019; Mueller et al., 2017b, 2017a, 2018; Recio et al., 2017; Tainio, 2015; Tobías et al., 2015; Veber et al., 2022). Nevertheless, all these previous studies provide mixed results. They employ different road traffic noise data sources (e.g. strategic noise maps or direct noise measurements), noise indicators (e.g. 24 h or only day time road traffic noise), methods to assign population noise exposure (e.g. by calculating the average road traffic noise exposure at city or census-tract level or by estimating the population exposed to distinct noise bands), ERFs and health outcomes (e.g. natural-cause or CVD mortality), assumptions on exposure length (i.e. short-term or long-term) and counterfactual exposure assumptions (**appendix 1 pp 214–216**). Accordingly, the estimated health impacts in these studies vary greatly, even when the same cities are assessed. The estimated health impacts presented here are generally lower compared to these previous assessments. Two potential reasons for this could be the main health outcome studied (i.e. mortality due to IHD) and the methodology to assign population noise exposure. Contrastingly to most of this previous research, which focused on mortality from all natural or CVD causes, we decided to focus on mortality from IHD as our main health outcome, following an accepted methodology outlined in the recent EEA noise report (EEA, 2020b). Given that the expected number of deaths due to IHD was smaller than the one from all natural or CVD causes, we estimated smaller death fractions due to road traffic noise. Similarly, our noise assignment method differed from most of the previous studies. We distributed the population in residential building units and assigned noise exposure at the building unit level. By doing so, we did not assume an equal noise exposure for the whole population of an administrative unit (i.e. city, district or census-tract), as has been previously done and which could lead to overestimations in population noise exposure (Iungman et al., 2021; Mitsakou et al., 2019; Mueller et al., 2017b, 2017a; Recio et al., 2017; Tobías et al., 2015). In this way, we provide a more refined procedure for noise exposure assignment, but that can also lead to lower estimates of road traffic noise exposure and its health impacts than those previously reported (Iungman et al., 2021; Mitsakou et al., 2019; Mueller et al., 2017b, 2017a; Recio et al., 2017; Tobías et al., 2015).

In addition, the recent EEA report on environmental noise provides the most recent data on population exposure to environmental noise and the associated health impacts in Europe, based on the tabular data on population noise exposure delivered by the countries under the END (EEA, 2020b; European Commission, 2002). In this study, we compared our road traffic noise exposure estimates to those reported for urban agglomerations and used in the EEA report (**appendix 1 pp 182–206**). The agreement between both estimates depended on the data format of the delivered strategic noise maps, the country and the specific city being compared. For certain countries and cities (e.g. in Austria, Switzerland, Czech Republic and Germany) our estimates were more comparable to the ones reported to the EEA than for others (e.g. cities in Spain, Italy and Poland). We believe that this variability is mainly due to the method employed to calculate the population exposure to road traffic noise. We followed a similar approach employed by local administrations to assign population noise exposure (Barcelona Public Health Agency, 2020; Madrid City Council, 2016). Nevertheless, the best available data that we had for all cities was the population distribution in 250 m grid cells (European Commission, 2019b). Thus, it is possible that by using more refined local datasets on population distribution in residential areas local administrations provide more accurate estimates on road traffic noise exposure that differ from our own. Moreover, local administrations might have access to better quality strategic noise maps than those submitted to the EEA, which would provide a better assessment of road traffic noise exposure. A quality assurance mechanism to ensure that the best-quality strategic noise maps are delivered under the END would help to address this issue and allow for more accurate evaluations of population noise exposure and health impacts.

4.4. Strengths and limitations

The main strengths of this study include a detailed assessment of the road traffic strategic noise maps delivered under the END, the gap filling methodology to estimate noise exposure in cities without available strategic noise maps and the health impact calculation procedure with Monte Carlo simulations to account for uncertainty in some of the parameters. Our initial estimates on the population distribution in 5-dB noise bands were at a 250 m resolution, which provided a greater level of detail than the tabular data delivered by the countries under the END and allowed us to develop the gap filling methodology for cities with missing data. The gap filling method was based on previous work by Houthuijs and colleagues (Houthuijs et al., 2018) and expanded to the cities and countries included in this study. We considered strong and previously well documented local predictors of road traffic noise levels including population density and the length of distinct road typologies. We have additionally expanded on the previous work by adding city level predictors to characterize the city size (i.e. area and population). Overall, the prediction models for gap filling had an acceptable performance, indicating that the gap filling method employed in this study could be valid to estimate the exposure to road traffic noise when strategic noise maps are not available. Finally, considering the uncertainties in the input parameters for the health impact calculation provides more realistic empirical CIs around the point estimates, leading to a more accurate evaluation of the uncertainty in the results.

Nevertheless, this study also has several limitations. We were mainly limited by the quality of the road traffic noise data, as detailed above. Another major limitation was the noise assignment method, in which we were limited by the available population dataset (European Commission, 2019b). We assumed that the population count was higher in building units covering bigger areas and we could not account for other relevant parameters such as building height, which could have led to overestimations of population exposure in areas of high-rise buildings. In addition, even though the gap filling models generally provided acceptable results, several things should be noted regarding the method. As for the criteria for model validation, the percentage of population classified in the same 5-dB noise band does not consider good classification by chance. Given that we were working with aggregated data, we could not use an indicator that would account for this issue, such as the weighted Cohen's kappa. Nonetheless, we believe that the additional validation parameters (i.e. the Pearson correlation and the RMSE) are complementary and provide an additional insight into model error. Moreover, when used for prediction, the ordered logistic regression models tended to predict similar road traffic noise exposure values for cities in a country, without the ability to detect outliers (e.g. cities with very low or very high road traffic noise levels). This issue was partially solved by including the city size predictors in our models. Despite this, future research should focus on identifying the specific city features that could explain variations in road traffic noise levels between cities and that could be employed to improve the prediction capacity of the models used for gap filling. Finally, regarding the Monte Carlo simulations, we only propagated the uncertainty in the input parameters for which the uncertainty distributions were known (i.e. the ERFs, the average noise exposure levels, the prediction models for gap filling and the average age of death). We did not consider the underlying uncertainty in two main parameters that could have an impact on our point estimates and 95% CIs, but for which we lacked the magnitude of error and the uncertainty distribution: the exposure–response relation for annoyance and the baseline noise levels shown in the strategic noise maps. As a consequence, the 95% CIs in our estimates, particularly for population exposure and annoyance, are quite narrow. Our last sensitivity analysis highlights the importance of propagating the uncertainty in the strategic noise maps to provide point estimates and 95% CIs that are more accurate and realistic, respectively (**appendix 1 pp 207–211**). Thus, we believe that the magnitude of error associated with the exposure levels shown in the strategic noise maps should be reported, so that the uncertainty in this parameter can be incorporated in future assessments of the health impacts of road traffic noise.

One last limitation relates to the ERFs. Similarly to our previous work (Khomenko et al., 2021) we found the greatest changes in our mortality estimates upon changes of the ERF (**appendix 1 pp 175–181**), highlighting the importance of the ERF choice. In this study we have chosen for our main analysis an ERF for IHD mortality previously accepted and used for HIA by the EEA (EEA, 2020b; van Kempen et al., 2018). Nevertheless, none of the *meta*-analysed risk estimates for the association between road traffic noise exposure and mortality reached statistical significance (Cai et al., 2021; van Kempen et al., 2018). Only the risk estimates derived from the Swiss cohort (of over 4 million individuals) showed more robust associations (Héritier et al., 2017). All in all, based on the stronger associations derived for the incidence of IHD (van Kempen et al., 2018) and for mortality from CVD causes from the Swiss cohort (Héritier et al., 2017), we believe that it is plausible to assume that road traffic noise exposure also increases the risk for mortality. Further research is needed to better assess the relation between road traffic noise exposure and mortality. Compared to other environmental stressors, such as air pollution, the health effects of environmental noise are often more difficult to evaluate. This is due to the fact that in many occasions there is a lack of high-quality data on environmental noise exposure. For instance, the strategic noise maps delivered under the END often do not include exposures below 55 dB L_{den}, not allowing to study the health effects of noise at exposures below this level. In addition, the outdoor noise levels might not be the best indicator of individual exposure to noise. Individual noise exposure might be affected by behavioural aspects and coping mechanisms (e.g. closing windows, wearing ear plugs) as well as the residential building features (e.g. bedroom orientation, window types, shielding materials). Thus, a better assessment of environmental noise exposure is needed, either through an improved evaluation of outdoor noise or through the measurement of individual exposure levels, e.g. at the bedroom level. An improved exposure assessment could provide better insights into the robustness of health effects of environmental noise and improve future assessments of the health impacts of road traffic noise through the provision of better-quality ERFs.

5. Conclusion

In conclusion, we have estimated road traffic noise exposure and the associated health impacts for a large number of European cities, to our knowledge, for the first time. With this study we were able to provide a detailed assessment of the strategic noise maps delivered under the END. We estimate that a considerable number of adults (i.e. almost 60 million and a median of 42% of the adult population) across the analysed cities are exposed to road traffic noise levels that are harmful for health (above 55 dB L_{den}). In addition, we show that reducing road traffic noise to WHO recommended levels could lead to improved health outcomes in terms of reduced number of people highly annoyed and mortality. Nevertheless, efforts to standardize the strategic noise maps and increase noise and disease data availability at the city level are still needed. These would allow for a more accurate and comprehensive assessment of the health impacts and further help local governments to address the adverse health effects of road traffic noise.

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CRediT authorship contribution statement

Sasha Khomenko: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing, Funding acquisition. **Marta Cirach:** Conceptualization, Methodology, Software, Writing – review & editing. **Jose Barrera-Gómez:** Methodology, Software, Writing – review & editing, Supervision. **Evelise Pereira-Barboza:** Methodology, Validation, Writing – review & editing. **Tamara Iungman:** Methodology, Validation, Writing – review & editing. **Natalie Mueller:** Methodology, Validation, Writing – review & editing. **Maria Foraster:** Methodology, Validation, Writing – review & editing. **Cathryn Tonne:** Methodology, Validation, Writing – review & editing. **Meelan Thondoo:** Validation, Writing – review & editing. **Calvin Jephcote:** Methodology, Writing – review & editing. **John Gulliver:** Methodology, Writing – review & editing. **James Woodcock:** Methodology, Writing – review & editing, Supervision. **Mark Nieuwenhuijsen:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2022.107160.

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