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Towards biodiversity-aware road traffic noise mitigation measures

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Abstract

Environmental noise of anthropogenic origin is increasingly recognized as a major threat to biodiversity in natural areas. These areas are often intersected by major highways, exposing large adjacent zones to road traffic noise. Current knowledge and guidelines on traffic noise mitigation are largely focused on human listeners. However, road traffic noise, outdoor sound propagation, mitigation measures, and auditory sensitivity of terrestrial animals are all strongly frequency dependent. As a result, their combined effect on animal sound exposure is far from straightforward. In this simulation study, the Harmonoise point-to-point propagation model, well suited to capture the complex sound propagation physics in natural environments, was used to predict road traffic noise exposure for terrestrial animals with diverse hearing threshold spectra. Energy-normalized reciprocals of these hearing thresholds were applied as species-specific weighting curves to calculate total noise exposure. The simulations suggest that the effectiveness of propagation-based mitigation measures, including noise screens, berms, and landscape undulations, can vary strongly among species and may therefore be tailored to conservation targets. Receiver distance from the road and receiver height emerged as key determinants of mitigation performance. In contrast, source-oriented measures such as speed reduction, truck ban, and low-noise road surface showed substantially less variation in effectiveness across species and receiver locations.

Keywords: *environmental noise, road traffic noise, outdoor sound propagation, bio-acoustics.*

1. Introduction

Anthropogenic noise is increasingly recognized as an important environmental stressor affecting terrestrial wildlife [1], [2]. As sound is fundamental to communication, predator avoidance, prey detection, navigation, and reproduction in many species [3], noise pollution can disrupt essential biological processes. Consequently, environmental noise is considered a contributing factor to ongoing biodiversity decline [4].

Although the adverse effects of anthropogenic noise on animals are becoming increasingly well documented, little is known about how commonly applied noise mitigation measures affect specific species or groups of species. Such knowledge is essential, as the effectiveness of a mitigation measure may strongly depend on the alignment between its spectral attenuation characteristics and the hearing sensitivity of the species of interest. A mismatch between these two may render noise abatements largely ineffective from an ecological perspective. Current environmental noise management remains strongly human-centric, relying predominantly on human loudness perception (or its A-weighted proxy) and human activity patterns, as reflected in indicators such as the day-evening-night equivalent sound pressure level L_{den} [5].

In this work, we initiate research into species-specific effectiveness of environmental noise mitigation through a simulation study involving a major highway intersecting a natural area. The impact of road traffic noise and various abatement measures is evaluated for a range of animal species along a transect perpendicular to the road.

Animal hearing exhibits remarkable diversity in spectral sensitivity. Following the prevailing focus on loudness-based environmental noise assessment, we use species-specific hearing thresholds as a first-order indicator of potential noise impact, while acknowledging that ecological responses to noise are often more complex.

Assessing such impacts is challenging because not only animal hearing, but also road traffic noise generation, sound propagation, and noise mitigation measures are all strongly frequency dependent.

Road traffic noise consists of both higher-frequency rolling noise and lower-frequency propulsion noise, with their relative contributions depending on vehicle type and speed [6].

Sound propagation phenomena, including atmospheric absorption and ground effects, are likewise strongly frequency dependent [7], [8]. Many terrestrial animals

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occur close to the ground, where interactions with undulating and porous soils can lead to phenomena such as diffraction-assisted ground effects [8], complicating accurate predictions. In contrast, flying species may experience noise exposure at substantially higher elevations within the atmospheric boundary layer, where geometrical divergence and atmospheric absorption might be the dominant effects.
Common mitigation measures, such as noise screens, are generally most effective at higher frequencies and provide considerably less attenuation at low frequencies. Integrating these multiple and interacting frequency dependencies is therefore essential for ecological noise impact assessment, yet remains far from straightforward. Consequently, existing knowledge and guidelines for road traffic noise mitigation, which have largely been developed from a human-centric perspective, cannot be directly translated to biological impact assessments.

2. Simulation study

In this work, noise mitigation efficiency is defined as the exposure in a reference situation, minus the exposure once a specific abatement measure is deployed, at exactly the same receiver location, and will be further called insertion loss.

2.1 Environmental geometry

The reference situation (see Fig. 1) consists of a 6-lane highway with a 4-m wide central reservation. The highway is bordered by flat grassland. A straight road segment of 6 km has been considered, while the receiver line extends up to 1 km normal to the border of the road, at fixed receiver heights of 0.5 m, 5 m and 50 m (relative to the local ground).

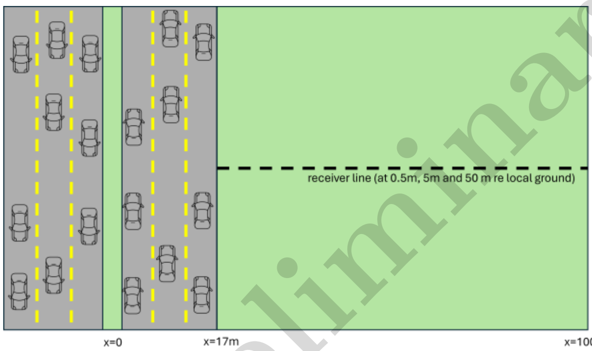

Figure 1. Road traffic noise configuration under study (plan view, not true to scale).

2.2 Road traffic source power model

The Harmonoise/Imagine road traffic source model [9] was used to calculate vehicle sound power emission. In the reference scenario, traffic intensity was set to 1000 vehicles/h per lane, with 20% heavy vehicles and a uniform speed of 120 km/h under steady-flow conditions. The Harmonoise/Imagine reference road surface [9] was assumed, representing acoustic characteristics intermediate between DAC-11 (Dense Asphalt Concrete with 0–11 mm aggregate size) and SMA-11 (Stone Mastic Asphalt).

2.3 Sound propagation model

Sound propagation was modelled using the Harmonoise point-to-point (HP2P) model [10], which is well suited for acoustically complex natural environments. This forward-propagation model connects each road segment and lane to each receiver position using a 2.5-D approach based on the concept of “propagation planes”. Ground impedance modelling accounts for both different natural soil types and impedance discontinuities. Terrain height variations are incorporated as a continuous diffraction process, providing flexibility, accuracy, and computational efficiency, while interactions between terrain diffraction and ground effects are explicitly included. Although the model supports detailed meteorological refraction calculations, meteorological effects were simplified here to atmospheric absorption (assuming 15 °C and 70% relative humidity) and moderate turbulent scattering.
The combined source-emission and propagation modelling framework has previously been validated against long-term measurements near a complex multilane highway bordered by a 7-m-high embankment with a pronounced ground impedance discontinuity along its slope [11]. Predicted sound pressure levels agreed with measurements within 0.5-1 dBA. In that case, the HP2P model achieved an accuracy comparable to that of a high-fidelity full-wave FDTD model [12] while requiring substantially lower computational effort.

2.4 Species hearing threshold weighting

Although efforts are underway to develop comprehensive hearing-threshold databases within a systematic species framework, the present study considers a selection of species with diverse hearing threshold spectra. Available hearing data typically focuses on the frequency ranges of highest auditory sensitivity. To enable assessments across the broad frequency spectrum of road traffic noise, hearing thresholds were extrapolated where necessary using average low- and high-frequency slopes derived from the available data. The reciprocals of the resulting hearing thresholds, normalized to equal energy and interpreted as species-specific weighting curves, are shown in Fig. 2.

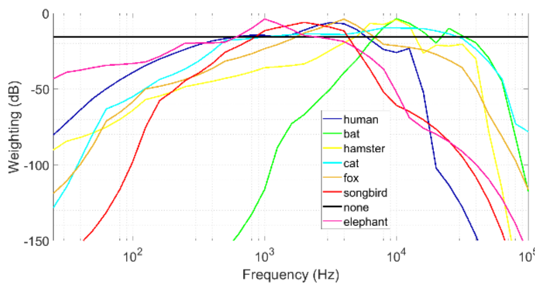

Figure 2. Hearing threshold based frequency weighting curves for the species considered in current work.

2.5 Noise abatement measures

Several noise abatement measures were considered (see Fig. 3), namely noise screens (with a height of either 3 m or 6 m), an asymmetric earth berm in combination with a symmetrical but smaller central reservation berm, a depressed road with a linear slope leading to a height difference of 10 m relative to the road surface, and a number of traffic management/source related measures: speed reduction (from 120 km/h) to 90 km/h, a truck ban (so leading to 800 vehicles/h per lane) and application of a poro-elastic road surface (PERS) [13].

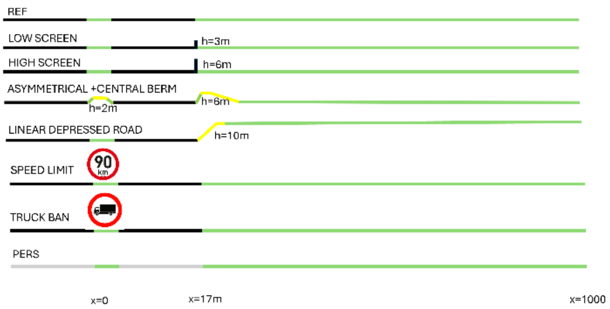

Figure 3. Road traffic noise abatement measures considered in this work, shown as cross sections (not true to scale). The green surfaces indicate grassland, the yellow forest floor. The asymmetrical berm is 20 m wide with a 4-m flat top. The slope near the depressed road is 20 m wide as well, while the first 5 m on top of the embankment was assigned a forest floor.

3. Results and discussion

3.1 Effect of a selection of abatements on different species

The effects of a few road traffic noise abatement measures are depicted in Figs. 4 to 8, showing total bio-weighted insertion losses in function of distance (on a logarithmical axis) at a receiver height of 0.5 m. Note that not for all species, this receiver height might be relevant.

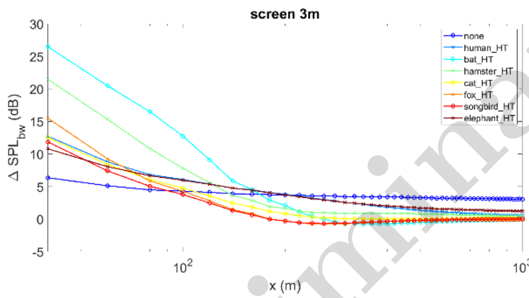

Figure 4. Bio-weighted insertion losses for all species considered, in case of a 3-m high noise wall, at a receiver height of 0.5 m.

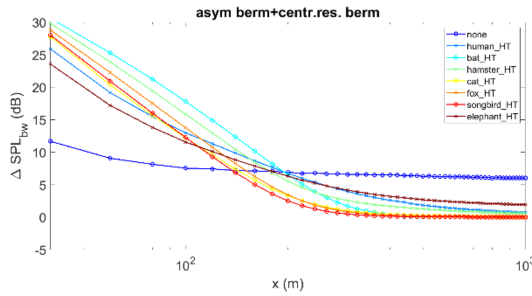

Figure 5. Bio-weighted insertion losses for all species considered, in case of the asymmetric berm + central reservation berm, at a receiver height of 0.5 m.

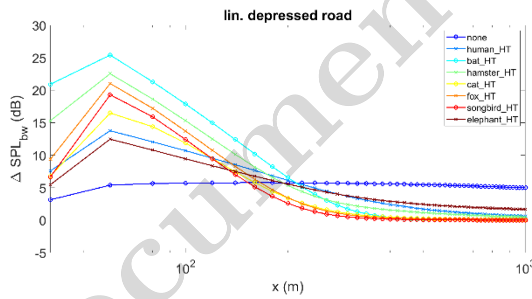

Figure 6. Bio-weighted insertion losses for all species considered, in case of the depressed road following linear slope, at a receiver height of 0.5 m.

The insertion loss of a conventional noise screen is strongly species-dependent, at least within the first few hundred meters. Barrier performance is governed by diffraction, which primarily attenuates higher frequencies. As a result, species with high-frequency–focused hearing experience substantially reduced exposure, whereas at larger distances the barrier effect diminishes and sound levels approach the reference situation and thus zero insertion loss.

The berm configuration provides strong near-field attenuation for all species considered. By partially preserving ground effects [11], [14], which are particularly relevant at lower frequencies, attenuation extends over a broader frequency range and is therefore less dependent on species-specific hearing characteristics.

For the depressed road configuration, near the slope edge there is near line-of-sight propagation from the far lanes, resulting in limited attenuation of low-frequency components and thus a benefit mainly for high-frequency–sensitive species. At intermediate distances, a maximum insertion loss is observed, with differences of up to 15 dB between species. Further away, the effect again becomes negligible.

In contrast, source-oriented measures such as speed reduction and truck ban show much weaker distance dependence. Speed reduction primarily reduces high-frequency spectral content, leading to slightly higher insertion losses for species with high-frequency hearing sensitivity.

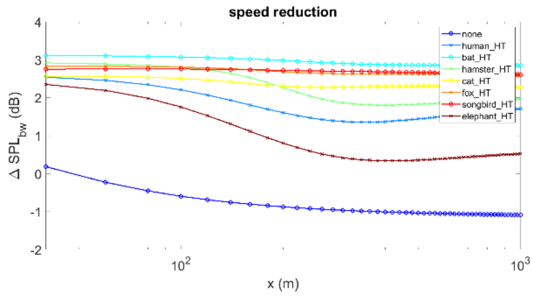

Figure 7. Bio-weighted insertion losses for all species considered, in case of the speed limit reduction, at a receiver height of 0.5 m.

A truck ban reduces not only traffic volume but also sound levels in the typical engine and rolling noise frequency ranges. Species with significant low-frequency hearing sensitivity benefit most from this measure. The variation with distance can be attributed to changes in ground-effect contributions, which may overlap with engine-noise frequency bands. These effects arise from phase shifts between direct and ground-reflected sound paths and thus vary with receiver position. However, due to the presence of multiple contributing propagation paths from different road segments, the resulting distance-dependent variability (e.g., for an elephant weighting curve) remains relatively small.

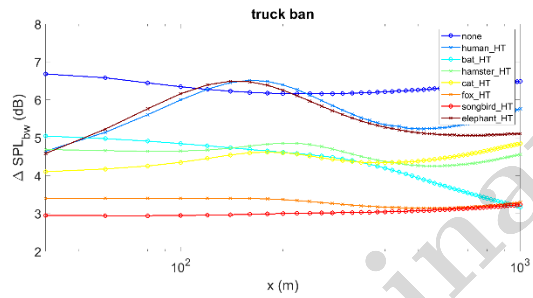

Figure 8. Bio-weighted insertion losses for all species considered, in case of a truck ban, at a receiver height of 0.5 m.

3.2 Effect on single species for all abatements

In Figs. 9 to 11, the insertion losses of all abatements considered are shown, for song-bird weighted levels at the 3 standard receiver heights.

Source-oriented measures show little dependence on receiver distance and height, whereas propagation-based measures are strongly influenced by both. A higher receiver height (5 m; e.g. birds in trees) does not necessarily correspond to lower insertion losses, since the overall attenuation results from the interplay between ground effects and diffraction. In cases where soft-ground effects are strong, they can dominate over diffraction, meaning that the loss of ground-related attenuation caused by installing a barrier can outweigh the additional attenuation provided by diffraction.

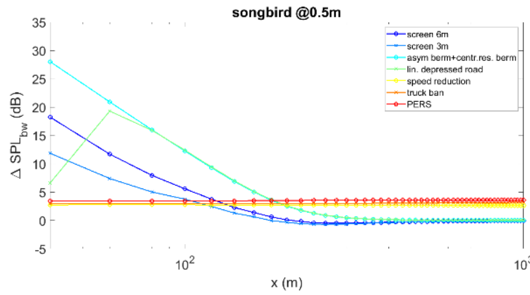

Figure 9. Bio-weighted insertion losses for a typical song-bird hearing threshold spectrum, for all abatements considered, at a receiver height of 0.5 m.

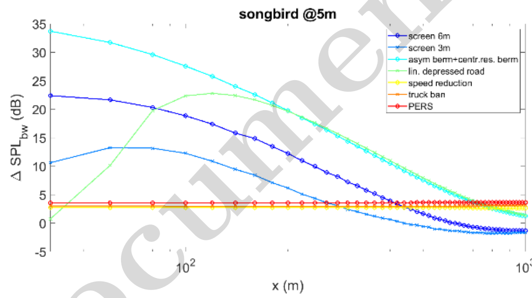

Figure. 10. Bio-weighted insertion losses for a typical song-bird hearing threshold spectrum, for all abatements considered, at a receiver height of 5 m.

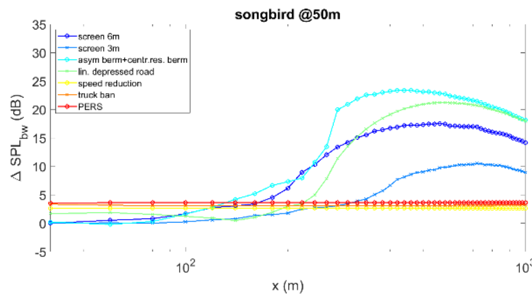

Figure 11. Bio-weighted insertion losses for a typical song-bird hearing threshold spectrum, for all abatements considered, at a receiver height of 50 m.

At very high receiver heights (50 m; e.g. birds in flight), line-of-sight propagation dominates close to the road, resulting in negligible insertion loss for propagation-based measures. Once the receiver enters the acoustic shadow zone, attenuation becomes substantial, although absolute sound levels may already be considerably reduced at that point.

Overall, the comparison across three receiver heights highlights that animal-oriented noise mitigation may differ substantially from conventional road traffic noise insights. In particular, propagation-based measures are not necessarily most effective near the source or closer to the ground in the presence of acoustically soft ground conditions.

4. Conclusions

The example calculations presented in this study suggest that road traffic noise abatement measures could, in principle, be tailored to specific species. The effectiveness of propagation-based measures is strongly influenced by species-specific hearing sensitivity, as well as by distance to the road and receiver height. In contrast, source-oriented measures produce more distance-independent effects, although some interspecies differences in insertion loss remain.

Given the focus on sound propagation through natural environments with predominantly porous soils, accurate modelling of ground effects appears crucial, particularly for low receiver heights where these effects are most pronounced.

5. Acknowledgments

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