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How can we plan for a good urban sound environment, focusing on road traffic noise?

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Abstract. Introduction. The sound environments in our cities are affected by unwanted sounds, i.e. noise, to an extent that is largely undesired, affecting health and wellbeing. The World Health Organization (WHO) has estimated the burden of disease from traffic-related noise within the western part of Europe and concluded that we each year lose at least one million disability-adjusted life years (DALYs) and that only air pollution has a larger disease burden among environmental factors. The burden of environmental noise is mainly sleep disturbance and annoyance. And the dominant source is road traffic.

Methods. This paper describes the mechanisms behind road traffic noise and how we can use them in an urban sound planning perspective to improve the sound environment, as an integral part of sustainable cities and communities. The results are based on calculations and measurements made in previous and ongoing projects.

Results. Treatments at source consider tyre, road, engine (whether electric or combustion), driving speed and acceleration, and further vehicle restrictions. Methods for reduction of noise during propagation and more general urban planning aspects include low-height barriers and ground treatments; acoustically absorbing facades and roofs of buildings, e.g. including vegetation; and building morphology and quiet side. Quantitative reductions, in decibels, as well as qualitative aspects are presented.

Conclusions. The described possible improvements to the urban sound environment, with focus on road traffic noise as the dominant impairing factor, inform us about how a good urban sound environment can be reachable. However, to reach a good sound environment in reality, the work process of applied urban sound planning demands work across disciplines, also at early-stage planning, instead of traditional noise control applied late in the planning process.

1. Introduction

There is evidence from large-scale epidemiological studies that environmental noise adversely effects human health and wellbeing [1]. The World Health Organization (WHO) has estimated the burden of traffic-related disease in the EU as a yearly loss of 1.6 million disability-adjusted life years (DALYs). This translates into a per capita loss of 1–2 days per year, and it is claimed that only air pollution imposes a larger disease burden. The largest adverse effects of traffic noise are sleep disturbance and annoyance. The dominant noise source is road traffic, which impacts on 54% of the EU population living in agglomerations with an average estimated noise exposure of $L_{den} \geq 55$ dB outside their homes. For rail and air traffic noise, the corresponding percentages are 8% and 4%, respectively [2]. The recent WHO Environmental Noise Guidelines for the European Region recommends that the day-evening-night noise level from road traffic should be below 53 dB [3].

Making sufficient improvement requires the consideration of all available tools. We need to mix classical and novel noise control engineering approaches and exploit the benefits of soundscaping. Reducing noise emissions from road vehicles is difficult and time-consuming for engineering and political reasons (e.g., [4]), which is why noise problems have to be addressed by measures on both the emission (source) and immission (receiver) sides. In addition, the large-scale and long-term perspectives on urban and rural planning must be improved to avoid unnecessarily damaging the sound environments and to enable cost-effective abatement measures. In this paper we present and describe the mechanisms behind road traffic noise and how we can use them within urban planning to improve the sound environment. The results originate from previous and ongoing projects involving numerical predictions, measurements and workshops.

An improvement of the urban acoustic environment is linked with the United Nations Sustainable Development Goals, mainly *Sustainable cities and communities* (Goal 11), for which targets for year 2030 include to reduce the adverse per capita environmental impact of cities and to provide universal access to safe, inclusive and accessible, green and public spaces [5]. Green and other public spaces demand sufficiently low noise levels to provide the desired function.

The structure of the paper is as follows. The noise generation mechanisms of road vehicles are introduced including ways to mitigate at source, followed by an overview of outdoor sound propagation effects including methods and modelling. Temporal and spectral characters of the acoustic environment and their weak links with single-number noise indicators are then brought to attention. The results section presents a large set of tools for improving the acoustic environment as well as exemplifies a holistic urban sound planning workshop.

2. Generation and propagation of sound

2.1. Principles of noise reduction

The level of noise reaching a recipient is determined by two main factors: the strength of the source and the path of propagation. To abate traffic noise in general, we need to address both factors, that is, on both the emission side (i.e., the source strength) and the immission side (i.e., noise reduction during propagation).

2.2. Introduction to the noise generation mechanisms and ways to mitigate at source

First, we should reduce the noise emission as much as is feasible. For road vehicles, the noise sources are of two main types: traction sources, originating from the tyre–road contact, and propulsion sources, originating from the engine and transmission and, for combustion engines, also from the exhaust system, air intake, fans, generators, and other auxiliary systems. There is also aerodynamic noise, which usually become dominant at higher driving speeds. The noise emissions of road vehicles can generally be seen as a problem for which three parties are responsible: the road vehicle industry, the tyre industry, and the road owners. Propulsion noise is linked mainly to the vehicle industry, whereas the traction noise is shared between the three parties.

For light vehicles, traction noise dominates above 30 km/h, whereas for heavy vehicles the transition occurs at approximately 70 km/h depending on the assumed number of wheel axles. (This can be estimated from the model as formulated in the European joint research initiative CNOSSOS-EU [6].) It should be noted that these are average results. For example, accelerating vehicles or uphill driving leads to increased propulsion noise, whereas the use of road surfaces with smaller stone sizes or porous surfaces leads to reduced traction noise. In addition, individual vehicles and driving styles lead to different results. Concerning use of electric engines, it would not make a large noise reduction for light vehicles (estimated to less than 3 dB at 30 km/h, ca 1 dB at 50 km/h, and further decreasing with speed [7]), whereas for heavy vehicles, the improvement would be substantial due to the stronger propulsion sound relative to the traction sound: ca 10 dB at 30 km/h, ca 5 dB at 50 km/h, and further decreasing with speed [7].

Due to the spectral and time pattern characteristics, propulsion sound may be audible even when traction sound dominates the A-weighted level. The performance of many noise abatement methods, including facade insulation, is normally better at higher than lower frequencies, meaning that the noise remaining after abatement is often more characterised by low-frequency sound (i.e., an increased proportion of propulsion noise sources).

For propulsion sources, possible methods of abating noise emissions include improved shielding of engine and power transmission (most relevant for heavy vehicles), improved sealing of engine bay, reduced maximum engine power, and improved mufflers to reduce noise from air intake and exhaust systems. In addition, the enforcement of using legal exhaust systems could be strengthened, also of relevance for mopeds and motorcycles.

Methods for reducing traction noise originating from tyres include developing less noisy tyres for lower maximum speeds (e.g., 150 km/h), in a combined effort including low rolling resistance, which would reduce fuel consumption. To reduce traction noise originating from roads, measures involve: quality control of newly laid surfaces, monitoring road pavement surfaces, optimising road texture, using smaller stones (especially relevant in Nordic countries), and using thin porous layer or open porous asphalt (single or double layer).

Appropriate test methods and politically determined limit values could push the development of quieter vehicles. Other political instruments can influence the market, e.g., encouraging the use of quieter vehicles and tyres. In addition, the purchase of vehicles (e.g., passenger cars, buses, trucks, and trams) by municipal and national governments could be more strongly guided by noise emission limit values.

2.3. Overview of outdoor sound propagation effects

As sound propagates outdoors from a source, the sound level at the receiver is determined by: the distance between source and receiver, the properties of the medium in which the sound propagates (our atmosphere), and the properties of the boundary, i.e., the ground material and profile, including obstacles like noise barriers, buildings, etc.

Distance

In free space, sound from a point source spreads spherically and decays by 6 dB with each doubling of the distance from the source, whereas sound from a line source spreads cylindrically and decays by 3 dB per distance doubling. Predictions of the maximum sound levels of road traffic noise are based on a single vehicle as the noise source, whereas predictions of the average, or equivalent, sound level (e.g., L_{den} and $L_{Aeq,24h}$, in which time-averaged energy is used) assume the whole length of the road to be the source. Therefore, the maximum noise level decays by 6 dB per doubling of distance from the road, whereas the equivalent level decays by 3 dB per distance doubling, assuming a long straight road, constant influence from the ground and insignificant influence of wind and other environmental factors. In general, when making noise-mapping calculations, the whole traffic network has to be considered along with the existing propagation conditions, sometimes including local meteorological statistics.

Medium

The acoustic properties of the noise propagation medium, air, relate to meteorological conditions such as wind speed and temperature. The largest effects of such factors occur when they lead to refraction, that is, the curving of sound paths. The degree of refraction is determined by the wind speed profile and the temperature variation with height, and the effect usually increases with propagation distance. As a result of downward curving, which may occur in the case of downwind sound propagation (i.e., wind blowing from the direction of the sound source and toward the receiver) or temperature inversion (i.e., increasing temperature with height), the noise levels may *increase* substantially. Upward curving, e.g., under headwind conditions, may greatly *reduce* levels compared with situations without such refraction.

In the engineering prediction model resulting from the HARMONOISE and IMAGINE projects, combinations of linear and logarithmic sound speed profiles are used to model different meteorological situations, divided into five wind speed classes and five stability classes (determined by cloud cover and time of day) [8]. As a result of that project work, and other studies, it can be concluded that refraction may significantly affect traffic noise even at medium propagation ranges [9]. At a distance of 40 m from a motorway, the predicted effect may be negligible, whereas at a distance of 160 m, the A-weighted sound level was predicted to increase by approximately 2–3 dB(A) under downwind conditions and to decrease by at most 9 dB(A) under upwind conditions, for wind speed class 3 (3–6 m/s wind at a height of 10 m), with reference to wind speed class 1 (0–1 m/s wind at a height of 10 m) and stability class 3 (under cloudy daytime conditions). At a distance of 320 m, an increase of at most 7 dB(A) and a decrease of at most 13 dB(A) were predicted using the same reference conditions. The results from a corresponding measurement campaign were used to validate the model development, indicating good overall agreement [10]. Temperature and humidity (and static pressure, to a smaller extent) influence the degree of air attenuation, i.e., the molecular absorption of sound during its propagation. The effect of air attenuation increases with distance and is of importance mainly at high frequencies. This can be heard e.g. when a thunderstorm is passing by: at longer distance, the lightning makes a booming (low-frequent) sound, whereas, at shorter distances, the sound is more sparking with a spectrum less dominated by low frequencies. Atmospheric turbulence, in the form of random fluctuations in wind velocity and temperature, distorts the sound waves. The effects can be seen as the scattering of sound into shadow regions and the reduced strength of both positive and negative interference. These effects are important mainly at high frequencies.

Boundary

In flat terrain, both direct sound from the source and ground-reflected sound can reach the receiver. The effect of the interaction between direct and reflected sound is called interference pattern or ground effect. At some frequencies, direct and reflected sound partly cancel each other out (*negative interference*), which causes the sound level to be lower than in absence of the ground. At other frequencies, the two sound waves reinforce each other (*positive interference*), making the level higher than without ground. For traffic noise propagating above dense asphalt, or other acoustically hard ground, the two sound waves added together will normally lead to a larger single-number noise level. However, above an acoustically soft ground, such as a lawn, the two waves may cancel each other out over a relatively broad frequency range, resulting in a lower noise level than without ground. At higher frequencies, the coherence between direct and reflected sound normally declines toward a purely energetic summation of the two contributions, for example, due to the effects of turbulence or of random ground roughness.

For conventional noise barriers, the height is the primary property, assuming the sound transmission through or around the sides of the barrier to be negligible. The insertion loss is low at low frequencies and increases with frequency. At higher frequencies, it tends to increase by 3 dB per doubling of frequency. At lower frequencies, the dependence on screen height is weaker than at higher frequencies. In real situations, the insertion loss can be reduced depending on meteorological conditions, mainly downward refraction under downwind propagation conditions and scattering by turbulence at higher frequencies.

If the top of the barrier is widened, the acoustic effect will be further improved. Concerning the barrier location, better performance is generally achieved if the barrier is placed near the source or near the receiver. In an inner-city environment, it may therefore be preferable to use noise barriers of a relatively low height if they can be located near the traffic sources. To further improve the performance of such barriers, their width can be increased and the materials on their top and faces be carefully chosen. The materials should be acoustically soft (e.g., porous), and in urban environments, characterised by multiple sound reflections, it is especially important to choose sound absorbing materials. In general, significant reflection can occur from the facades in street canyons, from the faces of noise barriers, and in vehicle bodies, particularly for large heavy road vehicles and rail vehicles.

In general, urban planning greatly affects noise exposure by addressing the placement and regulation of surface transport in connection with building form and function. As shown below, roof and facade treatments are used to reduce the noise level in shielded areas such as inner yards, which may lead to annoyance reduction by applying the *quiet side* concept to dwellings. Methods that act on the boundary include softening hard ground, roughening flat ground, appropriate barrier design, and using acoustically absorbent materials, such as vegetation substrate, on barriers, facades, and roofs. In noise-mapping calculations, all the above propagation effects could potentially be considered, and the effects of noise barriers, ground type, and terrain profile could be estimated. However, the simplifications made in current noise-mapping methods mean that the acoustic effects of many of the abatement tools presented here are not evident. Thereby there is a potential for improvement of noise-mapping methods. More advanced numerical modelling apply methods like the parabolic equations method (PE), the fast field program (FFP), finite-difference time-domain (FD-TD), or finite elements (for further reading, see e.g., [11]).

3. Methods and tools for a good urban sound environment

3.1. Noise indicators

To estimate the effects on health and wellbeing of various abatement measures, we need to keep in mind that single value noise levels are indicators with limited precision. Two different sound environments, for example, hearing a distant motorway or a nearby urban road, may correspond to the same L_{den} value. In addition, even for the same sound, the response varies between individuals. Different temporal patterns play a role as do the spectral characteristics, for example, the low-frequency booming character in the shadow of a noise barrier compared with the brighter direct sound of a nearby vehicle.

For instance, using a general relationship between reduction in A-weighted noise level and perceived improvement usually overestimates the perceived benefit of a noise barrier, but can underestimate the perceived benefit of abating high-frequency noise from a tramway [12]. Furthermore, in the case of facade insulation, the noise blocked by a barrier will not be reduced by as many dB(A) as will an unblocked noise transmitted through a window, due to the low-frequency shift caused by the barrier.

When examining perceived annoyance, it is of interest to consider the above aspects together with background sounds. Sounds from fountains and singing birds are typically perceived as positive and may improve the perceived soundscape (e.g. [13, Ch. 10]). The temporal character is important also since it influences sleep disturbance, which is strongly related to the number of events (e.g., car pass-bys) ([14]).

If many abatement tools are used at the same time, their individual single number effects in dB(A) cannot always be summed to predict the total effect. Additivity holds strictly only when the individual effects are the same at all frequencies. It is usually easier to reduce the higher frequencies in noise using passive methods for absorption or reducing transmission. To abate the lower-frequency components, larger devices are usually needed, or one might use resonant absorbers or even active elements such as shakers and loudspeakers.

3.2. Noise reduction tools

The set of tools presented here, for improving the urban sound environment, include quantitative reductions and qualitative aspects when relevant.

Traffic changes

In addition to the abatements at source, as presented above, the emitted sound can be altered by changing the traffic, as follows.

- By regulating vehicle access to selected areas (e.g., environmental zones), not allowing loud vehicles (currently aimed to heavy vehicles), or allowing them only during certain hours.
- By lowering the speed limit. (For example, a speed reduction from 70 to 60 km/h gives about 2 dB, from 60 to 50 km/h gives about 2 dB, and from 50 to 40 km/h gives about 1–2 dB, depending e.g. on traffic composition.)
- By calming the traffic and affecting driving behaviour, e.g. by changing the street space, reducing acceleration (reduce stop-and-go behaviour).
- By routing. When moving large parts of the traffic flows from interior streets of an area to a few streets at the outer edges of the area, a majority of the area will become much quieter and a smaller part of the area will become louder.

Noise reduction during propagation, including building morphology

The list below contains a selection of tools for reducing urban road noise during propagation. Further descriptions can be found in the respective references, including methods of validation (numerical, by measurements, or both).

- Acoustically absorbing facades in street canyons to reduce inner yard noise. Noise reduction from circa 4 dB in adjacent shielded inner yards (strongly dependent on reference condition) [15, 12, 16].
- Street canyon noise reduction using acoustically absorbing facades. Noise reduction circa 2–3 dB (limited due to direct sound from vehicles) [15, 12, 16].
- Acoustically absorbing roofs (e.g. green roofs). Noise reduction from circa 3 dB in shielded inner yards [15, 12, 16].
- Ground roughness elements placed on hard ground. Noise reduction from circa 4 dB (circa 2 m wide and 0.3 m tall) [15, 12, 16].
- Acoustically soft ground, e.g. a grass lawn. Noise reduction from circa 5 dB at 50 m distance. (Thicker porous layer improves acoustic performance.) [15, 12, 16]
- Building morphology, creating shielded side of dwellings. Noise reduction circa 20 dB (largely depending of geometry) [17].
- Urban acoustic screens of lower height, e.g. 1–1.4 m tall, with acoustically soft and absorbing surfaces, can be designed to be architecturally more acceptable than traditional noise barriers. Noise reduction from circa 4 dB. [18, 16] (Figure 1.)

In addition, tunnels may effectively shield road traffic noise; however, special care is needed for the relatively high sound power of the tunnel openings. It should also be noted that the use of shrubs and bushes is not judged to be a largely reliable or effective method; a few decibel of noise reduction can be attained, whereof a large part is due to an acoustically soft ground [16]. Also, the effect of trees in a street canyon is expected be very limited in most cases.

3.3. Work across disciplines

One of the main challenges when working with any environmental issue that has an impact on the built environment is the work across disciplines at the early stage of the planning process. Environmental concern, especially noise, is often considered when problems and complaints appear. At this stage, solutions may be very costly.

One effective way to avoid these late and often failed interventions is to have efficient policies, capable to embrace the work across disciplines. Experience from a recent project (SONORUS

Figure 1. Illustration example for use of an urban acoustic screen. (Illustrator Tove Hennix.)

– Urban Sound Planner [19]) has taught us that the holistic approach capable to include sound into the urban planning process is not a reality, and a lot of effort is still needed. A positive way to work which may increase the chances of success, is to include workshops where relevant stakeholders sit together, gathering different working groups including people from the city municipality, university, general public, experts and associations. Workshops following these ideas were carried out through the different study cases in the SONORUS project, demonstrating relevant and positive outcomes, with creative solutions and different perspectives, which can be used in the further planning.

The urban sound planning workshops were organised by the local university partner, together with the local municipality. They consisted mainly of four parts: (1) Introductory information, (2) Visit to the site, (3) Workshop, and (4) Presentation and outcome. The introduction and visit to the site were made in conjunction with the workshop or in advance. Representatives of the working groups from the municipality formed the workshop together with the SONORUS project students and their supervisors and other partners from the project. For example, in the case of the Frihamnen workshop, representatives from the City's working group of Frihamnen presented the project, explaining the current situation, expectations, possibilities, constraints, etc. (Frihamnen is a development area in Gothenburg, Sweden.) After this, the working group on Frihamnen within SONORUS presented their view on the project. A session followed with brainstorming, sketching, debating and looking for solutions and improvements of the urban sound planning. The workshop ended with group presentations and discussions in plenum, from which the outcomes could be used by the city.

4. Discussion

Urban sound planning applied early in the planning process will not necessarily lead to higher costs. Rather, the societal costs of the noise may become much lower at the same time as the construction costs can be kept reasonable. Construction costs due to noise interventions late in the process can become very costly.

Concerning planning for the future, it seems likely that the demand for mobility will persist. Linked with modes of transport, using aircraft, trains, buses, cars, pods, etc., there will be sounds, which we would want to keep in control. It should be pointed out that also electric vehicles can cause large noise exposure. As shown, for passenger cars at driving speeds of circa 30 km/h or more, the dominating noise comes from the traction (i.e., tyre–road noise), irrespective of the engine being of electric or combustion type. (Also, for quiet vehicles at low speed, e.g. electric vehicles, artificial sound is now being added for safety reasons, so-called Acoustic Vehicle Alerting System, AVAS.) Furthermore, as stated by the European Environment Agency: "Efforts to reduce environmental noise tend to be offset by an increase in the number of people being exposed to high noise levels, in particular due to increasing road and aviation traffic, and an increase in the number of city inhabitants." [20]

There are however significant win-win possibilities for health, climate and environment including noise, as stated by WHO International: ”Well-designed transport policies and infrastructure investment priorities can lead to far-reaching reductions in traffic-related health risks from air pollution, noise stressors and injuries, while reducing climate-forcing greenhouse gas emissions [21].”

5. Conclusions

The described possible improvements to the urban sound environment, with focus on road traffic noise as the dominant impairing factor, inform us about how a good urban sound environment can be reachable. However, to reach a good sound environment in reality, the process of applied urban sound planning demands work across disciplines, also at early-stage planning, instead of traditional noise control applied late in the planning process.

The improvement tools described here – well-known as well as more novel and innovative – are scalable, enabling a large positive impact on our sound environment, reducing the noise exposure and thereby its negative effects on our health and wellbeing.

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