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Calculation of weather-corrected traffic noise immission levels on the basis of emission data and meteorological quantities

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Abstract

The assessment methods for noise exposure from different modes of traffic are usually based on simplified models. Regarding meteorological influences, it is well known that weather conditions in favor of sound propagation can cause maximum noise levels which are not reflected in the averaged rating levels. Especially in larger distances from the emitter these effects become evident. Correction factors are not always sufficient to capture the strong impact of the actual atmospheric structure. An applicable and accurate meteorological model for obtaining the "real" immission load in residential areas can serve e.g. as a supplement to the averaged rating levels to better understand noise situation. In this study we look at the sound propagation models NMPB-Roads-2008 and Harmonoise, which include meteorological considerations. We compare them to the German RLS-90, discuss their advantages and drawbacks, and apply them to a simple weather-dependent test scenario to examine if their meteorologically corrected noise immission levels are feasible.

Keywords: noise immission; noise mitigation; sound propagation; meteorological models; RLS-90; NMPB; Harmonoise; meteorology; weather correction

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1. Introduction

Everyone knows from own experience that sound on the downwind side of an acoustic source is louder than on the upwind side. As simple as that sounds, the propagation of acoustic waves in the atmosphere actually is a highly complex issue and depends on many different factors – like e.g. the vertical gradients of wind speed and temperature, the relative humidity in air, local atmospheric turbulences, the terrain profile below the propagation path and the ground material itself. Weather conditions in favor of sound propagation can cause maximum noise levels, which are not reflected in the averaged rating levels. Especially in larger distances from the emitter these effects become evident. In particular, local microclimate (e.g. temperature inversion) can "bypass" already existing noise barriers by bending down sound propagation paths.

When it comes to the assessment of noise exposure originating from different modes of traffic, it is tempting to consider a full propagation model, which includes all phenomena of atmospheric acoustics, in order to calculate realistic immission loads in residential areas and accurate sound levels also in greater distances from the acoustic sources. However, due to the high complexity, such a model would become less practical for everyday use, the results would be less comprehensible for users and the calculation would require significantly more computing time. Moreover, using a detailed meteorological model presupposes that correspondingly detailed input data is available, which is not always the case – meaning that the accuracy one wants to achieve by including meteorological effects might get distorted in a way. To find a good balance between those aspects (i.e. level of detail, physical accuracy, comprehensibility, applicability and computing time) is one important task in the development of a high-quality sound propagation model. For practical use most noise assessment methods are based on simplified models and complex physical relations are often incorporated via corresponding correction factors. For instance, in the German guideline for protection from road noise (RLS-90) light downwind conditions and/or temperature inversion are assumed in general and further meteorological considerations are fully omitted. The preliminary calculation method for environmental noise from roads (VBUS2006), which is used for the noise mapping within the EU Environmental Noise Directive at present, adds a correction term C_{met} (following the approach in ISO 9613-2) to correct for the influence of meteorology on the long-term sound level. Even though both methods in most cases will overestimate the noise levels – in favor of the people concerned – they will fail in more complex situations and in individual weather-dominated scenarios, since correction factors are not sufficient to capture the strong impact of the actual atmospheric structure.

Several engineering models in Europe allow considering meteorological aspects. The extent to which this is implemented differs from model to model. In this manuscript the methods under investigation are the French NMPB-Roads-2008 and the European Harmonoise model. The RLS-90 (respectively VBUS) will serve as reference for a "non-meteorological" prediction method. In the next section these models are introduced, the respective meteorological framework is presented in more detail and after that a first comparison is carried out regarding the included meteorological features. In section 3 a simple test scenario is considered and the sound propagation is calculated for different weather profiles to quantitatively compare the results from the different engineering models. We will discuss the necessity for applying weather corrections and whether such corrections can serve e.g. as a supplement to the averaged rating levels to have a better basis for defining meteorological adjustment factors or a supporting guidance tool when planning noise mitigation measures.

2. Road noise prediction methods

2.1. RLS-90 and VBUS

The German guideline for protection from road noise (RLS-90) has been published in 1990 [RLS90] and is the basic computation method for noise exposure caused by road traffic in Germany. With the introduction of the European Noise Directive 2002/49/EC (END) and the responsibility to create noise maps of agglomerations and major roads [END2002], in 2006 a slightly modified version of RLS-90 has been put into practice [VBUS2006]. This preliminary calculation method for environmental noise from roads (VBUS) differs from the RLS-90 in a few minor points regarding the emission side, different noise indicators are used (separation in day, evening and night), there are no additions for crossroads, shielding effects are treated differently and meteorology is handled in a slightly different way. However, the basic concept is the same in both methods: Unlike the other models presented here, the RLS-90 and VBUS are not based on precise sound ray-tracing. Instead, the source emission is modeled based on the amount of traffic, traffic composition, vehicle speeds and other traffic-related conditions. Secondly, the line source is split into several single point sources and the contribution to the immission is then calculated for each point source by taking into account the underlying geometry. Here only one path from a point source to the immission point in the vertical plane is considered, i.e. the diffraction on side edges of obstacles is neglected. First-order reflections are taken into account via mirror sources. Corrections for the absorption in air, higher-order reflections, shielding and ground attenuation are added. The single contributions are summed up energetically to obtain the total immission at the respective immission point. The result is given as total sound level – no frequency bands are used.

In principle, the RLS-90 does not include any meteorological effects. The guideline states that "the calculated sound levels are valid for light wind (approx. 3 m/s) from the road towards the immission point and/or temperature inversion" [RLS90]. Furthermore, there is a correction term for attenuation due to ground and meteorology effects D_{BM} which, however, depends only on the distance between emission point and receiver and the average height of this connection line. In the presence of a barrier it is even neglected. Since the END requires the use of long-term average sound levels, the VBUS follows the approach of ISO 9613-2 [ISO9613] and uses an additional correction term D_{met} for different propagation conditions in the atmosphere. It reads:

$$D_{\mathrm{met}} = \begin{cases} 0, & s_0 \leq 10(h_{GE} + h_{GI}) \\ -C_0 \cdot [1 - 10(h_{GE} + h_{GI})/s_0], & s_0 > 10(h_{GE} + h_{GI}) \end{cases}$$

Where s_0 is the distance between emission and immission point, h_{GE} and h_{GI} the height of the emission and immission point above the ground, and C_0 the meteorological correction factor ($C_0 = 2$, 1 or 0 for day, evening and night, respectively).

2.2. NMPB-Roads-2008

NMPB-Roads-2008 is the French method for road traffic noise prediction and a revised version of the older standard NMPB-Roads-1996. The NMPB methods have been developed to calculate the sound level of roads in greater distance and consider the influence of different meteorological conditions on the sound propagation [Sétra2009]. According to the Sétra report the calculation distance validity limit is 800 m perpendicular to the infrastructure with a receiver > 2 m above the ground. Third-octave bands from 100 Hz to 5 kHz are used. Regarding the meteorology, the French model does not perform an exact simulation of weather-induced influences on the sound propagation. It rather calculates an averaged long-term sound level by energetically summing up two types of sound levels – namely, for homogeneous meteorological conditions and downward-refraction conditions – weighted by their respective probability of occurrence (see section 2.2.2).

2.2.1. Basic principles and sound propagation model

The engineering model behind NMPB follows a geometric approach and is based on point-to-point calculations, i.e. ray-tracing is used to identify the possible propagation trajectories between a given source S and a given receiver R. Beginning from modeling the noise source, the calculation procedure consists of six steps:

- Step 1: The line source S is broken down into several point sources. As many acoustically homogeneous sections as necessary are created, and the source line is placed in the center of each lane. The equivalent source height is set to 0.05 m to capture the dominance of the tyre/road noise.
- Step 2: The sound power level L_{Awi} for each point source i is calculated for a given third-octave band as power level per unit length. In the corresponding formula the vehicle type (light or heavy vehicle), vehicle speed, road surface parameters and hourly traffic flow rates are considered.
- Step 3: For each direction the probability of occurrence of downward-refraction conditions is determined. See section 2.2.2 for more details.
- Step 4: The propagation analysis is carried out, i.e. the trajectories representing the sound energy propagation are identified. Direct paths, reflections on vertical or slightly sloping obstacles and diffraction on side edges are taken into account here in a 2½-dimensional way.
- Step 5: This step basically contains the terms which are affected by meteorology. For each propagation path (from the point sources S_i to the receiver R) the sound level in downward-refraction conditions ($L_{i,F}$) and the sound level in homogeneous conditions ($L_{i,H}$) has to be calculated so that the long-term sound level for each path can be determined by energetically summing up $L_{i,F}$ and $L_{i,H}$ weighted with their respective average probability occurrence. More details follow in section 2.2.2.
- Step 6: In this final step the total long-term sound level at the receiver point $L_{Aeq,LT}$ follows from summing up the sound contributions from all point sources (including their potential image sources) and for all third-octave bands between 100 and 5 kHz.

2.2.2. Implementation of meteorology

Apart from atmospheric (molecular) absorption, the main influence on the propagation of an acoustic wave comes from the atmospheric conditions wind and temperature. A tool to describe this influence is the acoustic index $n(d,z)=c(d,z)/c_0$ of the propagation medium. It varies with the altitude z and the distance d between source and receiver. The effective sound speed at this altitude and distance is $c(d,z)$ and c_0 = 340 m/s is the reference sound speed. The acoustic index $n(d,z)$ can be separated into the average deterministic part $< n(d,z) >$, which accounts for the refraction of the sound waves induced by the horizontal stratification of the atmosphere [Sétra2009], and a stochastic part $\mu(d,z)$, which represents the random fluctuations of micrometeorological magnitudes (turbulences). Compared to a purely deterministic calculation, the inclusion of turbulences in a sound propagation model leads to a "smoothening" of the clean and distinct sound minima due to destructive interference and to a diffusion of sound inside shadow regions [Sétra2009]. The average part $< n(d,z) >$ is related to the average sound speed profile $< c(d,z) >$, which in turn depends on average wind and temperature profiles. Here NMPB uses a hybrid profile of logarithmic-linear type since it constitutes a good description of the strong vertical gradient of the sound speed near to the ground and the weaker changes at greater altitudes. Also, in good approximation the sound speed profile is assumed to be time and range independent:

$$\langle c(z)\rangle = c_0 + \mathrm{a}_{\log} \ln\left(1 + \frac{z}{z_0}\right) + b_{lin} z$$

Here z_0 is the roughness parameter, which depends on the type of ground, and the coefficients $a_{\log}$ and b_{lin} characterize the logarithmic and linear contribution in the profile, respectively. One can distinguish between downward-refraction conditions (positive vertical sound speed gradient), for which the sound rays are bent towards the ground (thereby acting favorable for the sound propagation), and upward-refraction conditions (negative vertical sound speed gradient), for which the acoustic energy is shifted towards the sky (thereby being unfavorable for the sound propagation). Since modeling upward-refraction conditions is not a trivial task, the so-called homogeneous conditions are used instead. In this case the propagation of sound occurs in a straight line. Homogeneous conditions work as an upper bound for the upward-refraction scenario.

The weighting of the two types of sound levels is performed according to the meteorological occurrence values for downward-refraction conditions on the site under investigation. These probabilities also depend strongly on the wind direction, meaning that they differ for different source-receiver propagation directions. There are several ways how the probabilities of occurrence can be obtained:

- Exploit the measurements and analyses of the official meteorological stations. In the official NMPB report [Sétra2009] this is done for the permanent stations in France, yielding tabulated occurrence values for 41 sites in directional steps of 20°, based on wind and temperature data from about 20 years.
- Perform own local measurements of thermal and aerodynamic characteristics over a minimum period of one year or use existing micrometeorological information. In combination with data from the closest official meteorological station, the local measurements can be analyzed and extrapolated to obtain estimations for the occurrences of downward-refraction conditions. This procedure of course is very time-consuming, complex and requires a lot of scientific expertise, but yields the most accurate results.
- Adopt the most suitable tabulated values for the site of interest. How well the probability values for downward-refraction conditions match the local situation depends on the details of the local topology.
- Use pre-defined occurrence values which surely overestimate the long-term sound levels. This will be less accurate and lead to oversized (and more expensive) noise abatement measures but on the other hand ensure the best noise protection.

Next we will have a closer look at how the sound levels $L_{i,F}$ and $L_{i,H}$ are calculated in step 5 and how the meteorology comes into play. $L_{i,F}$ ($L_{i,H}$) results from subtracting the total attenuation along the propagation path in downward-refraction conditions $A_{i,F}$ (homogeneous conditions $A_{i,H}$) from the sound emission power level L_{Awi}. The total attenuations $A_{i,F(H)}$ can be written as:

$$A_{i,F(H)} = A_{\text{div}} + A_{\text{atm}} + A_{\text{front},F(H)}$$

where A_{div} is the attenuation due to geometrical divergence, A_{atm} the attenuation due to atmospheric absorption (including the frequency-dependent coefficient α given for T = 15°C and a relative humidity of 70%) and $A_{\text{front},F(H)}$ the attenuation due to boundary effects in downward-refraction (homogeneous) conditions. Only the latter term is influenced by meteorology and can contain attenuation contributions from the ground effect $A_{\mathrm{sol},F(H)}$, from diffraction effects $A_{\mathrm{dif},F(H)}$ and due to reflections on embankments A_{talus}.

The ground attenuation mainly originates from the interference between direct and reflected sound. The interaction of the sound rays with the ground is determined by the absorption properties of the ground itself and strongly depends on how the sound rays are bent on their propagation path through the atmospheric environment. To acoustically characterize different ground types with respect to their porosity, a frequency-independent coefficient G is used, where $G = 0$ means fully reflective and $G = 1$ absorbing. In NMPB-Roads-2008 the calculation of the ground effect for homogeneous conditions (equations (7.4) - (7.7) in [Sétra2009]) takes into account the atmospheric refraction, multiple reflections on the ground and atmospheric turbulence. For the calculation in downward-refraction conditions height corrections δz_s and δz_r are applied to the heights z_s and z_r of the source and the receiver. This "simulates" the bending of the sound rays above flat ground by considering a curved ground and straight sound rays. Note that instead of real heights above the ground the concept of so-called "equivalent heights" is used, meaning that the (fictitious) mean ground plane between source and receiver is used as reference plane. Atmospheric turbulence is modeled via an additional height correction δz_T accounting for the coherence loss between direct and reflected rays due to turbulence effects [Dutil2010].

The need to consider the diffraction effect for a specific path and a specific third-octave median frequency is checked by calculating the path difference δ. If $\delta < -\lambda/20$, the path is considered as direct propagation path and $A_{\mathrm{dif}} = 0$. If $\delta \geq -\lambda/20$, the sound ray "meets" the diffraction edge and the attenuation due to the diffraction effect A_{dif} will be calculated. The calculation of A_{dif} then automatically includes the ground effect, so that A_{sol} does not have to be calculated separately.

$$A_{dif} = \Delta_{\mathrm{dif(S,R)}} + \Delta_{\mathrm{sol(S,O)}} + \Delta_{\mathrm{talus(S,O)}} + \Delta_{\mathrm{sol(O,R)}}$$

$\Delta_{\mathrm{sol(S,O)}}$ and $\Delta_{\mathrm{sol(O,R)}}$ are the attenuations from the ground effect (calculated as described above) on the source and receiver side, respectively (O is the diffraction point), $\Delta_{\mathrm{talus(S,O)}}$ is the attenuation from a possible bank on the source side and $\Delta_{\mathrm{dif(S,R)}}$ is the pure diffraction with no ground effect between source S and receiver R. For $\Delta_{\mathrm{sol(S,O)}}$ and $\Delta_{\mathrm{sol(O,R)}}$ one of course has to distinguish between homogeneous and downward-refraction conditions. In the diffraction part itself the ray bending is taken into account when the path difference is evaluated, applying Fermat's principle in the vertical plane containing the source and the receiver (see Appendix E of [Sétra2009]).

2.3. Harmonoise

The European Directive 2002/49/EC on Environmental Noise calls for a harmonized engineering model which all member states can use to carry out the obligatory noise mapping and obtain unambiguous comparable noise maps. Harmonoise has been developed from 2001 to 2004 to provide a first basis for such an engineering model [Harmo2005]. The major goals of Harmonoise are to give a more physical description of sound propagation than existing models do, to achieve a higher accuracy when predicting noise immission levels and to minimize errors when calculating the sound attenuation of the propagation path. In particular Harmonoise wants to avoid errors due to inaccurate assumptions about the influence of ground properties and wants to be able to perform separate calculations for different weather conditions. Harmonoise is meant to be applicable to an arbitrary terrain profile and uses the Fresnel weighting approach (similar to the Nordic method Nord2000). Regarding the frequency range, the engineering model is valid from 25 Hz to 10 kHz and results are given in third-octave bands.

2.3.1. Basic principles and sound propagation model

As the French model, Harmonoise starts from a 3-dimensional geometry and then projects the propagation paths to a vertical propagation plane to calculate the point-to-point attenuation on the relevant paths (2½-dim. approach). For this purpose the source (usually a line source) is represented by point sources situated in the centre of small line segments. The sound level at the receiver L is calculated from the following contributions:

$$L = L_{\mathrm{source}} + \Delta L_{\mathrm{prop}} = L_{\mathrm{source}} + \Delta L_{\mathrm{geo}} + \Delta L_{\mathrm{air}} + \Delta L_{\mathrm{excess}}$$

Here L_{source} is the source sound level and ΔL_{prop} the change of the sound level due to propagation effects, which in turn is composed of the geometrical attenuation ΔL_{geo}, the attenuation due to absorption in air ΔL_{air} and the excess attenuation $\Delta L_{\mathrm{excess}}$. The excess attenuation is the most complex part and includes all other physical effects influencing the propagation of sound waves, like refraction, scattering, reflection and diffraction.

The source description in Harmonoise is very detailed but shall be mentioned here only in a few words. Two steps are performed when classifying the source emission: First the single moving vehicles are characterized according to a vehicle categorization table which distinguishes five main classes with several sub-classes. Depending on the vehicle category the single sound power output is calculated at three heights (0.01 m, 0.30 m and 0.75 m above the road surface) and for each third-octave band. This is supposed to represent the three sub-sources rolling noise, traction noise and aerodynamic noise, respectively. In the equations also the horizontal and vertical directivity is considered and further corrections are applied for different road surfaces, road gradients and driving conditions. In the end the sound power output of a source line per unit length is obtained (for each sub-source height) based on the single source outputs, the average vehicle speed and the traffic flow.

2.3.2. Implementation of meteorology

The meteorological influence on the sound propagation is implemented in the excess attenuation ΔL_{excess}. In this context the ground profile plays an important role. It is separated into straight line segments between diffraction edges and – similar to the concept in NMPB-Roads-2008 – the atmospheric refraction is taken into account by curving the ground while keeping the sound rays straight. The equation for the excess attenuation reads

$$\Delta L_{\text{excess}} = 10 \log \left(10^{\Delta L/10} + 10^{\Delta L_{\text{scat}}/10}\right)$$

and contains the contributions from turbulent atmospheric scattering (ΔL_{scat}), ground reflections and screening/diffraction by obstacles (both included in ΔL). The ground attenuation effects are calculated for the line sections and the diffraction attenuations effect for the diffraction edges between the line sections.

For the segmentation of the ground profile three types of ground segments are considered: concave, convex and hull segments. The calculation formulae of the ground attenuation ΔL_G comprise the spherical-wave reflection coefficient Q, which depends on the path length R' of the reflected ray, the reflection angle θ, the wave number k and the normalized ground impedance Z. Moreover, the differences in free field and diffracted field between sources/receivers and image sources/receivers is considered via a geometrical weighting factor D_k [Salom2011]. Phase differences between direct and reflected sound arise due to the integration over frequency bands and due to turbulence effects. This kind of coherence loss is taken into account by a coherence factor C_k. Last but not least, the contributions from different ground segments are weighted using the Fresnel zone concept, thus being able to consider varying surface types more accurately. In order to improve the accuracy of the results at high frequencies, in Harmonoise the Fresnel weights are modified by using a frequency-dependent Fresnel parameter n_f (see [Salom2011] for more details).

The calculation of the atmospheric refraction is based on a linear-logarithmic profile of the effective sound speed in vertical direction $c_{\text{eff}}(z)$ of the following form:

$$c_{\text{eff}}(z) = c_0 + Az + B \ln(1 + z/z_0)$$

As in section 2.2.2, z_0 is the roughness ground parameter and A and B are the coefficients characterizing the logarithmic and linear contribution in the profile, respectively. These coefficients depend on the specific meteorological parameters of the considered meteorological class and have to be determined either by analyzing c_{eff} at a number of different heights or by relating the friction velocity $u*$, the temperature scale T* and the Monin-Obukhov length L to A and B via theory. Harmonoise also provides tables with estimates for A and B for various conditions [Harmo2005]. The default values for A and B are provided for 25 weather classes, i.e. for 25 combinations of wind speed and atmospheric stability (cloud cover). There is of course a trade-off between number of classes and accuracy. The classification of the meteorological classes in [Heima2003] showed that ignoring the influence of weather can lead to inaccuracies of up to 6 dB(A) at a distance of 200 m and up to 30 dB(A) at a distance of 1 km. By choosing 25 classes an accuracy of 2 dB is supposed to be achieved for distances between 200 m and 1 km.

The atmospheric refraction is taken care of by applying a conformal coordinate transformation to the system. This reproduces the effect of refraction in an indirect way: The ground is allowed to bend up/down with a radius of curvature which is determined by the vertical sound speed gradient (with source and receiver staying at the same relative heights as before) and the circular ray paths transform to straight paths, so that the simplified Harmonoise calculation scheme can be applied. This curved ground analogy turns out to be physically realistic and – despite some difficulties, see [Maerc2004, Bulle2012] – more accurate than simply applying correction terms, and at the same time allows performing calculations in an acceptable amount of time.

2.4. Comparison of the meteorological frameworks

Let us now compare the meteorological frameworks of the calculation methods under investigation. It goes without saying that RLS-90/VBUS do not really capture any weather-induced effects but rather try to give a generous upper estimate for the immission level at the receiver, thereby ensuring a good protection for the population also for conditions that are favorable for the propagation of sound. In fact in most cases this might even be sufficient (see e.g. the detailed comparisons in [Probs2010, Ecoti2012]) but, as already mentioned above, in single cases the negligence of meteorology can lead to inaccurate results and unexpectedly high noise exposures [Heima2003], especially farther away from the source. Problematic scenarios might arise for example when there is a frequent temporary increase of the immission load due to recurring weather conditions, which cannot be explained to the persons concerned by the standard calculation method, or when it comes to planning noise mitigation and an underestimation of the sound levels would lead to ineffective, low-sized measures.

Thus, consulting a more sophisticated model might be constructive in more complex cases. Both the French NMPB-Roads-2008 and the European engineering model Harmonoise are based on a simplified ray-tracing approach. For the identification of the trajectories between source and receiver both methods work in 2½ dimensions since a full 3-dim. calculation is extremely time-consuming. The use of Fresnel zones is also common in the two methods and accounts for the fact that a certain part of the reflection plane (depending on the incoming wave length) contributes to the reflection process and not just a single point. In general, one can state that in both models the attenuation contributions comprise geometric divergence, atmospheric absorption, reflection, diffraction, scattering as well as ground effects and atmospheric refraction. But here also lie the differences: The meteorological module in NMPB-2008 has a more model-like character and the implementation of all effects is based on the distinction between homogeneous and downward-refraction conditions. This substantially simplifies the calculations and ensures fast computation times. In order to justify the simplifications made, an extensive experimental validation has been carried out within the development of NMPB-2008. Harmonoise on the other hand works with precise input parameters and is based on a more physical approach, thereby being able to map real-world conditions very accurately, but also requires higher computation times. Due to the limited size of this manuscript, at this point the interested reader is referred to the references [Ecoti2012, Schad2004, Maerc2009 and Probs2010].

3. Application to a simple test scenario

3.1. Description of the test scenario

The area around the Federal Highway Research Institute (BASt) in Bergisch Gladbach has been identified to be well suited to apply the different engineering models. In the south of the building complex, the highway A4 – with an average daily traffic of 74834 vehicles (data from 2016) – is passing by. The air-line distance between the author's office and the highway is about 170 m. From the author's own experience the sound propagation from the highway towards the office buildings depends strongly on the wind direction and weather conditions. In the east and west of the BASt a residential zone with single family houses and an area with high apartment buildings are located, respectively. Both housing zones are separated by the highway through wood land. The area under consideration is shown in Fig. 1. All calculations are performed with *CadnaA* from *Datakustik* and the map was exported from *www.openstreetmap.org* [OSM2017]. The model is set up as follows: In general the buildings are 4 m high. For the BASt buildings in the center the heights are set to 10 m and the multi-family apartment complex (consisting of seven buildings) in the west is chosen to be 20 m high. These are not the actual heights of the housings but roughly represent the respective dimensions. Since the calculations are only compared to one another, such an approach is sufficient. The only noise source in the model is the highway A4 in the south with a 4 m high sound barrier on both sides (located 4 m from the center of the respective lane). For both lanes the emission for the day is set to $L_{m,E}$ = 78 dB(A) (averaged assessment level) in the RLS-90 and to L'_{WA} = 97.3 dB(A) in the NMPB (sound power level per unit length). For Harmonoise a traffic noise spectrum with L'_{WA} = 98.1 dB(A) as given in the NMPB emission guide is assumed [NMPBemi2008]. For comparability, these values are chosen in a way that in close proximity to the source the noise level is equal in all models. The immission at six houses (see labels in Fig. 1) is analyzed at 4 and 8 m above the ground. It is given as the average value over all exposed house facades. The L_{Day} noise map is also calculated for these two heights. The grid size is 4 m x 4 m. Regarding the different calculation methods, one has to keep in mind that in the RLS-90 the ground attenuation is automatically set to zero if there is a barrier in the sound propagation path. Thus, also

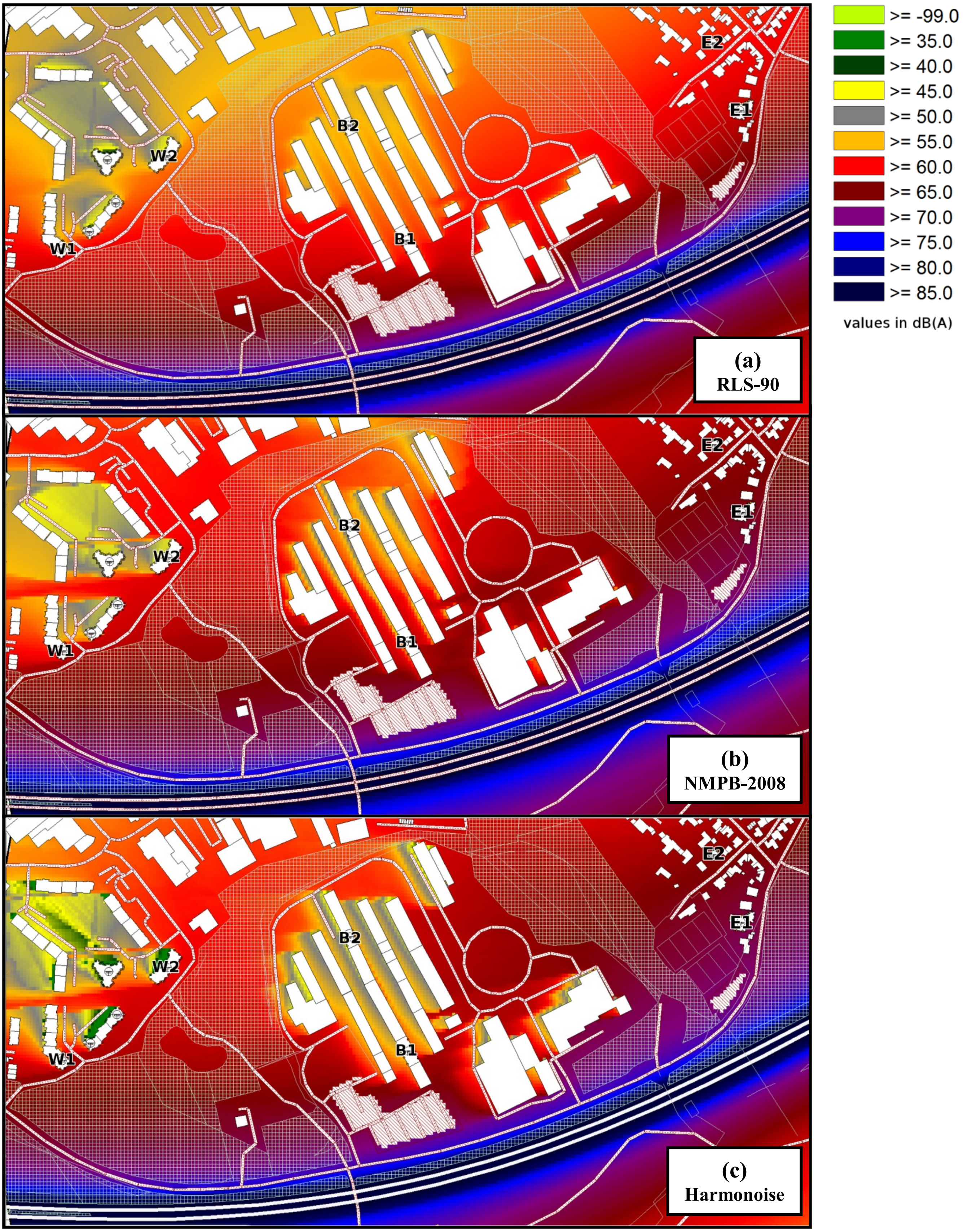

Fig. 1 Calculation area and calculated noise grid showing the L_{Day} at 8 m height for (a) RLS-90; (b) NMPB-2008 with favourable conditions in all directions and (c) Harmonoise with strong wind in northwest direction. The houses for which the immission is analyzed are marked with W1, W2, B1, B2, E1 and E2. The colour coding is noted next to subfigure (a). All values are given in dB(A). For more details about the chosen area and the model assumptions, see section 3.1.

for NMPB and Harmonoise the absorption due to the ground is assumed to be zero. In the NMPB calculation we probe three meteorological variants: homogeneous conditions in all directions, favorable conditions in northwest direction and favorable conditions in all directions. Similarly, the Harmonoise model is run once with the wind speed set to zero and once with a wind speed of 10 m/s in northwest direction. The stability class S1 is used (very small cloud coverage) and the temperature and relative humidity are set to 10°C and 70 %, respectively.

3.2. Comparison and discussion of calculation results

Due to the limited space, in Fig. 1 only three noise maps at 8 m height are shown: (a) RLS-90, (b) NMPB with favorable conditions in all directions and (c) Harmonoise with a wind speed of 10 m/s in northwest direction. The influence of the meteorology is very well seen in Fig. 1(b) and (c) in the center corridors between the BASt buildings (B1 and B2) and in the corridors between the high-rise apartment buildings in the west (W1 and W2). Here the favorable propagation of sound leads to locally enhanced noise exposures. On the other hand, one can see that the barrier effect is less pronounced in the RLS-90 calculation than in the French and European model. Thus, especially in some shadow regions, NMPB and Harmonoise predict a lower noise level than the German guideline does. Another effect that becomes evident in the calculations including weather is an increase of the L_{Day} in farther distance from the highway. Here NMPB and Harmonoise predict up to 5 dB(A) more than RLS-90, despite the presence of the sound barrier. In this case the sound rays "bypass" the barrier because of the downward refraction conditions. The calculations without wind (Harmonoise) and with homogeneous propagation conditions (NMPB) yield significantly quieter noise maps (not shown in Fig. 1) than the RLS-90 and clearly underestimate the degree of exposure, as expected from such exemplary lower limit assumptions.

Table 1. L_{Day} at selected immission points (see Fig. 1) for the different calculation models – averaged over all relevant facades. The 1st value in each cell refers to a height of 8 m, the 2nd value to 4 m. All values are given in dB(A).

① Immission point	② RLS-90	③ NMPB-2008 homogeneous	④ NMPB favorable	⑤ Harmonoise no wind	⑥ Harmonoise wind towards NW
W1	60 || 59	58 || 58	62 || 63	57 || 57	64 || 65
W2	57 || 57	55 || 54	62 || 61	54 || 52	62 || 62
B1	59 || 57	57 || 56	64 || 62	55 || 55	64 || 62
B2	54 || 50	49 || 49	57 || 49	43 || 41	56 || 52
E1	--- || 60	--- || 59	--- || 65	--- || 57	--- || 69
E2	--- || 58	--- || 52	--- || 61	--- || 41	--- || 62

Let us now have a look at the six immission points in Fig. 1. The corresponding L_{Day} values are averaged over all facades of the respective house and summarized in Tab. 1. The results for an immission height of 4 m are also included. It seems that the noise level does not vary much with height (2 dB(A) at most); however, the immission point B2 forms an exception. It is one of the farthest points in the model and, unlike the houses in the east and west, it has no fully screened facade. A maximum difference of 8 dB(A) arises for favorable propagation conditions in the NMPB calculation. This shows that considering different immission heights can be important when evaluating weather-dependent situations. The importance of weather effects also becomes obvious when comparing columns 4 and 6 with column 2. In the weather-dominated scenarios nearly all values are significantly higher compared to the RLS-90 results. Of course, the assumptions in "NMPB favorable" and the Harmonoise model with wind are rather unrealistic or rarely occurring, so these scenarios should be taken more as estimation for an upper limit. But since the immission point B1 represents the location of the author's office, the noise level at this point is known to depend strongly on the current meteorology.

In summary, the assumption of light downwind and/or temperature inversion, on which the formulae in the German guideline are based, seems to yield a satisfactory benchmark for a general evaluation of the present test setting. The predicted L_{Day} levels are about 2 – 3 dB(A) greater than predicted by the homogeneous environments of NMPB and Harmonoise, and about 2 – 5 dB(A) smaller than predicted for favorable sound propagation. Keeping in mind that those favorable conditions describe a pessimistic upper limit, the higher complexity in the models to explicitly include weather influences seems disproportionate with regard to their outcome. We also carried out calculations with NMPB assuming favorable conditions in northwest direction only (not included in Tab. 1 and Fig. 1), and surprisingly we obtain equal or even slightly lower values compared to RLS-90. However, the noise maps also show that special situations with enhanced noise exposure might arise, especially in greater distance from the source, where adequate weather corrections (based on an accurate physical model) might be helpful to understand variation of noise levels and plan noise mitigation accordingly.

4. Conclusion and outlook

The present manuscript recaps and summarizes different noise assessment methods with the main focus of attention being the modelling of meteorological effects on the sound propagation. The physical background of each method, in particular how meteorology is implemented, is elucidated. The comparison of the different theoretical frameworks shows that the ideas behind NMPB and Harmonoise are similar, but the implementation differs significantly. While NMPB distinguishes only two states, in the Harmonoise model a detailed input of the wind direction, the wind speed and the stability class is necessary. In both models the atmospheric refraction is based on "curving" the ground elements and working with straight ray paths. This keeps the calculation manageable. Anyway, here Harmonoise realizes the concept in a more accurate way (compared to the simple height corrections applied in NMPB-2008) and carries out a coordinate transformation to bend the ground and transform the circular paths to straight rays. The increasing degree of complexity also becomes evident from the computation times: With the RLS-90 the test setting is handled in 1.5 min, NMPB needs 3 min and Harmonoise more than 30 min. Since our calculation region is relatively small, this raises doubts about the applicability of Harmonoise for large noise maps with a higher number of emission sources. With the test calculations in section 3, the present manuscript picks up the question to what extent a simplified calculation model without meteorological module is sufficient to evaluate the noise exposure in cases with strong weather influences. The noise level in the chosen scenario is known to be prone to variations depending on the actual wind situation. As expected, the RLS-90 calculation does not represent the worst case scenario, however, when assuming moderate favourable conditions in Harmonoise or NMPB, the German guideline turns out to give a fairly similar picture. Differences in the sound distribution arise especially in corridor-like regions and in areas farther away from the road. From these first results we for now conclude, that an exact modelling of the meteorology for the purpose of noise mapping is not absolutely essential, but in individual cases authorities should have in mind that such tools exist. Unexpected noise levels can develop for special arrangements of buildings or in greater distance from the emission source and more physical models can then provide important information about why this happens, so that bad planning or inefficient decisions regarding protection measures can be avoided. However, in this context the issue of the meteorological data basis and its accuracy in relation to the desired calculation's accuracy remains problematic. In future investigations we will expand our considerations in this direction and also include the Scandinavian model Nord2000, which offers one of the most detailed weather handling at the moment. We will construct different (real-world) scenarios and systematically vary the meteorological parameters to illustrate their mechanisms. This will be backed up by measurements at selected immission points (noise exposure and meteorological parameters) to allow proper statements about the physical accuracy of the models. Eventually our goal is to obtain a detailed picture about (a) the possibilities to calculate weather-corrected traffic noise immission levels, (b) their validity and applicability and (c) their potential to support noise assessment in complex situations.

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