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Nord 2000. New Nordic Prediction Method for Rail Traffic Noise

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Abstract

A new Nordic method to predict rail traffic noise is proposed. It is based on a complete separation of source emission and sound propagation. Each train is modelled as a number of point sources each with a certain sound power with or without directivity. The source model is connected to point source sound propagation theory to yield the sound pressure level in an arbitrary receiver position. The propagation model is based on accurate analytical models and it is capable of predicting propagation effects both with and without the influence of meteorological parameters. In this first version the prediction method has to rely on old data for the noise emission of trains.

Key words: Prediction, rail traffic, train, noise, sound, propagation

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Preface

This prediction method has been developed within the frame of a Nordic project, Nord 2000. It would not have been possible without the generous support from authorities and research councils throughout the Nordic countries. The main financial support has come from the Nordic Council of Ministers but additional support, both to the main project and to related projects, has come from the following organizations:

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Nordtest

The prediction method was developed by a joint Nordic project group consisting of Jørgen Kragh and Birger Plovsing, DELTA Danish Electronics, Light & Acoustics, Denmark, Svein Storeheier and Gunnar Taraldsen, Sintef Telecom and Informatics, Norway, and Hans Jonasson, Mikael Ögren and Xuetao Zhang, SP Swedish National Testing and Research Institute. Juhani Parmanen, VTT Building Technology, Finland has been an observer.

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Conclusions

The new Nord 2000 prediction method for rail traffic noise makes it possible to calculate 1/3-octave band sound pressure levels with good accuracy in most situations. It is possible to mix different ground impedances, to have more than one barrier and to vary the meteorological conditions. Provided that the source strength data are the same the method will, in simple terrain situations, give similar results as the old 1996 model if a soft ground impedance of 500 kNsm^{-4} and a downwind component of 3 m/s along the horizontal normal to the road are used as input parameters.

1 Introduction

1.1 Background

In 1996 the revision of the current Nordic prediction methods for environmental noise started. Thus this new prediction method for rail traffic noise is the result of about 6 years of joint Nordic work. The aim has been ambitious, to develop methods physically correct to the largest possible extent and with a complete separation between source emission and sound propagation. The latter requirement was essential to make it possible to use the same propagation method both for road and rail traffic noise and for industrial noise. In addition there was a requirement to be able to deal also with varying weather conditions.

Another aim has been to obtain a method suitable for large-scale engineering applications. In order to comply with this aim, the propagation model used is based on analytical solutions. Thus the most advanced numerical methods have been used for verification purposes only as these methods still require unacceptably long computing times.

When making the new method we have tried to compromise as little as possible and make the method as accurate as possible. It may turn out afterwards that some parameters were not significant enough and that simplifications can be made without affecting the result too much. Examples of such simplifications could be a more limited frequency range, octave bands instead of one-third octave bands or fewer source positions to represent the vehicle as sound source. However, such simplifications can easily be made afterwards, once there is an accurate reference method.

As to source data this new method relies on the same source data as the old method. This is a limitation, which, however, can be remedied later.

1.2 Principle

Each train is treated as a moving source consisting of a number of sub sources emitting noise within a wide frequency range. The strengths of the sources depend on train category, speed, track quality (to be implemented later) and driving conditions. The sub sources are located at different heights above the rail surface. The strengths of the sources are expressed as sound power levels. The sources are either omni directional or assigned a specified directivity. All calculations are carried out in one-third octave bands. If input data are available for octave bands only, one third octave band level, are interpolated between the octaves and then normalized to give the same octave band level as before.

When the noise propagates from a source to a receiver it will be affected by spherical spreading, air attenuation, ground reflection, screening, scattering, etc. In some cases it will be amplified due to reflections from vertical surfaces. The propagation will also depend on vertical wind and temperature gradients. The attenuation during propagation is calculated for each point source. The propagation model is identical to the one for industrial noise and road traffic noise.

The noise contributions of each source are summed up by adding the sound exposure levels during pass-by. The rail track is divided into a number of track segments. First the sound exposure level of each sub source is calculated for each track segment. Then all sources and all segments are added and the L_{eq}-level is calculated. L_{eq} can be calculated for any combination of train categories, traffic flow and weather conditions. The only limitation is the availability of relevant input data.

The maximum sound pressure level (time weighting F) is calculated from the sound power level as described in clause 5.

1.3 What can and what cannot be calculated?

The prediction method can calculate L_{eq}, A-weighted or in frequency bands, for any combination of rail vehicles provided that suitable input data are available. The default calculation is the sound pressure level of the incident sound field, that is, in receiver positions near a façade, the last reflection from the façade is not included. It is also possible to calculate maximum sound pressure levels corresponding to time-weighting F. The maximum levels can be calculated from individual trains or combinations of trains with selected positions. However, the prediction method does not give statistical methods to calculate maximum levels of vehicle combinations.

The prediction method can also handle different uncomplicated weather conditions. However, very strong or varying wind gradients and layered atmospheric conditions have been excluded. By combining results from different weather conditions it is possible to calculate yearly averages such as the L_{den} proposed by the European Union, [11].

The prediction method can handle any number of and any combination of varying ground conditions with and without screens. In principle any number of screens could be dealt with but for practical reasons the algorithms have been limited to two screens. The screens can be thin or thick or wedge shaped. At present more complicated or sophisticated screen tops cannot be dealt with by the model itself and data on extra attenuation by such devices must be provided elsewhere.

The prediction method does not specifically deal with indoor noise. No special guidelines or data on windows or facade insulation are given.

1.4 Relation to the old prediction method

The old Nordic prediction method, [2], was last revised in 1996. This revision was quite extensive and both source data and propagation model was changed.

The new prediction method described in this report is similar to the old one in its basic structure. The main difference is the propagation model, which has been completely changed and which also allows for varying weather conditions. In addition tunnel openings have been included.

Input data have been taken from the old model although some of the data have been modified to account for the change in source and propagation model, see 2.3.1 and annex A. A comparison between the two methods is accounted for in clause 7.

1.5 Notation

a = sound absorption parameter used for tunnel calculations
C = correction to obtain sound power level from SEL-measurement;
$C_{e,\mathrm{tunnel}}$ = correction to obtain sound energy level in a tunnel opening from the sound power level of a passing train, in dB;
$C(v)$ = speed dependent correction = L_W - L_E, in dB;
C_w^2 = strength of wind turbulence;
C_t^2 = strength of temperature turbulence;
d = measurement distance (distance to track centre line), in m;
E_{Ta} = sound energy radiated from the opening of a tunnel with specific acoustic treatment, in joules;
E_{Tr} = sound energy radiated from the opening of a tunnel without any specific acoustic treatment, in joules;
h = height of tunnel, in m;
h_r = height of the microphone/receiver;
h_s = height of the source
i = index for the position of a source/sub source;
j = index for a sub source;
l = length of individual train, in m;
l_P = length of individual train used to calculate L_pFmax, in m;
L = general notation for calculated levels with index f for favourable, index h for homogeneous and index u for unfavourable propagation conditions;
L_den = day evening night weighted L_eq, in dB;
L_eq = equivalent continuous sound pressure level, in dB;
L_E = the sound exposure level, in dB;
$L_\mathrm{E,v}$; = sound exposure level due to an individual vehicle;
L_Fmax = maximum sound pressure level using time weighting F, in dB;
L_J = sound energy level, in dB;
L_p = sound pressure level, in dB;
L_t = length of tunnel, in m
L_W = sound power level, in dB;
$L_\mathrm{W,1m}$ = sound power level of 1 m train, in dB;
L_Wref = reference sound power level determined from a pass-by measurement, in dB
L_yav = L_den averaged over a typical year;
m = number of track segments or sub source positions used to approximate integration by summation;
n_j = number of sub sources of a specified vehicle category;
N_j = number of sources of category j during a specified time interval;
N_vc = number of vehicles of a specified category;
N_cat = number of vehicle categories;
p = probability (1=100%) for favourable (index f), homogeneous (index h) and unfavourable (index u) propagation conditions;
r_ij= the distance between point ij and the receiver;
r = radius of tunnel, in m
t = time, in s;
T = temperature, in Kelvins, or time, in s;
u = wind velocity, in m/s;
v = speed of vehicle, in m/s;
x = distance from tunnel opening to train position
w = the axle width of the track (= 1,435 m)
w_T = half the width of tunnels ;
W = notation for sound power, in watts
W_T = sound power in tunnel openings, in watts;

z = coordinate in the vertical direction;
α = sound absorption coefficient or angle;
ΔL_J = difference in sound energy level radiated through a tunnel opening between a tunnel without and with sound absorbing treatment respectively, in dB;
$\Delta L(\varphi)$ = correction for horizontal directivity, in dB;
$\Delta L(\psi)$ = correction for vertical directivity, in dB;
$\Delta \mathrm{L}(\phi)$ = correction for directivity of tunnel openings;
ΔL_{ij}= -10 lg$(4\pi r_i^2)$ + corrections due to ground influence, etc.;
Δx_i = length of track segment i;
$\Delta\alpha_i$ = angle of circular sector covering track segment i;

2 The source

2.1 General

The train is a complex noise source. The main sources are the power unit(s), the wheels, the rail and the sleepers. For high speed trains aerodynamic noise becomes important and the main sources will then be the bottom of the car body and the pantograph.

Power unit noise depends mainly on the type of engine and the revolutions per second (rps) of the engine. The speed dependence of the sound power level is in general about 30 lg(rps). The frequency range is rather wide up to about 2000 Hz. The power unit is either located in the locomotive, which is the normal location for old train categories, or in the bogies, which is a common location for modern trains. In the latter case it means that most of the noise will come from under the car.

Exhaust noise is dominated by low frequencies and it is, of course, only of interest for diesel driven trains. The exhaust is usually located on the roof of the locomotive.

Aerodynamic noise has a speed dependence of about 60 lg(speed). It is not important at low speeds but at higher speeds it may become important at low frequencies. The main sources will be the bottom of the car body and the bogies. If the lower part of the train is screened the pantograph may have some importance. As high-speed trains in the Nordic countries do not travel faster than about 200 km/h aerodynamic noise is not likely to affect A-weighted levels outdoors.

Wheel/rail interaction will be the dominating noise source under most conditions. The balance between wheel and rail will depend on the track construction. The noise generation may vary up to about 10 dB depending on the roughness of wheel and rail. In Germany the railway authorities get a 5 dB discount on predicted noise levels if they have an improved maintenance scheme for the rail. Thread-braked wheels, which are used by freight cars, are rougher and thus noisier than disc-braked wheels, which are used by modern passenger trains. The quality of the rail pads may affect the noise level by about 6 dB. The rail radiation is often most important between 500-1200 Hz. For higher frequencies the wheels will dominate. Damped wheels may radiate about 5 dB less noise than traditional wheels.

The sleepers may be an important noise radiator below 500 Hz.

2.2 Source model

In order to be able to calculate the excess attenuation due to screening and ground reflections the heights of the sources are important, in particular for high frequencies. For L_{eq}-calculations and moving vehicles the location along the train is not important. However, for L_{max}-calculations also these horizontal locations have to be considered at distances less than about the length of the train.

Unless other information is available all wheel/rail sources are assigned equal strength with the sound power distributed evenly. Emission from engines, unless bogie mounted, and aerodynamic sources above 0,7 m has to be determined individually whenever relevant. In principle, each train will be subdivided into the following sources, each situated above the nearest rail:

Table 2.1 Trains. Principle source locations.

	Height above top of rail (m)	**Horizontal location**
Source 1 Wheel/rail	0,01	Evenly distributed along the train
Source 2 Wheel/rail	0,35 x wheel diameter	Evenly distributed along the train
Source 3 Wheel/rail	0,70 x wheel diameter	Evenly distributed along the train
Source 4 Engine	Actual height	Centre of engine openings.
Source 5 Exhaust	Actual height of exhaust	Exhaust outlet
Source 6 Aerodynamic	To be determined in each case	To be determined in each case

Cars and locomotives should, if possible, be dealt with separately. In case no details are known the default model given in table 2.2 is recommended:

Table 2.2. Default values for source locations.

	Height above top of rail (m)	**Frequency range$^{1)}$ (Hz)**	**Horizontal location**
Source 1 Wheel/rail	0,01	200 - 10000	Evenly distributed along the train
Source 2 Wheel/rail	0,35	200 - 10000	Evenly distributed along the train
Source 3 Wheel/rail	0,70	200 - 10000	Evenly distributed along the train
Source 4 Engine/Exhaust	2,5	25 - 160	Centre of engine openings.

$^{1)}$ Often frequencies below 50 Hz and above 5000 Hz can be neglected.

In annex A.2 some source models are given for Swedish trains.

The horizontal directivity is not of major importance to determine SEL- or L_{eq}-values. To facilitate future improvements and to allow for more accurate predictions of maximum levels it is assumed to follow equation (2.1):

$$\Delta L(\varphi) = 10\lg(0,15+0,85\sin^2(\varphi)) + 2 \qquad (2.1)$$

where φ is the angle to the normal to the train, see figure 2.1. See [6] for an overview of the background to eq. (2.1). (2.1) has been normalized to yield 0 dB extra contribution to the sound exposure level, when superimposed on an omni-directional sound power level, see L_{Wref} in clause 2.3.1, when integrated during a pass-by with little excess ground attenuation.

As Swedish investigations indicate that the vertical directivity, $\Delta L(\psi)$, is small [10] as long as wheel/rail is not screened by the car body it is, for the time being, disregarded. However, provisions have been taken to make it easy to incorporate later.

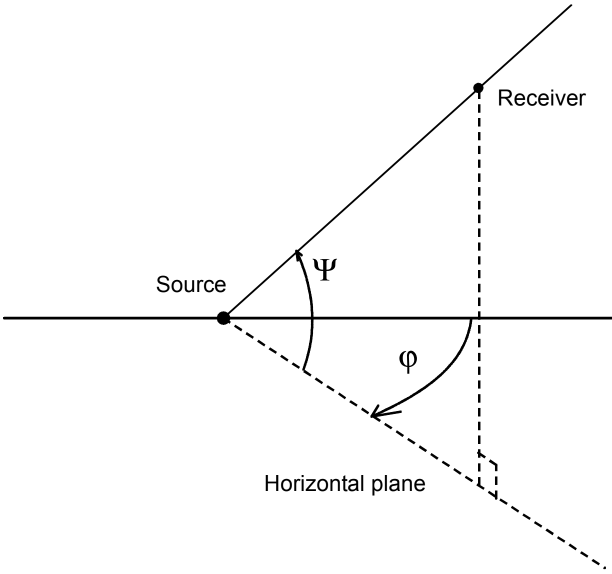

Figure 2.1 Sketch of angles of directivity

2.3 Source strength

2.3.1 General

Ideally the source strength of each sub source should be known. E.g. locomotives and cars should be dealt with separately. However, at present there is not enough data available. Thus the starting point is still pass-by measurements including all noise sources. The basic data is the sound exposure level from a pass-by from which the sound power level is determined. The total sound power is then distributed to the different sub sources according to the source model. The maximum sound pressure level is calculated from the sound power level using the source model. Because the sound power level is a kind of average level during a pass-by the calculated maximum sound pressure level will also be a kind of average maximum level. Such an average maximum sound pressure level during a train pass-by may be several dB smaller than L_{AFmax} measured near the track during pass-by of e.g. an axle with a particularly rough wheel or a noisy diesel engine. By separating locomotives and noisy cars from normal cars the correct maximum level can be calculated. If not, the calculated value has to be corrected using some kind of empirical correction.

This new prediction method has to rely on input data measured in connection with the revision of the old prediction method, that is from 1993-1995. These measurements were carried out at a distance 10-25 m from the track at a height of 2-3,5 m above the top of the rail. The sound exposure level was used as measure and it was normalized to 100 m train length using the relation:

$$L_{E,100m} = L_{E,actuallength} + 10\lg\left(\frac{100}{actuallength}\right) \tag{2.2}$$

It was then corrected to 10 m distance and 2 m height using the ISO 9613-2, [4], sound propagation model. This means that corrections up to about 2 dB were applied to account for excess ground attenuation between 10 m and 25 m. Finally these values were used to determine the sound power level. Because of differences in both source and propagation model these sound power levels will differ from those, which should have been obtained using the new model.

The 10 m SEL-values were said to be representative for propagation across 10 m (from track centre) flat ground with the microphone at 2 m. This is a rather unfortunate situation. If the propagation really is across flat ground the ground attenuation would be rather strong for some frequencies, that is it is necessary to have both an accurate source model, knowledge of the ground impedance and an exact propagation model. In principle our new method would make it possible to carry out accurate calculations provided that the 10m/2m/flat/soft-statement was true and we knew the ground impedance, which we don't. However, as most rail tracks have a significant elevation above the surrounding ground it must be assumed that most measurements have been carried out under these conditions, that is the ground attenuation has been considerably smaller than would have been the case for flat ground. It is a fact that, e.g., the Swedish measurements, see [5], were carried out with track elevations between 0,4 m and 3,25 m. Using the new source model the sound power level can be calculated from

$$L_{\mathrm{W}} = L_{\mathrm{E,10m}} + C(v) \qquad (2.3)$$

where $C(v)$ is determined for each geometry using the prediction method as described in 4.1 by calculating

$$C(v) = L_W - L_{E,10m} \qquad (2.4)$$

As $C(v)$ is constant apart from a distance dependence it is more practical to write (2.3) as

$$L_W = L_{E,10m} + C(50) + 10\lg\left(\frac{v}{50}\right) \qquad (2.5)$$

$L_{E,10m}$ = the sound exposure level normalized to 10 m, in dB;

So far input data have been handled as follows:

General
The basic sound power levels, expressed in dB/m train, have been taken from the present Nordic models and these levels are given in the annexes. Please note that the basic data are presented slightly differently. They are identical to the old ones but the coefficients *a* and *b* are defined differently. In addition the following national corrections have been made:

Sweden
Source models have been specified for some trains and the sound power levels have been adjusted to account for changes in the propagation and source models in relation to the old model, see annex A.2.

Norway
Source models have been specified for some trains and the sound power levels have been adjusted to account for changes in the propagation and source models in relation to the old model, see annex A.3.

In the future a new and more accurate method for emission measurements should be used. The test method should be based on prEN ISO 3095, [7], but with some amendments. The microphone positions should be chosen to minimize ground attenuation, the acoustic impedance should be measured in each case using Nordtest metod NT ACOU 104, [8], and the exact track and ground elevations should be determined. With these data it is possible to determine the sound power level accurately provided accurate source and propagation models are available.

The above means that the formal definition of the reference sound power level used as input is the following:

The sound power level, which, after distribution among the sub sources given by the source model, when integrated omni directionally during a vehicle pass-by, gives the sound exposure level measured according to the emission measurement method. In the following this sound power level will be denoted reference sound power level, L_{Wref}.

L_{Wref} will normally be distributed between a number of sub sources. The reference sound power level of sub source *j* will be denoted $L_{\mathrm{Wref,j}}$.

2.3.2 Classification of trains, tracks and driving conditions

The trains are divided into categories as shown in the following tables. The categories are specific to each country although some trains are in traffic in more than one country. The different sub categories will, in general, be different from country to country. Depending on available data other parameters such as the wheel roughness (in dB re 1 μm), probably as a roughness class based on a roughness spectrum, should be included. As in the present prediction method for maximum sound pressure levels the sound power level is referred to 1 m train length. In the future engine and car noise should be dealt with separately.

Table 2.4a Swedish train *categories. For sound power levels, see annex A.*

Main category	Sub category	Category name
1		**High speed trains (≥ 180 km/h)**
	1a	X2000
	1b	Arlanda train
	1c	Öresund train (Sweden and Denmark)
2		**Normal speed Inter-City trains**
	2a	With RC engine
	2b	
3		**Local and regional trains**
	3a	X10, X12 (el)
	3b	Y1 (diesel)
	3c	Y2 (diesel)
4		**Freight trains**
	4a	Normal, RC engine (el)
	4b	Normal, T44 engine (diesel + el)
	4c	Iron ore train (Sweden and Norway)
5		**Others**

Table 2.4b Danish train categories

Main category	Sub category	Category name
1		**Passenger train sets**
	1a	Diesel trains (IC3)
	1b	Electric trains (IR4)
	1c	Electric trainsets (ET) Øresund
	1d	Electric trainsets X2000

2		**Locomotive driven trains**
	2a	Diesel passenger trains with MZ or ME locomotive(MZ/P, ME/P)
	2b	Diesel goods trains with MZ or ME locomotive(MZ/G and ME/G)
	2c	Electric passenger trains with EA locomotive (EA/P)
	2d	Electric goods trains with EA locomotive (EA/G)
	2e	Electric goods train (EG)
3		**Regional trains**
4		**Local trains**
	4a	S-trains 2nd and 3rd generation
	4b	S-trains 4th generation
	4c	Diesel train sets (MR)
	4d	Y-trains, IC2 trains, RegioSprinter, RegioSprinter, Desiro
5		**Others**

Table 2.4c Norwegian train categories

Main category	**Sub category**	**Category name**
1		**High speed trains (≥ 180 km/h)**
	1a	Gardermoen train, Type BM 71
2		**Normal speed Inter-City/Express trains**
	2a	Type BM 70
	2b	Passenger train, El (locomotive driven)
	2c	Passenger train, Di (locomotive driven)
	2d	Type BM 73
	2e	Type BM 93
3		**Local trains**
	3a	Type BM 69
	3b	Type BM 92
	3c	Type BM 72
4		**Freight trains, locomotive driven**
	4a	Ordinary Goods, El
	4b	Container Express Goods, El
	4c	Goods, Di
5		**Others**

The railway tracks are divided into the following 4 main categories:

Table 2.5 Track categories

Main category	**Sub category**	**Name**
1		**Modern** (ballasted, concrete sleeper, welded joints with UIC 60 rail , soft pa
	1a	Well maintained (roughness < X)
	1b	Average (X ≤ roughness ≤ Y)
	1c	Worse than average (roughness > Y)
2		**Semi-modern** (ballasted, concrete sleeper, welded joints with UIC= , soft pads)
	2a	Well maintained (roughness < X)
	2b	Average (X ≤ roughness ≤ Y)
	2c	Worse than average (roughness > Y)
3		**Old** (ballasted, wood sleepers, unwelded joints with UIC= , soft pads)
	3a	Well maintained (roughness < X)
	3b	Average (X ≤ roughness ≤ Y)
	3c	Worse than average (roughness > Y)
4		**Track on steel bridge**
	4a	Well maintained (roughness < X)
	4b	Average (X ≤ roughness ≤ Y)
	4c	Worse than average (roughness > Y)

The following driving conditions are used:

Table 2.6 Driving conditions

Category	**Name**	**Objective description**
1	Cruising	Constant speed
2	Acceleration	Continuous acceleration1)
3	Deceleration	Continuous deceleration2)
4	Bends	Squeals

1) E.g. after stations or speed limit signs

2) E.g. before stations or speed limit signs

2.3.3 Sound power levels

As no new, systematic measurements on trains have been carried out since the last revision of the old prediction method also this new prediction method essentially has to rely on the old data. This means that the present sound power levels, normalized to 1 m train length, are used as they are, with the supplement that third octave band levels are interpolated between the octaves and then normalized to give the same octave band level as before. These data are given in annex A.

2.3.4 Corrections for track conditions

The intention is to have input data for different track conditions. However, at present there are no such data available. Thus, provisionally, unless suitable input data are available, the same corrections as those given in the current Nordic model should be used. This means that the sound power level per meter train is increased as given in table 2.7 during pass-by of the rail subject to the conditions described. The corrections are applied on each frequency band.

Table 2.7 Corrections for track conditions

Condition	Effective distance	Correction, in dB
Rails with joints	Continuously	+3
Switches and crosses	10 m/switch or crossing	+6
Bridge without ballast	Length of bridge	+6
Bridge with ballast	Length of bridge	+3

:

Other corrections may be applied if they are well documented by field measurements. Such corrections could be particularly bad or well maintained tracks.

2.3.5 Format for input data

In the future new data should be collected in one third octave bands with a better separation of different sources and with a better description of the quality of track, rail and wheels. These descriptions should follow the proposals of 2.3.2 but the decisions must be taken by the relevant national railway authorities.

2.4 Tunnel openings

2.4.1 General

Tunnel openings are regarded as special sound sources. Each train passing through a tunnel yields a certain sound energy level, L_J, through the tunnel opening. This energy depends on the total sound power level of the train and its speed, but it also depends on the sound propagation properties inside the tunnel.

At a certain moment a single train car is positioned inside the tunnel at the distance x from the tunnel mouth. For a stationary car, consider its sound power radiating through the tunnel opening to be W_T. In a short time interval Δt the corresponding energy ΔE through the opening will be $W_T \cdot \Delta t$. The time interval can be estimated by $\Delta x/v$, Δx and v being the driving distance and the speed respectively during the time Δt. Positioning it at subsequent equidistant positions can simulate the pass through of the car through the tunnel and thus the total radiated energy through the tunnel opening can be calculated. By summing over all cars and the engine the corresponding level for the train is obtained.

It can be shown [3] that the sound power W_T radiating through the tunnel opening due to a stationary sound source in the tunnel, is:

$$W_T(a,x) = \frac{W}{2}\left(1 - \frac{ax}{\sqrt{r^2 + (ax)^2}}\right) \tag{2.6}$$

W is the total sound power, in watts, of the source, x is the distance, in m, of the sound source from the tunnel mouth, r is the radius, in m, of the tunnel (in case of a semi-circular cross section), a is a parameter regarding the sound absorption inside the tunnel ($0 \le a \le 1$).

For a tunnel with a rectangular cross section, the sound power is [3]:

$$W_T(a,x) = \frac{W}{\pi}\tan^{-1}\left[\frac{w_T h}{\sqrt{x^4 + (w_T^{\ 2} + h^2)(ax)^2}}\right] \tag{2.7}$$

w_T is half the width, in m, of the tunnel mouth, h is the height, in m.

For a tunnel with a semi-circular cross section, the total energy radiating through the tunnel opening during a source passage through the tunnel is:

$$E_T(a) = \frac{W}{2}\frac{\Delta x}{v}\left[\sum_{i=0}^{i\max}(1 - \frac{ax_i}{\sqrt{r^2+(ax_i)^2}}\right] \qquad (2.8\ )$$

$x_i = \Delta x \cdot i$, $imax$ = INTEGER($L_t/\Delta x$) (after rounding), L_t = tunnel length, in m, v is the driving speed, in m/s.

For a tunnel with rectangular cross section, the corresponding total energy radiating through the tunnel opening is :

$$E_T(a) = \frac{W}{\pi}\frac{\Delta x}{v}\left\{\sum_{i=0}^{i\max}\tan^{-1}\left[\frac{w_T h}{\sqrt{x_i^{\,4}+(w_T^{\,2}+h^2)(ax_i)^2}}\right]\right\} \qquad (2.9)$$

To obtain the total sound energy of a whole train we have to sum eq. (2.8) and (2.9) over all cars. The result becomes the same as if we exchanged the sound power of the individual car, W, with that of the whole train.

2.4.2 Values of *a*

For a tunnel with a specified average sound absorption coefficient, α, the value of a is given by, [3]:

$$a \approx 1-\sqrt{(1-\alpha)} \qquad (2.10)$$

Table 2.7 gives some guidance to the value of α in case no other information is available. The sound energy radiated in case 1 is denoted E_{Tr}. This case is the reference case to determine the directivity of the sound emission from the tunnel mouth, see clause 2.4.3. The sound energy radiated in the other cases is denoted E_T.

Table 2.7 Sound absorption coefficient, α

Frequency range, Hz	f < 160	160-400	500-1250	f>1600
1. Reference, E_{Tr} Smooth concrete surfaces, reflecting rail bed	0,08	0,08	0,08	0,08
2. Rough concrete surfaces, reflecting rail bed	0,08	0,11	0,14	0,14
3. Concrete surfaces, ballast rail bed	0,1	0,2	0,3	0,3
4. Typical sound absorbing treatment	0,15	0,5	0,8	0,65

The effective value of a in case of tunnel sections with different a-values, is calculated by Eq. (2.11) :

$$a = \frac{1}{L_t}\sum_{j=1}^{j\max} a_j \cdot l_j \qquad (2.11)$$

where α_j and l_j are the α-value and length of the various sections respectively L'_t is the smaller of the total tunnel length L_t and 400 m. The sum includes the sections as seen from the tunnel mouth limited to the greater of the tunnel length L_t and 400 m (corresponding to *jmax*), whichever is applicable.

2.4.3 Calculation procedure

The calculation of the sound energy level caused by a single train's passage through the tunnel, is carried out according to the following steps :

1 Choose a value of Δx.
10 m is an appropriate default choice.

2 Determine sub-source distribution.
The sound energy level is distributed between 4 different sub-sources located according to table 2.8 and figure 2.2, for a semi-circular- and rectangular cross section respectively. The positions are expressed in terms of the cross section radius *r*, or the height *h* and half width *w*. The source positions are associated with approximately equal sub- areas of the tunnel opening. The positions are given relative to the track centre line, on the rail head.

Table 2.8 Point source distribution in the tunnel opening.

Source	**Semi-circular**		**Rectangular**	
	Horizontal	Vertical	Horizontal	Vertical
Source 1	0,5r	0,21r	0,5w	0,24h
Source 2	0,5r	0,68r	0,5w	0,75h
Source 3	-0,5r	0,21r	-0,5w	0,24h
Source 4	-0,5r	0,68r	-0,5w	0,75h

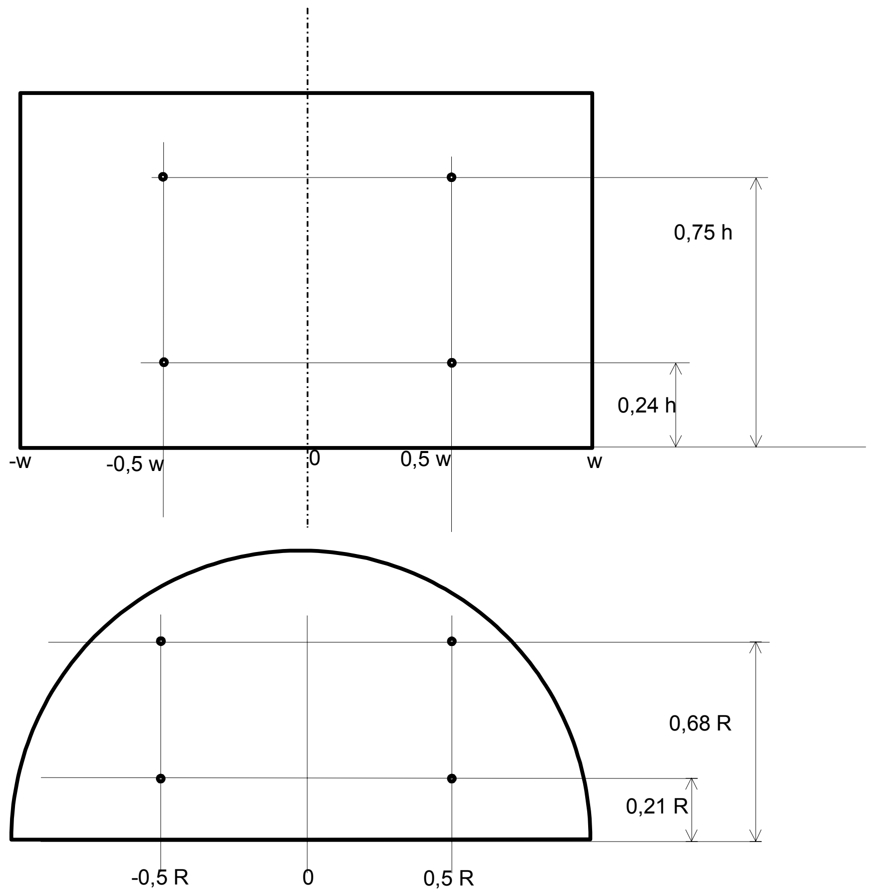

Figure 2.2 Point source distribution in tunnel openings

3 Determine sub-source strength

Assuming that the tunnel opening and the sub-sources radiate like point sources, the energy level radiating from the tunnel opening sub-source *j*, due to the passage of one train, is given by:

$$L_{J,j} = 10 \log(\frac{E_T}{10^{-12}}) + \Delta L(\phi) - 10 \log(n) \qquad (2.12)$$

n is the number of sub-sources (= 4), ϕ is the angle between a line parallel to the tunnel axis through the sub-source midpoint and a line from this midpoint towards the receiver. E_T is calculated using Eq.(2.8) or Eq.(2.9), applying the appropriate value of *a*. $\Delta L(\phi)$ (in dB) is the directivity correction.

Note :

The sound propagation from the tunnel opening will probably have some radiation directivity. No firm estimate of such directivity valid for train traffic has been available. Until specific data is available, the directivity correction is set to zero.

3 Propagation

3.1 General

Sound propagation from a point source is explained and described in [1]. Using the methods therein it is possible to calculate the sound attenuation during propagation from the source to the receiver. A point source, sub source number j, being in position i and having the sound power level L_{Wij} in the direction from position i to the receiver will yield the following sound pressure level at the receiver

$$L_{p,ij} = L_{W,ij} + \Delta L_{ij} \qquad (3.1)$$

where

$$L_{W,ij} = L_{Wref,j} + \Delta L(\varphi_j) + \Delta L(\psi_j) \qquad (3.2)$$

ΔL_{ij}= -10lg($4\pi r_{\mathrm{ij}}^2$) + corrections due to ground influence, etc. (3.3)

r_{ij}= the distance between point ij and the receiver

ΔL_{ij} can be calculated for different weather situations.

3.2 Necessary input data - nonrefracting atmosphere

In order to carry out the calculations the following input parameters are required:

- the geometry of each propagation path, including intersection points between different ground surfaces and vertical coordinates describing screens and height variations;
- the flow resistivity of each ground and screen surface under the propagation path;
- the roughness of each ground surface;
- the air temperature;
- the relative humidity;
- the strength of atmospheric turbulence

The flow resistivity is used to calculate the acoustic impedance of the ground. The basis for measurement and calculation is the Nordtest method NT ACOU 104, [8]. To simplify the use of the prediction method the ground surfaces are divided into 7 different flow resistivity classes:

Table 3.1 Impedance classes of ground surfaces

Impedance class	Representative flow resistivity σ(kNsm^{-4}, kRayls)	Range of Nordtest flow resistivity classes	Description
A	12,5	10, 16	Very soft (snow or moss-like)
B	31,5	25, 40	Soft forest floor (short, dense, heather-like or thick moss)
C	80	63, 100	Uncompacted, loose ground (turf, grass, loose soil)
D	200	160, 250	Normal uncompacted ground (forest floors, pasture field)
E	500	400, 630	Compacted field and gravel (compacted lawns, park area)
F	2000	2000	Compacted dense ground (gravel road, parking lot)
G	20000	20000	Hard surface (dense asphalt, concrete, water)

The soft ground of the old Nordic prediction method resembles class E above.

The large scale roughness of the ground is divided into three different roughness classes:

Table 3.2 Roughness classes

Roughness class	Roughness parameter	Range of surface height variation
N: Nil	0	$\leq$ 0,25 m
S: Small	0,25	$\pm$ 0,5 m
M: Medium	0,5	$\pm$ 1 m
L: Large	1	$\pm$ 2 m

The air temperature and the relative humidity is needed to determine the air attenuation. It is most important at high frequencies and long distances.

Suitable default values for general calculations are given in table 3.3.

Table 3.3 Suitable default values for general calculations

Property	Default value
Ground impedance Soft ground Rail bed	 Class E (500 kNsm^{-4}, kRayls) Class D (200 kNsm^{-4}, kRayls)
Roughness class	Class N (0)
Air temperature	15°C
Relative humidity	70%

3.3 Different weather conditions

Depending on the purpose of the calculations different weather conditions can be used as input data in the propagation model. One of the following three procedures should be used:

Table 3.4 Weather classes

Weather parameters	**Comment**
1. Neutral	Here it stands for zero wind and temperature gradients.
2. Actual condition	To be used for specific cases only
3. Yearly average Carry out three calculations: 1. Neutral (=homogeneous) 2. Downwind (= favourable) 3. Upwind (=unfavourable)	To be used to calculate long time average based on meteorological statistics

For calculations of yearly average downwind conditions are defined as conditions corresponding to a wind speed component of 3 m/s at 10 m above the ground. Actual weather statistics are required to determine the percentage of the time during which favourable (=downwind) conditions exist, see clause 4.5. Unfavourable(=upwind) conditions can usually be ignored as they contribute very little to the yearly average.

For actual propagation conditions the curvature of the sound rays is calculated using a logarithmic wind profile wind speed at specified height and roughness length of the ground as input parameters.

The following input data are required to carry out calculations:

- roughness length, normally 0,02-0,05 m
- temperature at ground level
- temperature gradient
- standard deviation of temperature gradients
- height for wind speed data
- wind speed, u, at specified height
- standard deviation, su, of wind fluctuations at specified height
- strength of wind and temperature turbulence, C_w^2 and Ct^2 respectively

If u> 3 m/s the following relationships can often be used:

su = 0,15 u for flat ground
su = 0,3 u for rough ground

For calculations under standard conditions the following default values are recommended:

Table 3.5 Suitable default values for standard conditions

Property	**Default value**
Roughness length	0,05 m
Temperature on ground level	15°
Temperature gradient	0 °C/m
Standard deviation of temperature gradient	0 °C/m
Height for wind speed indication	10 m
Wind speed at 10 m	
Favourable propagation	3 m/s
Homogeneous propagation	0 m/s
Unfavourable propagation	-3 m/s
Standard deviation of wind speed	
Favourable propagation	0,5 m/s
Homogeneous propagation	0 m/s
Unfavourable propagation	0,5 m/s

3.4 Multiple reflections

3.4.1 Basic situations

Vertical sound reflecting surfaces on both sides of the railway can cause multiple reflections. The main basic situations of this kind are:

1. City streets with adjoining or partly adjoining building facades on both sides,
2. City side streets exposed to traffic noise generated in the main street,
3. Depressed rail beds or parallel rail barriers.

3.4.2 Main principles

The propagation module, [1], describes how to handle single reflections assuming single sound sources. Multiple reflections regarding L_{eq} are dealt with accordingly by adding up the sound levels from the real and mirror sources incoherently. Normally the number of subsequent reflections can be limited to 2 or 3. In the following the basic principles are described using the first- and second order reflections in addition to the direct sound. This is thought to cover most practical situations, although the description can be extended to higher orders of reflection. A sound reflection in a vertical surface (building façade, noise screen, retaining wall, etc.) is associated with a loss in sound energy according to the energy absorption coefficient α of the surface. The energy reflection coefficient ρ may be given or estimated. The relation between α and ρ is given in Eq.(3.4):

$$\alpha = 1 - \rho \qquad (3.4)$$

ρ is given for some practical situations in [1]. Also see Section 3.5.

For all distributed point sources S_i, mirror sources and points of reflection shall be constructed with respect to the reflecting surface and the receiver position. The details are outlined in Annex B for the matter of convenience. In the case of city streets it is assumed that the adjoining facades form rather large surfaces. In addition the sound sources are distributed along the road line causing many sound level contributions to add up at the receiver positions. The Fresnel-zone considerations used when dealing with single source/single reflections in [1] are therefore omitted.

3.4.2.1 City streets with adjoining building facades

The basic situations are outlined in Figure 3.1. In situation a) the building facades are adjoining, and the two facades may, or may not, have the same sound absorption coefficient. A sub-source position S_{ij} is indicated, it belongs to one of the distributed sound sources of one road traffic line. The position of S_{ij} and the associated road segment length Δx_i is determined according to section 4.3.

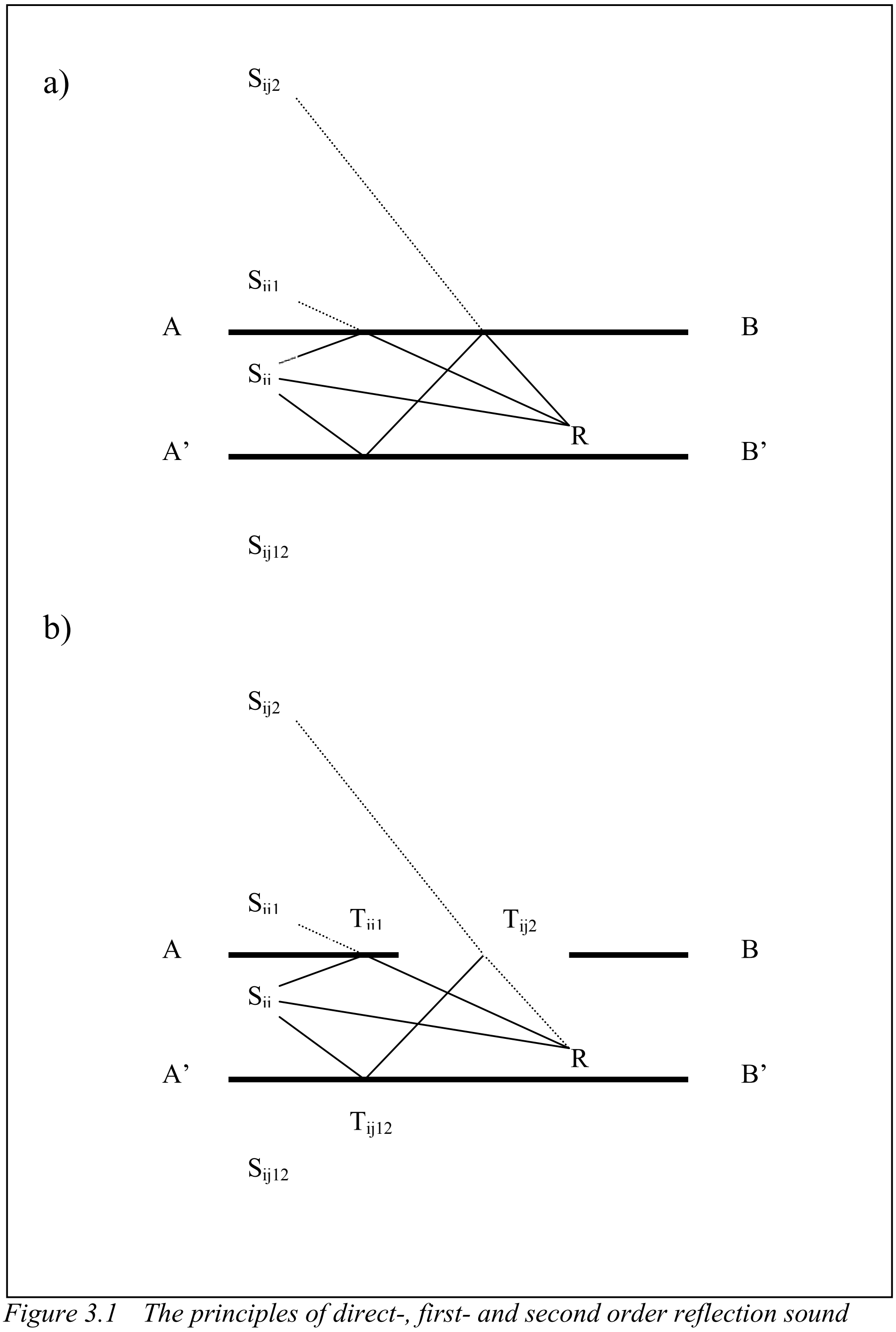

Figure 3.1 The principles of direct-, first- and second order reflection sound propagation in a city street. a) Adjoining facades, b) not adjoining facades.

It is assumed that the sound pressure level to be predicted represents *the incoming sound pressure level in front of the façade under study*. This means that it is sufficient to calculate the level contributions coming from the source along the direct path, the path including one reflection in the opposite façade, and the path including one reflection in the near façade followed by one reflection in the opposite façade. The associated mirror source positions S_{ij1}, S_{ij12} and S_{ij2} are indicated. The subscripts *i* and *j* refer to the position (road segment) *i* and the sub-source *j*. For the j^{th} sub-source position S_{ij} the mirror source positions have to be calculated. The details are outlined in Annex B.

S_{ij1} is calculated using the coordinates of the source S_{ij} and the reflection plane A – B. S_{ij12} is calculated using the coordinates of the source S_{ij} and the reflection plane A' – B'. S_{ij2} is calculated using the coordinates of the mirror source S_{ij12} and the reflection plane A – B. The coordinates of A, B (and A', B') are not critical provided they represent the surface of the respective facades.

An additional subscript *k* (= 0, 1, 2) is introduced to indicate the contribution from the sub-source by the direct path, and the paths of the first- and second order reflection. When considering the source levels, it is assumed that the source directivity is relevant only for the direct path, not for the reflected paths. The source strengths $L_{W,ijk}$ to be used are therefore:

The direct path: $L_{W,ij0} = L_{Wref,j} + \Delta L_j(\varphi) + \Delta L_j(\psi)$
Path of first reflection: $L_{W,ij1} = L_{Wref,j} + 10\lg(1-\alpha_1)$
Path of second reflection: $L_{W,ij2} = L_{Wref,j} + 10\lg(1-\alpha_1) + 10\lg(1-\alpha_2)$
(3.5)

$L_{Wref,j}$ is the sub-source strength according to section 2.3.1. α_1 and α_2 are the sound absorption coefficients of facades A – B and A' – B' respectively.
It is further assumed that the propagation effect given by ΔL_{ij} in Eq.(3.3) in these cases are limited to spherical divergence, air absorption and ground effects above the street (ground impedance of the street), all depending on the geometrical distance between source and receiver, r_{ij}. The relevant distances are given by:

The direct path: $r_{ij0} = | S_{ij}\, R |$
Path of first reflection: $r_{ij1} = | S_{ij1}\, R |$
Path of second reflection: $r_{ij2} = | S_{ij2}\, R |$
(3.6)

R is the receiver position.
The sound exposure level for the sub-source *j* in position *i* within the rail segment Δx_i, is then given by:

$$L_{E,ij} = 10\lg\left[\frac{\Delta x_i}{v_i}\sum_{k=0}^{2} 10^{(L_{W,ijk}+\Delta L_{ijk})/10}\right] \tag{3.7}$$

where $L_{W,ijk}$ and ΔL_{ijk} correspond to the source strengths and propagation effects given above. Eq.(3.7) is equivalent to Eq.(4.3) in Section 4.1. The L_{eq} from a vehicle flow is then obtained by inserting into Eqs.(4.4 – 4.7) in Section 4.1 and 4.2. $L_{F\,max}$ is calculated according to Eq.(5.1) based on the direct sound contributions.

3.4.2.2 City streets with partly adjoining building facades

In situation b) in Figure 3.1 the building facades are partly adjoining, leaving gaps in the façade surfaces. In this case the reflection points should be tracked. The reflection contribution corresponding to a reflection point in a gap should be excluded from the summation in Eq.(3.7). This is obtained by specifying the gap absorption coefficient equal to 1 (e.g. 0.99 for practical reasons). The formalism of Eq.(3.7) can then be used, and the calculation of L_{eq} from a vehicle flow is carried out as explained above. The positions of the reflection points (T) in the façade surfaces are needed. They can be calculated as shown in Annex B.

The use of Eq(3.7) which in principle covers gaps and varying absorption coefficients, makes this approach a rather general approach for city streets. $L_{F\,\mathrm{max}}$ is calculated according to Eq.(5.1) based on the direct sound contributions.

3.4.2.3 Side streets

In side streets which are exposed to sound generated by traffic in the adjoining main street, the concept of contributions from the sources by direct paths and paths including one and two reflections in the facades, can still be applied. These cases are slightly complicated by the fact that only a portion of the traffic line "is seen" from the receiver R. The rest is considered not to contribute due to the shielding effect by the corner buildings towards the main street.

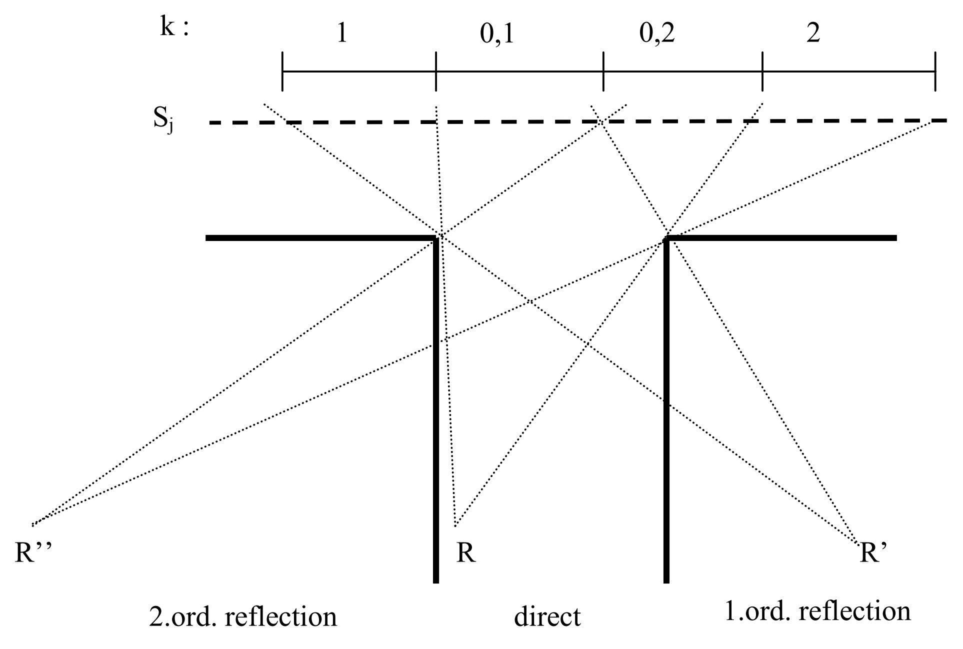

Figure 3.2 The principle of "visible sound sources" is shown for the side street situation. The sound source line is indicated by S_j.

Using the principle of “visible” sources, the contributing sources for the direct sound and sound that is reflected once and twice are indicated in Figure 3.2. R is the receiver in front of the façade A’ – B’. R’ is the mirror receiver regarding the reflecting surface of façade A – B. R’’ is the mirror image of R’ regarding the reflecting surface of façade A’ – B’. For a certain source S_{ij} (positioned according to Section 4.3) it must be determined if it is included in one or more of the selected source regions associated with the direct, once- or twice reflected sound. A graphical interpretation of this is shown in Figure 3.2. Again, the background of Section 3.4.2.1 and Eq.(3.7) can be used.

The graphical interpretation just mentioned indicates which of the k-values to be used in Eq.(3.7) for the current source S_{ij}. Also, the concept of gaps and varying absorption coefficients according to Section 3.4.2.2 is applicable to the conditions in the side street. $L_{\mathrm{F\,max}}$ is calculated according to Eq.(5.1) based on the direct sound contributions.

3.4.2.4 Depressed tracks or parallel rail barriers

These situations correspond closely to the city street situation discussed in Section 3.4.2.1, except that the receiver R is not in front of the façade A’ – B’, but at a certain position behind it at a greater distance from the traffic flow. The procedures of Section 3.4.2.1 can be applied, including the formalism of Eq.(3.7) provided the terminology is corresponding. The change in the receiver position R can have a significant effect on the propagation term ΔL_{ij} that enters into Eq.(3.7). The propagation may now also include diffraction effects due to a screened situation. The screen is formed by the upper edge of the vertical surface denoted A’ – B’ (or the top of a barrier in the parallel road barrier situation). The paths of the direct sound and the reflected sound may all be screened.

It is assumed that the reflecting surfaces associated with depressed roads are vertical (or almost vertical), with sufficient heights to give proper reflections. Walls that are not vertical should normally not cause any problems regarding single or multiple reflections.

3.5 Reflection in rail barriers

In the case of a barrier at one side of the rail, the sound reflection to the opposite side can be treated as single reflections. This case is similar to the city street situations discussed in Sections 3.4.2.1 and 3.4.2.2 above, except that the facade denoted A’ – B’ is absent. Therefore only the direct sound and the sound reflected once in the barrier are calculated. The procedures of Section 3.4.2.1 can still be used. Parameters related to second order reflections need not be calculated, i.e. S_{ij12}, S_{ij2}, r_{ij2}, $L_{\mathrm{W},ij2}$ and α_2. The summation in Eq.(3.7) is now restricted to k-values 0,1.

Modern noise barriers are normally tested according to EN 1793, [9], which means that sound absorption data (α) are available.

The point of reflection T_{ij1} in the barrier surface should be checked according to Annex B. The sound level contribution from the reflection can be omitted if T_{ij1} is on (or near) or above the barrier top. Else, in case of low height barriers, reflections according to the Fresnel-zone correction described in [1] should be considered.

The procedure described in this section applies to all reflecting surfaces on one side of and close to the road (long building facades, dense fences, retaining walls, etc.).

4 Calculation of L_{eq}

4.1 L_{E} from one moving point source

For calculation of L_{E} or L_{eq} the distribution of the sources in time is irrelevant as long as the sources pass during the observation time (T or t_2-t_1). Thus the following analysis of one point source is equally valid for all series of point sources constituting a train or sets of train.

A moving point source, index j, will during a pass-by yield the sound exposure level

$$L_{E,j} = 10\lg\left[\frac{1}{t_0}\int_{t_1}^{t_2} 10^{L_{p,j}(t)/10}\,dt\right] \tag{4.1}$$

where t_0 is a reference duration of 1 s, t_1 is the time when we start hearing the source and t_2 the time when the source is no longer audible. $L_{\mathrm{p,j}}(\mathrm{t})$ is the sound pressure level from source j at the receiver at the time t.

If, at time t, the source j is in position i, and moves with speed v_{i} along a track segment with length Δx_{i} at a distance r_{i} from the receiver, (4.1) can, for a short segment, be approximated by

$$L_{E,ij} = 10\lg\left[\frac{\Delta x_i}{v_i} 10^{L_{p,ij}/10}\right] \tag{4.2}$$

With (3.1) we now get

$$\boxed{L_{E,ij} = 10\lg\left[\frac{\Delta x_i}{v_i} 10^{(L_{W,ij}+\Delta L_{ij})/10}\right]} \tag{4.3}$$

where

$L_{\mathrm{W,ij}}$ is given by eq. (3.2) where, for trains,

$L_{\mathrm{Wref,j}}$ = the total sound power level of all sub sources j (one per m) of the train under study, that is the sound power level per meter of sub source j + 10 lg(length of train(s) during T).

The total sound exposure level at the receiver during a complete pass-by by the sources j then becomes

$$\boxed{L_{E,j} = 10\lg\left[\sum_{i=1}^{m} 10^{L_{E,ij}/10}\right]} \tag{4.4}$$

where m = the number of track segments used.

For a number n_j of sub-sources, each with a pass-by sound exposure level $L_{\mathrm{E,j}}$, representing one train of a certain category, the sound exposure level, $L_{\mathrm{E,v}}$, for this single train of this category is given by

$$L_{E,v} = 10\lg\left[\sum_{j=1}^{n_j} 10^{(L_{E,j}/10)}\right] \tag{4.5}$$

4.2 L_{eq} from a train flow

During a specified time period, T, a certain number, N_{vc}, of trains belonging to a specific train category will pass by, yielding the train-category L_{eq}-level

$$L_{eq,T,vc} = L_{E,v} - 10\lg(T) + 10\lg(N_{vc}) \tag{4.6}$$

For a number N_{cat} of train categories in the traffic flow, the total L_{eq}-level in the specified time period T, is

$$L_{eq,T} = 10\lg\left[\sum_{vc=1}^{N_{cat}} 10^{(L_{eq,T,vc}/10)}\right] \tag{4.7}$$

$L_{\mathrm{eq,T}}$ is calculated for each track or track segment. The final result is then obtained by summing up all tracks or segment contributions according to the principles given by (4.7).

4.3 Track segment length, Δ*x*

4.3.1 General

Each terrain profile must have its own track segment. As eq. (4.4) is a sum and not an integral, it is an approximation. Thus, if a track segment is large, it must be divided into smaller sub-segments even if the terrain profile is the same. At least at short and medium distances from the track, the sound exposure is sensitive to changes in the sound propagation conditions, i.e. by pronounced terrain variations, major changes in ground class, or the transition to or from a screened situation. This suggests that the track segment length should be relatively small.

Determining segment lengths is equivalent to the positioning of sound sources along the track as shown by eq. (4.3), with source heights and strengths according to chapter 2.2 and 2.3. The two basic principles for the positioning include that the sources are distributed equidistantly along the track, or distributed at constant view angles as seen from the receiver. A combination of the two is proposed in the following to get a practical procedure with due consideration to the density of source positions. The density should be adequate for reasons mentioned above, but at the same time kept to a minimum considering the computational time that is required. The procedure is split into two parts. First the basic track segments are determined, then sub-segments are determined if necessary.

4.3.2 Basic track segments

The basic track segments are established on basis of significant changes in:

i) the track curvature and/or track gradient, the traffic intensity, the track quality and the speed,

ii) the terrain profile between the track and the receiver position, including natural or artificial barriers or screens.

If the track is curved, its curvature is approximated by straight segments.
The track segments according to the parameters in i) are first established, while the parameters in ii) may lead to additional segments. The point is to obtain homogeneous conditions regarding the parameters mentioned in i) and ii), for each of the sectors defined by the basic track segment and the receiver position. The parameters represent the minimum general input data that is required to carry through a noise level calculation.

4.3.3 Track sub-segment lengths

When the basic track segments are established according to chapter 4.3.2, they usually have to be sub-divided. The following guidance is given for the sub-segmentation, the determination of the track segment length Δx and the position of the source point:

iii) If the current track segment length Δx is smaller than Δx_{min}, then the segment length is unchanged. Otherwise:
If the current segment angle β is greater than β_{max} or if the relative distance RD (the ratio $|P_1R| / |P_2R|$ of the shortest distance between the segment and the receiver to the greatest distance, see Figure 4.1) is less than RD_{min}, then the current segment is divided into two parts, as follows:
If the current segment angle β is greater than $\beta_{\text{max}}/2$, then the segment is split into two by the dividing line of $\beta/2$. Otherwise the segment is split into two at the segment midpoint.

iv) Step iii) is repeated for all new sub-segments until no new sub-segments are created.

v) The associated noise source position is as follows :
If the current segment angle β is greater than $\beta_{\text{max}}/2$, then the source point is positioned by the dividing line of $\beta/2$. Otherwise the source point is positioned at the current segment midpoint.

The values of Δx_{min}, β_{max}, and RD_{min} are chosen according to practical considerations. The following values can be used as a guide :

Δx_{min} = 5-10m, the lowest figure is used when close to the road.
$\beta_{\text{max}} = 10°$ (0.175 rad.),
$\text{RD}_{\text{min}} = 0.75$.

:

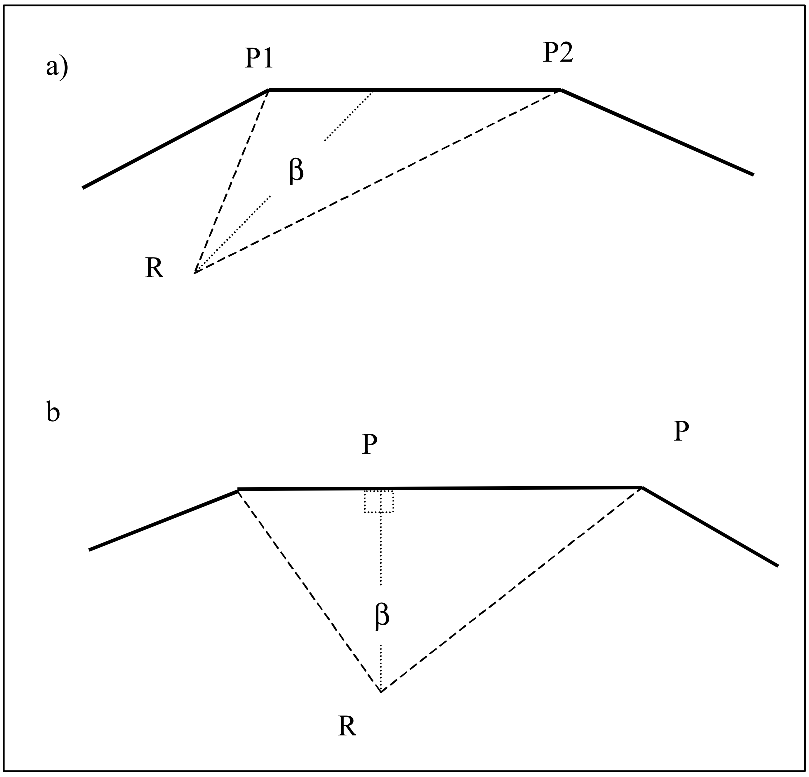

Figure 4.1 Basic rail segments, segment angle β, distances $|P_1 R|$ and $|P_2 R|$. Schematic plan view.

4.4 L_{eq} from a tunnel opening

A tunnel opening is stationary and the source strength is, according to 2.13, described in terms of the sound energy level. The sound exposure level at the receiver point, due to the tunnel passage by one train, is calculated for each tunnel sub-source *j* according to

$$L_{E,j} = L_{J,j} + \Delta L_{ij} \tag{4.10}$$

where ΔL_{ij} is given by eq. (3.3), *ij* indicating the location of the tunnel opening and its sub source *j*.

The sound exposure level at the receiver, radiated from the tunnel opening due to the passage of one train of a certain category, then becomes

$$L_{E,v,tun} = 10\lg\left[\sum_{j=1}^{nj} 10^{(L_{E,ij}/10)}\right] \tag{4.11}$$

where n_j = the number of tunnel opening sub-sources used.

During a specified time period, T, a certain number, N_{vc}, of trains belonging to a specific category will pass through the tunnel, yielding the train-category L_{eq}-level

$$L_{eq,T,vc,tun} = L_{E,v,tun} - 10\lg(T) + 10\lg(N_{vc}) \tag{4.12}$$

For a number, N_{cat}, of train categories in the traffic flow, the total L_{eq}-level in the specified time period T, is

$$L_{eq,T,tun} = 10\lg\left[\sum_{vc=1}^{N_{cat}} 10^{(L_{eq,T,vc,tun}/10)}\right] \tag{4.13}$$

This is the contribution of the tunnel opening to the overall L_{eq}.

4.5 Day, evening, night weighting

Within the European Union it has been proposed to use L_{den}, where

$$L_{den} = 10\lg\left[\frac{1}{T_{day} + T_{evening} + T_{night}}\right] + 10\lg\left[T_{day}10^{L_{eq,day}/10} + T_{evening}10^{(L_{eq,evening}+5)/10} + T_{night}10^{(L_{eq,night}+10)/10}\right] \tag{4.14}$$

that is evening and night movements get the penalties 5 and 10 dB respectively. Alternatively the number of vehicles in the evening and at night could be multiplied by 3 and 10 respectively. Standard values for day evening and night are 07.00-19.00, 19.00-23.00 and 23.00-07.00 respectively, that is T_{day}, T_{evening} and T_{night} are 12 h(43200 s), 4 h(14400 s) and 8 h (28800 s) respectively. Each member state may decide the day, evening and night time intervals individually.

4.6 Yearly average

In order to get the yearly average some simplifications have to be made because it is too complicated to carry out calculations for each possible set of weather conditions. The approach recommended here is to divide the weather conditions into 3 different classes: *f*, *h* and *u* respectively standing for favourable (downwind), homogeneous (neutral) and unfavourable (upwind).

Using the notation p for p % of the time and L for the calculated L_{eq} and adding the different indices the yearly average is calculated from

$$L_{yav} = 10\lg\left[0{,}01\left(p_f 10^{L_f/10} + p_h 10^{L_h/10} + (100 - p_f - p_h)10^{L_u/10}\right)\right] \tag{4.15 }$$

In order to get a more accurate yearly average it may become necessary to take varying ground conditions into account.

5 Calculation of $L_{F\max}$

$L_{F\max}$ is calculated from the sound power levels $L_{W,j}$ of the *n* subsources of the noisiest train. For the time being the only available data is the sound power level per meter train. This sound power has to be distributed to a finite number of sources. If the train is very long only parts of the train will contribute to the maximum sound pressure level at short distances. Practically the sound power distribution and the number of sources can be done in many ways. One procedure that will give a satisfactory accuracy is the following:

Define the length

$$l_P = \min(l, 15 \cdot d) \tag{5.1}$$

where *l* is the length of the noisiest train and *d* the distance between the receiver and the train where it is loudest. The sound power level relevant to the maximum level of this train will become

$$L_W = L_{W,1m} + 10\lg(l_P) \text{ dB} \tag{5.2}$$

Distribute L_W equally over 7 horizontally distributed sound sources, each consisting of sub sources according to the source model, each with the sound power level

$$L_{W,i} = L_W - 10\lg(7) \text{ dB} \tag{5.3}$$

The horizontal locations of these 7 sources are in the middle of the train, ± $l_P/2$, ± $l_P/4$ and + $l_P/8$ respectively.

$L_{\max}$ is then calculated from

$$L_{p\max} = \max(L_{p\max}(i)) = \max\left[10\lg\sum_{j=1}^{n} 10^{(L_{W,ij} + \Delta L(\varphi) + \Delta L(\psi) + \Delta L_{ij})/10}\right] \tag{5.4}$$

where

i indicates the position of the train and max($L_{\max}$(i)) the maximum level of all positions *i* which the vehicle has during a complete pass-by. *j* is the 21 sources of the train. The maximum position *i* is defined as the position giving the highest A-weighted sound pressure level.

$L_{p\max}$ in equation (5.4) is a kind of average maximum because it is based on a sound power level which has been calculated from the sound exposure level which is a time-integrated measure. In practice it turns out that this maximum is rather close to time-weighting S. To calculate $L_{pF\max}$ we have to consider the fact that local effects, such as a wheel that is noisier than average, will increase the level further. As the local effects are more pronounced near the train they will be distant dependant. Until better information is available the following frequency independent corrections, derived from data given in [5], are valid

$$L_{pF\max} = L_{p\max} + 3 - 2\lg\left(\frac{d}{10}\right) \text{ dB} \tag{5.5}$$

Tunnel openings are assumed not to increase the maximum levels.

6 Uncertainty

The new Nordic propagation model still needs testing and validation. Until extensive validation has taken place the uncertainty will not be known. Until further it is recommended to assume the following approximate uncertainties for A-weighted values:

Source of error	**Expected standard deviation**	
	Standard conditions	Other cases
Source data	$\sigma_s = 1,5$	$\sigma_s = 3$
Description of terrain	$\sigma_t = 1$	$\sigma_t = 2$
Favourable or homogeneous propagation, or $(h_s+h_r) \geq 0,1\ d$	$\sigma_f = 1$	$\sigma_f = 2$
Unfavourable propagation, or $(h_s+h_r) \leq 0,1\ d$	$\sigma_u = 3$	$\sigma_u = 5$

Standard conditions are defined as follows:

Source data	Well defined standard track with large traffic of commonly occurring train categories
Description of terrain	Smooth ground surfaces with known impedances and not more than one well-defined barrier
Favourable or homogeneous propagation, or $(h_s+h_r) \geq 0,1\ d$	Only one ground reflected ray
Unfavourable propagation, or $(h_s+h_r) \leq 0,1\ d$	Receiver not in the shadow zone

As an example the total prediction error, expressed as standard deviation, is, for the most favourable conditions given by, given by:

$$\sigma_{tot} = \sqrt{\sigma_s^2 + \sigma_t^2 + \sigma_f^2} \quad = \sqrt{4,25} = 2,1 \text{ dB} \qquad (6.1)$$

The uncertainties above refer to one specific occasion. If comparisons are made with measurements averaged over several different occasions the uncertainty will improve

7 Comparisons with the 1996 Nordic model

7.1 Background

The present Nordic prediction method is based on calculations in octave bands but many calculation programs present the result as A-weighted sound pressure level only.

The result of the calculations depends on the input data and the excess sound attenuation. In the 1996 model input data are given as sound power levels. In principle Nord 2000 has taken over these data although some small corrections have been made. These corrections are not likely to affect the A-weighted sound pressure levels outdoors significantly.

In the 1996 model the maximum level is given as an arithmetic energy average which should be comparable to that of Nord 2000.

As to the excess sound attenuation due to propagation effects Nord 2000 includes several effects, which are not included in the 1996 model. Examples of such effects are different ground impedances and wind speed components. In the 1996 model we only talk about hard and soft ground and it is stated that the meteorological conditions correspond to downwind conditions. In the following comparisons we will primarily use impedance class E (500 kRayls) for soft ground and carry out the Nord 2000 calculations for 0 – 3 m/s at 10 m in a direction downwind and along the horizontal normal to the road and with different speed standard deviations.

In the following calculations the Nord 2000 integration during vehicle pass-bys has been limited to about ±80º. For calculations according to the 1996 model the commercial software by Trivector has been used.

7.2 Some comparisons

Case 1
Flat. Soft rail bed (200 kRayls) and soft ground (500 kRayls).

$L_{eq,24h}$ for 1000 m train

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**								
1996	54,6	54,6	51,0	51,0	47,1	47,1	42,8	42,9	
0/0 m/s	55,4	55,9	50,8	52,1	44,0	47,1	36,0	39,5	
3/0,5 m/s	55,6	55,9	52,0	52,3	48,1	48,3	44,4	43,9	
Diff									
0/0 m/s	0,8	1,3	-0,2	1,1	-3,1	0,0	-6,8	-3,4	-1,3
3/0,5 m/s	1,0	1,3	1,0	1,3	1,0	1,2	2,4	1,0	1,3
S-Pass	**130 km/h**								
1996	55,0	55,0	51,3	51,4	47,4	47,5	43,2	43,3	
0/0,0 m/s	55,3	56,2	50,5	52,1	43,4	46,9	34,7	39,0	
3/0,5 m/s	55,5	56,3	51,8	52,4	48,1	48,4	44,7	44,2	
Diff									
0/0,0 m/s	0,3	1,2	-0,8	0,7	-4,0	-0,6	-8,5	-4,3	-2,0
3/0,5 m/s	0,5	1,3	0,5	1,0	0,7	0,9	1,5	0,9	0,9
S-X10	**100 km/h**	**50 m**							
1996	48,8	**48,9**	45,0	45,1	41,1	41,2	36,9	37,0	
0/0,0 m/s	49,7	50,5	44,9	46,4	38,4	41,2	31,2	33,7	
3/0,5 m/s	49,9	50,5	46,0	46,7	42,2	42,5	38,8	38,2	
	0,9	1,6	-0,1	1,3	-2,7	0,0	-5,7	-3,3	-1,0
	1,1	1,6	1,0	1,6	1,1	1,3	1,9	1,2	1,4

L_{Amax}

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**	**140 m**							
1996	92,7	92,5	87,4	87,4	80,7	80,8	74,3	74,4	
0/0 m/s	92,6	93,0	87,5	88,7	79,7	82,7	69,6	73,3	
3/0,5 m/s	92,7	93,0	88,5	88,8	83,2	83,5	77,5	77,0	
Diff									
0/0 m/s	-0,1	0,5	0,1	1,3	-1,0	1,9	-4,7	-1,1	-0,4
3/0,5 m/s	0	0,5	1,1	1,0	2,5	2,7	3,2	2,6	1,7
S-Pass	**130 km/h**	**200 m**							
1996	91,4	91,3	86,4	86,4	80,2	80,3	74,2	74,2	
0/0,0 m/s	90,8	91,7	85,7	87,2	78,0	81,4	67,7	72,2	
3/0,5 m/s	91,1	91,8	86,9	87,4	82,2	82,5	77,0	76,5	
Diff									
0/0,0 m/s	-0,6	0,4	-0,7	0,8	-2,2	1,1	-6,5	-2,0	-1,2
3/0,5 m/s	-0,3	0,5	0,5	1,0	2,0	2,2	2,8	2,3	1,4
S-X10	**100 km/h**	**50 m**							
	82,4	82,3	75,8	75,8	67,9	67,9	61,1	61,2	
0/0,0 m/s	82,7	83,3	76,4	77,6	67,7	70,4	57,5	60,4	
3/0,5 m/s	82,8	83,4	77,2	77,8	70,8	71,2	64,6	64,0	

Case 2
Flat. Soft rail bed (200 kRayls) 0,5 m above ground and soft ground (500 kRayls).

$L_{eq,24h}$ for 1000 m train

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**								
1996	54,7	54,7	51,1	51,0	47,4	47,3	43,1	43,2	
0/0 m/s	56,2	56,5	52,8	53,0	47,1	49,5	38,8	42,9	
3/0,5 m/s	56,2	56,5	53,2	52,9	49,2	49,5	45,2	44,9	
Diff									
0/0 m/s	1,5	1,8	1,7	2,0	-0,3	2,2	-4,3	-0,3	0,5
3/0,5 m/s	1,5	1,8	2,1	1,9	1,8	2,2	2,1	1,7	1,9

L_{Amax}

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**	**140 m**							
1996	92,7	92,5	87,4	87,4	80,7	80,8	74,3	74,4	
0/0 m/s	93,3	93,6	89,4	89,4	82,7	84,8	72,7	76,7	
3/0,5 m/s	93,3	93,6	89,6	89,3	84,4	84,5	78,2	77,9	
Diff									
0/0 m/s	0,6	1,1	2,0	2,0	2,0	4,0	-1,6	2,3	1,6
3/0,5 m/s	0,6	1,1	2,2	1,9	3,7	3,7	3,9	3,5	2,6

Case 3
Flat. Soft rail bed (200 kRayls) 2 m above ground and soft ground (500 kRayls).

$L_{eq,24h}$ for 1000 m train

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**								
1996	54,7	54,7	51,1	51,0	47,4	47,3	43,1	43,2	
0/0 m/s	55,5	56,3	52,5	52,7	50,0	49,8	44,3	46,7	
3/0,5 m/s	55,6	56,4	52,6	52,8	49,4	49,4	46,4	45,4	
Diff									
0/0 m/s	0,8	1,6	1,4	1,7	2,6	2,5	1,2	3,5	1,9
3/0,5 m/s	1,9	1,7	1,5	1,8	2,0	2,1	3,3	2,2	2,0

L_{Amax}

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**	**140 m**							
1996	92,7	92,5	87,4	87,4	80,7	80,8	74,3	74,4	
0/0 m/s	92,7	93,5	88,9	89,2	85,3	84,6	78,3	79,9	
3/0,5 m/s	92,8	93,6	89,0	89,3	84,3	84,5	79,3	78,4	
Diff									
0/0 m/s	0,0	1,0	1,5	1,8	4,6	3,8	4,0	4,5	2,7
3/0,5 m/s	0,1	1,1	1,6	1,9	3,6	3,7	5,0	4,0	2,6

Case 4

Flat. Soft rail bed (200 kRayls) 6,0 m in front of a 3 m high absorbing screen on soft ground (500 kRayls).

$L_{\mathrm{eq,24h}}$ for 1000 m train

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**								
1996	43,3	45,1	39,4	40,2	34,8	35,2	29,7	30,0	
0/0 m/s	37,7	40,8	34,3	35,0	31,2	31,3	26,0	27,8	
3/0,5 m/s	38,3	39,6	35,6	35,9	35,1	33,2	37,0	34,8	
Diff									
0/0 m/s	-5,6	-4,3	-5,1	-5,2	-3,6	-3,9	-3,7	-2,2	-4,2
3/0,5 m/s	-5,0	-5,5	-3,8	-4,3	0,3	-2,0	7,3	4,8	-1,0

L_{Amax}

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**	**140 m**							
1996	76,7	78,8	71,2	72,3	64,7	65,2	58,6	58,8	
0/0 m/s	74,6	77,7	70,2	71,0	65,9	65,6	58,8	60,3	
3/0,5 m/s	75,1	76,5	76,2	71,3	71,7	67,9	67,0	68,5	
Diff									
0/0 m/s	-2,1	-1,1	-1,0	-1,3	1,2	0,4	0,2	1,5	-0,3
3/0,5 m/s	-1,6	-2,3	5,0	-1,0	7,0	2,7	8,4	9,7	3,5

C*ase 5*
2 m depressed rail bed (200 kRayls) on soft ground (500 kRayls).

$L_{eq,24h}$ for 1000 m train

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**								
1996	48,9	52,4	43,1	44,6	37,5	38,5	31,9	32,2	
0/0 m/s	42,9	46,8	36,1	38,7	30,4	31,9	25,5	25,8	
3/0,5 m/s	44,3	47,8	39,8	40,7	40,3	37,0	39,7	36,8	
Diff									
0/0 m/s	-6,0	-5,6	-7,0	-5,9	-7,1	-6,6	-6,4	-6,6	-6,4
3/0,5 m/s	-4,6	-4,6	-3,3	-3,9	2,8	-1,5	7,8	4,6	-0,3

L_{Amax}

	25m/2m	25m/4m	50m/2m	50m/4m	100m/2m	100m/4m	200m/2m	200m/4m	Average
S-X2	**200 km/h**	**140 m**							
1996	84,3	89,6	75,8	77,5	66,7	69,0	60,3	60,6	
0/0 m/s	80,1	84,0	72,6	75,2	65,4	67,0	58,0	55,0	
3/0,5 m/s	81,3	84,9	75,6	77,0	74,4	71,2	72,3	68,8	
Diff									
0/0 m/s	-4,2	-5,6	-3,2	-2,3	-1,3	-2,0	-2,3	-5,6	-3,3
3/0,5 m/s	-3,0	-4,7	-0,2	-0,5	7,7	2,2	12,0	8,2	2,7

7.3 Discussion and conclusions

It is not quite easy to draw any firm conclusions. For simple cases like flat ground with or without an elevated track bed the difference between the 1996 model and Nord 2000 is rather small although there is a small tendency that Nord 2000 yields slightly higher values.

When there is screening the situation gets complicated. Occasionally there are large differences. The general trend, if any, is that Nord 2000 with neutral conditions yield higher attenuation while the opposite is the case when 3 m/s downwind conditions are used.

8 References

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[4] ISO 9613-1,2:93,96 Attenuation of sound during propagation outdoors –
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Annex A Source data

A.1 General

The sound power level is described in dB/m train and given in the following form:

$$L_{W,1m} = a \cdot \lg\left(\frac{v}{100}\right) + b \quad \text{dB per 1 m train}$$

where v is the speed in km/h and the coefficients a and b are given in the tables given below. Thus, if the total train length is l m

$$L_W = L_{W,1m} + 10\lg(l)$$

The measurements have in general taken place at normal cruising speeds of the trains. This means that the data given should not be extrapolated to very low speeds.

A.2 Sweden

The Swedish data have been taken from table B1b in the present Nordic model, [2], and converted to dB/m using eq. (2) in that model. 1/3 octave data have been obtained from interpolation between the octaves and then normalized to the correct octave band sound power level. Provisionally, as [2] only covers 63-4000 Hz, 31,5 Hz has been chosen to the value of 63 Hz and 8000 Hz to the value of 4000 Hz –10 dB. At the boundaries 25 Hz and 10000 Hz have been given the values of 31,5 Hz and 8000 Hz respectively.

Table A.1 Input data for Swedish trains. N.B. the corrections in table A.2.

Cat	**1a** **X2**		**2a** **Pass**		**Pass/wood**		**3a** **X10**		**4b** **Freight-Di**		**4a** **Freight-El**	
Freq. Hz	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*	*a*	*b*
25	32,0	88,0	18,0	90,0	20,0	89,0	20,0	92,0	-2,0	95,0	10,0	91,0
31,5	32,0	88,0	18,0	90,0	20,0	89,0	20,0	92,0	-2,0	95,0	10,0	91,0
40	32,0	88,0	18,0	90,0	20,0	89,0	20,0	92,0	-2,0	95,0	10,0	91,0
50	31,6	88,1	19,0	89,9	21,3	88,9	20,5	92,0	-2,0	94,7	10,0	90,8
63	31,6	88,1	19,0	89,9	21,3	88,9	20,5	92,0	-2,0	94,7	10,0	90,8
80	32,6	87,8	16,3	90,2	17,9	89,2	19,1	92,0	-2,0	95,7	10,0	91,5
100	35,0	86,6	12,0	90,2	12,6	88,5	17,7	91,8	-2,0	97,1	10,0	91,8
125	36,0	86,3	9,3	90,5	9,3	88,9	16,4	91,8	-2,0	98,1	10,0	92,4
160	34,3	88,0	9,3	92,2	9,3	91,9	14,4	92,5	-2,0	98,8	10,0	94,4
200	32,5	90,6	11,5	94,4	10,8	96,1	11,5	93,3	-4,9	99,1	9,3	97,0
250	30,8	92,3	11,5	96,1	10,8	99,1	9,5	94,0	-4,9	99,7	9,3	99,0
315	28,1	92,9	8,2	97,1	9,2	100,7	9,5	94,7	3,1	101,1	10,9	100,4
400	23,4	93,5	0,6	98,1	4,0	103,2	8,0	95,6	16,9	103,6	13,8	102,3
500	20,8	94,1	-2,7	99,1	2,3	104,9	8,0	96,2	24,9	105,0	15,5	103,7
630	22,1	94,5	2,3	99,8	10,6	103,9	14,7	96,2	24,9	103,3	15,5	103,0
800	24,0	95,1	10,9	100,8	25,0	102,0	25,6	96,2	21,3	100,2	15,0	101,7
1000	25,4	95,5	15,9	101,5	33,3	101,0	32,3	96,2	21,3	98,5	15,0	101,0
1250	29,7	94,5	19,3	100,8	38,3	99,7	34,0	95,6	24,0	98,2	15,0	100,3
1600	36,7	93,2	23,9	99,9	42,5	98,4	34,4	95,1	28,6	98,8	15,0	100,0
2000	41,0	92,2	27,2	99,3	47,5	97,0	36,1	94,4	31,3	98,5	15,0	99,3
2500	41,3	90,2	23,9	97,6	47,5	95,0	34,4	92,1	30,6	96,5	15,0	97,3
3150	39,8	88,0	16,8	95,8	45,0	93,0	30,8	89,1	28,3	94,0	15,0	95,0
4000	40,2	86,0	13,4	94,1	45,0	91,0	29,1	86,8	27,7	92,0	15,0	93,0
5000	40,2	82,6	13,4	90,8	45,0	87,6	29,1	83,4	27,7	88,6	15,0	89,6
6300	40,0	77,9	15,0	85,9	45,0	82,9	30,0	78,9	28,0	83,9	15,0	84,9
8000	40,0	74,6	15,0	82,6	45,0	79,6	30,0	75,6	28,0	80,6	15,0	81,6
10000	40,0	74,6	15,0	82,6	45,0	79,6	30,0	75,6	28,0	80,6	15,0	81,6

As the sound power levels given in table A.1 has been obtained using different propagation and source models compared to Nord 2000 they have to be corrected. The corrections to apply are given in table A.2.

Table A.2 Corrections to apply to table A.1

Frequency				
25-160	-3			
200-315	-3			

The source models to be used for the most common Swedish trains are given in the following tables:

Table A.3 Source locations for X2 and X10, X11 and X12.

	Height above top of rail (m)	**Frequency range[1)] (Hz)**	**Horizontal location**
Source 1 **Wheel/rail**	0,01 (0,21 above rail bed)	200 - 10000	Evenly distributed along the train
Source 2 **Wheel/rail**	0,35 (0,55 above rail bed)	200 - 10000	Evenly distributed along the train
Source 3 **Wheel/rail**	0,70 (0,9 above rail bed)	200 - 10000	Evenly distributed along the train
Source 4 Engine	1,8 (2,0 above rail bed)	25 - 160	Centre of locomotive.

Table A.4. Source locations for trains with RC locomotives.

	Height above top of rail (m)	**Frequency range[1)] (Hz)**	**Horizontal location**
Source 1 **Wheel/rail**	0,01 (0,21 above rail bed)	400 - 10000	Evenly distributed along the train
Source 2 **Wheel/rail**	0,01 (0,55 above rail bed)	400 - 10000	Evenly distributed along the train
Source 3 **Wheel/rail**	0,70 (0,9 above rail bed)	400 - 10000	Evenly distributed along the train
Source 4 Engine	2,8 (3,0 above rail bed)	25 - 315	Centre of locomotive.

A.3 Norway

The Norwegian data have been taken from table B1a in the present Nordic model, [2], and converted to dB/m using eq. (2) in that model. In addition data for some newer trains are taken from estimates given in [13], intended for preliminary use. (The categories are market with an * in Table A.3.1). 1/3 octave data have been obtained from interpolation between the octaves and then normalized to the correct octave band sound power level. Provisionally, as [2] and [13] only covers 63-4000 Hz, 31,5 Hz has been chosen to the value of 63 Hz and 8000 Hz to the value of 4000 Hz –10 dB. At the boundaries 25 Hz and 10000 Hz have been given the values of 31,5 Hz and 8000 Hz respectively.

Table A.3.1 Input data for Norwegian trains

Cat.	***1a-2d-3c**		**2a**		**2b**		***2c-3b**		***2e**	
Freq. Hz	a	b	a	b	a	b	a	b	a	b
25	20.0	92.0	20.0	89.0	20.0	92.0	10.0	99.0	20.0	92.0
31,5	20.0	92.0	20.0	89.0	20.0	92.0	10.0	99.0	20.0	92.0
40	20.0	92.0	20.0	89.0	20.0	92.0	10.0	99.0	20.0	92.0
50	20.0	92.2	19.6	89.1	19.6	92.2	10.0	98.8	20.0	92.2
63	20.0	92.2	19.6	89.1	19.6	92.2	10.0	98.8	20.0	92.2
80	20.0	91.6	20.9	88.8	20.9	91.6	10.0	99.5	20.0	91.6
100	19.4	90.0	23.8	87.8	23.8	90.0	10.0	100.6	19.3	89.7
125	19.4	89.3	25.1	87.4	25.1	89.3	10.0	101.2	19.3	89.1
160	21.0	90.7	23.4	88.8	23.4	90.7	10.0	101.2	21.0	91.1
200	23.0	92.7	19.5	89.7	19.5	91.7	8.5	100.8	22.9	94.2
250	24.6	94.0	17.8	91.1	17.8	93.1	8.5	100.8	24.6	96.2
315	26.6	95.0	19.5	94.1	19.5	96.1	13.1	101.5	26.6	97.2
400	29.5	96.5	21.1	98.9	21.0	100.8	19.6	102.6	29.5	98.5
500	31.5	97.5	22.8	101.9	22.7	103.8	24.3	103.2	31.5	99.5
630	31.8	97.1	27.5	101.6	27.4	103.8	28.9	103.2	31.8	99.1
800	31.7	96.5	35.6	100.7	35.4	103.3	35.4	103.3	31.7	98.5
1000	32.0	96.2	40.2	100.4	40.1	103.3	40.1	103.3	32.0	98.2
1250	32.4	95.2	39.2	98.7	39.1	102.3	39.1	102.3	32.4	97.2
1600	32.7	94.0	35.6	96.5	35.7	101.0	35.7	101.0	32.7	96.0
2000	33.1	93.0	34.6	94.8	34.7	100.0	34.7	100.0	33.1	95.0
2500	33.4	92.0	34.3	93.2	34.3	98.7	34.3	98.7	33.4	94.0
3150	33.8	91.4	34.2	91.8	34.2	97.6	34.2	97.6	33.8	93.4
4000	34.2	90.4	33.8	90.1	33.8	96.3	33.8	96.3	34.2	92.4
5000	34.2	87.1	33.8	86.8	33.8	93.0	33.8	93.0	34.2	89.1
6300	34.0	81.9	34.0	81.9	34.0	87.9	34.0	87.9	34.0	83.9
8000	34.0	78.6	34.0	78.6	34.0	84.6	34.0	84.6	34.0	80.6
10000	34.0	78.6	34.0	78.6	34.0	84.6	34.0	84.6	34.0	80.6

Table A.3.1 (Cont.) *Input data for Norwegian trains*

Cat.	**3a**		**4a**		***4b**		***4c**	
Freq. Hz	a	b	a	b	a	b	a	b
25	10.0	93.0	20.0	95.0	20.0	92.0	10.0	99.0
31,5	10.0	93.0	20.0	95.0	20.0	92.0	10.0	99.0
40	10.0	93.0	20.0	95.0	20.0	92.0	10.0	99.0
50	10.0	93.1	19.6	95.2	20.0	92.2	10.0	98.8
63	10.0	93.1	19.6	95.2	20.0	92.2	10.0	98.8
80	10.0	92.8	20.9	94.6	20.0	91.6	10.0	99.5
100	10.8	91.9	23.8	93.0	19.2	89.3	10.0	100.6
125	10.8	91.6	25.1	92.3	19.2	88.6	10.0	101.2
160	8.8	92.6	23.4	93.7	20.9	91.6	10.0	101.2
200	2.6	93.4	19.5	95.1	22.8	96.5	8.4	100.7
250	0.6	94.4	17.8	96.4	24.5	99.5	8.4	100.7
315	7.3	96.7	19.5	98.8	26.5	100.2	13.0	101.7
400	18.1	100.7	21.4	102.7	29.5	100.7	19.8	103.7
500	24.7	103.0	23.1	105.0	31.5	101.4	24.5	104.7
630	29.4	102.0	27.7	104.0	31.9	101.0	29.1	103.7
800	35.7	100.2	35.7	102.0	31.7	100.5	35.7	102.0
1000	40.4	99.2	40.4	101.0	32.0	100.2	40.4	101.0
1250	39.4	97.2	39.4	99.7	32.4	99.2	39.4	99.7
1600	35.6	94.7	35.7	98.1	32.7	98.0	35.7	98.1
2000	34.6	92.7	34.7	96.7	33.1	97.0	34.7	96.7
2500	34.3	91.0	34.3	96.1	33.4	96.0	34.3	96.1
3150	34.2	89.8	34.2	96.3	33.8	95.4	34.2	96.3
4000	33.8	88.1	33.9	95.6	34.2	94.4	33.9	95.6
5000	33.8	84.8	33.9	92.3	34.2	91.1	33.9	92.3
6300	34.0	79.9	34.0	86.9	34.0	85.9	34.0	86.9
8000	34.0	76.6	34.0	83.6	34.0	82.6	34.0	83.6
10000	34.0	76.6	34.0	83.6	34.0	82.6	34.0	83.6

As the sound power levels given in Table A.3.1 has been obtained using different propagation and source models compared to Nord 2000 they have to be corrected. The corrections to apply are given in table A.3.3

The source models to be used for the Norwegian trains are given in the following table (valid default values to be used until specific information is available) :

Table A.3.2 Source locations.

	Height above top of rail (m)	**Frequency range1) (Hz)**	**Horizontal location**
Source 1 Wheel/rail	0,01 (0,21 above rail bed)	200 - 10000	Evenly distributed along the train
Source 2 Wheel/rail	0,35 (0,55 above rail bed)	200 - 10000	Evenly distributed along the train
Source 3 Wheel/rail	0,70 (0,9 above rail bed)	200 - 10000	Evenly distributed along the train
Source 4 Engine	2.5 (2,7 above rail bed)	25 - 160	Centre of locomotive.

Table A.3.3 Corrections to apply to $L_{W,1m}$ *resulting from Table A.3.1.*

Frequency	
25	-3
32	-3
40	-3
50	-2
63	-1
80	0
100	0
125	0
160	-1
200	-2
250	-2
315	-2
400	-2
500	-2
630	-2
800	0
1000	1
1250	1
1600	1
2000	1
$f \geq 2500$	0

A.4 Denmark

Train type	A&D		B, C, H & I		E		F2 & F3		F4	
	a	b	a	b	a	b	a	b	a	b
25	18,0	84,6	10,0	92,6	10,0	90,6	20,0	89,6	18,0	79,6
31,5	18,0	84,6	10,0	92,6	10,0	90,6	20,0	89,6	18,0	79,6
40	18,0	87,9	10,0	95,9	10,0	93,9	20,0	92,9	18,0	82,9
50	19,0	93,9	10,0	102,4	8,6	100,2	16,8	98,7	16,4	88,7
63	19,0	97,3	10,0	105,7	8,6	103,5	16,8	102,0	16,4	92,0
80	16,3	96,3	10,0	103,4	13,6	101,8	27,1	101,7	21,0	91,7
100	11,7	93,6	10,0	98,1	23,7	98,2	47,9	100,2	30,0	90,0
125	9,1	92,6	10,0	95,8	28,7	96,5	58,2	99,9	34,6	89,7
160	9,1	92,9	10,0	96,8	23,7	96,2	49,2	99,9	32,0	90,4
200	10,0	93,3	8,5	98,5	12,5	96,2	24,9	98,8	24,3	90,9
250	10,0	93,6	8,5	99,5	7,5	95,9	15,9	98,8	21,6	91,6
315	10,0	95,0	11,9	101,5	10,2	95,9	30,2	101,8	25,6	93,2
400	7,7	97,4	16,1	104,8	15,0	95,9	57,9	107,3	30,8	96,0
500	7,7	98,8	19,4	106,8	17,6	95,9	72,2	110,3	34,8	97,6
630	17,0	97,8	24,7	106,2	22,0	96,2	69,9	109,0	43,8	97,3
800	33,0	96,0	32,6	104,8	28,6	96,7	62,1	106,3	60,0	96,9
1000	42,3	95,0	37,9	104,1	32,9	97,0	59,8	105,0	69,0	96,6
1250	44,0	94,0	39,9	103,1	31,6	97,4	56,8	103,3	60,7	93,9
1600	42,9	93,2	41,6	102,3	28,6	98,4	52,1	101,4	43,0	89,9
2000	44,6	92,2	43,6	101,3	27,3	98,7	49,1	99,7	34,7	87,3
2500	40,9	90,2	40,3	98,9	24,6	96,7	51,7	98,4	33,3	85,9
3150	34,3	87,9	33,9	96,1	20,9	93,9	58,1	97,8	34,5	85,3
4000	30,6	85,9	30,6	93,7	18,3	91,9	60,7	96,4	33,1	84,0
5000	28,6	82,9	29,2	90,7	15,3	88,9	58,1	92,1	34,5	82,3
6300	27,0	78,8	28,7	86,8	11,6	84,8	52,2	85,4	37,2	80,1
8000	25,0	75,8	27,3	83,8	8,6	81,8	49,5	81,1	38,6	78,4
10000	25,0	75,8	27,3	83,8	8,6	81,8	49,5	81,1	38,6	78,4

Annex B : Calculation of mirror source position and point of reflection

B1 Mirror source position

B1.1 General

The position of the source, S, the receiver R and the reflecting surface are given :

(XS,YS,ZS) are the (x,y,z)-coordinates of the source position,
(XR,YR,ZR) are the (x,y,z)-coordinates of the receiver position,
(XA,YA,ZA) are the (x,y,z)-coordinates of the first upper corner (A) of the of the reflecting surface.
(XB,YB,ZB) are the (x,y,z)- coordinates of the second upper corner (B) of the reflecting surface.
The position of the *mirror source S'* given by the (x,y,z)-coordinates, is calculated by :

$$XS' = XS-2(XS-(YS+XS/F1-YA+F1\cdot XA)/(F1+1/F1))$$
$$YS' =YS+(XS-XS')/F1$$
$$ZS' = ZS$$

Key :

$F1 = (YB-YA)/(XB-XA+\Delta)$
Δ = is a small number supplied to avoid numerical problems (f.ex. 10^{-6}).

B1.2 Application to city streets

The receiver position R is in front of the façade A' – B'. The façade on the opposite side is denoted A – B. The current source point (sub-source j, position i) is denoted S_{ij}.

The first order mirror source S_{ij1} regarding the reflection surface A – B is calculated using the coordinates of the source S_{ij}.
The first order mirror source S_{ij12} regarding the reflection surface A' – B' is calculated using the coordinates of the source S_{ij}.
The second order mirror source S_{ij2} regarding the reflection surface A – B is calculated using the coordinates of the mirror source S_{ij12}.

The coordinates of the facades A - B and A' - B' are not critical provided they represent the surface of the respective facades.

B1.3 Application to side streets:

For the selected sources S_{ij} which contribute to 1.order reflections, and the selected sources S_{ij} which contribute to the 2.order reflections, the procedure is analogous to that described in Section A1.2, provided the corresponding terminology is applied.

B2 Point of reflection

B2.1 General

The position of the *point of reflection T* in the reflecting surface (or its extension) given by the (x,y,z)- coordinates, is calculated by:

$$XT = (YS'-YA+XA \cdot F1-XS' \cdot F2)/(F1-F2)$$
$$YT = (YA-F1 \cdot (XA-XT))$$
$$ZT = ZS+(ZR-ZS) \cdot F3/F4$$

Key :
$F2 = (YR-YS')/(XR-XS'+\Delta)$
$F3 = ((XS'-XT)^2 + (YS'-YT)^2)^{0.5}$
$F4 = ((XS'-XR)^2 + (YS'-YR)^2)^{0.5}$

The definition of the coordinates is given in section A1.1.

B2.2 Application to city streets:

The receiver position R is in front of the façade A' – B'. The façade on the opposite side is denoted A – B. The first and second order mirror sources S_{ij1}, S_{ij12} and S_{ij2} are calculated according to section A1.2.
The first order reflection point T_{ij1} in the façade A – B is calculated using the coordinates of the mirror source S_{ij1}, facade A – B and receiver R.
The second order reflection point T_{ij2} in the façade A – B is calculated using the coordinates of the mirror source S_{ij2}, facade A – B and receiver R.
The first order reflection point T_{ij12} in the façade A' – B' is calculated using the coordinates of the mirror source S_{ij12}, facade A' – B' and receiver T_{ij2}.

B2.3 Application to side streets

For the selected sources S_{ij} which contribute to 1.order reflections, and the selected sources S_{ij} which contribute to 2.order reflections, the procedure is analogous to that described in Section A2.2, provided the corresponding terminology is applied.