The Harmonoise sound propagation model: further developments and comparison with other models

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Introduction

The Harmonoise sound propagation model ('the Harmonoise engineering model') [1] was developed in the European project *Harmonoise* (2001-2004) for road and rail traffic noise. Further developments of the model were performed in the European project *Imagine* (2004-2006), including extensions of the model to aircraft noise and industrial noise. In 2008, CSTB Grenoble and TNO Delft have prepared a detailed description of the various steps involved in a calculation with the Harmonoise model. In the course of this joint project, some elements of the model were further improved. In 2009, test calculation were performed with the model, and results were compared to results of other models, both accurate reference models and the Scandinavian Nord2000 model [2,3].

In this article we present results of the comparisons. First we give a brief overview of the Harmonoise model, including salient features such as the convex hull approach, Fresnel weighting for irregular terrain, and ground curvature to account for the effect of atmospheric refraction.

Harmonoise model

A detailed description of the Harmonoise model can be found in Ref. [1]. Here we present a brief overview.

As usual for the modelling of road or rail traffic noise, source lines are divided into segments and each segment is represented by a central source point for the calculation of the point-to-point excess attenuation, which is defined here as the sound level relative to free field (so a positive excess attenuation corresponds to a higher sound level). In this study we focus on point-to-point model comparisons.

For a point-to-point calculation, a ground profile consisting of an arbitrary number of segments is assumed. Figure 1 shows an example with three diffraction points (P_2, P_5, P_6) above the source-receiver line *SR*. The excess attenuation is calculated as a sum of diffraction attenuations and ground attenuations. In the example of Fig. 1 there are three diffraction attenuations, and four ground attenuations corresponding to the ground sections between the diffraction points (P_0-P_2, P_2-P_5, P_5-P_6, and P_6-P_8).

The diffraction attenuations are calculated with a theoretical formula for diffraction by a wedge. The ground attenuations are calculated with a theoretical formula that represents a weighted average between two solutions, one for relatively flat ground and one for valley-shaped terrain. The solutions contain a coherence factor accounting for various effects resulting in coherence loss; for the model comparisons presented here we included only coherence loss due to frequency-band averaging. The solutions are sums of contributions from different ground segments, with Fresnel weights as weighting factors. A Fresnel weight for a ground segment is basically equal to the fraction of the Fresnel ellipse (see Figure 2) that is covered by the segment. Thus, a Fresnel ellipse can be considered as a measure of the (frequency-dependent) 'thickness' of the sound ray reflected at the ground surface.

The effect of atmospheric refraction is taken into account by applying a coordinate transformation (conformal mapping) to the ground vertices P_j. In the case of downward refraction, for example, a flat ground surface is transformed into a valley-shaped terrain. This approach assumes a linear sound speed profile $c = c_0 + az$, where $c_0 = 340$ m/s is the sound speed at the ground, z is the height, and a is the sound speed gradient. The linear profile is considered as an approximation of the logarithmic profile $c = c_0 + b\ln(1+z/z_0)$, with parameters b and $z_0 = 0.1$ m.

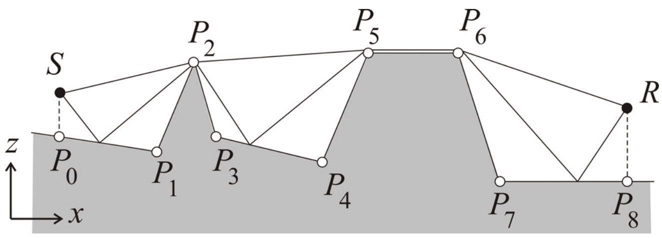

Figure 1: Example of a ground profile with eight vertices P_i, source *S*, and receiver *R*.

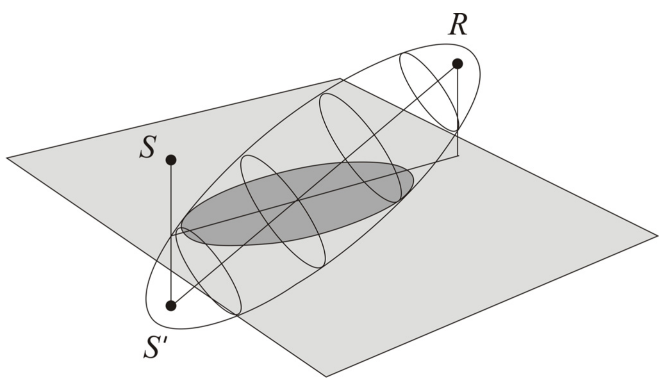

Figure 2: Fresnel ellipsoid around image source *S'* and receiver *R*. Also shown is the Fresnel ellipse (dark area): the intersection of the Fresnel ellipsoid and the ground surface.

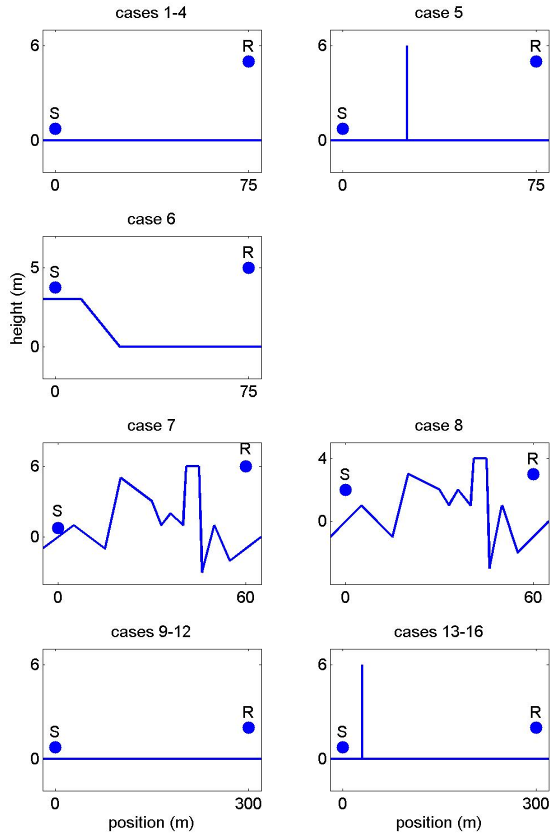

Figure 3: Geometries of 16 cases.

case	ground	wind
1	hard	zero
2	100k	zero
3	hard	lin
4	100k	lin
5	20000k	zero
6	20k	zero
7	200k	zero
8	200k	zero
9	100k	lin/log
10	100k	zero
11	hard	lin/log
12	hard	zero
13	100k	lin/log
14	100k	zero
15	hard	lin/log
16	hard	zero

Table 1: Ground flow resistivity (hard = ∞) in Pa s m^{-2}, and atmospheric wind profile (zero: non-refracting atmosphere, lin: $a = 0.2$ s^{-1}, lin/log: $a = 0.177$ s^{-1}, $b = 1$ m/s) for 16 cases.

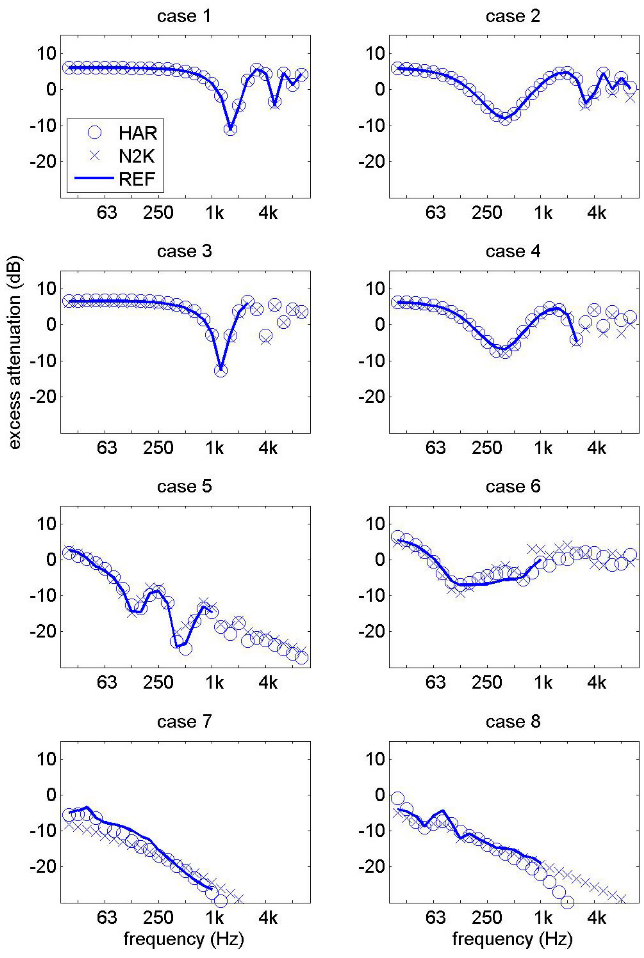

Figure 4: Results for cases 1-8.

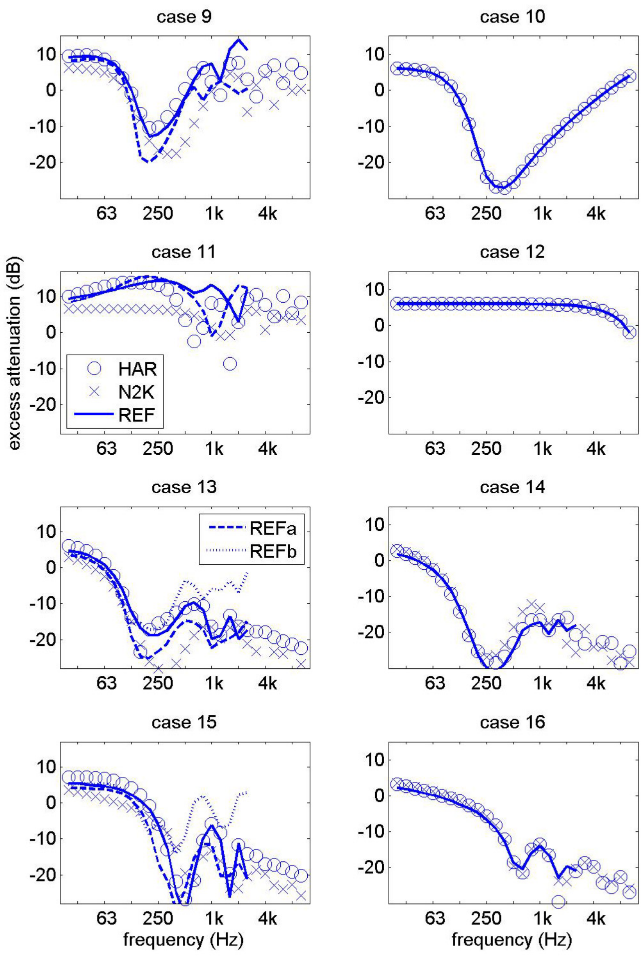

Figure 5: Results for cases 9-16.

Model comparisons

We have performed point-to-point calculations for the cases specified in Table 1. The calculation geometries are shown in Figure 3. Figures 4 and 5 show the results of the calculations.

We will now describe the parameters and discuss the results for each case separately.

Case 1. Distance 75 m, source height 0.75 m, receiver height 5 m, hard ground, non-refracting atmosphere. Results of Harmonoise (HAR), Nord2000 (N2K) agree will with a reference solution (REF), which is an analytical solution [4] in this case.

Case 2. As case 1, with absorbing ground. Similar agreement between three solutions.

Case 3. As case 1, with linear sound speed profile. Ground minimum at 1600 Hz in case 1 is shifted to 1250 Hz. Good agreement between three solutions. Reference solution calculated with a Parabolic Equation (PE) model [4].

Case 4. As case 2, with linear sound speed profile. Good agreement.

Case 5. As case 1 with a 6 m high barrier at 30 m from the source, and ground flow resistivity 20000 kPa s m^{-2}. Reference solution calculated with Boundary Element Method (BEM). Good agreement.

Case 6. Distance 75 m, source 0.75 m above 3 m high berm, receiver height 5 m, highly absorbing ground. Reference solution calculated with Boundary Element Method (BEM). Slightly larger deviations from REF for N2K than for HAR.

Case 7. Distance 60 m, irregular absorbing terrain. Reference solution calculated with Boundary Element Method (BEM). N2K deviates a few dB at low frequency.

Case 8. Slight modification of case 7. HAR and N2K deviate above 1 kHz, but excess attenuations below -20 dB are usually irrelevant in practice due to sound paths not included here.

Case 9. Distance 300 m, source height 0.75 m, receiver height 2 m, absorbing ground. Two PE reference solutions are included, one for a logarithmic sound speed profile with b = 1 m/s (REFa), and one for the linearized profile with $a = 0.177\ s^{-1}$ (REF) which was also used for HAR and N2K. For the linear profile, HAR agrees slightly better with REF than N2K does, but the high excess attenuation of 15 dB at 2 kHz is not reproduced by HAR and N2K. For the logarithmic profile (REFa), however, excess attenuations are considerably lower (5 – 15 dB for 500 – 2000 Hz). Consequently, HAR and N2K agree slightly better with REFa, but deviations are still up to 10 dB.

Case 10. As case 9, but with a non-refracting atmosphere. Without wind there is perfect agreement between the three solutions.

Case 11. As case 9, with hard ground. Again two reference solutions: for the logarithmic profile (REFa) and the linearized profile (REF). REF and REFa show excess attenuations above 10 dB for a much wider frequency range than for case 9. HAR agrees better with REF and REFa than N2K does, although there are considerable deviations at high frequency. It is surprising that HAR follows the reference solutions so well until 500 Hz, as the high excess attenuation levels are partly due to multiple ground reflections (see Fig. 6), which are ignored with the Harmonoise model.

Case 12. As case 11, but with a non-refracting atmosphere. Without wind there is perfect agreement between the three solutions.

Case 13. As case 9, with a 6 m high noise barrier at 30 m from the source. In addition to the reference solutions REFa for the logarithmic profile and REF for the linearized profile, we have included reference solution REFb for a realistic range-dependent profile taking into account the effect of the barrier on the wind speed profile (see Fig. 7) [4,5]. Solution REFb yields considerably larger levels than the other solutions do, owing to large wind speed gradients near the barrier top (see Fig. 7), which are ignored by the other solutions.

Case 14. As case 13, but with a non-refracting atmosphere. Without wind there is a much better agreement between the three solutions.

Case 15. As case 13, with hard ground. Again, reference solution REFb for the realistic range-dependent wind speed profile yields considerably larger levels than the other solutions do.

Case 16. As case 16, but with a non-refracting atmosphere. Without wind there is a much better agreement between the three solutions.

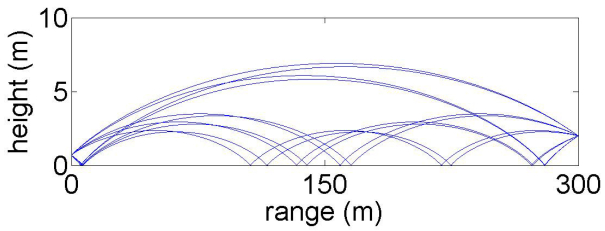

Figure 6: Sound rays for cases 9 and 11 with a logarithmic sound speed profile with b = 1 m/s.

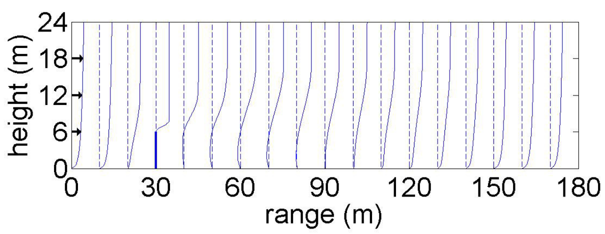

Figure 7: Range-dependent windspeed profile near a 6 m high barrier at range 30 m (thick line), for a logarithmic inflow profile $b\ln(1+z/z_0)$, with z_0 = 0.1 m and b = 1 m/s. The horizontal deviation from the vertical dashed lines represents the windspeed. The recirculation region extends to 20 times the barrier height, so to range 150 m.

Concluding remarks

The Harmonoise propagation model is an elegant engineering model for outdoor sound propagation, and is certainly a 'step forward' with respect to older engineering models such as the ISO model [6]. Harmonoise is applied to arbitrary terrain profiles with a Fresnel weighting approach that was initially based on the Nord2000 approach and was further developed and fine-tuned by comparison with reference solutions.

Harmonoise differs from Nord2000 by the way in which atmospheric refraction is taken into account. While Nord2000 employs curved sound rays, Harmonoise accounts for refraction by ground curvature. The nice idea of ground curvature seems to work well, at least for moderate propagation distances. For large distances, however, multiple ground reflections become important (in particular for hard ground), and these reflections are not taken into account by Harmonoise. In contrast, Nord2000 includes a correction term to account for multiple ground reflections in a downward refracting atmosphere. Nevertheless, it was found in this study that Harmonoise performs better than Nord2000 for a case with downward refraction over 300 m flat ground, both for hard ground and for absorbing ground.

Both Harmonoise and Nord2000 are restricted to linear sound speed profiles. In this study we have investigated the effect of linearizing the sound speed profile. For propagation over 300 m we found considerable differences between reference solutions for a logarithmic profile and the linearized profile. Further we have investigated the influence of the indirect effect of a barrier on sound propagation through the barrier-induced modification of the wind speed profile (a barrier 'blocks' the wind). Again we found considerable effects, which are not reproduced by the engineering models Harmonoise and Nord2000. This implies that the small differences HAR-REF and N2K-REF reported in [3] (standard deviations of 2.5 and 3.0 dB, respectively) may be too optimistic in some cases.

From the 16 cases studied here we conclude that Harmonoise is slightly more accurate than Nord2000 is. This was also concluded in Ref. [3], except at very low frequency.

Finally, we mention that the application of a point-to-point model such as Harmonoise or Nord2000 to full calculations for complex situations in an urban environment is not straightforward. The problem in an urban environment is that we have to deal with multiple reflections and diffractions by buildings. In principle this problem can be solved by introducing image sources and image receivers, and using Fresnel weighting to account for the reduction of reflection efficiency with increasing order of reflection (due to the finite ratio of building height over wavelength) [7]. The challenge is to implement these ideas while keeping the model practical and efficient.

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