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Cardiovascular effects of environmental noise exposure

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Abstract

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The role of noise as an environmental pollutant and its impact on health are being increasingly recognized. Beyond its effects on the auditory system, noise causes annoyance and disturbs sleep, and it impairs cognitive performance. Furthermore, evidence from epidemiologic studies demonstrates that environmental noise is associated with an increased incidence of arterial hypertension, myocardial infarction, and stroke. Both observational and experimental studies indicate that in particular night-time noise can cause disruptions of sleep structure, vegetative arousals (e.g. increases of blood pressure and heart rate) and increases in stress hormone levels and oxidative stress, which in turn may result in endothelial dysfunction and arterial hypertension. This review focuses on the cardiovascular consequences of environmental noise exposure and stresses the importance of noise mitigation strategies for public health.

Keywords: Cardiovascular disease, Noise, Pollutants, Sleep, Hypertension, Myocardial infarction, Stroke

Introduction

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The Nobel Prize Winner Robert Koch predicted in 1910 that ‘One day man will have to fight noise as fiercely as cholera and pest’. Acutely, noise interferes with communication, disturbs sleep, and causes annoyance. At the same equivalent noise level, annoyance and self-reported sleep disturbance are usually highest for aircraft noise, and higher for road compared with rail traffic noise ([Figure 1](#)).¹ Further, long-term exposure to relevant noise levels has been shown to be associated with negative health outcomes. Importantly, an impact on cardiovascular and autonomic homeostasis has been shown, even for noise levels that are quite commonly observed in urbanized regions: it is estimated that ~40% of the population in European Union countries is exposed to road traffic noise at levels exceeding 55 dB of L_{DN} (‘day–night level’, a measure of noise which summarizes average noise exposure >24 h, see [Table 1](#)) and that

Indeed, the activation of fight–flight and defeat reactions is thought to involve subcortical regions of the brain like the hypothalamus, which has inputs to the autonomic nervous system, the endocrine system, and the limbic system.^{10,11} Such stress responses, in turn, result in changes in a number of physiological functions and in the homeostasis of several organs, including blood pressure, cardiac output, blood lipids (cholesterol, triglycerides, free fatty acids, phosphatides), carbohydrates (glucose), electrolytes (magnesium, calcium), thrombosis/fibrinolysis, and others.¹²

Experimental laboratory studies, observational field studies, and epidemiological studies all play important roles in elucidating the effects of environmental noise on cardiovascular health. *Figure 2* shows a proposed reaction scheme for the effects of noise on the organism (from Sørensen *et al.* and Schmidt^{72,95}). As described above, noise may exert its effects either directly, through synaptic interactions, or indirectly, through the emotional and the cognitive perception of sound. In other words, both the objective noise exposure (sound level) and its subjective perception determine the impact of noise on neuroendocrine homeostasis.

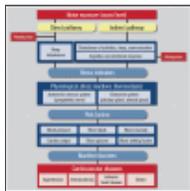


Figure 2

Noise effects reaction scheme. Adapted from Babisch.^{71,94}

Effects of nocturnal noise exposure on sleep and the cardiovascular system [Go to:](#)

Sleep is a complex and very active process, incorporating many vital physiological processes (e.g. protein biosynthesis, excretion of specific hormones, memory consolidation) that, in a broad sense, serve recuperation and preparation for the next wake period. Acute and chronic sleep restriction or fragmentation has been shown to be associated with inadequate pancreatic insulin secretion,¹³ decreased insulin sensitivity,¹⁴ changes in appetite regulating hormones,¹⁵ and increased sympathetic tone and venous endothelial dysfunction.¹⁶ At the same time, epidemiologic studies have shown that habitual short sleep (<6 h per night) is associated with obesity,^{17,18} diabetes,^{18,19} hypertension,²⁰ cardiovascular disease,²¹ and all-cause mortality,^{22,23} stressing the importance of undisturbed sleep of sufficient length for health in general and cardiovascular health specifically. For these reasons, sleep disturbance is usually considered the most severe non-auditory effect of environmental noise exposure.^{24,25}

The Ascending Reticular Activating System is part of the body's arousal system. It receives input from several sensory systems (including the auditory) and relays this information, for instance, to cardio-respiratory brainstem networks and through the Thalamus to the Cortex. Thus, we recognize, evaluate, and react to environmental sounds even while asleep.²⁶ The Thalamus has a gating function, i.e. based on the sensory information and the current central nervous system state, information may be relayed to or withheld from the Cortex.²⁷ If the information is passed on to the Cortex, it may lead to a Cortical arousal, that, if the subject is sleeping, may disturb or fragment sleep. Therefore, the organism's reaction to noise is not based on an all-or-nothing principle (i.e. not every noise event will lead to a conscious awakening). Rather, the reaction is fine-graded ranging from an isolated vegetative reaction (e.g. increase in heart rate and blood pressure) to a full cortical arousal with regaining of waking consciousness that usually includes body movements. Cortical arousals are regularly associated with vegetative arousals, and stronger cortical activations are associated with longer and more severe vegetative activations.^{28,29}

Whether noise will induce an arousal and the degree of the arousal depends on the number of noise events and their acoustical characteristics,³⁰ but also on situational moderators (like current sleep stage³¹) and noise susceptibility of the exposed subject.²⁷ Repeated noise-induced arousals reduce sleep quality

through changes in sleep structure that includes delayed sleep onset and early awakenings, fewer deep and rapid eye movement sleep, and more time spent awake and in superficial sleep stages.^{30,31} Although these effects are not specific for noise,³² and usually less severe compared with clinical sleep disorders like obstructive sleep apnoea,³³ several laboratory and field studies unequivocally demonstrate that traffic noise causally disturbs sleep and, depending on noise levels, may impair performance, well-being and cardiovascular functions during the subsequent wake period.^{29,34–41}

Exposure–response relationships have associated several traffic noise sources (e.g. road, rail, and aircraft noise) with awakenings, briefer cortical arousals, and vegetative arousals in both laboratory and field settings. These functions usually show monotonously increasing reaction probabilities with increasing maximum sound pressure levels (SPL). In fact, maximum SPLs as low as L_{Amax} 33 dB have been shown to induce physiological reactions during sleep, i.e. once the organism is able to differentiate a noise event from the background, physiologic reactions can be expected (albeit with a low probability at low noise levels).³⁵ At the same maximum SPL, aircraft noise has been shown to be less likely to induce both cortical and vegetative arousals compared with road and rail traffic noise, which was partly explained by the frequency distribution, duration, and SPL rise time of the noise events.^{30,36} Of note, subjective feelings of annoyance follow a different pattern, with a less pronounced effect of railroad noise, and a more pronounced effect of aircraft noise at the same equivalent noise level (*Figure 1*).¹

Subjects exposed to noise usually habituate to the noise exposure. For example, the probability that noise causes physiologic reactions is in general higher during the first nights of a laboratory experiment compared with the last nights³⁰ and exposure–response relationships derived in the field (where subjects have often been exposed to the noise for many years) are usually much shallower than those derived in laboratory settings, which often include exposure to unfamiliar noise events in an unfamiliar environment.^{35,42} Habituation is a reasonable mechanism that preserves energy resources. However, habituation is not complete, i.e. subjects continue to react to noise events even after several years of noise exposure. Unfortunately, little is known about individual differences in the ability to habituate to noise and potential predictors. Importantly, activations of the vegetative nervous system have been shown to habituate to a much lesser degree to noise compared with cortical arousals.³⁰

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In a field study, nocturnal aircraft noise exposure played back with loudspeakers in the subjects' bedrooms was shown to dose dependently affect parameters of vascular function (*Figure 3*), including endothelial function as measured by flow-dependent dilation of the brachial artery. Although this study was limited to single-night exposures to different levels of noise, a priming effect of noise was detected, i.e. the effect of noise was more pronounced if the subject had previously been exposed to noise. As expected, the changes in arterial function were paralleled by increased catecholamine production and impaired sleep quality, but morning plasma levels of cortisol and inflammatory markers IL-6 and C-reactive protein were unaffected by noise exposure.

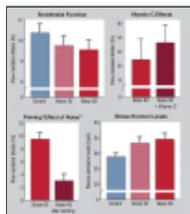


Figure 3

Effects of simulated aircraft noise (noise 30 and 60 reflecting 30 or 60 playback aircraft noise events) on endothelial function (as measured by flow-mediated dilation) and (lower right) stress hormone levels of healthy volunteers (adapted from Schmidt ...

These findings provide biologic plausibility for an association between nocturnal noise exposure and cardiovascular health. Increasingly, epidemiologic studies indicate that nocturnal noise exposure may be more relevant for cardiovascular health than day-time noise exposure (for a detailed discussion of

epidemiologic studies and both day- and night-time noise exposure, see below). For aircraft noise, the HYENA study ('Hypertension and Exposure to Noise near Airports') found no significant association for day-time noise, but a significant increase in blood pressure with increases in night noise.⁴³ Compatible with this evidence, it has been demonstrated that road traffic noise exposure has a larger impact in those who sleep with open windows or whose bedroom faces the road.⁴⁴ A sustained decrease in blood pressure during the night (so-called dipping) seems to be important for resetting the cardiovascular system and for long-term cardiovascular health.⁴⁵ Repeated nocturnal autonomic arousals may prevent blood pressure dipping and contribute to the risk for developing hypertension in those exposed to relevant levels of environmental noise for prolonged periods of time.^{46,47} In line with this, it was found that the risk to develop hypertension was higher in those sleeping with open windows during the night, but it was lower in those with sound insulation or where the bedroom was not facing the main road.⁴⁸ A recent Swiss study showed an adverse effect of railway noise on blood pressure, that was more strongly associated with night-time exposure.⁴⁹

The Night Noise Guidelines for Europe were published by the WHO in 2009 and constitute an expert consensus correlating four noise exposure ranges to negative health outcomes ranging from 'no substantial biological effects' to 'increased risk of cardiovascular disease'.⁵⁰ The WHO considers average nocturnal noise levels of $L_{Aeq, outside}$ 55 dB as an interim goal when the recommended guideline value of 40 dB is not feasible in the short term for the prevention of noise-induced health effects.

In sum, nocturnal noise has been shown to affect both autonomic regulation (via increases in heart rate mediated by sympathetic activation and/or parasympathetic withdrawal⁵¹⁻⁵³ and with increases in blood pressure⁵⁴) and, directly, vascular function through the induction of endothelial dysfunction. Importantly, both endothelial dysfunction and reduced heart rate variability have been demonstrated to have prognostic value in patients with peripheral artery disease, arterial hypertension, and patients with an acute coronary syndrome or chronic stable coronary artery disease.⁵⁵⁻⁵⁷ Taken together, these observations provide a biological rationale for the increased incidence of arterial hypertension, myocardial infarction, and stroke in subjects with long-term exposure to relevant noise levels as described in the following paragraphs.

Epidemiological studies

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Studies on chronic exposure to road traffic and/or railway or aircraft noise have reported a relationship with elevated blood pressure, hypertension or the use of antihypertensive medication, ischaemic heart disease including fatal myocardial infarction, stroke, dementia, and diabetes mellitus. Different study designs and methods for the assessment of the exposure, the disease, and potentially confounding factors were used. Based on these differences, the strength of the associations varies significantly across studies. Overall, however, studies demonstrate that environmental noise carries a health burden that has medical and economic implications: in the UK, day-time noise levels of ≥ 55 dB have been estimated to cause an additional 542 cases of hypertension-related myocardial infarction, 788 cases of stroke, and 1169 cases of dementia, with a cost valued at around £1.09 billion annually.⁵⁸

Road traffic noise, blood pressure, and hypertension

A meta-analysis of 24 cross-sectional studies on the relationship between road traffic noise and the prevalence of hypertension reported an odds ratio (OR) of 1.07 (95% confidence interval (CI) = 1.02–1.12, $P < 0.05$) per 10 dB increase of the 16-h day-time average road traffic noise level (L_{Aeq16h}) in the range of < 50 to > 75 dB.⁵⁹ A certain degree of heterogeneity among studies was detected with respect to age, gender, the way the exposure was assessed, the noise reference level used, and the duration of the exposure. For example, in the HYENA study, road traffic noise was linked to hypertension in men but not in women,⁴³ and in the Groningen study and the PREVENT cohort road traffic noise was

significantly associated with hypertension only in people aged 45–55 years.⁶⁰ Similarly, a significant higher systolic blood pressure per 10 dB increase of the road traffic noise level was found in middle-aged subjects participating in a large Danish cohort study, with stronger and significant associations in men and older subjects.⁶¹ In this study, road traffic noise was not associated with diastolic blood pressure or self-reported hypertension. Co-morbidity was also found to be an effect modifier of the association between road traffic noise and blood pressure readings. For example, in the SAPALDIA 2 study, this association was only found in diabetics.⁶²

Road traffic noise, coronary heart disease, and stroke

Road traffic noise was associated with myocardial infarction in case–control^{63–65} and cohort studies.^{66,67} The strength of this association increased when subjects with hearing impairment were excluded.

Of note, studies where no clear association was shown have also been published.^{44,69,70} A meta-analysis including four cohort and one case–control study on the relationship between road traffic noise and the incidence of hypertension reported an OR of 1.17 (CI = 0.87–1.57, $P = \text{n.s.}$) per 10 dB increase of the 16-h average road traffic noise level (L_{Aeq16h}) in the range of <60 to >75 dB.⁶⁸ An updated meta-analysis of 12 studies (17 individual estimates, submitted for publication) reports an OR of 1.08 (95% CI = 1.04–1.13, $P < 0.05$) per 10 dB increase of the weighted day–night-noise level L_{DN} within the range of 50–75 dB.⁷¹ While the older meta-analyses referred to noise levels from <60 to >75 dB, this more recent one refers to noise levels between <55 and >75 dB. Taken together, these data suggest that the exposure to sounds in the range between 55 and 60 dB, which would include large fractions of the population, may also contribute to the burden of disease.

Finally, exposure to residential road traffic noise was associated with a higher risk for stroke among people older than 64.5 years of age, showing a risk increase per 10 dB increase of the noise level (L_{DEN}) (incidence rate ratio = 1.27, CI = 1.13–1.43, $P < 0.0001$).⁷² In sum, given the ubiquitous exposure, road traffic noise should be considered a relevant risk factor for cardiovascular disease.

Railway noise

Railway noise has not been studied as much as noise from other transportation means in epidemiological studies. In the Danish cohort study mentioned above, a non-significantly higher risk was found in subjects that lived in areas where the cumulative noise level (railway + road) L_{DEN} exceeded 60 dB.⁶¹ In the Swiss SALPADIA 2 study, railway noise, particularly during the night, was found to be significantly associated with systolic (0.84 mmHg, CI = 0.22–1.46 mmHg per 10 dB increase (L_{DEN}), $P < 0.01$) and diastolic blood pressure (0.44 mmHg, CI = 0.06–0.81 mmHg; $P < 0.05$) readings of the study subjects.⁶² With respect to self-reported doctor's diagnosis of cardiovascular diseases, a borderline significant increase of risk was found in subjects exposed to railway noise levels (L_{DEN}) of 50 dB and more (OR = 1.55, 95% CI = 1.00–2.40; $P < 0.10$).⁷³

Aircraft noise

Several studies within the last 10 years demonstrate a higher prevalence of annoyance, cardiovascular disease, or medication intake in persons exposed to aircraft noise.

Aircraft noise and arterial hypertension

In 2001, an increased prevalence of arterial hypertension in the vicinity of Stockholm airport was reported.⁷⁴ Similarly, a dose–response relationship has been shown in the HYENA study with respect to night-time noise.⁴³ A 14% increase in OR (CI = 1.01–1.29; $P < 0.05$) for arterial hypertension was in

this study associated with every 10 dB increase in L_{night} ; in contrast, no effect was found for day-time aircraft noise exposure (L_{Aeq} : OR = 0.93, CI = 0.83–1.04; $P = \text{n.s.}$). Data from the European Union-funded RANCH (Road Traffic and Aircraft Noise Exposure and Children's Cognition and Health) study reported an association between both day-time and nocturnal noise exposure at home and blood pressure values in 9- to 10-year-old children living near Schiphol (Amsterdam) or Heathrow (London).⁷⁵ A meta-analysis of four cross-sectional and one cohort study on the relationship between air traffic noise and the prevalence of hypertension reported an OR of 1.13 (CI = 1.00–1.28; $P < 0.05$) per 10 dB increase of the day–night weighted noise level (L_{DN}) in the range of <55 to >65 dB.⁷⁶

Studies carried out repeatedly in the area neighbouring Amsterdam's Schiphol airport reported a higher prevalence of prescriptions for cardiovascular medications (OR ranging between 1.2 and 1.4 between high and low noise groups).⁷⁷ Likewise, a cross-sectional study from the Cologne airport region in Germany demonstrated higher individual rates of cardiovascular medicine prescriptions in residents exposed to high aircraft noise levels, particularly during the night and the early morning hours (3–5 h).⁷⁸ Higher risks were found for subjects for whom the average noise level during the late night period exceeded 40 dB. Results from the HYENA study also suggest an effect of aircraft noise on the use of antihypertensive medication, but this effect did not hold for all participating study centers.⁷⁹ Results were more consistent across centres for the increased use of anxiolytics in relation to aircraft noise.⁷⁹

Aircraft noise and coronary heart disease

The relationship between aircraft noise and coronary heart disease is less well investigated so far. Earlier studies carried out around Amsterdam's Schiphol airport gave some hints of a higher risk of cardiovascular disorders in subjects that lived closer to the airport.^{80,81} More recent studies, however, provided evidence of a higher cardiovascular risk for subjects who reside near airports. In an ecological study carried out around Heathrow airport, London, an increased risk of stroke and coronary heart disease was reported in relation to day- and night-time exposure to aircraft noise in people that were more exposed to aircraft noise than others.⁸² This exposure-dependent relationship was adjusted for aggregated data regarding ethnicity, social deprivation, incidence of lung cancer as a proxy for smoking, road traffic noise exposure, and air pollution. In another new census-block-based ecological study carried out ~89 North American airports using hospital admission registry data, it was found that persons living in areas at the 90th percentile of noise exposure among census blocks within zip codes had a higher risk of hospitalization for ischaemic heart disease and cerebrovascular disease. The results were adjusted for age, sex, and race as well as area level of socioeconomic status and ethnicity.⁸³

A large cohort study in Switzerland reported an increased mortality due to myocardial infarction with increasing exposure levels and duration of aircraft noise, with a non-significant hazard ratio of 1.3 when persons exposed to noise levels ($L_{\text{DN}} \geq 60$ dB) compared with those exposed to <45 dB after adjustment for several individual and geographical variables, including air pollution. As mentioned above, this hazard ratio increased to 1.5 (CI = 1.0–2.2; $P < 0.10$) and was significant when only residents exposed to noise for at least 15 years were included.⁸⁴ In contrast, none of the other endpoints, including all-cause mortality, cerebrovascular disease, and stroke, was associated with aircraft noise. Furthermore, with increasing exposure to noise, the proportion of persons with tertiary education declined, whereas the proportion unemployed, the proportion of foreign nationals, and the proportion of people living in old and unrenovated buildings increased. Finally, in the cross-sectional HYENA study an association between (self-reported) heart disease or stroke (combined endpoint) and nocturnal aircraft noise was described.⁸⁵ The association was particularly strong in subjects that had lived in the same place for ≥ 20 years. An OR of 1.25 (CI = 1.03–1.51; $P < 0.05$) per 10 dB increase of the night-noise level (L_{Night}) was found.

Limitations of research in the area of environmental noise

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A number of factors may modify the impact of noise on health. These include exposure-modifying factors such as the location of rooms and the quality of sound insulation, the habit to sleep with open or closed windows and length of residence and other behavioural risk factors. Most of the epidemiological studies controlled their results for a basic set of potentially confounding factors such as age, gender, socioeconomic status, smoking, body mass index, physical activity, alcohol intake, and/or ethnicity. Particularly, those studies where the subjects are actually seen provide a lot of additional information based on clinical interviews. However, response rates are sometimes low, which implies a possible selection bias. Ecological and other studies using health registries, on the other hand, do not suffer from the problem of low response rates, but individual data regarding personal risk factors are often missing. Since many behavioural risk factors that are related with worse health outcomes are correlated with socioeconomic status, they can partly be controlled. Aggregated indices of areal deprivation and socioeconomic status may serve as surrogates if individual data are not available. The fact that noise effects were seen when different methods and study types were applied supports the reasoning for an association. For example, cohort and case-control studies have a high analytic power, but observational cross-sectional studies may also provide information on relationships. Differences in study type (prospective, case-control, cross-sectional, ecologic) and the degree and quality of adjustment for confounding (i.e. residual confounding) may explain some of the discrepancies found between individual epidemiological studies. The fact that studies often only find noise associations with some but not all of their cardiovascular endpoints, and that not everybody will be affected (e.g. only men, only those within a certain age range) stresses the need to further investigate the exact mechanisms of how noise affects the cardiovascular system and why some are more susceptible than others. Of note, the question of 'what comes first' (temporality) may be easier to address with regards to noise epidemiology as compared with other associations between suspected risk factors and disease prevalence as it is unlikely that the decision to relocate to noisier areas might be determined by the presence of a disease.

There is evidence that ambient particle concentrations are also associated with the incidence of cardiovascular diseases.⁸⁶ The potential confounding effect of air pollution was therefore considered in more recent studies, and, given the stronger association with air pollution, particularly in road traffic noise studies. Complicating these considerations, however, adjustment for air pollution indicators in multivariable statistical models is complex because modelled indicators of both exposures refer to the same input data (e.g. traffic volume and composition, traffic flow and speed, proximity to the road). It is an advantage of noise assessment that meteorology plays less of a role compared with air pollution within urban distances where houses are close to the streets. The fact that noise effects are also seen for noise sources other than road traffic (e.g. aircraft noise, railway noise, occupational noise that do not contribute as much to the air pollution exposure of the dwellings where the people live) supports the concept of an independent effect of noise. This is addressed in the present issue of the European Heart Journal.⁸⁷ Using data from the German Heinz Nixdorf Recall Study, a population-based cohort study, the authors have demonstrated independent associations of long-term exposure to both fine particulate matter (PM) and road traffic noise with thoracic aortic calcification, a reliable measure of subclinical atherosclerosis.⁸⁷ In this study, PM_{2.5} (PM with an aerodynamic diameter $\leq 2.5 \mu\text{m}$) and L_{night} (average level of nocturnal noise), but not L_{DEN} , were associated with an increasing coronary calcification-burden, and the association remained valid after mutual adjustment. The authors concluded that long-term exposure to fine PM and night-time traffic noise are both independently associated with subclinical atherosclerosis and may both contribute to the association between road traffic and coronary artery disease. In a recent systematic review, it was concluded that confounding of cardiovascular effects by noise or air pollutants was low,⁸⁸ even though this may have to do with the quality of the assessment methods of air pollutants.

Regarding effect modification, the studies showed a tendency towards stronger effects in middle-aged subjects and a tendency towards stronger effects in males. However, this was not consistent across

studies. Furthermore, pre-existing co-morbidity was also found to be an effect modifying factor. Finally, a cumulative effect of noise from multiple sources of noise (e.g. work and traffic noise) has been shown.^{89,90}

Conclusions

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Taken together, the present review provides evidence that noise not only causes annoyance, sleep disturbance, or reductions in quality of life, but also contributes to a higher prevalence of the most important cardiovascular risk factor arterial hypertension and the incidence of cardiovascular diseases. The evidence supporting such contention is based on an established rationale supported by experimental laboratory and observational field studies, and a number of epidemiological studies. Meta-analyses have been carried out to derive exposure–response relationships that can be used for quantitative health impact assessments.⁹¹ Noise-induced sleep disturbance constitutes an important mechanism on the pathway from chronic noise exposure to the development of adverse health effects. The results call for more initiatives aimed at reducing environmental noise exposure levels to promote cardiovascular and public health. Recent studies indicate that people's attitude and awareness in particular towards aircraft noise has changed over the years.^{92,93} Noise mitigation policies have to consider the medical implications of environmental noise exposure. Noise mitigation strategies to improve public health include noise reduction at the source, active noise control (e.g. noise-optimized take-off and approach procedures), optimized traffic operations (including traffic curfews), better infrastructural planning, better sound insulation in situations where other options are not feasible, and adequate limit values.

Funding

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Conflict of interest: none declared.

Supplementary Material

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Supplementary Data:

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