Prediction of Sound radiated from Tunnel Openings

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Summary

Road or railway tunnels are taking into account in noise prediction programs with the traffic flow ending at the tunnel mouth. The sound radiated from inside the tunnel through the tunnel mouth into the environment is calculated using an additional point or area source. Some investigations have been published /1 – 9/ where the source strength of the radiating tunnel mouth has been calculated from analytically derived propagation relations inside the tunnel. In the meantime sound propagation inside rooms can be modelled more precisely even for complex environments, where the basic algorithms have been selected and improved based on measurements in more than 150 rooms and halls /10, 11, 12/. These techniques have been standardized /13/ and in the meantime after about 8 years of experience with the application of these strategies they form an experimentally well and computer based method that can be used to solve many of these special problems. In the following the procedure is used as a part of an integral approach to calculate the noise radiated from tunnel openings. It can be used for different and even complex configurations and may help to integrate this very special noise source in environmental modelling for noise calculation.

Introduction

The radiation from tunnel-mouths has been studied in some papers theoretically and practically /1 – 9/. Most of these investigations are based on analytically closed solutions of sound propagation inside the tunnel caused by a source inside. In the meantime calculation procedures and software packages for the prediction of sound propagation in closed rooms are available, that have been developed on the basis of measurements in more than 150 rooms and halls /10, 11, 12/ and that are even standardized /13/ - this is a much better and experimentally verified starting point to predict sound propagation inside the tunnel even with absorbing panels near the tunnel mouth. It allows to configure the describing parameters of tunnels in a way that can directly be used to calculate the sound propagation outside and to predict the increase of noise levels caused by the tunnel mouth. In the following a method is presented, that can directly be implemented in noise calculations. To simplify the application, in the first step the results are summarized and presented as “directions for use” and afterwards the theoretical background and the model calculations are presented.

It is the aim of this work to faciltate the prediction of A-weighted mean sound pressure levels related to defined time intervals – e. g. day and night. This restriction shall be mentioned, because only related to energetically averaged mean levels the source inside the tunnel is a line source. As it is shown later only based on these conditions the sound field in a tunnel is diffuse – this is not the case if the sound distribution inside the tunnel produced by a moving car or train shall be predicted. It is shown that the application of ray tracing techniques provide exactly the same results, if this time averaging is applied. The application of such ray tracing techniques offers the advantage that even complex tunnel constructions with partially absorbing covered surfaces can be treated. These techniques allow to take into account the sound diffracted at the tunnel edges by an adequate directivity of the tunnel mouth source.

Problem definition

Roads and railways are guided through tunnels to prevent sensitive living environments from noise exposure or to cross under hilly terrain to avoid costly mountain roads. If the noise of such roads shall be predicted the sound radiated by the road inside the tunnel is generally neglected and this subpart of the road inside the tunnel is simply deleted from the model (if modern graphic oriented software is applied).
But the sound radiated from the tunnel mouth into the environment may produce a level increase that can not be neglected. Related to a given receiver position near the tunnel opening three different sound parts have to be taken into account.
The first part is radiated from the part ds of the track inside the tunnel that can be seen from the receiver and propagates without diffraction. It can be taken into account if this part ds would be included in the calculation. But this is only a solution for fixed receiver locations – when noise maps are calculated ds will be different for each grid point.

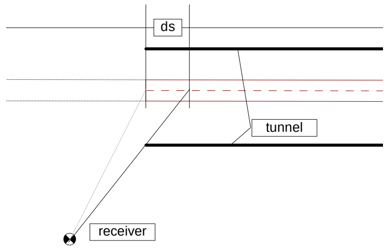

Figure 1 The part of the track ds that radiates towards the receiver without diffraction

The second part is the sound that is radiated from the track inside the tunnel and is diffracted over a tunnel edge towards the receiver. It can be determined by subdividing the track in small parts and by applying a usual diffraction calculation.

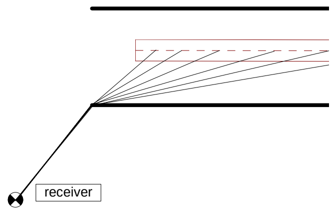

Figure 2 The direct sound from inside the tunnel diffracted at the tunnel edge

The third level contribution is caused by sound that is reflected at the inner surfaces. It depends on the absorption of these surfaces up to what orders these reflections play a role.

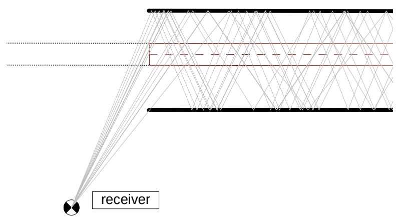

Figure 3 Reflected sound radiated from inside the tunnel to the receiver.

How to take a tunnel opening in noise prediction calculations into account

Roads and railways are characterized by an emission value that may be different for different time intervals – e. g. L_{day} and L_{night}. According to national or other calculation guidelines these emission values are produced by the software applied from the acoustically relevant parameters like traffic flows, speeds and road surfaces.
The tunnel is characterized by its cross section a x b – if rectangular - or by the circumference U of the open cross section and by the energetic sum of the emission values of all tracks or traffic lines inside.
With rectangular cross section

$$U = 2 \cdot (a + b) \tag{1}$$

with half circle circumference with radius r

$$U = (2 + \pi) r \tag{2}$$

If N traffic lines or tracks with emission values $L_{E,n}$ are inside the tunnel, one emission value is calculated from

$$L_{Emission} = 10 \lg \left(10^{0,1 \cdot L_{E,1}} + 10^{0,1 \cdot L_{E,2}} + \ldots . 10^{0,1 \cdot L_{E,N}} \right) dB \tag{3}$$

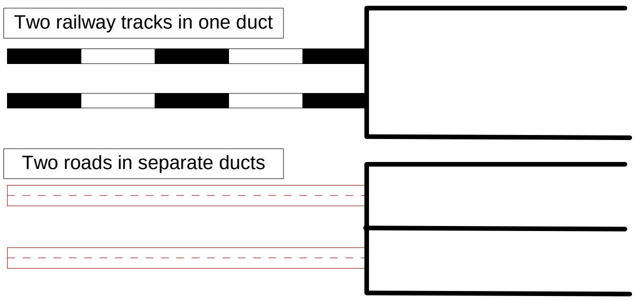

Figure 4 Railway tunnel with one and road tunnel with two ducts

With example figure 4 the emission values of the railway tracks have to be added according to equation (3), while the emission value of each road has to be assigned to the relevant duct.
These emission values $L_{emission}$ are different according to different national calculation methods. . Using the correction values $C_{emission}$ from table 1 the emission value $L_{emission}$ is transformed to the length related sound power level L'_{WA}.

$$L'_{WA} = L_{emission} + C_{emission} \qquad (4)$$

Table 1 Correction $C_{emission}$ to convert national emission values to length related sound power levels.

Country/Source	Guideline	Emission Value	$C_{emission}$
International	ISO 9613-2	LW'	**0.0**
Germany	RLS-90	Lm,e	**19.1**
England	CRTN	L10,18h	**15.1**
France	NMPB (G=0)	LAW'	**0.9**
Austria	RVS04	L1A,eq	**4.0**
Swiss	STL86	Lr,e	**3.2**
Swiss	SonRoad	LwA'	**-0.4**
Scandinavia	Nordic Pred. Meth.	Laeq*,10m	**14.2**
Czech	Liberko	Laeq,7.5m	**12.7**
USA	TNM	Ltraf,ref	**18.1**

The emission from a tunnel opening is simulated by a vertical area source with shape and size of the opening. This area source closes the duct like a cap.
If the walls and surfaces inside the tunnel are characterized by the same absorption everywhere – no additional absorption is applied near the opening – the area related sound power level of this vertical area source at the opening is

$$L''_W = L'_W - C_1 \qquad (5a)$$

Where L'_W ist he length related sound power level of all traffic lines in the tunnel according to (4) and C_1 is a correction that can be taken from figure 5 or calculated with equation (6). With figure 5 two typical cross sections of the tunnel are taken into account.

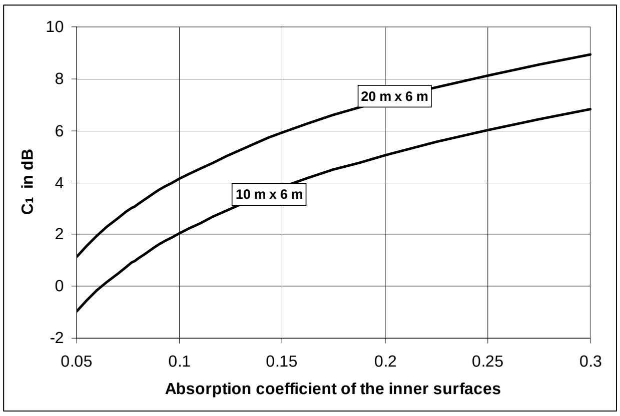

Figure 5 Determination of correction C_1

Correction C_1 can with any cross section be determined from

$$C_1 = L'_W - L''_W = 10\lg(U / X_0) + 10\lg(\alpha) - 3\ dB \qquad (6)$$

with

L'_W Level of the length related sound power of all traffic lines in the duct according to (4)
L''_W Level of the area related sound power of the vertical area source simulating the opening
X_0 Reference length 1 (m)
U Length of the inner perimeter of the duct in (m)
α mean absorption coefficient of the surfaces inside the duct – default value 0,1

If walls and ceiling inside the tunnel are covered with absorption material at a given length behind the opening, the emission is reduced by a correction C_2, that can be taken from the diagram figure 6.

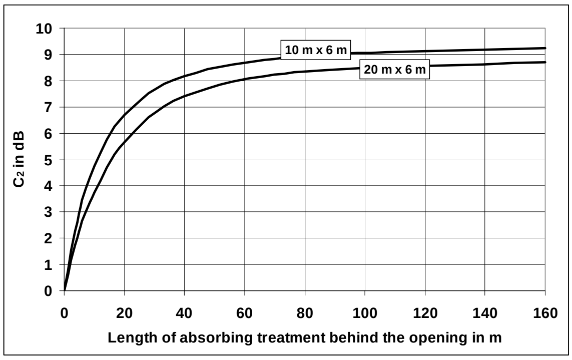

Figure 6 Correction C_2 in dependence of the length of the absorbing part

The two curves in figure 6 are again related to the two typical cross sections of the tunnel.
If absorption is applied, equation (5b) is used instead of (5a).

$$L''_W = L'_W - C_1 - C_2 \qquad (5b)$$

Further the directivity of the radiation has to be taken into account.
If the tunnel is not treated with absoption, the directivity correction is

$$D = -0{,}115 \cdot \psi + 3{,}08\ dB \qquad (7a)$$

If tunnel walls and ceiling are covered with absorption material behind the tunnel opening this correction is

$$D = -0{,}165 \cdot \psi + 6{,}95\ dB \qquad (7b)$$

ψ ist he angle between the center line of the tunnel and the line from the center of the tunnel opening to the receiver position. ($0 \le \psi \le 90°$). Equation (7b) has been developed using 100 m length of the absoptive part of the tunnel and a value C_2 of 9 dB.

If less than 100 m length behind the tunnel opening is treated with absorption and C2 is determined using figure 6 and applied in equation (5b), the following expression – an interpolation of (7a) and (7b) – should be used to define the directivity:

$$D = -0{,}115 \cdot \psi - 5{,}55 \cdot 10^{-3} \cdot C_2 \cdot \psi + 0{,}43 \cdot C_2 + 3{,}08 \qquad (7c)$$

The diagram figure 7 shows the directivity according to equations (7a) and (7b).

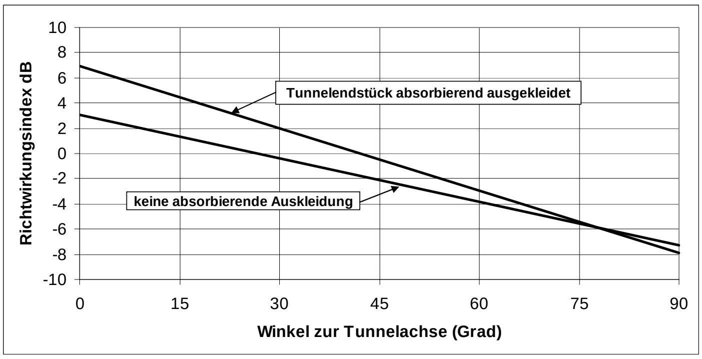

Figure 7 Directivity correction D of the source „tunnel opening“

These directivity corrections have been calculated based on ray tracing techniques as mean values for the two cross sections 10 m x 6 m and 20 m x 6 m. An absorption coefficient of 0.8 was assumed for walls and ceiling in the case of absobing treatment at a length of 100 m behind the tunnel opening. The dependence of directivity from these parameters is so weak, that it can be recommended to use these two cases generally.

Some remarks about the correct modelling:

- The vertical area source “tunnel opening” must radiate the complete sound power into the half space in front of the opening – taking into account the ground it is a quarter shere radiation. This is taken into account by a “K0 w/o Ground” of 3 dB in propagation programs like CadnaA /14/.
- The directivity correction shown in figure 7 has been determined subtracting the levels calculated with omnidirectional int the quarter spherical space radiating source from the levels calculated with ray tracing methods. This directivity correction D must be added arithmetically to the level calculated with omnidirectional radiating source. The values taken from figure 7 should not be normalized to 0 mean value before applying them in propagation calculations.

Example:
The radiation of a road tunnel shall be calculated and presented as a noise map:
Daily traffic 10.000 Kfz/24h
Percentage of heavy vehicles 20 %
Vmax 80 km/h

The tunnel with concrete surfaces has a cross section of 10 m x 6 m and is not treated with absorption.

Solution:
- Applying the calculation method RLS-90, the emission value based on these traffic data is
  $L_{m,E}$ = 69,2 dB
- with equation (4) and table 1 the length related sound power level is
  L'_{WA} = 88,4 dB
- for the tunnel without absorbing treatment an absorption coefficient of 0.1 is assumed and the perimeter of the tunnel inside is 32 m
- from figure 5 a correction of
  C_1 = 2 dB
  and an area related sound power level of the source „tunnel opening“ of

L''_{WA} = (88,4 – 2) dB = 86,4 dB
...can be determined.

The vertical area source is located in front of a wall that is presented by a building or by contour lines as it is shown in figure 8. This source is characterized by this emission of 86.4 dB, by a correction – for radiating into the half space in front – K0 of additionally 3 dB and by a directivity according to figure 7 (untreated tunnel).

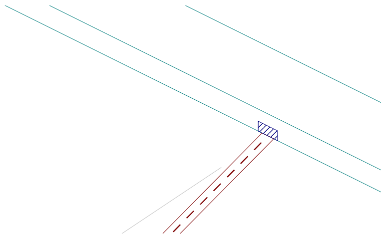

Bild 8 Modellierung der Tunnelöffnung als vertikale Flächenquelle

Calculation of a noise map for road and tunnel opening, then for the road alone and subtracting these two grids arithmetically produces a map that shows the level increase caused by the radiation from the opening.

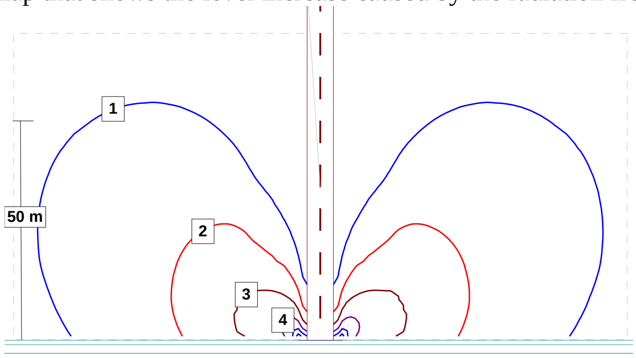

Figure 9 Increase of level caused by the radiation from the tunnel opening

With this example up to a distance of 50 m a relevant level increase can be expected. But this is only true if the road is straight. Figure 10 shows the same example with a curved road – even for large distances straight in front of the tunnel opening the level increase is about 1 – 2 dB.

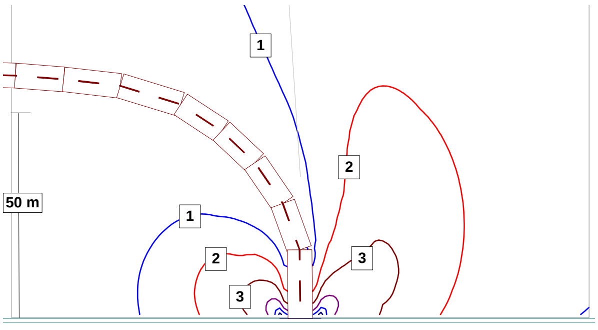

Figure 10 Increase of level with curved road.

Based on these procedures it is possible to handle the noise from tunnel openings with different national guidelines and even in special cases and to integrate tunnel openings in the models for usual prediction calculations.

The sound pressure level inside the tunnel and in the opening and the radiation into the environment

Methodology

In the following the relations presented above are derived from basic acoustic principles. The results are validated and extended using a software program that was developed to calculate sound pressure levels in rooms with any distribution of absorption inside /13/. These techniques are applied to calculate the sound power striking the opening cross section. Finally another software for sound propagation /14/ outside is used to calculate the sound power radiated through the tunnel opening to the environment taking into account reflections inside up to high orders. This allows to determine the radiation in dependence of the direction and to generalize these results.

The sound radiated from inside the tunnel to the opening cross section – analytic solution

The upper part of figure 11 shows a longitudinal section of a tunnel for roads or railways with the acoustically relevant elements. The traffic flow is extended along the tunnel duct, thats length is assumed to be large relative to the dimension of the cross section. The sound pressure level at the receivers shown in the middle cross section shall be determined.

This is performed using a simple thought experiment. As it is shown in the lower part of figure 11, a piece of the tunnel is separated from the rest by two completely reflecting planes. The distance X between these reflecting walls shall be similar to the dimensions of the cross section.

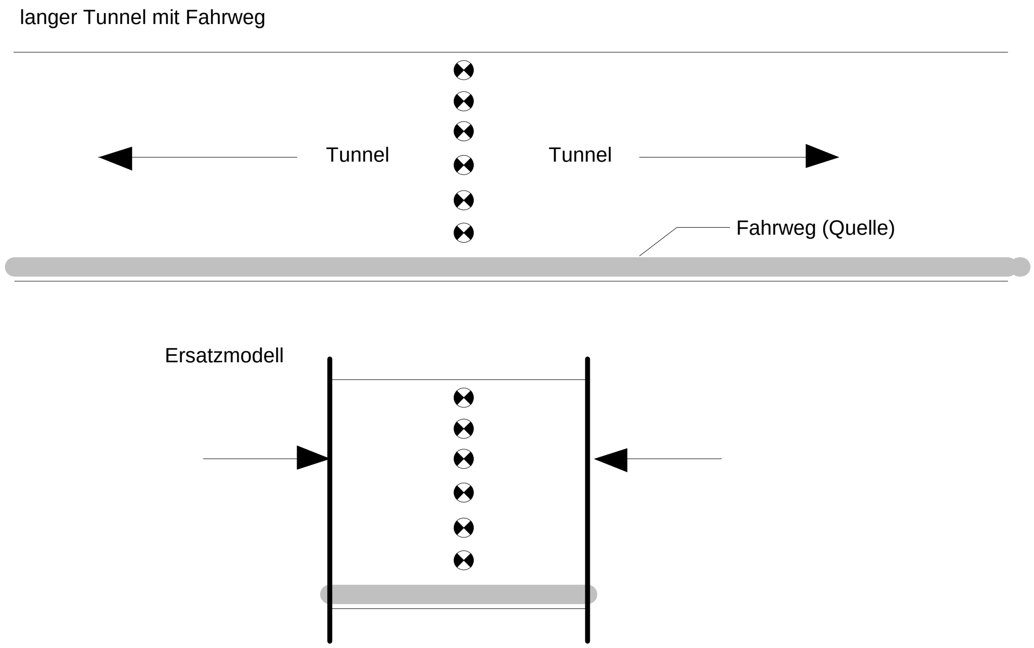

Bild 11 Ersatzmodell zur akustischen Simulation des unendlich ausgedehnten Tunnels

If the sound pressure level in this artificial room is calculated using mirror image method, the reflected rays originally coming from the piece of road are assumed to come from the mirror image of this source – the sound level inside this room is identical to the level in the extended tunnel (upper part of figure 11) with the same cross section. Therefore the determination of the sound pressure level in the infinite extended tunnel is reduced to the calculation of the sound pressure level in the artificial room with two reflecting walls. The sound pressure level in our artificial room can be calculated applying the equations for diffuse sound fields, because the room fulfils these requirements ideally.

At a first glance it may surprise that the sound pressure level in the room with a relatively arbitrary length X should not depend on this length. But the source is extended from wall to wall – an increase of X will enlarge the volume of the room by the same factor as the sound power of the source – this means that the resulting level remains the same.

The sound field produced by a single source – e. g. a car driving through the tunnel – is not at all diffuse, as it is shown in the spatial decay curve figure 12. But if the sound pressure level is integrated over times when many cars cross the tunnel, then this mean level obeys the rules given by diffuse field theory.

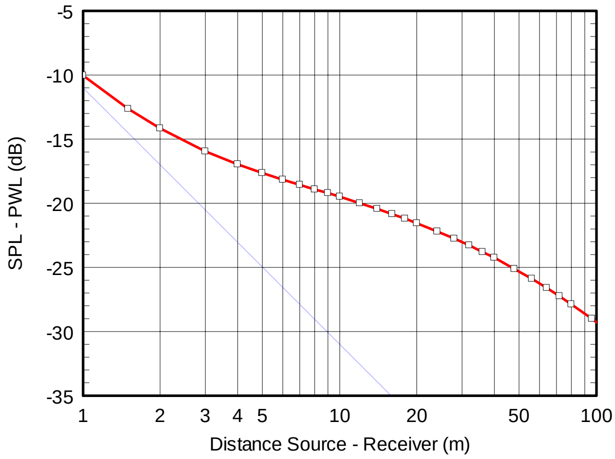

Figure 12 Sound propagation according to /13/ in a tunnel with extension 500 m, cross section 10 m x 6 m and absorption coefficient 0,1

Following the above mentioned ideas, the time averaged sound pressure level in an infinitely extended tunnel can be calculated with the relations of diffuse field theory, if the surfaces inside are not too absorbent. The fitting of walls and ceiling over a certain length behind the tunnel openings can be included in a second step by applying a correction according to figure 6.

If the sound pressure level in the middle of the tunnel is known, the level at the tunnel opening can be assumed to be 3 dB lower, because the rays penetrate this cross section only from one side.
Based on these ideas the sound pressure level in the tunnel and at the tunnel openings caused by reflections up to highest orders can be calculated.

With input data

L'_W	Level of the length related sound power of the traffic lines in the tunnel
X	Lenght of the cutted out piece of the tunnel
X_0	Reference length 1 (m)
S_0	Reference area 1 (m²)
U	Perimeter of the tunnel cross section (m)
α	mean absorption coefficient of the tunnel surfaces inside

the sound power level inside the artificial room of extension X (tunnel piece with reflecting walls) is

$$L_W = L'_W + 10\lg\left(X / X_0\right) \qquad (7)$$

The equivalent absorption area inside this artificial room is

$$A = \alpha \cdot U \cdot X \qquad (8)$$

and the resulting sound pressure level is

$$L_{innen} = L_W - 10\lg\left(A / S_0\right) + 6\,dB \qquad (9)$$

ergibt. Durch Einsetzen von (7) und (8) in (9) wird die Länge des Teilraums X erwartungsgemäß eliminiert und der Pegel im Tunnel ergibt sich zu

$$L_{innen} = L'_W - 10\lg\left(U / X_0\right) - 10\lg\left(\alpha\right) + 6\,dB \qquad (10)$$

In the tunnel opening the level is 3 dB less because sound rays strike this cross section only from one side

$$L''_W = L'_W - 10\lg\left(U / X_0\right) - 10\lg\left(\alpha\right) + 3\,dB \qquad (11)$$

α is the mean absorption coefficient inside the tunnel. If a portion k (k = $U_{absorbing}$/U) of the perimeter is covered with absorption with α_{ref} absorption coefficient of the reflecting and α_{abs} absorption coefficient of the absorbing part, the mean absorption coefficient to be applied in (10) or (11) is

$$\alpha = k \cdot \alpha_{abs} + (1-k) \cdot \alpha_{ref} \qquad (12)$$

This is only applied for absortion that is relevant fort he complete tunnel – fittings of a restricted length of the tunnel behind the opening are taken into account with a correction according to figure 6.

The sound radiated from inside the tunnel to the opening cross section – numeric solution

In a second step a software package was used that allows to calculate the sound propagation in rooms according VDI-Guideline 3760 /12/ or ISO 11690-3/15/ and that has been extended /11/ to take into account locally varying distributions of absorption.
The general procedure is based on the calculation of sound propagation as proposed by Kuttruff and Jovicic – it includes multiple reflections inside a room that’s shape is approximated by a box and takes into account sound dispersion at statistically distributed objects. These methods have been developed for the noise prediction in work rooms, but the applied algorithms and procedures are nevertheless applicable for any type of room.

Both tunnel cross sections 10 m x 6 m and 20 m x 6 m have been included in this investigation. The software CadnaR was applied to calculate the sound propagation in two rectangular 500 m x 10 m x 6 m and 500 m x 20 m x 6 m. Using symmetry relations, it was sufficient to calculate the sound pressure level at 6 receivers (figure 13) distributed in one part of the cross section a small distance d away from the opening that was modelled by a wall with absorption coefficient 1.

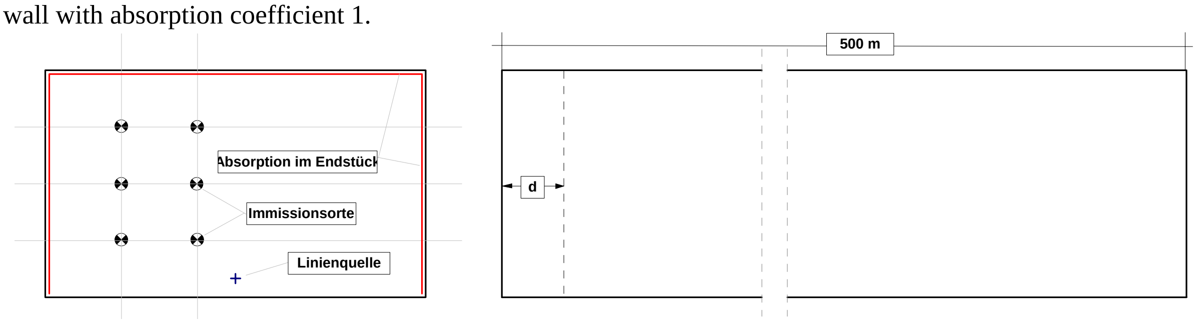

Figure 13 Left side cross section at opening, right side longitudinal section of tunnel

The traffic line is modelled by a line source 0.5 m above ground (figure 13 left side).

The mean sound pressure level in the opening was calculated with the tunnel extension varying from 50 m up to 500 m with a mean absorption coefficient 0.1 of the surfaces inside
The calculation is performed by

- separating the line source inside into small parts and replacing each part by a point source
- calculating the direct sound and reflections up to the order 20 for each part and summing up these contributions for all 6 receivers
- averaging energetically these 6 levels.

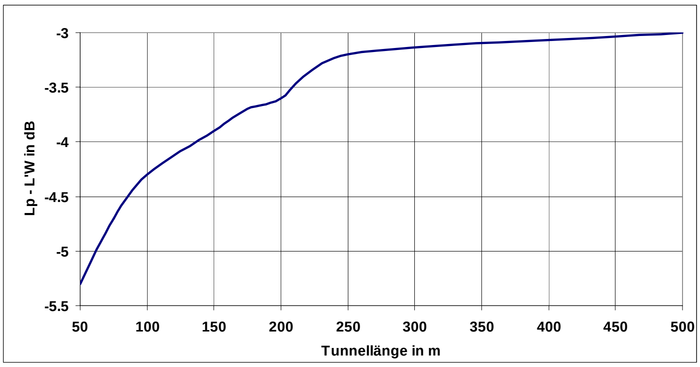

Figure 14 The mean sound pressure level in the opening in dependence of tunnel extension, normalized by the length related sound power level of the source

The resulting sound pressure level – normalized with the length related sound power level L'_W of the source inside the tunnel – is shown in figure 14. Related to direct sound – without reflections – this value is – 15 dB and therefore the sound pressure level is completely determined by reflected sound.
The diagram shows that the level in the opening increases with the length of the tunnel up to about 300 m – this length represents roughly the infinite long tunnel. With a larger mean absorption coefficient that 0.1 – the assumed value in this case – even with a shorter tunnel the conditions for infinite length are reached.

With a next step the two walls and the ceiling where assumed to be absorbent at a varying length from 0 to 100 m behind the tunnel opening – these calculations where performed with absorption coefficients of 0.1 up to 0.3 for the other surfaces of the tunnel with infinite length.The results are shown in the diagrams figure 15 and figure 16 for the two different cross sections 10 m x 6 m and 20 m x 6 m.

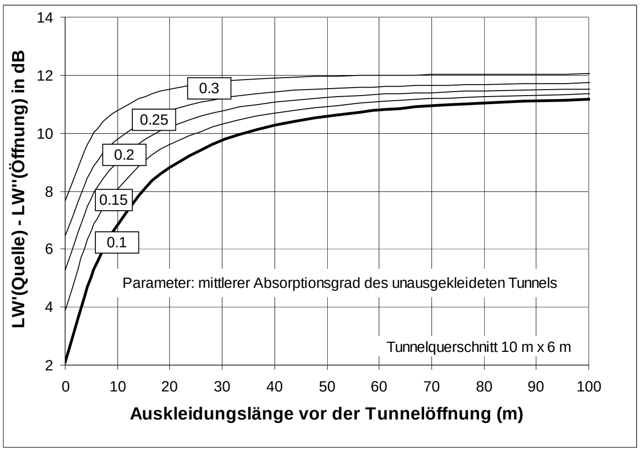

Figure 15 Difference of length related sound power level of the source and sound pressure level in the opening with cross section 10 m x 6 m

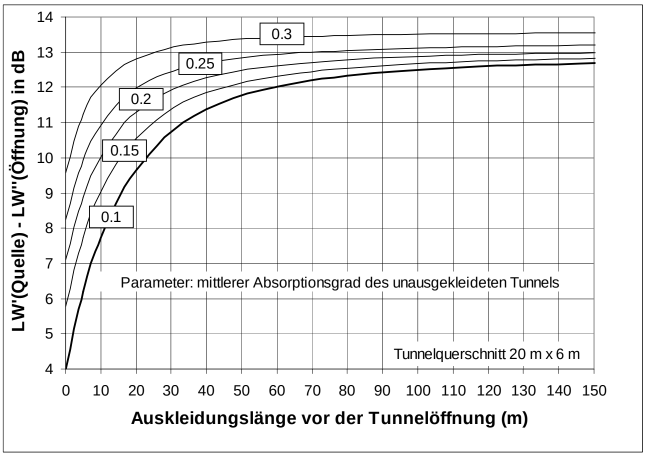

Figure 15 Difference of length related sound power level of the source and sound pressure level in the opening with cross section 20 m x 6 m

At the marking of the ordinates of these figures the sound pressure level in the opening is replaced by the area related sound power level LW''of the opening-source. Here it must be taken into account that the angle error is neglected, that results from a crossing of these rays with different angles and produces a difference of the levels based on intensity and pressure squared.

It is interesting to compare these sound pressure levels in the opening that have been determined by summing up the contribution of the rays geometrically calculated in detail with the levels resulting from the diffuse field model discussed above. In table 2 these values obtained with completely different methods are shown for different mean absorpion of the surfaces inside and fort he two cross sections.
The table proves that the application of diffuse field theory is not an approximation, but an acceptable description of the sound field in a tunnel. The sound field produced by a line source in tunnel of infinite length is a perfect diffuse.

Tabelle 2 Values of LW'(source) – Lp (opening) calculated with ray tracing (12, 13) and with equation (6) – (diffuse field theory).

Absorptionsgrad	Tunnelquerschnitt			
	10 m x 6 m		20 m x 6 m	
	Strahlen	Diffus	Strahlen	Diffus
0.10	2.1	2.1	4.0	4.2
0.15	3.9	3.8	5.8	5.9
0.20	5.3	5.1	7.1	7.2
0.25	6.4	6.0	8.2	8.1
0.30	7.7	6.8	9.6	8.9

Therefore equation (6) can generally be used to calculate the sound pressure level in a tunnel of infinite length.

Directivity of the source „tunnel – opening"

In the next step the rays inside and outside the tunnel have been calculated to get all the effects caused by partial absorbent fittings inside and by diffraction at the edges at the opening. This was performed by modelling the tunnel like a chimney vertical to the ground, because this configuration allows to include the real 3-D-rays even for all reflections at the 4 surfaces inside the tunnel. The model of the tunnel – vertical to the ground – was extended 500 m and the receivers are located in angle steps of 10° in two planes vertical to one another. This procedure is necessary because the applied calculation method ISO 9613-2 does not allow to include the ground in a real mirror image calculation if the tunnel is modelled horizontally.

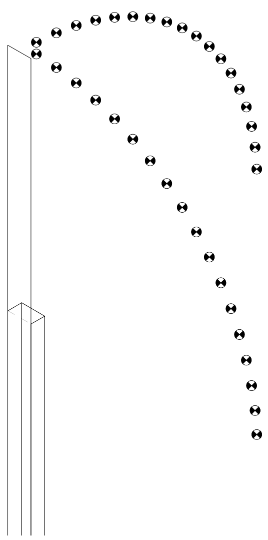

Figure 17 The tunnel modelled „vertical" with receivers located on circles with 100 m radius centered around the tunnel opening.

Inside the tunnel the line source is replaced by 500 point sources with spacing 1 m and lined in 0.5 m distance from the wall simulating the ground.
The mean sound pressure level is calculated on a receiver grid in the opening and at the point sources located outside on the circles. Then the sound pressure levels at the points on the circles are calculated with an area

source „tunnel opening“ radiating with the emission value equal to the mean sound pressure level calculated in the first step. The directivity correction is the difference of the levels calculated at the points on the circles with the two steps.
In the diagrams figure 18 to figure 21 these directivities are shown.

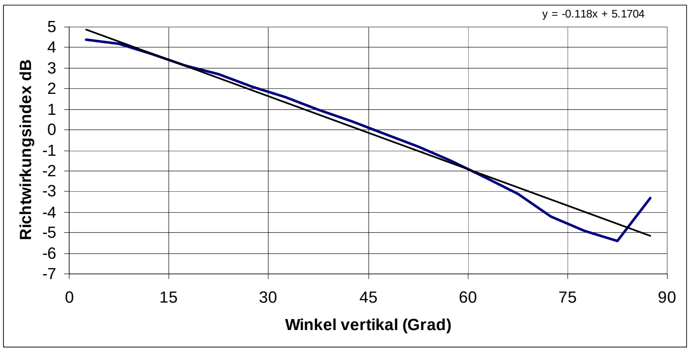

Figure 18 Directivity vertical with tunnel 10 m x 6 m without additional absorption (absorption coefficient 0.1)

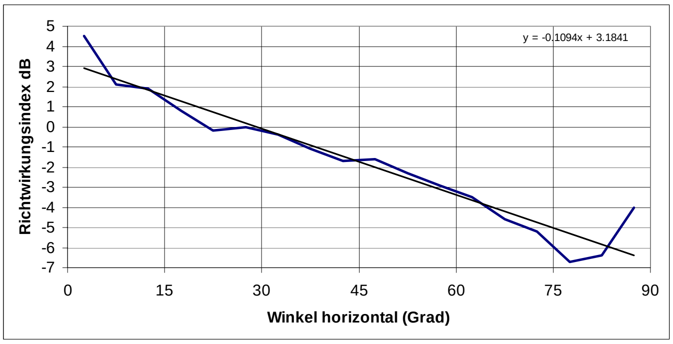

Figure 19 Directivity horizontal with tunnel 10 m x 6 m without additional absorption (absorption coefficient 0.1)

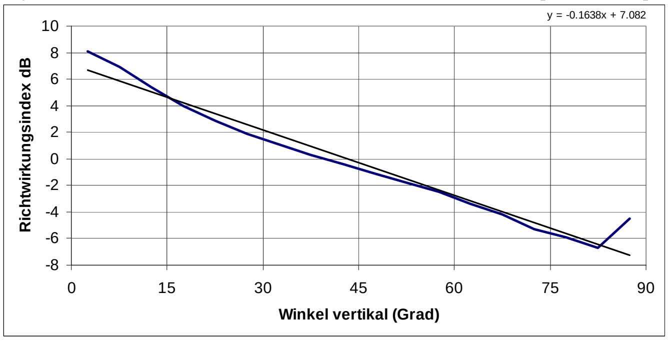

Figure 20 Directivity vertical with tunnel 10 m x 6 m, 100 m absorption (absorption coefficient 0.8)

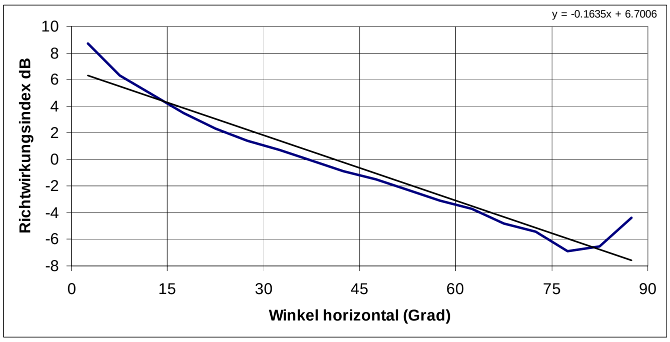

Figure 21 Directivity horizontal with tunnel 10 m x 6 m, 100 m absorption (absorption coefficient 0.8)

The same procedure has been applied with a tunnel cross section 20 m x 6 m – the results are shown in figures 22 to 25.

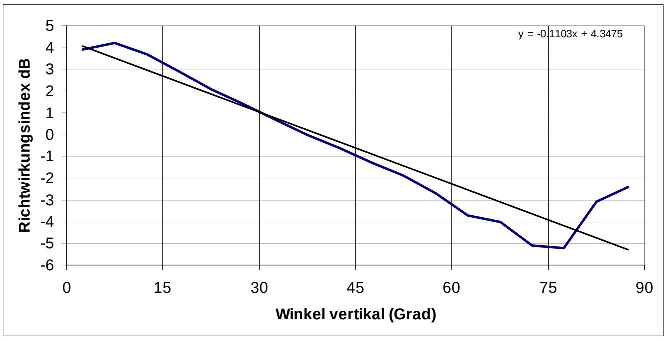

Figure 22 Directivity vertical with tunnel 20 m x 6 m without additional absorption (absorption coefficient 0.1)

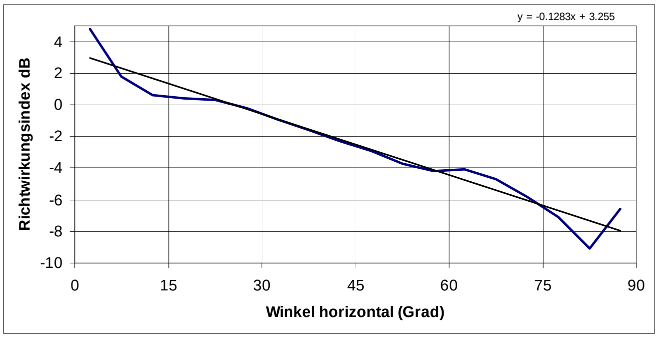

Figure 23 Directivity horizontal with tunnel 20 m x 6 m without additional absorption (absorption coefficient 0.1)

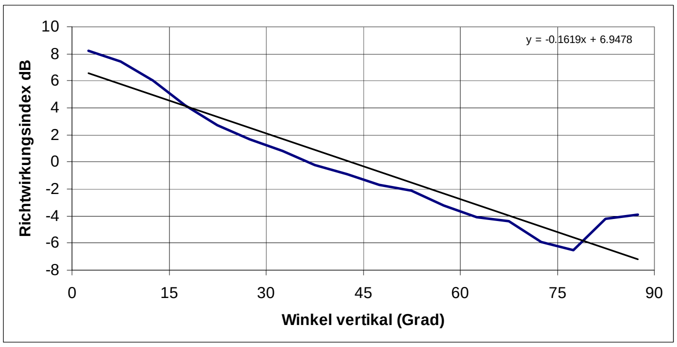

Figure 24 Directivity vertical with tunnel 20 m x 6 m, 100 m absorption (absorption coefficient 0.8)

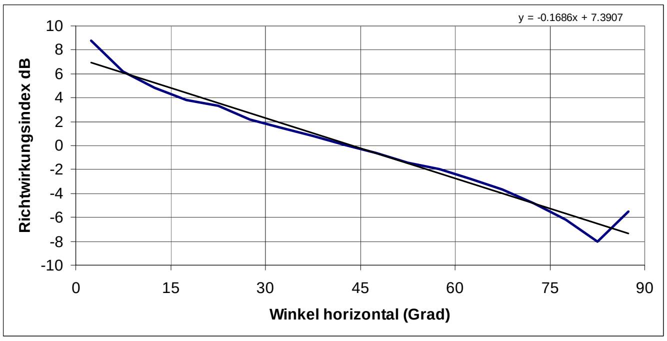

Figure 25 Directivity horizontal with tunnel 20 m x 6 m, 100 m absorption (absorption coefficient 0.8)

These results show – as it can be expected from physical principles – that tunnels radiate with more directivity if walls and ceiling near the opening are treated with absorption. This investigation shows further that the influence of the cross section on the directivity in the far field is rather small. Therefore it is acceptable to distinguish only the two cases according to figure 7 or equation (6a) and (6b) with and without absorption.

This calculation of directivities was also performed separately for frequency bands – figures 26a and b show the results for cross section 10m x 6m, where the calculation of figure 26b is based on an absorbing treatment of the 100 m behind the opening with absorption coefficient 0.8. The effect of the frequency dependent diffraction around the edge can be seen with angles near 90°.

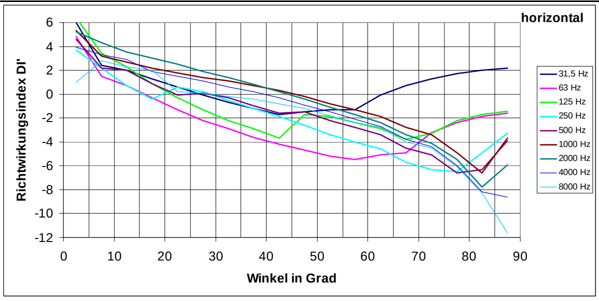

Figure 26a Frequency dependent directivity without absorption behind the opening

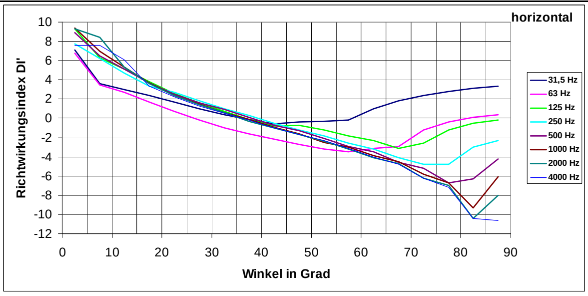

Figure 26b Frequency dependent directivity with absorption behind the opening

The presented relations should be detailed enough to determine the radiation from tunnel openings and to include this source in the modelling for noise calculations. If special cases have to be evaluated, the methodology presented can directly be applied using the actual system parameters.

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