Hans G. Jonasson & Xuetao Zhang

Modelling of Railway Noise Sources with Applications on Swedish Trains

KFB, the Swedish Transport and Communications Research Board, project 1998-0643

Swedish Rail Administration, project S98-4167/08
Abstract

In order to be able to apply point source sound propagation theory to the propagation of railway noise it is necessary to describe the train/track system as a number of point sources. In this report different source models will be tested on Swedish trains. The basic idea behind most tests has been to study the sound propagation pattern of real trains. By combining advanced sound propagation theory with different source models and by comparing calculations with measurements in several receiver positions it is possible to evaluate assumptions with respect to number and positions of the point sources selected to describe the noise emission of the train.

Special features which have been studied using measurements and simulations are the acoustic properties of the track bed, rail damping, the directivity, the time history during pass-by and the height distribution of sources.

The results indicate that although the rail bed is difficult to model correctly because of reflections from rails and sleepers it still gives reasonable results to model it as a soft ground impedance. The damping of rail vibration is rather small. It seems to be of the order 0.5 dB/m. The vertical directivity is of little importance, at least as long as the car body does not screen the wheels. The horizontal directivity, as taken from the literature, is of little importance for the sound exposure level during a complete pass-by. However, it may be important if all propagation takes place under oblique angles. In most cases the wheel/rail noise sources can be modelled using 3 different source heights. For more complicated screening cases more heights may be required. The low frequency sources for the most common Swedish trains can be modelled using two different source heights: One very low representing the radiation from the track and one high representing different kinds of engine noise. Trains with all engine equipment under the car body do not need the high source.

Key words: Railway, noise, source, model, prediction, train, directivity, track
## Contents

**Abstract**  
2

**Contents**  
3

**Preface**  
5

**Conclusions**  
6

1. **Introduction**  
7

2. **Sound propagation over the rail bed**  
8

2.1. The acoustic impedance of the rail bed  
8

2.2. Hemi-anechoic measurements  
10

2.3. Measurement site at Sandared  
11

2.4. Measurement results  
12

2.4.1. Rail l/hs=0.12m above top of rail (D112)  
12

2.4.2. Rail1/hs=0.45m above top of rail (D113)  
13

2.4.3. Rail3/0,12/hor2 (D121)  
14

2.4.4. Rail3/0,45/hor2 (D126)  
15

2.4.5. Rail3/0,12/hor3 (D127)  
16

2.4.6. Rail3/0,45/hor3 (D129)  
17

2.4.7. Rail3/0,12/hor4 (D133)  
18

2.4.8. Rail3/0,45/hor3 (D135)  
19

2.4.9. Rail1/0,45/hor2 (D140)  
20

2.5. **Conclusions**  
21

3. **Propagation of rail vibration**  
22

3.1. **Introduction**  
22

3.2. **Equipment used**  
22

3.3. **Carrying out**  
22

3.4. **Results**  
23

3.5. **Conclusions**  
27

4. **Vertical directivity**  
28

4.1. **Introduction**  
28

4.2. **Test site**  
28

4.3. **Train types**  
29

4.4. **Measurements**  
29

4.5. **Results**  
30

4.5.1. **X2**  
30

4.5.2. **X 11 train**  
32

5. **Horizontal directivity**  
33

6. **Time histories**  
35

6.1. **General**  
35

6.2. **Measurements**  
35

6.2.1. **Measurement site**  
35

6.2.2. **Microphone positions**  
37

6.2.3. **Equipment**  
38

6.3. **Results**  
39

6.3.1. **A-weighted levels**  
39

6.3.2. **X 2000 – 1/3 octave bands**  
40
6.3.3 Intercity trains 41
6.3.4 Freight trains 43
6.4 Conclusions 44

7 Source heights 45
7.1 General 45
7.2 Some theoretical simulations 46
7.3 Conclusions 48

8 Input data 49
8.1 General 49
8.2 Some comparisons with measurements 49
8.3 Sound power level of the Arlanda train 50

9 References 51

Annex – Complete time histories of some trains 52
A.1 X 2000 train (data ID16, on the near track) 52
A.2 Intercity train (data ID13, on the near track) 55
A.3 Freight trains train (data ID24_1, on the near track) 59
Preface

This project has been funded by KFB, the Swedish Transport and Communications Research Board, project 1998-0643 and by the Swedish Rail Administration, project S98-4167/08. KFB has now been replaced by Vinnova and the project number there is dur 2001-03250.

The test rig at Surahammar was supplied by Chalmers Railway Mechanics (CHARMEC) and Adtranz Wheelset and the sound propagation theories used originated from the Nord 2000 Nordic project for the development of new prediction models for environmental noise.

Håkan Andersson, SP, made and reported the measurements on rail vibration and Mohammad Jalaian, SP, took part in some field measurements.

All the above supports are gratefully acknowledged.

Borås 2002-02-27

Hans Jonasson & Xuetao Zhang
Conclusions

The rail bed is difficult to model correctly because of reflections from rails and sleepers. However, modelling it as a soft ground impedance seems to give reasonably good results.

The damping of rail vibration is rather small. It seems to be of the order 0.5 dB/m.

The vertical directivity is of little importance, at least as long as the car body does not screen the wheels.

The horizontal directivity, as taken from the literature, is of little importance for the sound exposure level during a complete pass-by. However, it may be important if all propagation takes place under oblique angles.

In most cases the wheel/rail noise sources can be modelled using 3 different source heights. For more complicated screening cases more heights may be required.

The low frequency sources for the most common Swedish trains can be modelled using two different source heights: One very low representing the radiation from the track and one high representing different kinds of engine noise. Trains with all engine equipment under the car body do not need the high source.
1 Introduction

In [1] an overview of different source models is given. In this report different models will be tested on Swedish trains. The basic idea behind most tests has been to study the sound propagation pattern of real trains. By combining advanced sound propagation theory, see [2], with different source models and by comparing calculations with measurements in several receiver positions it is possible to evaluate assumptions with respect to number and positions of the point sources selected to describe the noise emission of the train. Thus the work has involved a large number of calculations and trial and error with different source models.

Some of the results of this report have already been incorporated in the new Nordic model, Nord 2000, for the prediction of rail traffic noise, see [6]. Version 1.0 was finalized in December 2001. It is expected that additional results from this report will be incorporated in a revised report, version 1.1.

This report does not make many references to international literature. There are two reasons for that. One is that there are large differences in opinions between different researchers. As was shown in [1] it seems to be possible to find support for almost any model. The other reason is that trains and tracks usually differ from country to country. It is a risky business to extrapolate experiences from one country to another.
2 Sound propagation over the rail bed

2.1 The acoustic impedance of the rail bed

In order to calculate sound propagation over the rail bed using propagation theory as outlined in [2] we have to know its acoustic impedance. Unfortunately it is not possible to measure it using the method of [3]. Reflections from the rail will disturb the sound field too much. It may also turn out to be impossible to use a simple impedance. Rail and sleepers make the bed far from homogeneous. However, it is worth a try.

Another way of estimating the impedance is to determine the sound absorption which can be determined if the impedance is known. Using the one parameter impedance model used in [3] we get

\[ Z_a = 1 + 9,08\left(\frac{1000f}{\sigma}\right)^{-0.75} + i 1,9\left(\frac{1000f}{\sigma}\right)^{-0.73} \] (2.1)

where \( f \) = frequency and \( \sigma \) = the specific flow resistance per unit thickness.

Provided that the surface is locally reacting the sound absorption coefficient for perpendicular incidence is given by, see e.g. [4]:

\[ \alpha_0 = 1 - \left[ \text{abs}\left(\frac{z-1}{z+1}\right) \right]^2 \] (2.2)

and for diffuse incidence by

\[ \alpha_{st} = 8 \frac{z_r}{z_r^2 + z_i^2} \left[ 1 - \frac{z_r}{z_r^2 + z_i^2} \ln\left(\left(1 + z_r\right)^2 + z_i^2\right) + \frac{z_r^2 - z_i^2}{z_r^2 + z_i^2} \cdot \arctan\left(\frac{z_i}{1 + z_r}\right) \right] \] (2.3)

where \( z_r \) and \( z_i \) indicate the real and imaginary part respectively of the impedance.

In figure 2.1 some absorption data taken from other references are shown and in figure 2.2 some calculated examples are give. A comparison indicates that a specific flow resistivity in the range 100-630 kRayls could be reasonable. Rayl is not part of the SI system but for practical reasons it will be used in the following. 1 Rayl = 1 Ns/m².
Figure 2.1 Measured ballast sound absorption.

Figure 2.2 The sound absorption coefficient for diffuse (o0o) and normal (full line) incidence for 100 and 630 kRayls respectively.
2.2 **Hemi-anechoic measurements**

The loudspeaker to use for propagation measurements across the rail bed was tested in a hemi-anechoic room as shown in figure 2.3. The rail was simulated by two parallel wooden studs of the same height (0.2 m) as the rail and measurements were carried out with two different source heights and several receiver heights at a distance of 3 m. The results are shown in figure 2.4 and 2.5. We can see that the influence of the rail is in general less than 2 dB with the exception of the range around 400 Hz with a low source position, see figure 2.4.

*Figure 2.3  Set-up without rail in the hemi-anechoic room.*

*Figure 2.4  Difference with and without simulated rail at different receiver heights.*
Figure 2.5 Difference with and without simulated rail at different receiver heights.

Because of the influence of the rail it was decided not to try to use calibrated values for the sound source but rather to look at the difference between two microphone heights.

2.3 Measurement site at Sandared

The measurement site is shown figure 2.6. The source was a loudspeaker located with its axis at 0.12 m and 0.45 above the top of the rail, see figure 2.7. The sound propagation was studied from rail no 3, see figure 2.6 across rail no 1 and 2, that is track no 1, and from rail no 1. The rail was of type UIC 60 with a height of 0.18 m, which means that the source height above the surrounding rail bed was approximately 0.4 m and 0.7 m respectively. Microphones were located at different heights 2.61 and 8.94 m from rail no 1, which was the "edge" rail. The microphones were also moved horizontally parallel with the track in steps of x m. The c/c distance between two rails is 1,435 m.

Figure 2.6 The test site at Sandared. From right to left rail no 1, 2 and 3.
2.4 Measurement results

2.4.1 Rail 1/hs=0,12m above top of rail (D112)

The aim of this measurement was to verify that the sound propagation over ground complied with traditional, analytical sound propagation theory. Because of problems with the calibration of the sound source, the rails influenced the sound power level, only the difference in sound pressure levels between two microphones is studied. The following two figures show a reasonable agreement between theory and measurements, in particular for the high microphone positions where the rails are less likely to interfere with the propagation. The measurement path was perpendicular to the rail.

![Graph](image)

Figure 2.8 Calculated and measured difference between 0,8 m and 2,0 m 8,9 m from the source 0,4 m above the railbed.
2.4.2 **Rail1/hs=0.45m above top of rail** (D113)

This case is identical to that of 2.4.1 but with the source at about 0.7 m in stead of at about 0.4 m. As before the agreement is quite good for the high microphone positions.
2.4.3 Rail3/0.12/hor2 (D121)

In this case the loudspeaker was located above rail 3 and the microphone was moved sideward along the rail until the distance loudspeaker – microphone was 16.4 m. The following two figures show that the agreement is not as good as before, most likely because of reflection from rails and sleepers between the source and the microphones.

Figure 2.11 Calculated and measured difference between 2.0 m and 4.0 m 8.9 m from the source 0.457 m above the railbed.

Figure 2.12 Calculated and measured difference between 0.8 m and 2.0 m 16.4 m from the source 0.4 m above the railbed.
Figure 2.13 Calculated and measured difference between 2,0 m and 4,0 m 16,4 m from the source 0,4 m above the railbed.

2.4.4 Rail3/0,45/hor2 (D126)

This case is identical to that of 2.4.3 with the exception that the loudspeaker axis is 0,45 m above the railhead.

Figure 2.14 Calculated and measured difference between 0,8 m and 2,0 m 16,4 m from the source 0,7 m above the rail bed.
Figure 2.15 Calculated and measured difference between 2 m and 4 m 16,4 m from the source 0,7 m above the railbed.

2.4.5 Rail3/0,12/hor3 (D127)

In this case the microphone has been moved further away parallel to the rail until the oblique distance to the loudspeaker is 23 m.

Figure 2.16 Calculated and measured difference between 0,8 m and 2,0 m 23 m from the source 0,4 m above the rail bed.
Distance/source height: 23/0.4 m

Figure 2.17 Calculated and measured difference between 2 m and 4 m 23 m from the source 0.4 m above the rail bed.

2.4.6 Rail3/0.45/hor3 (D129)

This is identical with 2.4.5 but with a higher loudspeaker.

Distance/source height: 23/0.7 m

Figure 2.18 Calculated and measured difference between 0.8 m and 2.0 m 23 m from the source 0.7 m above the rail bed.
Figure 2.19 Calculated and measured difference between 2 m and 4 m 23 m from the source 0,7 m above the railbed.

2.4.7 **Rail3/0,12/hor4 (D133)**

In this case the microphone has been moved further along the rail until the distance to the loudspeaker is 29,8 m.

Figure 2.20 Calculated and measured difference between 0,8 m and 2 m 29,8 m from the source 0,4 m above the rail bed.
2.4.8 Rail3/0,45/hor3 (D135)

This case is identical to that of 2.4.7 but with a higher loudspeaker.

Figure 2.21 Calculated and measured difference between 2 m and 4 m 29,8 m from the source 0,4 m above the rail bed.

Figure 2.22 Calculated and measured difference between 0,8 m and 2,0 m 29,8 m from the source 0,7 m above the rail bed.
Figure 2.23 Calculated and measured difference between 2 m and 4 m 29.8 m from the source 0.7 m above the rail bed.

2.4.9 Rail1/0.45/hor2 (D140)

This is another case with propagation over ground only. All rails are behind the loudspeaker.

Figure 2.24 Calculated and measured difference between 0.8 m and 2.0 m 16.9 m from the source 0.7 m above the rail bed.
Figure 2.25 Calculated and measured difference between 2 m and 4 m 16,9 m from the source 0,7 m above the rail bed.

2.5 Conclusions

It does not seem to be possible to get perfect agreement between measured and calculated values using a simple impedance model of the rail bed. However, the agreement is far better than could be expected considering the presence of rail and sleepers. In the cases tested a reasonable agreement is obtained using a soft impedance corresponding to a specific flow resistivity of 100 - 250 kRayls.
3 Propagation of rail vibration

3.1 Introduction

In order to study the damping of vibration in the rail some measurements were carried out on the test rig in Surahammar described in [1]. The result is of importance in order to determine the horizontal distribution of wheel/rail excited sound power.

3.2 Equipment used

Two accelerometers type B&K 4381 with mounting magnets were used. The “three-legged” type of mounting magnet was chosen as the surface of the rail was not flat enough for the flat type of mounting magnet. A thin layer of grease was applied on the mounting surface to improve the mounting stiffness.

The two charge amplifiers used, B&K 2635, were set to velocity operation mode and adjusted to output level 1000 mV/(mm/s). The band limiting filters were set to 10 Hz and 30 kHz.

A Larson Davis 2900 was used for analysis of the vibration signal. It was set to 15 s linear integration and no filters except 20-10000 Hz band-limitation were used. Prior to the measurements the measurement chains were calibrated with a vibration calibration exciter B&K 4294.

3.3 Carrying out

The vibration velocity was measured at three points on the rail profile as indicated in figure 3.1.

![Figure 3.1 Measurement points on the rail profile.](image)

The measurement points along the rail were distributed from the excitation point to a point 13 m in one direction. The rails ended in sand in both directions. The rail was excited by a vibrator both horizontally and vertically.
3.4 Results

The vibration velocity level referred to the excitation point is given in figure 3.2 to 3.5.

**Figure 3.2** Vibration velocity level as a function of distance from the excitation point.

**Figure 3.3** Vibration velocity level as a function of distance from the excitation point.
Figure 3.4  Vibration velocity level as a function of distance from the excitation point.

Figure 3.5  Vibration velocity level as a function of distance from the excitation point.

The level decay for the different 1/3 octave bands are given in figure 3.6 - 3.9. The decay has been calculated using the least square method and linear regression analysis. Two quality indexes are also given, the standard error of the decay value and the regression coefficient r², a value between 0 and 1 indicating how well the equation from the regression analysis fits the input data.

The lateral vibrations have been measured in position B.
Figure 3.6  Decay rate of lateral vibration levels with lateral excitation.

Figure 3.7  Decay rate of vertical vibration levels with lateral excitation.
Comparisons between point B and C

The vibration level in position C has been measured in parallel to position B in five points: 0; 0,97; 1,29; 2,23; and 2,61 m from the excitation point. The level difference between position B and C is given in figure 3.10.
Figure 3.10  Difference between the vibration level in point B and C

3.5 Conclusions

For lateral rail vibrations, which is expected to radiate sound most, the vibration level decay is in the range 0.2 to 0.8 dB/m except for frequencies below 315 Hz and around 4 kHz where the decay is larger.

For vertical rail vibrations, the vibration level decay is about 0.5 dB/m except for frequencies below 630 Hz and around 4 kHz where the decay is larger.

As a “rule of thumb”, the over all vibration level decay can be estimated to 0.5 dB/m. This means that the rail source is not as local as the wheel sources.

The measurements in position C may indicate that a rail profile segment acts like a stiff beam with one free and one fixed end for frequencies up to 3.15 kHz.
4 Vertical directivity

4.1 Introduction

As was shown in [1] the acoustic literature gives a strange picture of the vertical directivity of trains. As an example some references claim that hardly any sound radiates horizontally. One explanation for such findings could be that the ground attenuation was high. It is also possible that the directivity can vary between different countries as both tracks and trains are different from the ones we have in Sweden. In any case it is necessary to carry out some measurements on national level.

4.2 Test site

As test site was chosen the railway between Borås and Göteborg where the elevation was high in order to minimize the ground attenuation. The test site is shown in figure 4.1 and 4.2.

![Test site at Sandared](image-url)

*Figure 4.1 Test site at Sandared*
4.3 Train types

Table 4.1

<table>
<thead>
<tr>
<th>Identification</th>
<th>Engine</th>
<th>Total length</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>ld 11</td>
<td>X2</td>
<td>88 m</td>
<td>54 km/h</td>
</tr>
<tr>
<td>ld 12</td>
<td>X11</td>
<td>50 m</td>
<td>88 km/h</td>
</tr>
<tr>
<td>ld 13</td>
<td>RC 6</td>
<td>115.5 m</td>
<td></td>
</tr>
<tr>
<td>ld 14</td>
<td>X 11</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>ld 15</td>
<td>RC 4</td>
<td>92.5 m</td>
<td></td>
</tr>
<tr>
<td>ld 16</td>
<td>X 2</td>
<td>88</td>
<td>100 km/h</td>
</tr>
<tr>
<td>ld 17</td>
<td>Work vehicle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ld 18</td>
<td>RC 6</td>
<td>115.5 m</td>
<td></td>
</tr>
<tr>
<td>ld 20</td>
<td>RC 6</td>
<td>115.5 m</td>
<td></td>
</tr>
</tbody>
</table>

4.4 Measurements

The sound exposure level was measured simultaneously in 8 microphones as shown in figure 4.1 with coordinates as shown in table 4.2. All measurements are normalized to the distance 11.1 m using the correction 10 lg(distance) for the SEL level.
Table 4.2  Microphone positions

<table>
<thead>
<tr>
<th>Microphone no</th>
<th>Horizontal distance from top of rail, m</th>
<th>Height re top of rail, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10.6</td>
<td>-2.8 (0.2 m above ground)</td>
</tr>
<tr>
<td>2</td>
<td>11.1</td>
<td>-1.5</td>
</tr>
<tr>
<td>3</td>
<td>11.1</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>11.1</td>
<td>1.0</td>
</tr>
<tr>
<td>5</td>
<td>9.8</td>
<td>3.5</td>
</tr>
<tr>
<td>6</td>
<td>9.8</td>
<td>4.9</td>
</tr>
<tr>
<td>7</td>
<td>9.8</td>
<td>6.4</td>
</tr>
<tr>
<td>8</td>
<td>9.8</td>
<td>7.8</td>
</tr>
</tbody>
</table>

4.5  Results

4.5.1  X2

The train can be seen in figure 3.3 and the results are given in figure 3.4 and 3.5. Apart from the significant ground effect at -2.8 m and -1.5 m there seems to be very little directivity. -2.8 m is very close to the ground. Thus we get a +6 dB reflection at low frequencies and some extra ground attenuation at high frequencies. At -1.5 m we get destructive interference at low frequencies and some excess ground attenuation at high frequencies.

Figure 4.3  The X2 train set in Id 11 and Id 16
Figure 4.4 Normalized SEL-levels during pass-bys of an X2 train at 54 km/h.

Figure 4.5 Normalized SEL-levels during pass-bys of an X2 train at 100 km/h.
4.5.2  X 11 train

The train can be seen in figure 4.6 and the result is given in figure 4.7. As for the X2 train there is no significant directivity.

Figure 4.6  X11 train of measurement, Id 12

Figure 4.7  Normalized SEL-levels during pass-bys of an X11 train at 88 km/h.
5 Horizontal directivity

In [1] it is concluded that a commonly used directivity function for railway noise in the horizontal plane is

\[ \Delta L(\varphi) = 10 \log(0.15 + 0.85 \sin^2(\varphi)) \]  
(5.1)

![Figure 5.1 Sketch of angles of directivity](image)

If (5.1) is applied to a passing train consisting of a number of omnidirectional point sources, each with the sound power level \( L_W \), then each source gets the sound power level

\[ L_W(\varphi) = L_W + \Delta L(\varphi) \]  
(5.2)

If the sound exposure level during a pass-by at 10 m with a receiver height of 3.5 m above the top of the rail is calculated then the difference between an omnidirectional source and one with the directivity of (5.2) is given in figure 5.2.

![Figure 5.2 Difference between the pass-by integration of an omnidirectional source of one with the directivity given in eq. (5.2)](image)
For practical reasons it is convenient to use the omnidirectional sound power as reference and to normalize the directivity function to yield the same sound exposure level during pass-by. Thus we have to add 2 dB, that is the frequency average of figure 5.2, to the directivity function and we get

$$\Delta L(\phi) = 10 \log(0,15+0,85 \sin^2(\phi)) + 2$$  \hspace{1cm} (5.3)$$

The plot in figure 5.3 shows that this directivity function will only have a limited effect on the sound exposure level during a complete pass-by. However, if all propagation takes place under oblique angles, the result will, of course, be much more affected by the directivity.

*Figure 5.3 Difference in SEL between a directional sound source according to (5.3) and an omnidirectional one at 25 m from the nearest rail.*
6 Time histories

6.1 General

Trains are often very long. When calculating maximum levels it is important to know if the noise emission is distributed evenly along the train or if the major emission comes from the locomotive or some other source. For this purpose it is interesting to record the time history of the instantaneous sound pressure level at a microphone position not too far from the train. In some cases the time history can also be used to estimate the horizontal directivity.

Twice train pass-by measurements were carried out at the Alingsås site, on 2000-09-14 and 2001-09-20 respectively. The valid data of the measurements are the data of eight X 2000 train pass-bys (four on near track and four on far track), seven Intercity train pass-bys (five on near track and two on far track), one Post train pass-by (on near track) and eight freight train pass-bys (two on near track and sex on far track). The closest microphone stand for the measurements on 2000-09-14 is 12 m from the nearest rail. For the measurements on 2001-09-20 one ground microphone had been used and it was put on the track bed (0,5 m from the nearest rail). At this time the closest microphone stand is 6.17 m from the nearest rail.

It is found by the investigation that the recordings on the microphones closer (6.17 m) to the rail will much clearly show some information, which is useful for the source modeling. And, the other recordings are still useful for supporting the understandings.

6.2 Measurements

6.2.1 Measurement site

The measurement site which is close to Alingsås on the main railway line between Göteborg and Stockholm is shown in figure 6.1. The railway there has two tracks. The track closer to the measurement side (near track here after) is for trains in the direction from Göteborg to Stockholm. The other track (far track here after) is for trains in opposite direction. Between the flat farming field and the railway there is a simple grit road with a width of about 4 m. The traffic on this road is quite small: about 5 car pass-bys during the daytime. There were bushes along the railway bed but they were cut off between the first and the second day of measurement.

The measured ground impedances at the site were: 400 kRayls for the stubble field and 20000 kRayls for the road.
Figure 6.1 The measurement site at Allingstä, Pictures were taken on 2000-09-14 with bushes and on 2001-09-20 without bushes.
6.2.2 Microphone positions

In figure 6.2 the settings of microphones for the first measurements are shown. The digits of heights for microphones are relative to the ground at which the stand is located. In the total three microphone stands were used.

For the second measurement series, see figure 6.3, three microphone stands were still used, but with different settings. One stand was put as close as possible to the nearest rail. Two microphones, at the height of the railhead and 4 m above respectively, were mounted on this stand. This setting is specially designed for extracting the detail information of noise sources, because at this distance (for the terrain profile at this site) the most of reflecting energy can't reach the high receiver, for trains running on the near track. The second stand was located 25 m from the nearest rail and with two microphones of heights 2 m and 4 m above the ground. The third stand was located 25 m from the nearest rail too but also 20 m from the second stand, with one microphone at the height 4 m above the ground. The purpose of the third stand was to check the horizontal directivity. In addition, one ground microphone was put on the railway bed (0.13 m below the railhead) 0.5 m from the nearest rail. The purpose of the ground ground microphone was to record information of rolling noise.
6.2.3 Equipment

The measurements of train pass-by at Alingsås were carried out via recordings on a SONY PC 208A 8-channel digital-analogue tape recorder with an acoustic front end B&K type 5966. Free field microphones of Larson Davis type 2541 mounted on preamplifiers of Norsonic type 1201 were connected to the DAT.

All calibrations were made with a B&K calibrator of type 4231.

A Larson & Davis 2900 real time frequency analyser was used for getting the time history data, together with the use of the tape recorder mentioned above. The time weighting used was 1/64 s.
6.3 Results

6.3.1 A-weighted levels

Some examples are given in figure 6.4-6.6. Figure 6.4 showing two X2000 pass-bys indicates that the locomotive is about 10 dB noisier than the individual cars, that each car emits about the same amount of noise and that the low microphone position for the far track is subject to significant ground attenuation/screening.

![Image 6.4](image)

*Figure 6.4* The time history of $L_{pa}$ data for X2000 trains. The left one refers to the near track at 6.2 m distance and the right one to the far track at 11.6 m distance.

Figure 6.5 and 6.6 on the other hand indicate large variations between different cars and not consistently higher emission from the locomotive. It seems that the wheel maintenance is significantly better for X2000 than it is for inter-city and freight trains.

![Image 6.5](image)

*Figure 6.5* The time history of $L_{pa}$ data for Inter-city trains, on the near track.

![Image 6.6](image)

*Figure 6.6* The time history of $L_{pa}$ data for freight trains. The left one refers to the near track at 6.2 m and the right one to the far track at 11.6 m.
6.3.2 X 2000 – 1/3 octave bands

Figure 6.7 The time history in spectra for an X 2000 train (data ID16, on the near track).
Figure 6.7 shows some examples of X 2000 time histories during pass-by. A complete set of measurement data is given in annex 1.

The high locomotive peaks primarily occur above 1 kHz, which obviously are due to wheel/rail noise. At 1250 Hz the peak is almost 15 dB higher than for the cars. At 315 Hz there is also a small but distinct peak, which most likely is fan noise. As can be seen in annex 1 the peak can be seen also at 400 Hz and to a smaller extent at 200 and 250 Hz as well.

The graphs indicate that the low microphone receives proportionately more sound energy at high frequencies than it does at low frequencies. This is an indication that wheel/rail noise dominates at high frequencies and that the low frequency sources primarily are located higher up on the train.

6.3.3 Intercity trains

![Picture of a Swedish RC train](Picture from different site)

Figure 6.8  Picture of a Swedish RC train (Picture from different site)

Figure 6.9 shows some examples of time histories of intercity trains during pass-by. A complete set of measurement data is given in annex 1.

One feature, which to a smaller extent also was found for the X 2000, is the distinct peaks for the locomotive at 250, 315 and 400 Hz. At 250 Hz this peak is more than 10 dB higher than the corresponding peaks for the individual cars. These peaks are obviously due to engine noise, or, in this case, the cooling system. A view on the train indicates that the source is located at the openings close to the roof, that is at a height of about 3 m above the top of the rail. These peaks cannot be seen in the A-weighted levels which are dominated by higher frequencies. However, for calculation of A-weighted indoor sound pressure levels, these low frequencies may be very important as the sound insulation normally is much worse at low frequencies than it is at high frequencies.

As for the X 2000 trains the graphs indicate that the low microphone receives proportionately more sound energy at high frequencies than it does at low frequencies.
This is an indication that wheel/rail noise dominates at high frequencies and that the low frequency sources primarily are located higher up on the train.

Figure 6.9  The time history in spectra for an Intercity train (data ID13, on the near track).
6.3.4 Freight trains

For freight trains some examples are given in figure 6.10. As before more complete data can be found in annex 1.

![Graphs of time history in spectra for a freight train (data ID24_1, on the near track).]

One surprising feature in figure 6.10 is that there is no peak for the locomotive at 250 Hz although the locomotive is basically the same as for IC-trains. One explanation for this is that the car noise is in general higher for the freight train than it is for the IC-train and thus, locomotive peaks become less obvious. Another explanation could be that the cooling fan was working in half speed only during the pass-by.

It is also interesting to notice that the wheel/rail noise is about 10 dB lower for some cars than it is for the average car.
6.4 Conclusions

The main conclusions of the analysis of the time histories are:

- For X 2000 trains the noise level caused by the locomotive will be up to 15 dB higher than that of the carriages. The locomotive peak contains frequency components above 1 kHz and has its maximum around 1250 Hz, which indicates that the main noise source is the wheel/rail. There are also some smaller peaks around 315 Hz.
- For Intercity trains locomotive peaks will primarily occur at 250 Hz – 400 Hz. Although these peaks are not important for the A-weighted sound pressure levels outdoors, they may become important indoors.
- For freight trains the locomotive only show some small peaks around 250 Hz.
- Wheel roughnesses seem to vary more for freight trains and IC-trains than for X 2000 trains.
- At frequencies below about 500 Hz the differences between the two microphone heights indicate that the low frequency sources are located higher up in the train than the high frequency sources.

The above conclusions may become different under different operating and rail conditions.
7 Source heights

7.1 General

It is well known that there are several different sources on trains. The most important source is wheel/rail and numerous investigations have shown that the wheel primarily radiates noise above about 1000 Hz and that the rail with rail bed, sleepers and rail also radiate low frequencies. For some trains traction noise may become important. Many Swedish trains have cooling fans radiating noise within the frequency range 200-500 Hz. High speed trains also have aerodynamic noise sources around the body of the cars. The task is to find a source model, which, when combining the different sources yield the correct sound propagation behaviour.

In 6 there were strong indications that the low frequency sources primarily are located higher than the wheel/rail sources. Another indication is the measurements shown in figure 6.1. The measurements have taken place at the Alingsås site, see 6, where the rail bed has the height 0.3 m and the measurement distance is 24.3 m from the nearest track (25 m from track centre line). 2 different microphone heights, one about 2 m above the ground and the other about 4 m above the ground, have been used and the difference in sound exposure level between these two heights is shown. According to sound propagation theory a low frequency source will yield about the same sound pressure level on both heights. However, as can be seen in figure 7.1 this is not the case. There is a distinct peak at 315 Hz. Principally all the different trains seem to behave in about the same way. As will be shown in the following the only way to explain the peak at 315 Hz is to introduce at least one high source.

![Figure 7.1 Pass-by measurements of SEL at the Alingsås site at 25 m. The graph shows the difference between the two microphones at 4 m and 2 m respectively.](image)

Figure 7.1 Pass-by measurements of SEL at the Alingsås site at 25 m. The graph shows the difference between the two microphones at 4 m and 2 m respectively.
7.2 Some theoretical simulations

In figure 7.2 two measurements from figure 7.1 are shown together with the calculated difference between the two heights using different source combinations. Each source height shown in the legend has been given the same sound power level. Thus 0.01/0.01/0.56 means that 2/3 of the sound power radiates from 0.01 m above the rail bed and 1/3 from 0.56 m. The following observations can be made:

- It is obvious that the peak at 315 Hz cannot be explained by a low source only.
- Using only one high low frequency source will yield both a high peak at 315 Hz and a low trough at 160 Hz. As this is not consistent with the measurements this source description is most likely too simple.
- By combining a very low low frequency source which could represent rail, sleeper and rail bed radiation a good agreement can be achieved up to at least 1600 Hz. Below 250 Hz the best fit is obtained by distributing the sound power 50/50% between the sources. At 315 Hz a better agreement is obtained by assigning 2/3 of the sound power to the high source.
- It is more difficult to draw firm conclusions at high frequencies although it is obvious that one low source at 0.01 m gives a very bad fit at 4000 Hz. By distributing the sources across the wheel a better agreement is achieved.

![Graph](image)

Figure 7.2 The average of a few X2 and IC pass-bys at the Alingsås site together with calculated values for different source combinations.

In figure 7.3 a corresponding figure for the Arlanda train is given. The data has been taken from [1]. In this case we do not find any low frequency peak. This is quite logical as the Arlanda train has all traction equipment located below the car body while the other trains studied in figure 7.1 and 7.2 have locomotives with high fan noise sources. The fit is quite good for the low source up to about 2000 Hz while the distributed wheel sources give a much better agreement around 2500 Hz.
Figure 7.3  The Arlanda train. Difference in SEL at 25 m between 3.5 m and 1.5 m above the ground.

In figure 7.4 another example is given. The data is from [5] but unfortunately they were only available in octave bands. The rail bed is 1.5 m above the ground. In this case also low sources give a rather good fit at low frequencies. This is due to fact that the rail bed already is high which makes even low train sources look like high sources. The distributed wheel source gives very good agreement at 2000 and 4000 Hz.

Figure 7.4  Some measurements at 25 m, from [5]. The lengths in the legend refer to the train length.
7.3 Conclusions

In general it seems to be possible to model Swedish trains rather good using 5 point sources at different heights. Reasonable heights relative to the rail bed are 0.01 m for the rail, 0.21 – 1 m for the wheels and around 3 m for the low frequency source. For frequencies below 1250 Hz the lowest and the highest sources should be used in combination. Above 1250 Hz 3 wheel sources will usually work well. For practical reasons it might become appropriate to let the lowest wheel source coincide with the rail source.
8 Input data

8.1 General

In the new Nordic model, version 1.0, [6], input data has been taken from the old model, [7]. As the old data only covered octave bands 1/3 octave band values have been interpolated between the octaves keeping the total level constant. In addition some qualified guesses were made to widen the frequency range. However, the sound power levels were calculated using the old source model and the old propagation model. Thus there is a possibility that there are some systematic errors which should be corrected for. One difference in the source model is the source heights. The old model uses 1 source only for each frequency band and the height varies from at most 2 m at 63 Hz down to 0,3 m at 500 Hz. At 250 Hz the height is 0,8 m.

8.2 Some comparisons with measurements

Some comparisons have been made between calculations using the sound power levels of [7], the propagation model of [2] and a source model using two sources at 0,01 m and 3,2 m respectively below 1250 Hz and 3 sources at 0,21 m, 0,56 m and 0,91 m respectively above 1000 Hz. The results are shown in figure 8.1.

![Graph of calculated vs measured SEL, dB vs Frequency, Hz.](image)

Figure 8.1 Difference between calculated and measured values at Alingsås. The notation is train type/speed(km/h)/train length.

Figure 8.1 indicates rather large overestimates between 200 and 630 Hz. This is also normally the most critical frequency range as far as the source height is concerned.
8.3 Sound power level of the Arlanda train

In [1] some measurements have been reported on the Arlanda train. From these measurements the sound power level/m train has been calculated using the source model given in 7. The result is shown in figure 8.2. As a comparison the corresponding level for X2 is given. We can see that X2 is much noisier around 250 Hz which, according to 8.2, also happens to be the range within which the old sound power level seems to be overestimated.

![Sound power level graph](image)

*Figure 8.2 Estimated sound power level of the Arlanda train compared with that of X2 in the old Nordic model.*
References

[1] Zhang, Jonasson & Holmberg, Source modelling of train noise - Literature review and some initial measurements

Part 1: Propagation in an atmosphere without significant refraction  
Part 2: Propagation in an atmosphere with refraction


Annex – Complete time histories of some trains

A.1 X 2000 train (data ID16, on the near track)
A.2 Intercity train (data ID13, on the near track)
A.3 Freight trains train (data ID24_1, on the near track)