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Report

Preliminary

Nordic Environmental Noise Prediction Methods, Nord2000

Summary Report

General Nordic Sound Propagation Model and Applications in Source-Related Prediction Methods

Client: Nordic Noise Group

AV 1719/01
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Summary

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DELTA, 31 May 2002

Jørgen Kragh
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Contents

Summary

The overall aim of the Nordic project has been to work out prediction methods for various types of environmental noise sources, such as road and railway traffic, industrial plants and wind turbine generators. The project was initiated in 1996 and completed in 2001.

Nordic environmental authorities identified by the mid-1990s the need for harmonizing the prediction methods for noise from various types of sources, as well as the need for putting into practical use the results of 20 years of development in acoustical understanding and in computer power and availability having taken place since the present Nordic methods were first published. They initiated a project to improve computations of the noise exposure of the population in the Nordic countries in order to optimize noise mitigation action.

The work has been financed by the Nordic Council of Ministers and by Nordic authorities and Research Councils. The Nordic Noise Group has acted as a project Steering Committee. Project work has been carried out by SP, Sweden, SINTEF, Norway, and DELTA, Denmark. The work has been coordinated by a Technical Committee with representatives from the three institutes, supplemented by VTT, Finland.

The present report summarizes the results. The report has been divided into two parts. In Part 1 a general description can be found which serves as an executive summary. Part 1 contains background, requirements and aims, an outline of the propagation model and prediction methods for road and rail traffic and a discussion of applicability and accuracy of the method and comparison with older prediction models. Part 2 contains a more detailed description of the propagation model.

The new models have been validated to some extent based on results of measurements and by comparison with results of calculation using accurate numerical models. Further validation of the new models would have been useful for augmenting their reliability, but time and economical constraints have prevented such validation. In spite of this, the models are believed to be the best models available today.

Foreword

The work on new Nordic prediction methods for environmental noise has been financed primarily by the Nordic Council of Ministers (Nordisk Ministerråd). Also the following organisations have contributed:

Denmark
Environmental Protection Agency (Miljøstyrelsen)
Road Directorate (Vejdirektoratet)
National Railways (Banestyrelsen)

Finland
Ministry of the Environment (Miljöministeriet)
Road Administration (Tiehallinto)

Norway
State Pollution Authority (Statens Forurensningstilsyn)
Road Directorate (Vegdirektoratet)
Rail Administration (Norske Statsbaner)

Sweden
National Board of Building Research (Byggforskningsrådet)
National Board of Health and Welfare (Socialstyrelsen)
Environmental Protection Agency (Statens Naturvårdsverk)
Road Directorate (Vägverket), Sweden
Transport & Communications Research Board (KFB)

Nordtest
Nordtest

The project steering committee has been the Nordic Noise group:

Þór Tómasson (chairman since 1999-01-01)
Environmental Protection Agency, Iceland

Hugo Lyse Nielsen (chairman until 1997-01-01)
Environmental Protection Agency, Denmark

Sirkka-Liisa Paikkala (chairman 1997-01-01 to 1998-12-31)
Ministry of the Environment, Finland

Jan Boe Kielland
State Pollution Authority, Norway

Sten Ljunggren
Royal Technical University, Sweden

Bo G. Pettersson
National Board of Health and Welfare, Sweden

The work was carried out by:

DELTA, Acoustics & Vibration (DELTA), Denmark

SP Swedish National Testing & Research Institute (SP), Sweden

SINTEF Telecom and Telecom and Informatics (SINTEF), Norway

DELTA, SINTEF and SP have also contributed in financing the work.

The work was coordinated by a technical committee with representatives from the above-mentioned three institutes, supplemented by:

VTT Building Technology, Acoustics (VTT), Finland

Requests for reports should be directed to the institutes, the addresses of which can be found at the back of the report. Reports may also be downloaded from www.delta.dk/nord2000/.

Part 1

General Description

1. Background and Requirements

In 1996, the Nordic Council of Ministers decided to establish a new generation of environmental noise prediction methods utilising results of research and development having taken place since the first Nordic prediction methods were published in the 1970s and early 1980s.

The idea was to develop sound propagation models and to build up source-related prediction methods for road and rail traffic and other environmental noise sources, all applying the same propagation models.

The propagation models should predict the sound pressure level, generated by a point source, in one-third octave bands from 25 Hz to 10 kHz at a receiver, based on the one-third octave band sound power levels of the source.

The propagation models should predict for a variety of weather conditions so that noise from different types of environmental noise could be treated in the same way rather than according to the present models that are valid for different weather conditions. This latter fact is due to historical rather than technical reasons.

Complicated terrain should be handled by an explicitly elaborated procedure. In previously used prediction methods it has been essential to have a skilled user interpret the terrain and decide how to present it in the calculation. Such a subjective practice will necessarily lead to undesirable variation in calculated results. With the new Nordic propagation models an explicit procedure can be carried out by a computer leading to unambiguous results.

In the selection of the prediction methodology, the accuracy should be balanced against the calculation time efficiency considering present computer technology.

To meet the objectives it was presupposed that only existing knowledge should be used without further basic research.

2. Aims

The chief aim of the project was to abandon the concept of empirical propagation models. Instead, the propagation models should directly apply theory algorithms in frequency band calculations. Such direct application of theory would be a novelty. In present and past Nordic prediction methods developed in the 1970s and 1980s, approximate or empirical solutions have been used because theoretical solutions were too complicated and too time-consuming.

With the increased availability of computers and the rapid growth in their abilities there seemed to be no immediate need for avoiding calculations according to theory, at least as far as calculation in single points was concerned. However, at the beginning of the project it was still uncertain whether simplifications were needed for making noise level contour maps or other presentation to obtain reasonable calculation times.

It was expected that very accurate numerical methods like the Parabolic Equations (PE) approach, Boundary Element Method (BEM) or Fast Field Program (FFP) were not directly useful in engineering prediction methods, due to the excessive calculation times required. However, it was expected that they could be applied in the work of developing approximate methods, thereby to some extent replacing the expensive series of measurements traditionally forming the basis of approximate calculation methods.

The aim concerning source models was not to provide a complete mapping of sound power levels and positions of subsources for all kinds of vehicles (road and rail), but to develop preliminary models based on available information and to adapt the sound power levels of the existing prediction methods to the new source models. It was originally planned also to include a description of how to handle industrial noise sources. However, due to lack of funding, this part of the project has been postponed. It has been discussed whether aircraft noise should be included, but no decision has been made so far.

3. Selected Propagation Model

The new Nordic prediction methods provide one-third octave frequency band results from 25 Hz to 10 kHz. The model allows calculation for specified weather conditions including rapid turbulent motions of the atmosphere. Therefore, the model applies to calculation of short-term levels for time periods less than 30 minutes or 1 hour. For longer time periods the effect of slowly varying large-scale motions of the atmosphere has to be taken into account by other means as described in Section 6.

In the propagation model the calculation of ground effect has been based on geometrical ray theory and screen effect on geometrical theory of diffraction. Ray acoustics have been found to provide a fine compromise between computation time and accuracy. Ray acoustics have proven to produce accurate results for propagation in a homogeneous atmosphere above flat ground with homogeneous finite impedance and with thin screens placed on flat ground. In the case of non-flat and non-homogeneous ground, multiple screens, screens with multiple edges, and propagation in an inhomogeneous atmosphere with vertical sound speed gradients, heuristic semi-analytical modifications have been introduced to obtain a general model. Although results obtained by the Nordic model for complicated propagation conditions will be less accurate than results obtained for the simple cases within the normal validity range of the ray models, the accuracy is still improved considerably compared to that of available empirical models.

The terrain profile is approximated by a number of straight-line segments. The Nordic model has no limitation on the number of segments that can be included, but in practice, the maximum number has to be no more than 10-15 segments to obtain reasonable computation times. Examples of segmented terrain are shown in Figure 1. The terrain surface properties of each segment are defined by the acoustical impedance and the roughness.

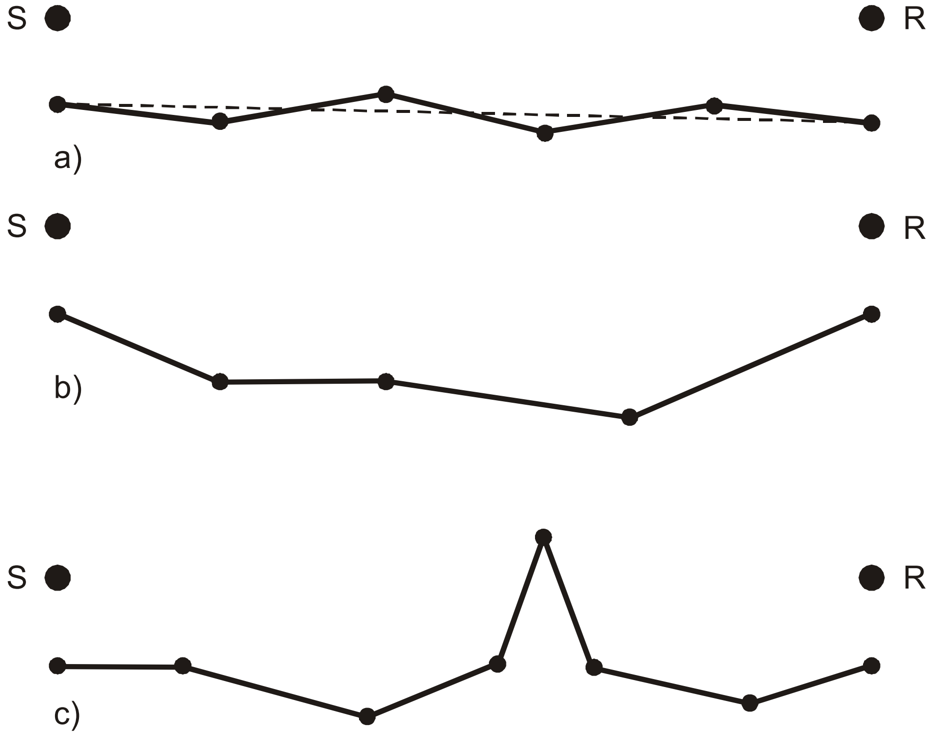

Figure 1
Examples of segmented terrain: a) virtually flat terrain, b) valley-shaped terrain, c) hill-shaped terrain.

Barrier profiles are also represented by a number of straight-line segments with the surface property defined by the acoustical impedance. Only the two most significant diffracting edges are considered. With multiple barriers, the two most efficient barriers are included in the calculations. In case of finite length of screens, the contribution from diffraction around the vertical edges is included. The effect of specially designed screens (screens with special shapes and made of special material) cannot be calculated. Instead, a special screen has to be replaced by a thin screen, and its attenuation in excess of the attenuation provided by the thin screen shall be specified in a table.

Meteorological parameters such as wind and temperature gradient are used to approximate the vertical effective sound speed profile. The effective sound speed is the sum of the sound speed and the component of the wind speed in the direction of propagation, but will in the following simply be called the sound speed. If the sound speed varies with the height (the vertical sound speed gradient differs from 0), atmospheric refraction will occur. Refraction is the effect where a sound wave is bent towards regions where the sound speed is low. If the wind is blowing from the source towards the receiver (downwind propagation), or if the temperature is increasing with the altitude (positive temperature gradient) which frequently happens at night, the sound wave will be bent towards the ground (downward refraction). On the other hand, if the wind is blowing from the receiver towards the source (upwind propagation), or if the temperature is decreasing with the altitude (negative temperature gradient) which frequently occurs in daytime particularly on sunny days, the sound wave will be bent away from the ground (upward refraction).

In Nord2000, refraction is modelled by using curved sound rays. The curvature of the rays depends on the vertical sound speed profile and is determined using a semi-analytical approach. In this approach, it is assumed that the sound speed varies linearly with the height above the ground in which case the rays will be circular arcs leading to fairly simple equations. Most often, the weather conditions are better represented by an approximately logarithmic sound speed profile. Therefore, a principle has been elaborated for determining the equivalent linear sound speed profile for such sound speed profiles. Short-term time averaging and decorrelation effects are included based on short-term variation of meteorological conditions and on turbulence strength parameters. Generally, the Nord2000 model is valid only for moderate refraction defined as weather where the ground effects are not dominated by multiple ground reflections and shadow zones. To extend the applicability of Nord2000, methods have been elaborated to include the effect of additional rays from multiple ground reflections in case of strong downward refraction and the effect of shadow zones in case of strong upward refraction. However, these methods are rough approximate methods.

Air absorption is calculated according to ISO 9613-1.

Nord2000 may also predict sound propagation through “scattering zones” which are urban areas and vegetation. In urban areas the sound propagation is influenced by multiple reflections, diffuse scattering by irregularities of building facades, diffraction at house corners and absorption by buildings and ground surfaces. In case of vegetation, mainly forests, the sound propagation is influenced by reflection, scattering, and absorption due to trunks, branches and foliage. In such areas, sound propagation is much too complicated for a deterministic model, and it has been necessary to use a statistical scattering model. Such a model will not predict the exact sound pressure level at a specified location, but rather the average sound pressure level at a specified distance from the source. Thus, the sound shadow behind an object and the increase in sound level in front of the object are not taken into account. Methods have been elaborated for combining the statistical scattering model with the rest of the Nord2000 propagation model.

More details about the propagation model can be found in Part 2 of the present report: "Propagation Model", and a complete description can be found in [17] and [18].

4. Propagation Model Variables

The input variables that may be taken into account by the Nord2000 propagation model are:

- The terrain profile defined by start and end coordinates of the straight-line segments and the ground flow resistivity and roughness (unevenness) of each segment
- Height of source and receiver above the first and last terrain point, respectively
- Aerodynamic roughness length of the ground (used to define the wind speed profile)
- The average wind speed component in the direction of propagation and the height the wind speed is specified for
- The standard deviation of variations in wind speed component
- Temperature at the ground
- Average temperature gradient
- Standard deviation of temperature gradient variations
- Turbulence strength parameters due to wind and temperature, respectively
- Relative air humidity

Although no final decision has yet been made, it is most likely that only some of the parameters will be available in a public implementation of Nord2000 for normal types of calculation. Particularly, the standard deviation of the wind speed, the standard deviation of the temperature gradient and the turbulence strength parameters are not easily estimated by the common user and are likely to be fixed by appropriate values. Some of the other parameters (like the temperature gradient) are likely to be determined indirectly based on a verbal description of the weather type (e.g. daytime and overcast, nighttime and clear sky, etc.). Ground flow resistivity and ground roughness will also be defined by verbal descriptions as shown in Table 1 for ground types.

Ground class	**Representative flow resistivity σ (kNsm^{-4})**	**Description**
A	12.5	Very soft (snow or moss-like)
B	31.5	Soft forest floor (short, dense heather-like or thick moss)
C	80	Uncompacted, loose ground (turf, grass, loose soil)
D	200	Normal uncompacted ground (forest floors, pasture field)
E	500	Compacted field and gravel (compacted lawns, park area)
F	2000	Compacted dense ground (gravel road, parking lot)
G	20000	Hard surface (dense asphalt, concrete, water)

Table 1
Classification of ground impedance types.

The effect of scattering zones is determined on the basis of:

- The position of scattering zones
- The density and the average size and reflection properties of houses or trees

It is not likely that a public implementation of Nord2000 will contain these variables, but they will be determined indirectly based on a verbal description of the type of scattering zone like e.g. “detached housing area” or “dense spruce forest”. However, such classification has not yet been made.

5. Sources Modules

New source models for road and rail vehicles have been developed and are described in [5] and [6]. Each vehicle is represented by at least three sources, at different heights. The source height is important for the attenuation due to screening and ground reflection. The sources are located at the nearest wheel side, not at the centre line as in earlier methods, and the calculations have to be carried out for each lane or track separately. A vehicle pass-by is simulated by a distribution of point sources placed along the line of travel. The source models contain horizontal directivity, which is particularly important in calculations of maximum noise levels. Sound power levels in third octave bands are given for three categories of road vehicles and for twenty types of train.

Besides source models, the source modules contain a description of noise emission from tunnel openings and how to handle multiple reflections in city streets or in the case of depressed roads and roads with parallel barriers.

5.1 Road Traffic Noise

In the source module for road traffic, source sound power levels have been derived from new measurement results. The new results have not been collected as a part of the Nord2000 project, but have been made available from other projects [38]. In the road traffic noise module [6] vehicles are divided into 5 main categories: light vehicles (cars), dual-axle heavy vehicles, multi-axle heavy vehicles, motor cycles and mopeds, and the first 3 categories are further divided into 2-4 subcategories. Road surfaces are divided into 8 main categories, most of them containing subcategories, and driving conditions are divided into 6 categories.

In the preliminary source model data only exist for vehicle categories 1, 2 and 3 (light vehicles, dual-axle heavy vehicles, multi-axle heavy vehicles) and only for dense asphalt and the driving condition “cruising”.

Source data in the new source model expressed by L_{AE} at 10 m from the road compared with source data in the old prediction method [41] are shown in Figure 2. The new data for light vehicles (DK1) show a fine agreement with the old data at speeds below 80 km/h, but slightly higher values at 85-120 km/h. New data for medium trucks (DK2) correspond approximately to the old data for mixed heavy trucks, and heavy trucks (DK3) are a few dB higher. With a mix of medium and heavy trucks as assumed in the old prediction method, the new source module would give approximately 1 dB higher values than the old method.

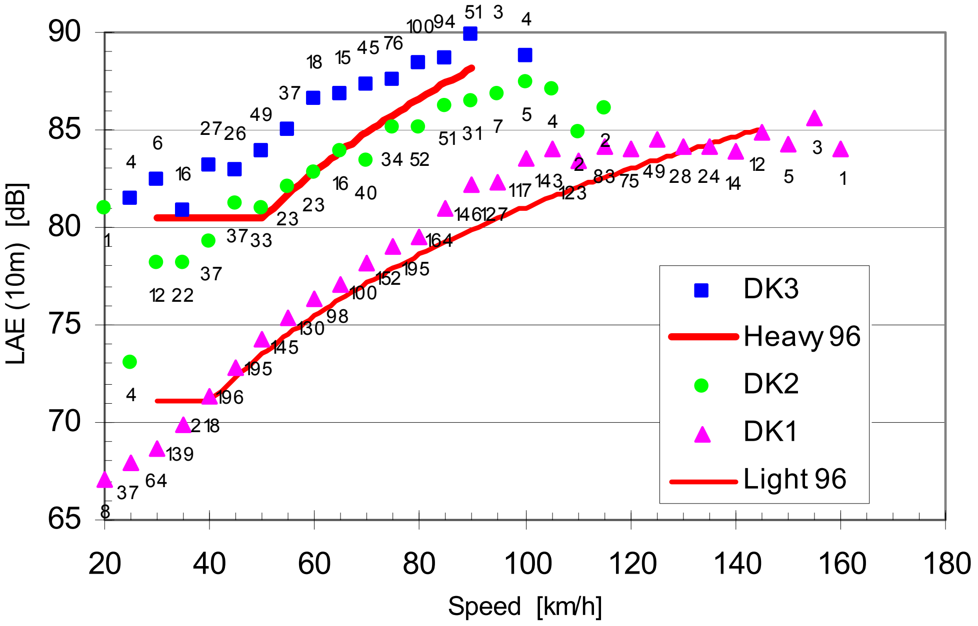

Figure 2
L_{AE}(10m) calculated using the source sound power levels determined in the Danish measurement series [38] compared with the basis values in [41]. The data labels show the number of vehicle pass-bys represented by each data point.

5.2 Rail Traffic Noise

In the same way as for road traffic, train types are divided into a number categories and subcategories, but these categories are in general more representative of a single train type than of a group of trains as was the case for road vehicles. Furthermore, individual classification has been made for each Nordic country. Track types are divided into 4 main categories with 3 subcategories each. Driving conditions are divided into 4 categories.

Source sound power levels have been obtained by adapting the sound power levels of the existing prediction method [40] to the new source model. The data of the existing method given in octave bands have been converted to one-third octave bands by interpolation as described in [6] and corrected for differences in predicted ground effect according to the old and new method at the measurement sites. For Swedish and Norwegian trains the train types are the same as given in [40]. The Danish train data were published in 1998 [36] and intended for future inclusion in [40].

The Swedish trains include:

- The high-speed passenger train X2
- Conventional passenger trains, mainly with Rc locomotives
- Goods trains, mainly with Rc locomotives
- Goods trains, mainly with T44 locomotives
- A suburban train, which also includes the types X10 and X12

The Norwegian trains include:

- Suburban train B65, which also includes B67 and B68
- Suburban train B69
- Intercity train B70
- Long-distance passenger trains
- Goods train

The Danish trains include:

- Passenger train sets: diesel trains (IC3), electric trains (IR4)
- Locomotive-driven trains: diesel passenger trains with MZ or ME locomotive, diesel goods trains with MZ or ME locomotive, electric passenger trains with EA locomotive, electric goods trains with EA locomotive
- Diesel train sets (MR), Y-trains, IC2 trains, RegioSprinter, Desiro
- S-trains of 2nd and 3rd generation
- S-trains of 4th generation

6. *Applicability*

In Nord2000 the source model is separated from the propagation model, and the same propagation model is assumed to be applicable for all kinds of sources. At present only source modules for road and railway noise have been developed as described above. However, it should not be difficult to use the propagation model to calculate the noise from wind turbines or from industrial plants if point source representations of the real sources can be identified in the latter case. The propagation model is also applicable for aircraft noise, but in this case, the aircraft noise data bases containing noise-power-distance data (NPD) should be converted into sound power levels including directivity characteristics.

Noise from roads and railways and from a point source can be calculated at a single receiver using the free demonstration software DN2000 which can be downloaded from www.delta.dk/nord2000/.

Basically, the Nord2000 model allows calculation of short-term levels for specified weather conditions such as short-term equivalent sound pressure levels or maximum levels.

Long-term noise levels can be obtained by combining the short-term noise levels calculated by Nord2000 with meteorological statistics. In practice, the short-term level calculations are made for a limited set of meteorological classes, and the long-term levels are the weighted average of these results. This approach makes it possible to calculate long-term levels such as the yearly average L_{den} and L_{night} specified as noise indicators in the EU Directive on environmental noise [37], maximum noise levels for longer periods, or even complete statistical distributions of noise levels.

7. Accuracy of the Model

The ambition has been to obtain good accuracy up to 1000 m and acceptable accuracy up to 3000 m. However, no precise definition of “good” and “acceptable” has been established. The model has only been validated by measurements at distances up to 200 m where a good accuracy has been found (deviations within ±2 dB of overall A-weighted sound pressure levels in most cases). To some extent the model has, however, been validated by other accurate calculation methods (such as e.g. PE) at larger distances. Although it has not been truly validated, the model is also expected to be accurate for high sources.

The model is particularly accurate at small distances. Although people in general are situated at some distance from a noise source, the accuracy at small distances may be of interest and even crucial when determining sound power levels. If the conversion of sound pressure levels measured at small distances to sound power levels is failing, the error from the conversion is fully imposed on the calculated results at larger distances. Two measurement results for small distances are shown in Figure 3 and Figure 4. Predictions by Nord2000 show a fine agreement with the measurements whereas the predictions by the Nordic model for noise from industrial plants [39] show substantial deviations.

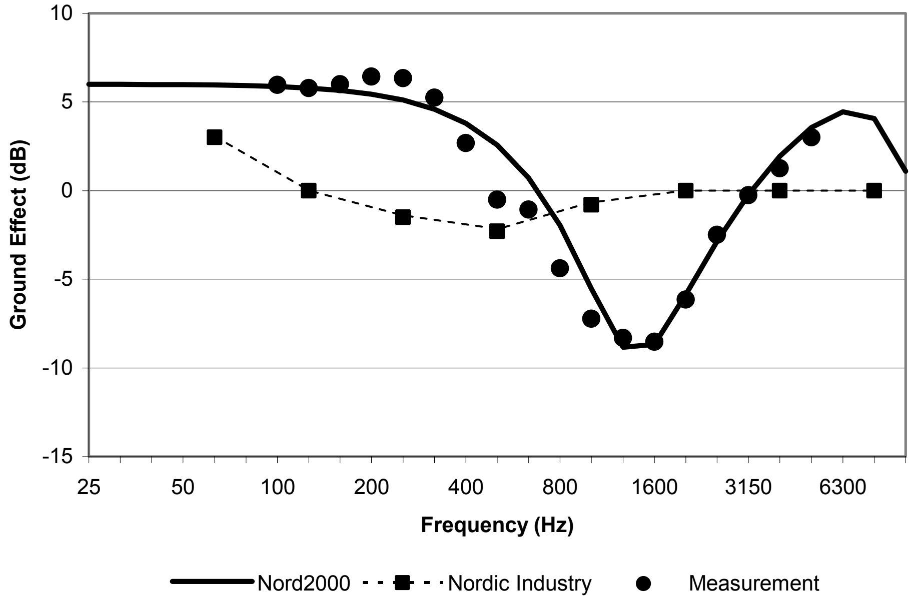

Figure 3
Propagation over flat grass-covered ground, propagation distance 4.5 m, source and receiver height 0.25 m.

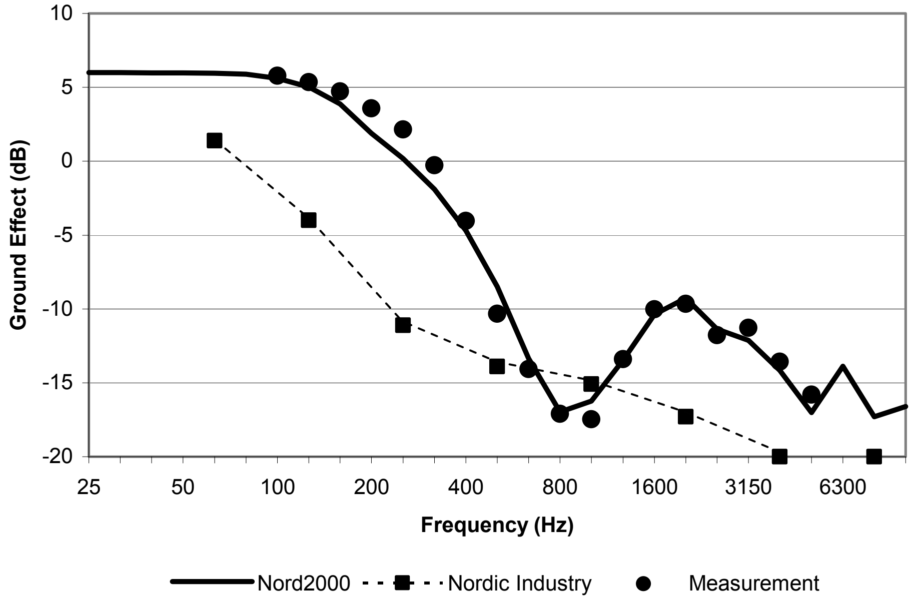

Figure 4
Same geometry as in Figure 3, but with a 1 m high screen placed 1.5 m from the source.

An example of propagation over 20 m non-flat terrain with a screening effect is given in Figure 5. Again a fine agreement is obtained by Nord2000 and less good agreement by the Nordic industry model. The measurement has been made in a calm atmosphere while the latter model is a downwind model. However, due to the moderate propagation distance the weather should not influence the result.

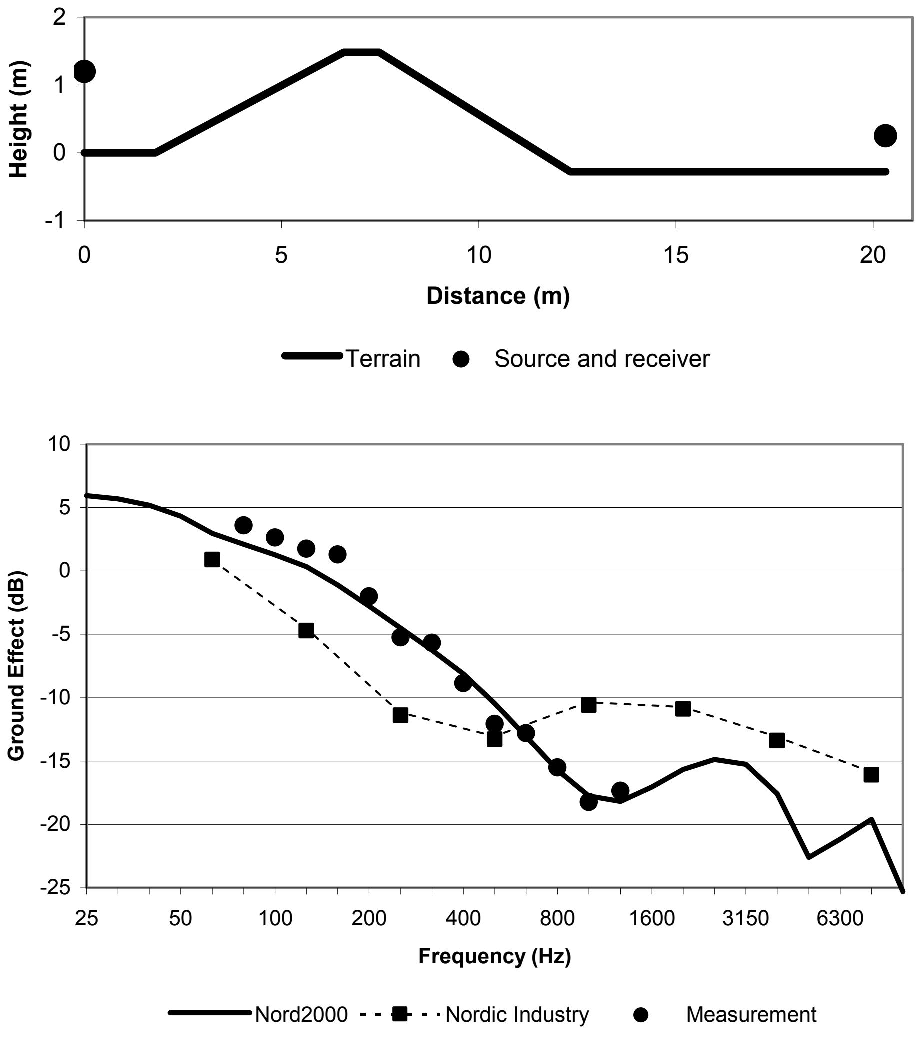

Figure 5
Propagation over non-flat terrain with a screening effect. Propagation distance 20 m, source height 1.2 m, receiver height 0.25 m.

Another example of propagation over 60 m of valley-shaped terrain is given in Figure 6 which shows that a good agreement is obtained by Nord2000. The agreement obtained with the Nordic industry model is acceptable above 300 Hz although some underestimation is observed above 1 kHz. However, below 300 Hz severe underestimation is taking place. Again, the measurement has been made in a calm atmosphere while the Nordic industry model is a downwind model. However, due to the shape of the terrain the weather is not expected to influence the result significantly.

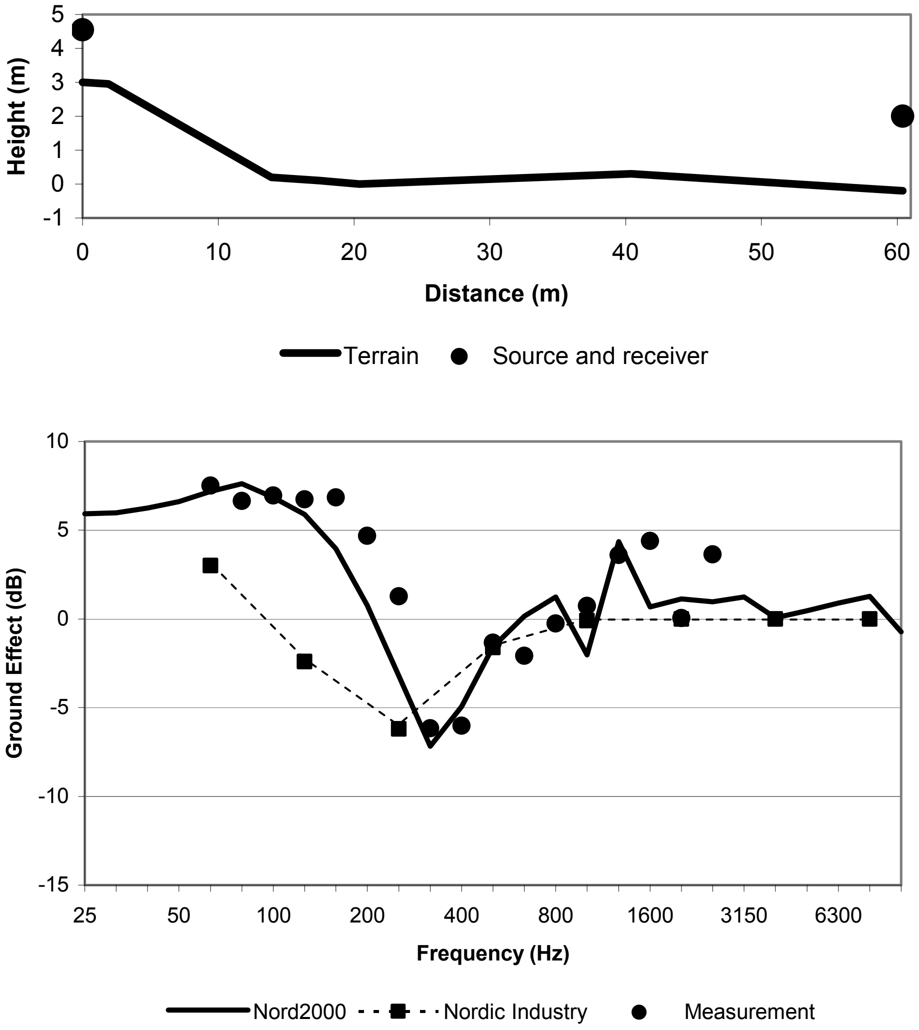

Figure 6
Propagation over a valley-shaped terrain. Propagation distance 60 m, source height 1.55 m, receiver height 2 m.

8. Comparison with Older Methods

Limited comparison between predictions by Nord2000 and by the old road and rail traffic prediction methods [41] and [40] has been carried out and is described in [5] and [6], respectively.

8.1 Road Traffic Noise

The Nord2000 propagation model will predict higher attenuation than the old road traffic noise prediction method [41] for a homogeneous atmosphere without vertical wind and temperature gradient. This is not surprising, as the old method has been shown to give rather good agreement with results of measurements made under moderate downwind conditions. Simulating such conditions with Nord2000 yields a rather good agreement between the two methods.

The old prediction method uses the same frequency spectrum for all calculations of the ground and barrier attenuation. As Nord2000 uses actual spectra for all speeds, this will cause a difference in excess attenuation when expressed as overall A-weighted sound pressure levels. The limited comparisons in [5] indicate that the spectrum variation will normally affect the A-weighted excess attenuation by less than 2 dB.

8.2 Rail Traffic Noise

It is not easy to draw any firm conclusions based on the limited comparison in [6]. For simple cases like flat ground with or without an elevated track bed, the difference between the old model and Nord2000 is rather small although there is a tendency that Nord2000 yields slightly higher sound pressure levels.

When screening occurs, the situation gets complicated. Occasionally, there are large differences. The general trend, if any, is that Nord2000 with neutral conditions yields higher attenuation while the opposite is the case when 3 m/s downwind conditions are used.

Part 2

Propagation Model

A. Basic Components

The sound pressure level L_R at the receiver is predicted by the following equation for each frequency band:

$$L_R = L_W + \Delta L_d + \Delta L_a + \Delta L_t + \Delta L_s + \Delta L_r$$

where

L_W is the sound power level within the considered frequency band,

ΔL_d is the propagation effect of spherical divergence of the sound energy,

ΔL_a is the propagation effect of air absorption,

ΔL_t is the propagation effect of the terrain (ground and barriers),

ΔL_s is the propagation effect of scattering zones,

ΔL_r is the propagation effect of obstacle dimensions and surface properties when calculating a contribution from sound reflected by an obstacle.

The propagation effects mentioned above are assumed to be independent and can therefore be predicted separately. The only exception is the effect of the terrain ΔL_t and the effect of scattering zones ΔL_s which may interact to some extent as a decrease in coherence introduced by the latter effect may affect the prediction of the former effect.

The propagation effects are determined on the basis of propagation parameters measured along the propagation path from the source to the receiver. The propagation path is the projection of the source-receiver line onto the horizontal plane. Normally, the propagation path is a straight line between the source and the receiver. However, when sound is diffracted around the vertical edge of a screen with a finite length or reflected by an obstacle, the propagation path will be a broken line.

If the point source is not omnidirectional, but has a directivity pattern, L_W is determined as the sound power level of the equivalent monopole which produces the same sound pressure level in the direction of the propagation path as the directivity-dependent source. L_W should therefore be interpreted as the combination of the sound power level and the directivity correction.

B. Air Absorption

The calculation of air absorption is based on predictions at the centre frequency of the one-third octave band by ISO 9613-1, but is supplemented by an analytical method for estimating the attenuation in the frequency band on the basis of this value.

C. Ground Effect

One of the cornerstones in the Nord2000 propagation model is the ground effect model which predicts the propagation effect of a flat homogeneous ground surface. The model is based on geometrical ray theory.

A sound wave transmitted from a point source is a spherical wave where the sound energy is spread equally in all directions. Therefore, for a spherical sound field the amplitude decreases with the distance from the source. Furthermore, the phase of the sound field changes with distance due to the propagation time. How fast the phase is changing depends on the frequency, as the phase will shift 360° each time the sound wave has travelled a distance equal to the wavelength.

When sound propagates close to the ground, the sound wave transmitted directly from source to receiver interacts with the sound reflected from the ground as shown in Figure 7. If the ground is not hard, but has a finite impedance, which e.g. is the case for grassland, the sound wave will be attenuated at the reflection and also shifted in phase. The attenuation and phase shift are expressed by the so-called spherical-wave reflection coefficient. The spherical-wave reflection coefficient depends on the propagation distance R_2, the grazing reflection angle Ψ_G and the ground impedance. Due to the difference in travelling distance and the phase shift from the reflection, there will be a difference in phase between the direct and reflected sound wave. In general, the phase difference increases with frequency.

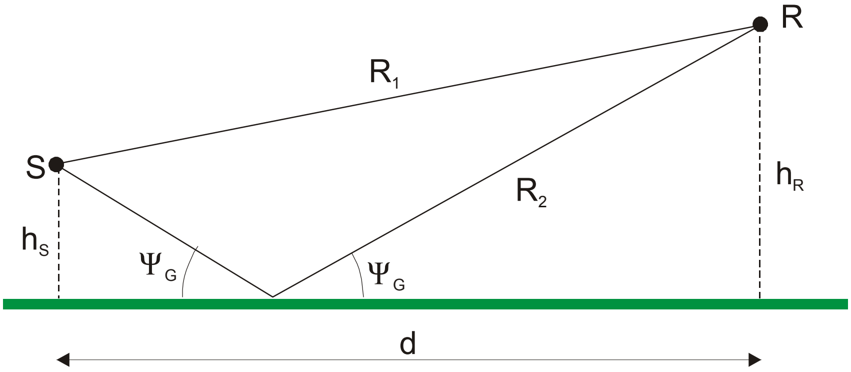

Figure 7
Propagation over flat ground.

At very low frequencies, the phase difference is small, and the combined sound pressure is doubled relatively to the sound pressure without the ground leading to a ground effect of +6 dB. The ground effect is defined as the difference between the sound pressure level in the presence of the ground and the free-field sound pressure level. At a higher frequency, the phase difference will increase to 180° (out of phase) in which case the direct and reflected fields tend to cancel each other. However, due to small differences in amplitude caused by the difference in travelling distance and by the attenuation at the reflection, the sound field is not totally cancelled. Increasing the frequency further, the phase difference becomes 360° (in phase) creating another constructive interference with a ground effect close to 6 dB. This pattern where destructive and constructive interferences are replacing each other is continuing at higher frequencies. However, as the pattern is repeated approximately on a linear frequency scale, due to averaging within the bands, it is often not observed at high frequencies when the results are shown as one-third octave band spectra.

The propagation effect of the ground surface can be seen in Figure 8 for three different kinds of surface. The propagation distance and the source and receiver heights are the same for all three surfaces, and the considerable variation in the frequency of the first interference dip is due to difference in the ground impedance. Ground impedance is mentioned in Section D.

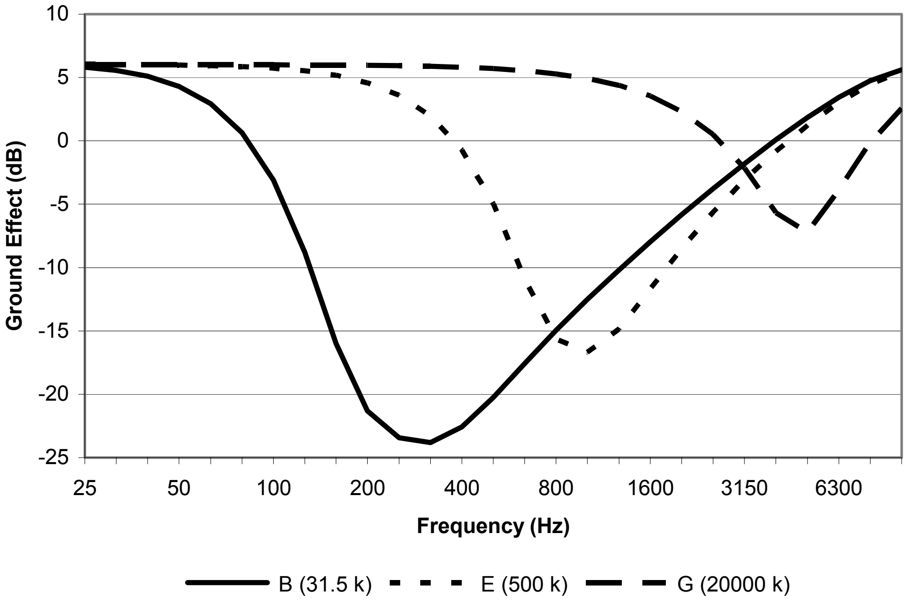

Figure 8
Ground effect of flat ground.

D. Ground Impedance

In Nord2000 the acoustical properties of a ground surface are determined by the normalized characteristic impedance. However, the impedance is defined indirectly by specifying the flow resistivity of the ground surface. The flow resistivity is a parameter describing the “softness” of the ground. The smaller the flow resistivity, the “softer” the ground. A fully reflecting ground corresponds to an infinite flow resistivity. When used in Nord2000, the impedance is calculated on the basis of the flow resistivity by the “Delany and Bazley” impedance model.

In Nord2000 ground surfaces are divided into 7 ground classes as shown in Table 1, Part 1.

E. Screen Effect

Another basic model in the Nord2000 propagation model is the screen effect model which predicts the sound pressure level when the receiver is in the shadow zone behind a barrier. The screen effect model is based on geometrical theory of diffraction.

The model is valid for a wedge-shaped screen as shown in Figure 9. In the model the screen effect depends on the distances R_S and R_R from the top edge of the wedge to the source and receiver, the diffraction angles θ_S and θ_R, and the wedge angle β. Different surface impedances may be assigned to the two wedge faces. Generally, the screen effect will increase when θ_S-θ_R is increased and decrease when R_S and R_R are increased.

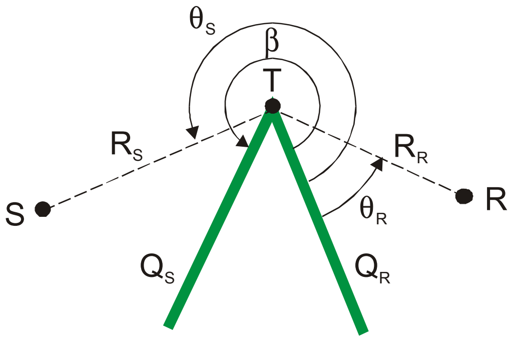

Figure 9
Diffraction by a wedge-shaped screen.

In the model, it is assumed that the screen is infinitely long. In case of screens with finite length, the contribution from sound diffracted around the side edges is taken into account in an approximate manner.

F. Double-Edge Screen and Two Screens

In case of two screens as shown in Figure 10 or one screen with two edges as shown in Figure 11, approximate methods are applied based on the solution for the wedge-shaped screen. Shortly explained, the screen effect is calculated for each edge separately, placing the source or receiver on top of the other edge. After calculation of individual screen effects, the combined effect is calculated using a procedure which differs slightly in the two-wedge and two-edge case.

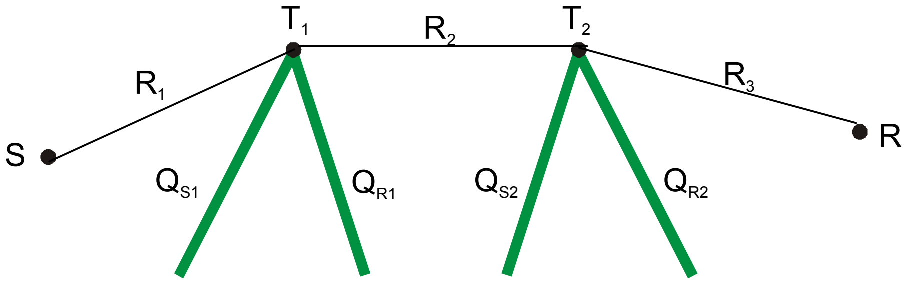

Figure 10
Diffraction by two wedge-shaped screens.

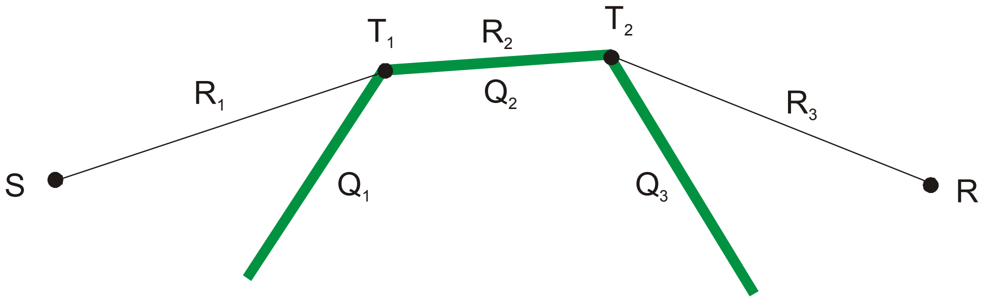

Figure 11
Diffraction by a screen with two edges.

In principle, the procedure for combining the effect of individual diffracting edges can be extended to any number of screens and screens with any number of edges. However, this will increase the complexity of the calculations very much, and it is doubtful whether the accuracy will increase significantly. Therefore, only the two most significant diffracting top edges are considered in the calculations which may be one screen with two edges or two screens with one edge each.

G. Special Screens

It has been a requirement that all propagation parameters that significantly affect the noise level should be taken into account in the new Nordic prediction methods, and it has been considered particularly important that any serious attempt at noise reduction should be reflected in the calculation result. As the acoustic performance of specially designed barriers (barriers with special shape or barriers made of special material) may be significantly better than the performance of a plane and reflecting barrier, the propagation model should make allowance for such improvement.

The methods of Nord2000 do not allow direct calculation of the effect of a specially designed screen, but instead such a screen is replaced by a thin screen, and the attenuation of the special screen in excess of the thin screen attenuation is included in tabular form.

H. Scattering of Sound into the Shadow Zone of a Screen

Turbulence caused by random wind and temperature variation causes part of the sound energy to be scattered into the shadow behind a screen and thus reduces the effect of the screen, particularly for high frequencies.

In Nord2000, a model is included for predicting the contribution of energy scattered into the shadow zone which is added to the result of the screen model. The predicted result depends on the screening geometry, the turbulence strength and the frequency.

I. Combination of Ground and Screen Effect

When a screen is placed on the ground, the effect of reflection from the ground surface before and after the screen is combined with the screen effect according to the so-called “image method”. The model combines contributions from four rays as shown in Figure 12: 1) source S – receiver R, 2) image source S' – receiver R, 3) source S – image receiver R' and 4) image source S' – image receiver R'. For each ray the sound pressure p_i, where subscript i is the ray number, is calculated using the diffraction model described in Section E. Ray no. 2 is reflected by the ground on the source side of the screen, and the contribution is therefore obtained by multiplying the sound pressure p_2 by the spherical-wave reflection coefficient Q_1. In the same way p_3 has to be multiplied by Q_2 for ray no. 3 and p_4 by Q_1Q_2 for ray no. 4 as reflections take place on both sides of the screen in the latter case. The combined sound pressure is obtained by adding the four contributions:

$$p = p_1 + Q_1\, p_2 + Q_2\, p_3 + Q_1\, Q_2\, p_4$$

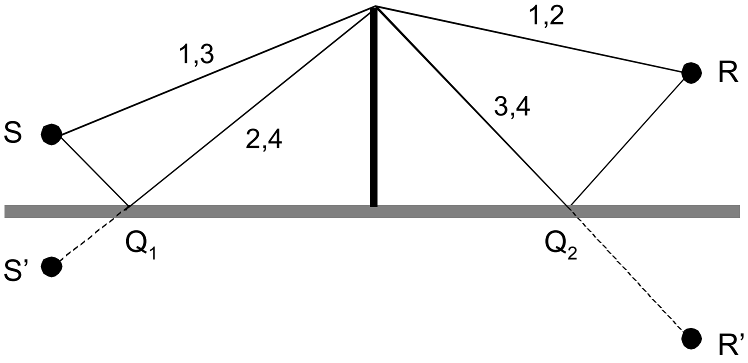

Figure 12
Combining ground and screen effect. One screen

In the case of two screens, a similar principle is used, but due to the reflection between the screens, the number of rays in the model will be eight as shown in Figure 13.

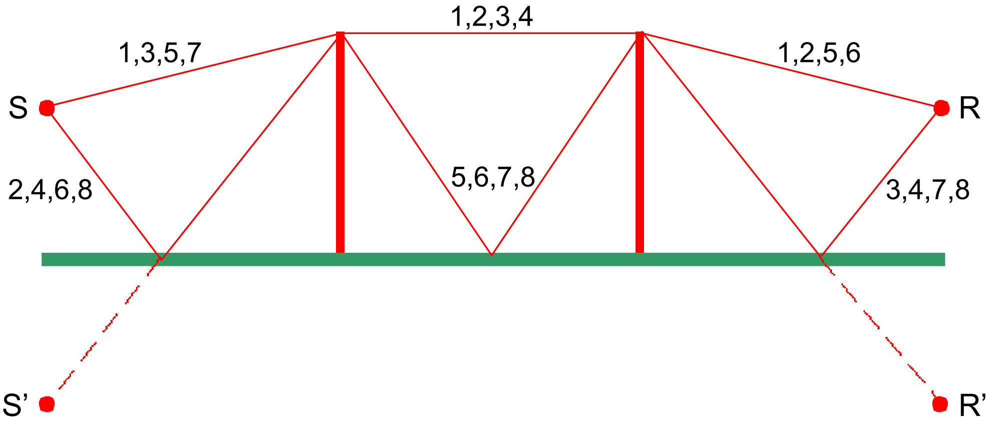

Figure 13
Combining ground and screen effect. Two screens

J. Fresnel-Zones

The concept of Fresnel-zones has been widely used in the Nord2000 model. In the calculation of ground effect, the sound field at the receiver is assumed to be determined by the surface properties in a region around the reflection point which is denoted the Fresnel-zone.

The determination of the size of the Fresnel-zone is based on the Fresnel ellipsoid which is defined as the locus of points P where the sum of the distances to the source S and receiver R minus the direct distance between S and R is a fraction F of the wavelength λ:

$$|SP| + |RP| - |SR| = F\lambda$$

The foci of the ellipsoid are placed at S and R. The Fresnel ellipsoid is a way of quantifying the effective size of the sound field. Generally, it can be said that only the part of the sound field inside the Fresnel ellipsoid will contribute to the sound pressure at the receiver. The Fresnel ellipsoid will narrow with increasing frequency. Depending on the purpose, F will be in the range from 1/16 to 1/2.

When the sound field is reflected by a plane surface, the Fresnel-zone is defined by the intersection between the plane and the Fresnel ellipsoid with foci at the image source point S' and the receiver R as shown in Figure 14. The shape of the Fresnel-zone is therefore an ellipse.

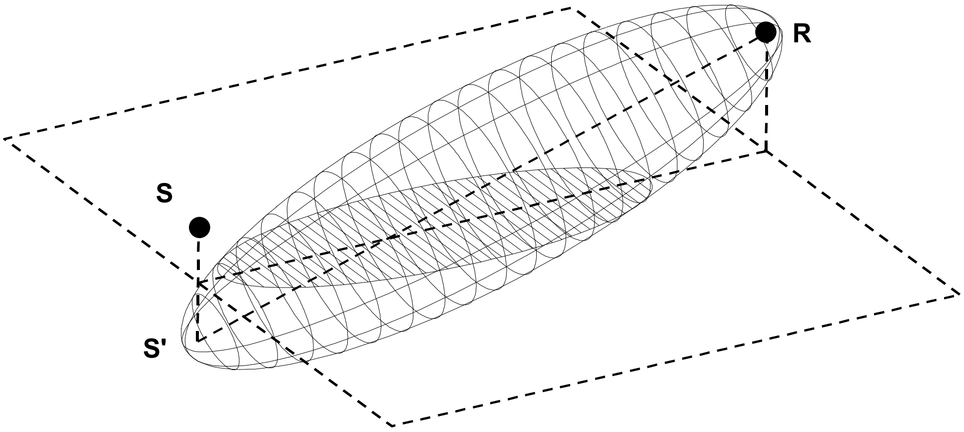

Figure 14
Fresnel ellipsoid and Fresnel-zone.

For practical purposes, this elliptical shape is very inconvenient to work with when calculating subareas within the Fresnel-zone and it has been chosen in Nord2000 to use the circumscribed rectangle.

K. *Flat Terrain. Varying Ground Surface Properties*

A typical example of variation in ground surface types is propagation from a vehicle on a road with a hard surface to a receiver placed over grassland with low impedance. If only one type of ground exists within the Fresnel-zone, the calculation of ground effect is performed for this type alone. If more ground types appear, the ground effect is determined for each type within the Fresnel-zone using the base model for a homogeneous ground surface. The fraction denoted the Fresnel-zone weight of each ground surface type within the Fresnel-zone is then calculated and used to interpolate between the calculated ground effects of each ground surface type. In case of flat terrain and varying surface properties F = ¼ is used. The principle is illustrated in Figure 15 for the surface type changing along a straight line. The sizes of the cross-hatched area and the hatched area relative to the total size of the Fresnel-zone are used in the interpolation.

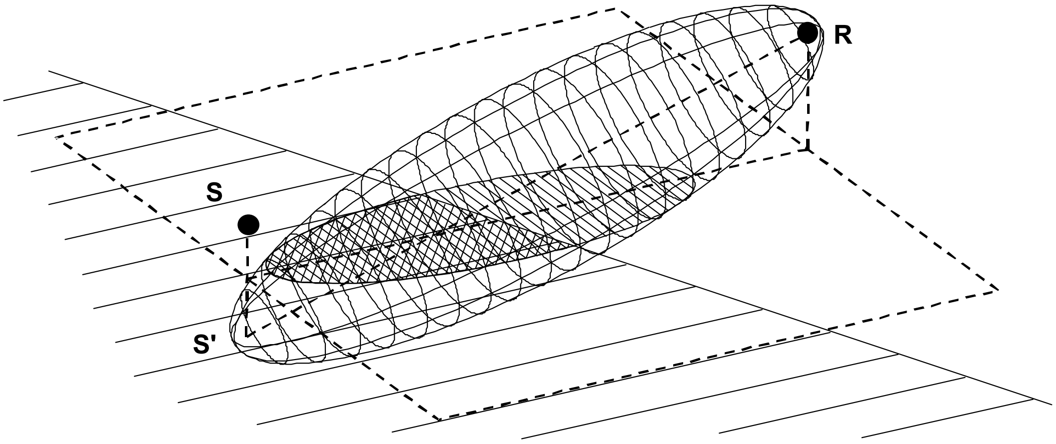

Figure 15
Fresnel-zone in case of a ground type change.

L. Non-Flat Terrain

Also in the case of non-flat terrain, the Fresnel-zone method has been found to be applicable using an F-value of 1/16. For a terrain without screens, the ground surface is approximated by a number of straight-line segments as shown in Figure 16.

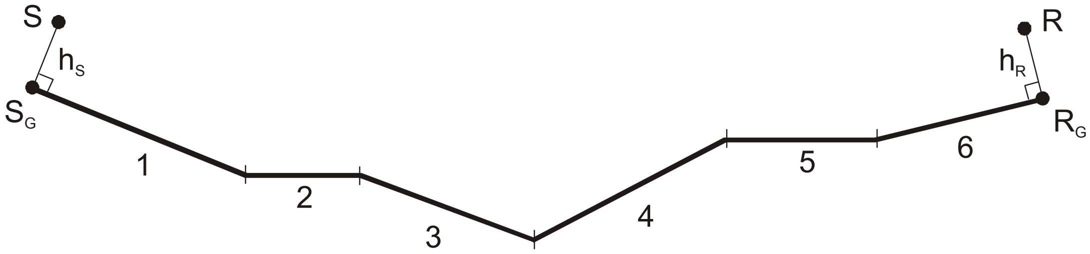

Figure 16
Valley-shaped non-flat terrain.

For all segments except no. 4 the ground effect can be calculated by the base model, using the horizontal propagation distance and source and receiver height measured relatively to the extended segment. In the same way, the Fresnel-zone weight of each segment defined by the size of segment within the Fresnel-zone relative to the entire size of the Fresnel-zone is calculated. For segment no. 4 where the receiver is below the extension of the segment, neither the ground effect base model nor the Fresnel-zone concept is longer applicable. In such cases, the ground effect is calculated using the screen model and the Fresnel-zone weight by a modified principle. The overall ground effect is then obtained by adding the contributions of each segment, which is the calculated ground effect multiplied by the Fresnel-zone weight.

The Fresnel-zone method is also applicable for non-flat terrain with a screen, although the calculations become somewhat more complicated. The calculation of the combined screen and ground effect is performed for each combination of terrain segments before and after the screen. A Fresnel-zone weight is calculated for each segment before and after the screen with receiver or source replaced by the screen top. The calculation result of each combination of terrain segments is multiplied by the corresponding product of the Fresnel-zone weights before and after the screen and added together to an overall propagation effect. The method may also be used for two screens, in which case the segments between the screens and the corresponding Fresnel-zone weights are included in the combinations.

M. Incoherent and Averaging Effects

In the basic propagation models, it is assumed that contributions from interacting rays are added coherently. However, such models produce much stronger dips in the attenuation spectrum at high frequencies than are observed in outdoor measurements. In practice, incoherent and averaging effects will smooth out the interference pattern in the frequency spectrum.

A method for including incoherent and averaging effects has been included in Nord2000 and comprises:

- Effect of frequency band averaging
- Effect of fluctuating refraction
- Effect of turbulence
- Effect of surface roughness
- Effect of scattering zones

The effect of frequency band averaging covers the averaging within each one-third octave band.

The effect of fluctuating refraction covers the averaging due to short-term fluctuations in atmospheric refraction mainly due to fluctuations in the wind speed and direction.

The effect of turbulence covers the reduction in coherence between the rays imposed along the ray path by atmospheric turbulence.

The effect of surface roughness covers the effect that is observed when a reflecting surface is not perfectly even, but contains random height variations.

Finally, the effect of scattering zones covers the reduction in coherence obtained when the sound field is passing a scattering zone. The scattering zone may be a housing area or a forest. The effect of scattering zones is described in general in Section P, but may influence the propagation effect of terrain and screens by reducing the coherence.

N. Weather Influence

Meteorological parameters such as wind and temperature gradients are used to approximate the vertical effective sound speed profile. The effective sound speed is the sum of the sound speed and the component of the wind speed in the direction of propagation, but will in the following simply be called the sound speed. If the sound speed varies with height (the vertical sound speed gradient differs from 0), atmospheric refraction will occur. Refraction is the effect where a sound wave is bent towards regions where the sound speed is low. If the wind is blowing from the source towards the receiver (downwind propagation), or if the temperature is increasing with the altitude (positive temperature gradient) which frequently happens at night, the sound wave will be bent towards the ground (downward refraction). On the other hand, if the wind is blowing from the receiver towards the source (upwind propagation), or if the temperature is decreasing with the altitude (negative temperature gradient) which frequently occurs during daytime, particularly with a clear sky, the sound wave will be bent away from the ground (upward refraction).

In Nord2000, refraction is modelled by using curved sound rays. The curvature of the rays depends on the vertical sound speed profile and is determined using a simple approach. In this approach, it is assumed that the sound speed varies linearly with the height above the ground, in which case the rays will be circular arcs leading to fairly simple equations. Examples of the bending of rays in downward and upward refraction are given in Figure 17. In downward refraction, the difference in path length between the direct and reflected path and the grazing reflection angle will increase while the opposite will happen in upward refraction. Generally, the resulting effect will be that the interference frequency dips move towards lower frequencies in downward refraction and towards higher frequencies in upward refraction.

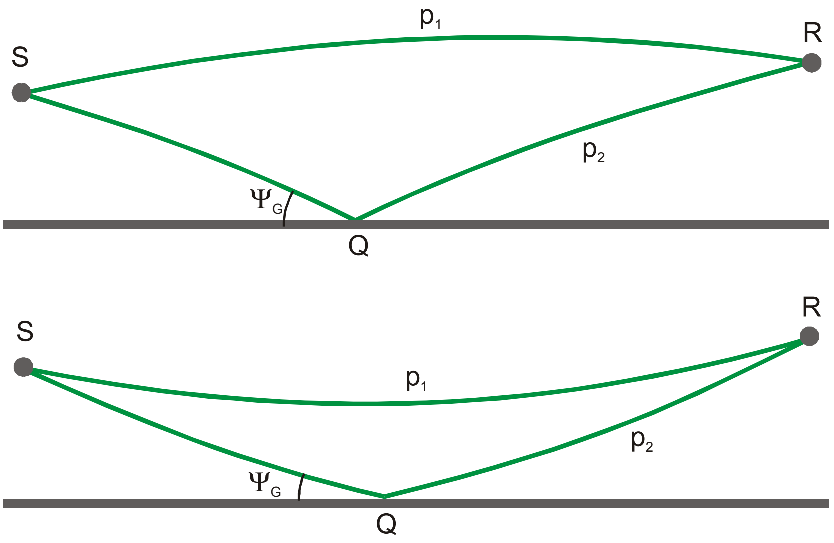

Figure 17
Curved ray paths. Top: Downward refraction. Bottom: Upward refraction.

Most often, the weather conditions are better represented by an approximately logarithmic sound speed profile. Therefore, a principle has been elaborated for determining of the equivalent linear sound speed profile for such sound speed profiles.

The screen effect is also affected by the weather in a number of ways as shown in Figure 18. The diffraction angles are affected by the bending of the rays, reducing the screen effect in a downward refracting atmosphere and increasing it in an upward refracting atmosphere. At the same time, the ground effect part of the propagation effect will be affected by the ray curvature on each side of the screen in the same way as described for flat terrain.

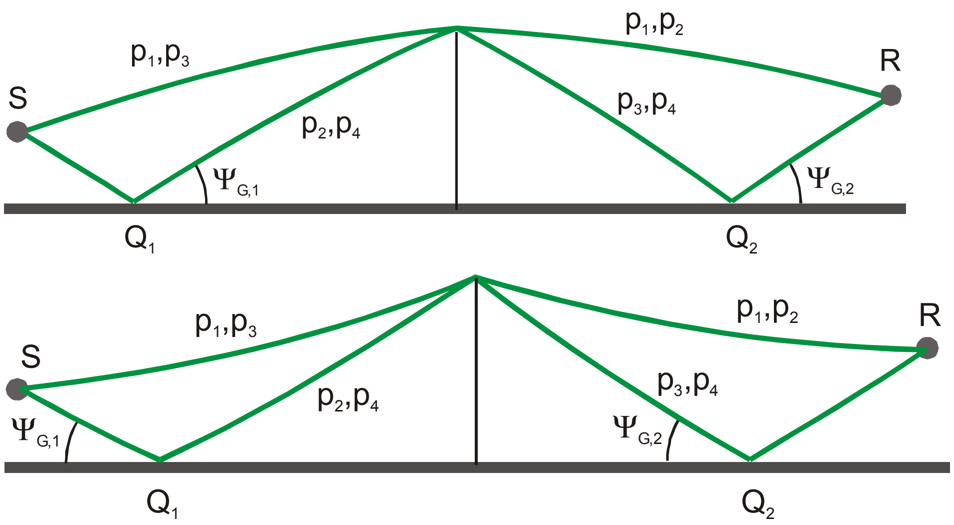

Figure 18
Curved ray paths in case of a screen. Top: Downward refraction. Bottom: Upward refraction.

In case of refraction, the calculation of Fresnel-zones has to be modified to deal with the circular rays. This is done by bending the Fresnel-zone ellipsoid so that its axis of rotation follows the curved ray. In practice, it is done by transforming the curved ray case into a straight-line ray case leading to modified source and receiver positions S' and R' and modified image source S". The transformed straight-line case is defined by the grazing angle ψ_G and the distances R_S and R_R determined for the circular rays. This is illustrated in Figure 19.

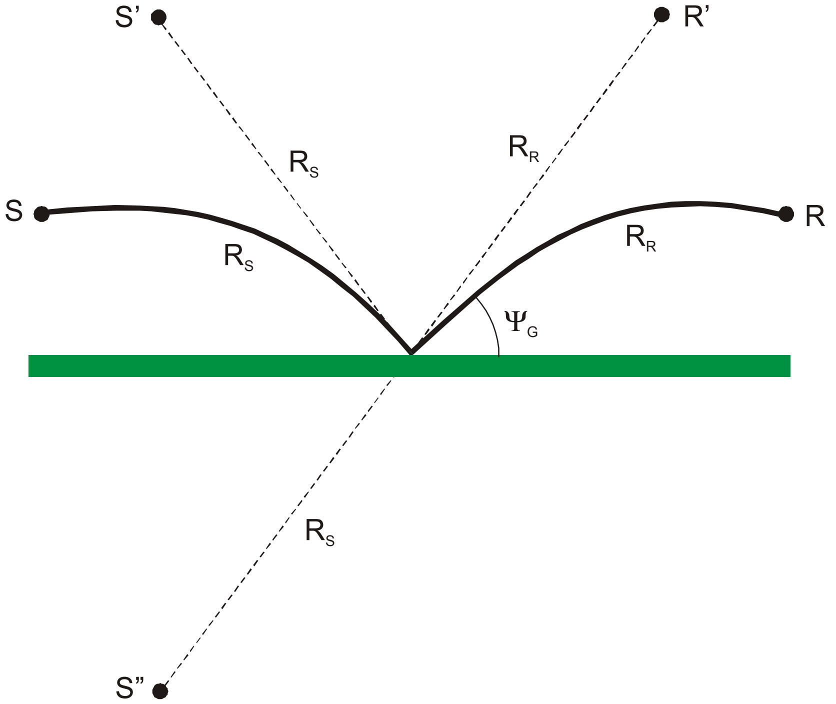

Figure 19
Curved rays represented by straight-line rays and modified source, receiver and image source

Generally, the Nord2000 model is valid only for moderate refraction defined as weather where the propagation effects are not dominated by multiple ground reflections and shadow zones. To extend the applicability of Nord2000, methods have been elaborated to include these effects.

In strong downward refraction, the number of rays will increase because the sound field may be reflected by the ground surface more than once. This is called multiple reflections. A method has been included for calculating the contributions from rays in excess of those already included in the base models. In the method, the number of additional rays and the corresponding energy are determined, and the latter is added to the result of the ray model.

In strong upward refraction, the receiver may be in a shadow zone as illustrated in Figure 20. In that case, no ray will reach the receiver, and the sound pressure has to be determined by other means than a ray model. In Nord2000, a simple approximate approach has been elaborated.

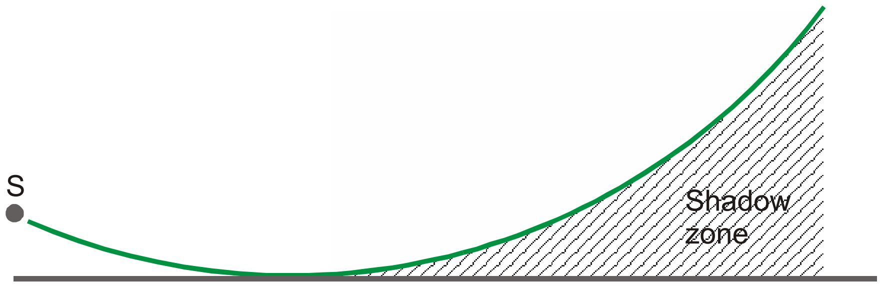

Figure 20
Illustration of a shadow zone.

O. Reflections from Vertical Obstacles

Sound reflected from an obstacle such as a building facade or a noise screen is dealt with by introducing an extra ray path from the source via the reflection point to the receiver. The reflection point is defined as the intersection between the straight line from the image source to the receiver and the plane which contains the reflecting surface. The reflection point may be outside the real surface.

The propagation effect of a reflected ray path is predicted by the same propagation model as used for a direct path, but a correction is made for the efficiency of the reflection. The reflected sound is added incoherently to the direct sound. The efficiency of the reflection is determined by the following equation:

$$\Delta L_r = 10\log(\rho_E) + 20\log\left(\frac{S_{refl}}{S_{Fz}}\right)$$

The first term in the equation is a correction for the effective energy reflection coefficient of the surface ρ_E, and the second term is a correction for the size of the reflecting surface. S_{refl} is the area of the surface within the Fresnel-zone in the plane of reflection, and S_{Fz} is the total area of the Fresnel-zone. The calculation of Fresnel-zones is in this case based on a fraction F = 1/8. In this way, the second term will be zero if the reflecting surface is larger than the Fresnel-zone and will decrease when the surface becomes smaller. If the surface is outside the Fresnel-zone, the second term will become minus infinity. Using this method, a partial reflection may be obtained in cases where the reflection point is outside the real surface. This is a deviation from the previous methods, but more correct from a physical point of view.

P. Scattering Zones

In Nord2000, it is possible to predict the propagation effect of “scattering zones” which are urban areas and vegetation. In urban areas the sound propagation is influenced by multiple reflections, diffuse scattering by irregularities of building facades, diffraction at house corners and absorption by buildings and ground surfaces. In vegetation, mainly forests, the sound propagation is influenced by reflections, scattering, and absorption due to trunks, branches and foliage. In such areas, sound propagation is much too complicated for a deterministic model, and it is necessary to use a statistical scattering model. Such a model will not predict the exact sound pressure level at a specified location, but rather the average sound pressure level at the specified distance from the source. Thus, the sound shadow behind an object and the increase in sound level in front of the object are not taken into account. Methods have been elaborated for combining the statistical scattering model with other parts of the Nord2000 propagation model.

The effect of scattering zones depends on the length of the ray path through the scattering zone as shown in Figure 21.

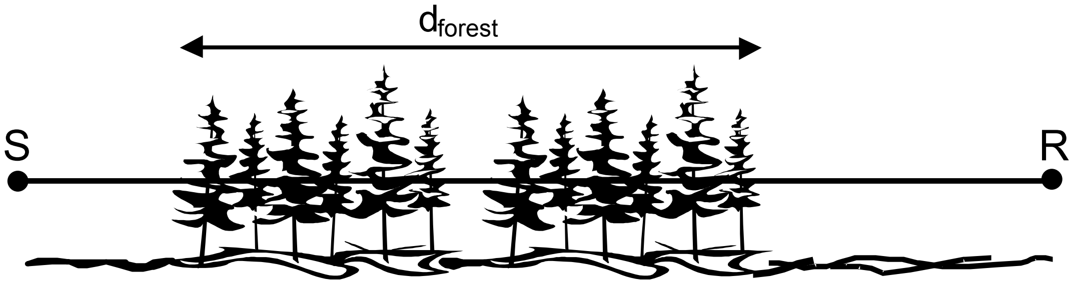

Figure 21
Ray path through a forest.

The effect of the scattering zones also depends on the density and size of the scattering objects and their reflection coefficients. A basic parameter used to quantify density and size is the product nQ of the average object density and average scattering cross section. For housing areas, nQ is determined on the basis of the fraction of the plan area of all buildings to the total area of the scattering zone, the surface area (sum of walls and roof surfaces) of an average building, the height of the highest building and the average building plan area. For forests, nQ is determined on the basis of the density of trees and the mean trunk diameter.

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