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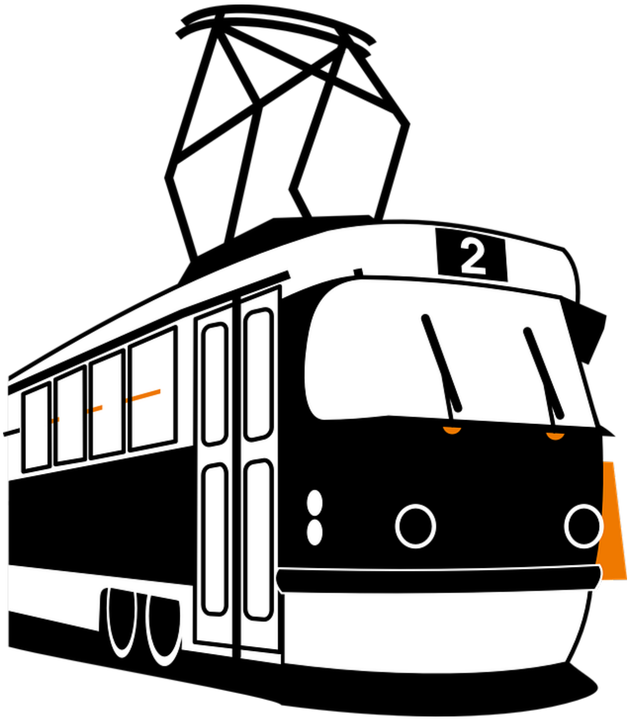

Distance Attenuation of Tram Noise in Open Urban Areas

Master of Science Thesis in Acoustics

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Gothenburg, Sweden, 09 2018

Master's thesis BOMX02-18-7

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Typeset in LaTeX
Department of Architecture and Civil Engineering
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Abstract

The aim of this work was to investigate how the rate of the sound attenuation from a tram changes over distance in an open city environment, and to get a better general understanding of the tram as a sound source. By setting up an array of microphones with an internal distance of approximately 8 meters, perpendicular to the tram tracks, measurements were carried out at three different locations in Oslo as well as two in Gothenburg, and the sound attenuation was analyzed for a total of five different tram types. The sound pressure level as a function of time, the average maximal A-weighted SPL at the various microphone positions, the rate of the sound attenuation at various distances, the spectral content as well as the spectral attenuation of the various tram types are presented and analyzed. The measurements are compared with simulations performed in Matlab. Parameters which seem to affect the rate of the sound attenuation are the strength of any point sources present (individual wheels or the engine) as well as the width of the sound source. Strong point sources dominating the sound field close to the tram lead to a high rate of the sound attenuation in this region, and a wide sound source leads to low attenuation further away from the tram. A wide sound source can for instance mean that strong point sources are located at the edges of the tram (front and rear) or that there is substantial noise coming from the rails in front of and behind the tram. The spectral content varies a lot between different tram types, and seems to depend on the speed of the tram. The spectral attenuation depends in the same way as for the total SPL attenuation on the distribution of the sound sources along the tram, as well as their individual spectral contents. An evenly spread low frequent rumbling of the tram body would for example have a lower rate of sound attenuation with increasing distance than the distinct (perhaps more high frequent) sound originating from an individual wheel.
The measurements show that there are clear differences between the various tram types regarding sound attenuation and spectral content, and in Oslo there are also large variations from one measurement location to another within individual tram types. This can be due to the fact that the measurement conditions were less optimal in Oslo, and it might be wise to distinguish between a completely open environment, and a semi-open city environment when looking at sound attenuation from trams. In order to more accurately be able to predict the sound attenuation from trams in the future, the placement and strength of important sound sources should be localized and their spectral content determined. How the speed of the tram affects

the individual strength and spectral content of the various sources should also be further studied so that predictions can be made for different city locations where the tram speed varies.

Keywords: Trams, sound, distance attenuation, point source, line source, sound pressure level, sound power level, sound spectrum, Oslo, Gothenburg.

Acknowledgements

We would like to give our warmest thanks to Sigmund Olafsen of Brekke & Strand for taking the initiative to create the thesis proposal that led to this thesis, and for being our mentor regarding tram- and community noise, introducing us to the measurement process and answering any questions emerging during the progression of the project. We would like to express our dearest thanks to Jens Forssén, our supervisor at Chalmers, for guiding us throughout the thesis, suggesting ways on how to interpret the measurement data and being a part in the process of developing appropriate simulation tools for the intended task. We would also like to send out a large thank you to everyone in the staff at the Division of Applied Acoustics at Chalmers University of Technology for always being helpful and friendly and for making our time in the Master's program a very pleasant one. Finally, a big thank you to everyone at Brekke & Strand for showing great hospitality during the writing of our master thesis and for making us feel at home.

Emil Regnström and Mattias Willig, Gothenburg, Sweden, 09 2018

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Introduction

1.1 Background

The use of rail bound traffic is increasing in our cities, and in the inner city the most suitable kind is the tram. It is problematic to model tram noise at distances ranging from 2 up to 32 meters due to significant differences in sound source characteristics between different tram types and between individual trams. There are also large variations in surrounding geometry (houses and reflecting surfaces) from one location to another, as well as different tram speeds which affect the sound sources of the trams and hence also the sound attenuation. In order to plan tram traffic and to keep the noise from trams at an appropriate level it is important to understand how to measure and predict tram noise. This thesis exists for this reason and will be a complement to a series of projects at the company 'Brekke & Strand' regarding noise and vibration of rail bound traffic.

1.2 Purpose

The purpose of this thesis is to explain the sound attenuation from trams in an open city environment as well as the characteristics of the tram as a sound source.

1.3 Limitations

This thesis only treats tram noise in an open city environment, within a distance ranging from 2 up to 32 meters from the tram tracks. The measurement locations are limited to Oslo and Gothenburg with a total of five different measurement sites as well as five different tram types. A total of four microphone positions are used for each passing tram. The microphones are placed approximately 1,6 meters above ground, which is about the height of an average persons ear.

2
Theory

This chapter presents the theory that is needed to understand the work that has been done in this project. However, it is assumed that the reader has some basic knowledge about sound and vibrations.

2.1 Sound

Sound can be produced by any material or source that creates pressure fluctuations in an elastic medium by vibrating in a certain frequency. The velocity of the sound propagation depends on the physical attributes of the medium, such as density, hardness and elasticity. Sound in air, at 20 °C, travels at 343 m/s.
The sound which is audible to humans lies in the frequency range of 20 Hz to 20 000 Hz, which makes frequencies outside of this range insignificant to this study. [4]

2.1.1 Noise

The term noise is commonly used to describe sound which in any way is disturbing, and the type of noise treated in this thesis should more accurately be called community noise. In the field of acoustics though, the term noise is more finite, it is basically used to describe a signal that does not contain any significant meaning. [4]

2.1.2 Sound pressure level

The loudness, or magnitude, of sound is measured in pascal. As the pressure can produce very large numbers, which are not very easy to comprehend, a logarithmic scale has been developed. The scale is called the Bel scale and is often measured in units of decibel, dB. 0 dB is defined as the threshold of hearing at 1000 Hz, and the least noticeable pressure fluctuation at this frequency is 20 µPa.

$$L_p = 10log\left(\frac{p}{p_0}\right)^2 = 20log\left(\frac{p}{p_0}\right) \tag{2.1}$$

$$p_0 = 20\,\mu\text{Pa} \tag{2.2}$$

The sound pressure level, SPL, varies in both the time and the frequency domain.

2.1.3 SPL in the frequency domain

To simply present the SPL values might not always be the most effective and pedagogic way to go. Therefore, electronic filters are often used in order to characterize the sound so that it is more alike the perceived values. There are several standardized filters that are used in electronic filtering, such as A, B, C, D and Z-weighting. In this report only A-weighting will be used. The A-weighting is used in an attempt to create a relative loudness, to better demonstrate how the sound would be perceived by the human ear. The A-weighting (as well as B and C-weighting) is shown in Figure 2.1. Our ears are built in such a way that sounds are more audible in frequencies between approximately 500 Hz and 2500 Hz and less audible outside of that interval.[5] When A-weighted values are used in this report it will be specified as dBA values.

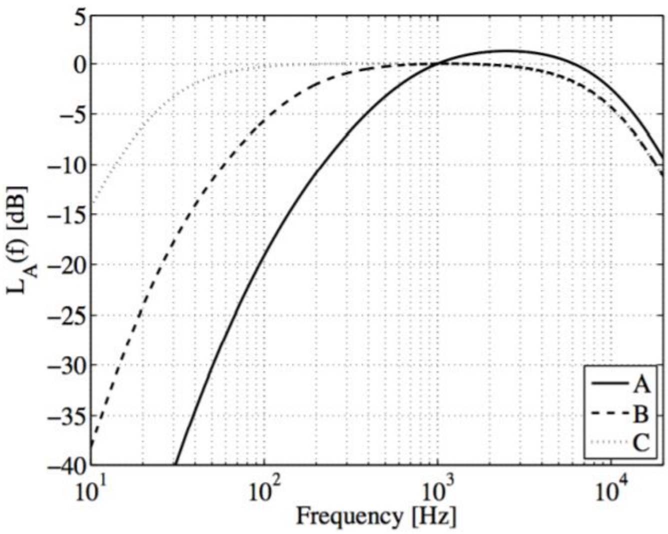

Figure 2.1: A, B and C-weightening. [1]

2.1.4 Equivalent sound pressure

When talking about community noise, simple SPL-values of a certain event might not be a proper way to present the data. Community noise affects people over a long time and thus it is often more convenient to adapt to a so called equivalent level, often presented as $L_{Aeq,T}$. It is the A-weighted sound pressure level equivalent to the total energy over a specified time interval. [4]

$$L_{Aeq,T} = 10log\left\{\frac{1}{T}\int_0^T 10^{L_p/10}dt\right\} \tag{2.3}$$

Usually the time intervals of interests are 8 or 24 hours, showing how the equivalent sound pressure level is during a night or a full day.

2.1.5 Sound Exposure Level

Sound exposure level, SEL, is a useful measure when comparing noise levels of different magnitude and exposure length. It is based on the integral of the squared

A-weighted sound pressure levels over the entire time that the source is active, expressed in a normalized one second value. The SEL-value makes it more convenient to compare different pass-bys, as the passages differ in both sound pressure level and time.

$$SEL = 10log\left\{\int_{t_1}^{t_2} \frac{p^2(t)}{p_{ref}^2(t)}dt\right\} \tag{2.4}$$

The integration limits t_1 and t_2 are chosen as the instances in time when the SPL is 20 dB below the maximum level, meaning just before and just after the pass-by. The SEL-value can be used when calculating the equivalent sound pressure level, $L_{Aeq,T}$. [6]

2.2 Sound propagation

2.2.1 Distance attenuation

The attenuation of sound depends on the distance traveled (geometrical spreading), atmospheric absorption as well as the surrounding environment. Atmospheric absorption works in the way that some of the energy of the sound wave is converted into heat during its propagation and is hence dissipated in the air. Since higher frequencies travel a longer distance between two points due to higher fluctuations, these frequencies are to a higher extent damped by atmospheric absorption than lower frequencies. The terrain also interferes with the sound propagation. If source and receiver both are close to the ground, the reflected wave can interfere destructively with the direct wave resulting in a lower sound pressure level for some frequencies. This is called the ground effect. The ground effect is dependent on the ground type since the impedance of the ground affects the time shift caused by the reflection. Reflecting surfaces, such as houses or cars, can focus or block the sound waves emitted by the source and in this way affect the sound pressure level at a specific location. Other factors affecting the outdoor sound propagation are for example wind, temperature and humidity. But at such short distances relevant for this report, these factors are of little significance. [7]

2.2.2 Various source types

There are a lot of different source types, all of which have different radiation and propagation characteristics as well as different distance attenuation due to spreading. In this thesis focus is given to point- and line sources, and the comparison between the two.

2.2.2.1 Point source

A point source, monopole, is a small source with spherical spreading. The sound pressure level from a spherical wave is reduced by 6 dB per distance doubling. [5]

2.2.2.2 Line source

A line source is an elongated sound source with a cylindrical spreading pattern. If a line array is created with numerous point sources or if a single source is extended in one direction it can be viewed as a line source. The sound pressure level from a cylindrical wave is reduced by 3 dB per distance doubling. [6]

2.3 Sources of tram noise

A tram consists of a large number of different sound sources with varying strengths and spectral characteristics. The resulting noise from a tram is the summation of all the individual sources.

2.3.1 Rolling noise

The dominant part of the noise from conventional rail bound traffic is the rolling noise from the contact between the wheel and the rail. Important parameters here are the roughness of the wheel and the rail. As the rolling noise originates from the vibration of the wheel and the rail. So if the contact between them can be as smooth and vibrant free as possible, the rolling noise will be kept at a minimum. [6]

2.3.2 Curve squeal

Tonal components that causes high disturbance. It mostly originates from that the edges of the wheel slides on the rails due to the rigidness of the boogies. [6]

2.3.3 Ground vibration and noise

Different ground designs have an impact on the noise from the trams, for example the tram rails on grass, so called green tracks have a positive impact on the noise. [6]

2.3.4 Engine noise

Different trams have different engines, the characteristics of the engine affects the characteristics of the sound spectra. [6]

2.4 Tram models

A total of five tram models are analyzed in this report, three models in Gothenburg and two models in Oslo.

2.4.1 Gothenburg trams

In Gothenburg there are four different models in the conventional city rail traffic. The models are M28, M29, M31 and M32. The M28 and M29 are small wagons and can be driven individually, however most of the time they are connected to form a single, longer tram. In this thesis they are only taken into consideration in their connected state and are hence presented as the model M28/M29.

Table 2.1: Measurements of the tram types in Gothenburg [2]

Tram model	Length [m]	Weight [tons]
M28/M29	30.3	33.8
M31	30.6	34.5
M32	29.5	40.5

2.4.2 Oslo trams

There are two different tram models who occupy the tram tracks in Oslo, the model SL79 and the model SL95.

Table 2.2: Measurements of the tram types in Oslo [3]

Tram model	Length [m]	Weight [tons]
SL79	22.2	32.0
SL95	33.1	64.2

3
Implementation

The Nordtest method, NT ACOU 098, was used as a guideline throughout the measurements, though some deviations from the method occur. Notable is that the method is mainly used to measure train noise, and in this work it is implemented on trams. The NT ACOU 098 will simply be referred to as the Nordtest method in this thesis. [8]

Measurements of tram noise in an open environment, both in Oslo and in Gothenburg, have been conducted. This chapter describes how the measurements were carried out and how the data was analyzed. All measurements were carried out during 2017.

3.1 Measurement setup

3.1.1 SQuadriga II

The SQuadriga II is a 24 bit multichannel recorder that supports up to 6 channels and since it has a wide range of applications and is light and compact it is very versatile. The SQuadriga II was used for all measurements conducted in this thesis work. The data is stored on a removable SD memory card, and the data can be analyzed with the software ArtemiS SUITE. ArtemiS SUITE is developed by HEAD acoustics which also is the company behind the SQuadriga II. Artemis SUITE was only used to extract the data, all of the analyzing was made in MATLAB, and thus we will not go into detail about Artemis SUITE.

3.1.2 Setup

Four microphone positions placed in a line perpendicular to the rail and with a distance of 2 to 30 meters from the rail were used (see Figure 3.1). The first microphone was placed 2 meters from track 1 (when possible), and the other microphones were placed with a distance of eight meters between each other. The fourth microphone is thus placed 26 meters from track 1. The distance between track 1 and track 2 varies for different measurement locations, and the distance to the closest microphone position was not always possible to keep at two meters from the rail, hence the distance between track 2 and microphone 4 is in the furthest case 32 meters. The microphones were placed at 160 cm above the ground, as this height is assumed to be the ear height of an average person. The tram track closest to the microphones is referred to as "track one", and the track furthest away from the microphone array is referred to as "track two".

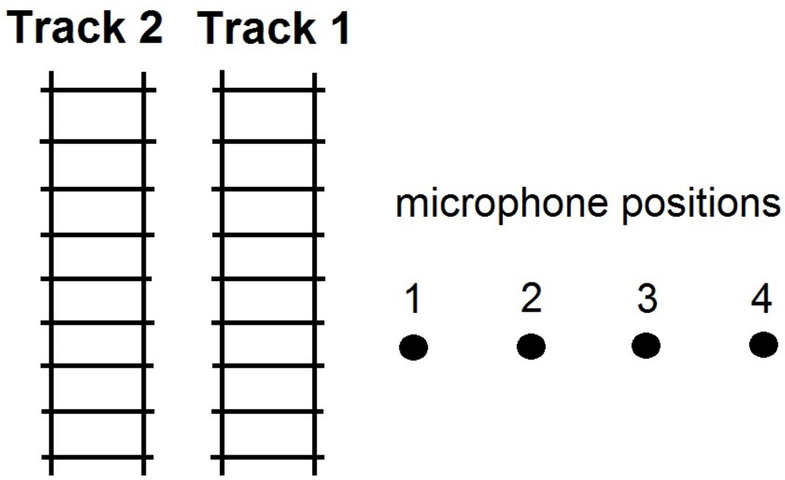

Figure 3.1: Schematic illustration of the measurement setup.

3.2 Measurements in Gothenburg

In Gothenburg, three characteristics where sought after when deciding where to conduct the measurements. All three tram models of interest should be passing by, the rail should be as straight as possible and the surrounding environment is as open as possible. Two different locations for the measurements were chosen were these three criteria are fulfilled, Eketrägatan, Figure 3.2, and Kålltorp, Figure 3.3. As suggested in the Nordtest method, no measurements were carried out during a rainy day and the mean wind speed was below 8 m/s.

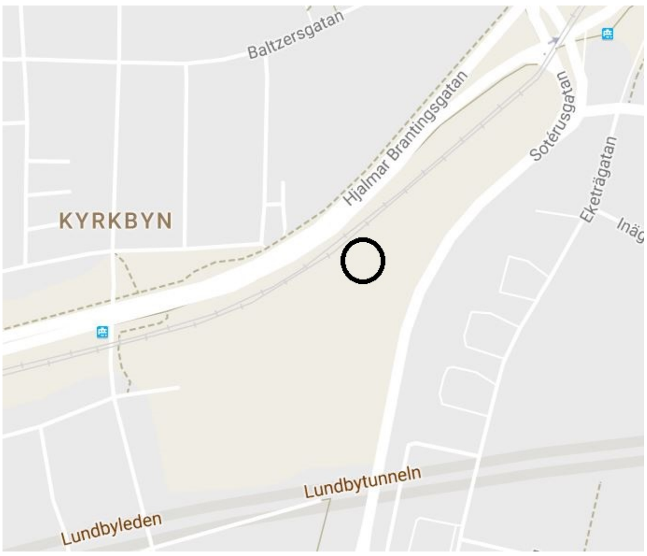

Figure 3.2: A map of Hjalmar Brantingsgatan close to the big buss stop Eketrägatan, one of the two measurement sites in Gothenburg. Measurements were carried out at the location marked by a circle in the figure.

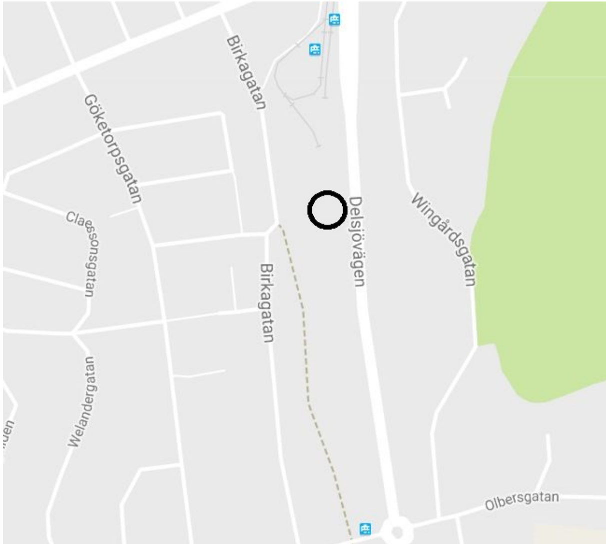

Figure 3.3: A map of Delsjövägen in Kålltorp, the second measurement site in Gothenburg. Measurements were carried out at the location marked by a circle in the figure.

3.2.1 Course of action

SQuadriga II was used for all measurements conducted in Gothenburg. Measurements were carried out during week 10-11 and 18 in 2017 and the microphone setup was as described in Section 3.1. With a distance of 3 meters between the tracks the maximum distance between tram and microphone (track 2 and microphone 4) was 29 meters. All microphones were calibrated at 1000 Hz. The setup was identical for Eketrägatan and Kålltorp. Two ICP-microphones were connected directly to the SQuadriga II and two microphones were connected via an amplifier. The ICP-microphones were used on microphone position 1 and 2.

The measurements were carried out in the way that when a tram was approaching in the distance, the recording was started and went on until the tram had passed and was not audible over the background noise. The recorded values were max-values in third octave bands, as well as the real time values for the whole pass-by. The speed of each tram was also measured using a stop watch. The max-values are used to present the distance attenuation, and the real time values are used to calculate the SEL-values of the passages and as a template for a sound source when setting up a simulation of a tram pass-by. Since higher speed tend to lead to higher max-values but shorter exposure time it is interesting to compare different types of tram passages, and hence the SEL-values can be used. In this report the SEL-value is used to attune the simulated pass-by of the tram type M32 in Section 4.7. The Nordtest method states that each measurement series should include at least 3 passages at a total length that exceeds 500 meters for each tram type.

3.3 Measurements in Oslo

The measurements in Oslo were carried out in two parks, at three different locations, where both tram models were passing by. The two parks were Birkelunden, Figure 3.4, and Olaf Ryes Plass, Figure 3.5. Measurements carried out in the western part of Birkelunden (the red circle) will be referred to as "Birkelunden west" and the measurements carried out in the north (the black circle) will be referred to as "Birkelunden north". As suggested in the Nordtest method, no measurements were carried out during a rainy day and the mean wind speed was under 8 m/s. Though during week 7, there was a thin layer of snow on the ground.

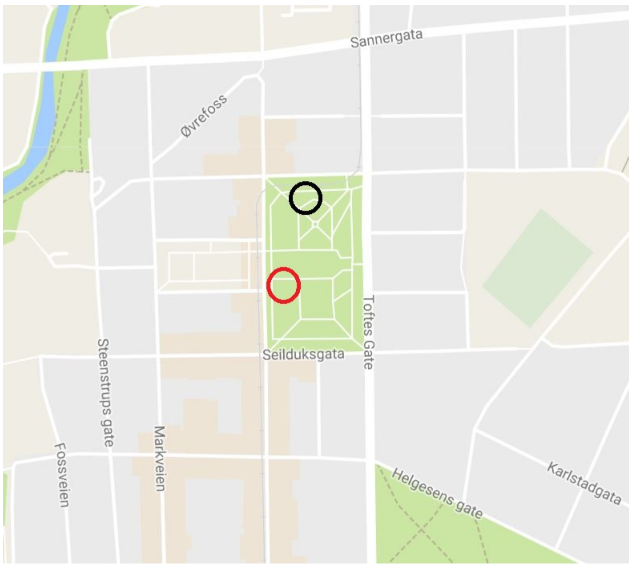

Figure 3.4: A map of the park Birkelunden, one of the measurement sites in Oslo. Measurements were carried out at two locations, marked by circles in the figure.

Figure 3.5: A map of the park Olaf Ryes Plass, one of the measurement sites in Oslo. Measurements were carried out at one location, marked by a circle in the figure.

3.3.1 Course of action

The measurements in Oslo were carried out in week 7 and week 12 in 2017. Four different microphone positions were used, as explained in Section 3.1. Due to the placement of the tracks in the road at Birkelunden both measurement locations (Birkeluden west and north) had an increased distance to the first track. The distance from tack 1 to microphone position 1 was 4 meters, so the array of microphones were moved 2 meter away from the original setup. The same microphone placement was used for both measurements. All microphones were calibrated at 1000 Hz. Two microphones were connected to an amplifier, and two ICP-microphones were connected directly to the SQuadriga II. The same principle for the measurement procedure was used in Gothenburg. Nordtests method states that at least a total of 500 meters of trams needs to be measured, this condition is not fulfilled for all cases in Oslo.

3.4 Data analysis

The measured data was exported from the software Artemis into excel files, which were then imported into and analyzed using the software Matlab. Since a high number of tram passages were treated in this report, new matlab-scripts were made in order to analyze the large quantities of measurement data. The scripts were used to average tram passages, find and exclude measurements containing errors, and to create adequate plots in order to analyze the results effectively. The data exported from Artemis was the maximal A-weighted sound pressure levels for the passages as well as the A-weighted sound pressure level as a function of time. In order to determine the characteristics of the tram as a sound source, a tram passage was modeled in Matlab and compared with measured tram passages. The results from the simulation can be seen in section 4.7.

3.4.1 Total SPL attenuation

In Section 4.1 the sound attenuation for the various tram types are presented in Figure 4.1-4.6. In order to determine how the rate of the sound attenuation changes with distance from the tracks, the attenuation per distance doubling are read from each curve at two instances, using a logarithmic x-axis. Once relatively close to the track, and once a bit further away. The close case is read as the difference between the SPL at microphone position 2 and the SPL on the curve at half the distance. The "further away" case is read as the difference between the SPL at microphone position 4 and the SPL on the curve at half the distance. With a logarithmic x-axis a straight line means that the rate of the sound attenuation is constant.

3.4.2 Tram pass-by

In Section 4.4 the sound pressure level as a function of time for one pass-by of each tram type is presented in Figure 4.9-4.14.

3.4.3 Spectral SPL attenuation

In Section 4.6, Figure 4.24-4.32, the sound attenuation is presented as a function of 1/3rd-octave bands for the various tram types and measurement sites. The attenuation at a specific microphone position is calculated as the difference between the SPL at that microphone position and the SPL at microphone position one. This is calculated for each 1/3rd-octave band respectively.

3.5 Simulations in MATLAB

This section explains the simulation that was carried out using MATLAB. The results from the simulation are presented in Section 4.7.

The simulation is based on trying to create a simulated pass-by which is similar to a measured pass-by regarding SPL as a function of time. In order to obtain adequate sources for the tram model the maximum frequency spectrum at 2 meters from a pass-by of a M32 was used to create a sound power spectrum for the source. The sources were then combined in a way so that the simulated pass-by mimics a real pass-by. After a sufficient source combination was found, the strength of the combined sources was attuned to make it realistic regarding SPL. To do this the SEL-value was calculated for the real pass-by of the M32 and then the same SEL-value was created for the simulated case. This was done once with only the main sound sources of the tram, the wheel boogies, and once with additional sources added in front of and behind the tram with a distance of 5 meters between each other. These sources decrease in strength with increasing distance from the tram.
Furthermore, with the intent to see in what way a more complex source distribution

with different spectral content would effect the spectral sound attenuation of the simulated pass-by, a case with low frequent sound sources added along the tram in addition to the original sound sources was also performed. This would represent a low frequent rumbling of the tram body. The simulation in MATLAB only treats attenuation due to geometrical spreading.

4
Results

The data from the Gothenburg measurements is treated in a slightly different manner than that obtained in Oslo. The Oslo data is presented and analyzed for both tram types on each individual measurement site. The reason for this is that the data differs a lot between the different sites in Oslo. The Gothenburg measurements will be presented for each individual tram model as averages of the data obtained in both of the two measurement sites in Gothenburg.

4.1 Total SPL attenuation

The total A-weighted maximal SPL for each individual microphone position is plotted in order to display how the total attenuation behaves for the various tram types and measurement sites. The data from every pass-by is presented and the mean value is displayed with a line. The rates of the sound attenuation close to the tram as well as further away from the tram for the two tracks are presented along with the graphs.

4.1.1 Gothenburg

The results from Gothenburg are obtained from two different measurement sites, and three tram models were measured at each location. The results are presented as an average of these two locations in Figure 4.1 - 4.3. The rates of the sound attenuation for the various tram types are presented in Table 4.1 - 4.3.

Table 4.1: Sound attenuation per distance doubling for tram type M28/M29. Level difference taken from Figure 4.1

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
10/5	3.8	-
26/13	3.6	-
13/6.5	-	6.5
29/14.5	-	3.7

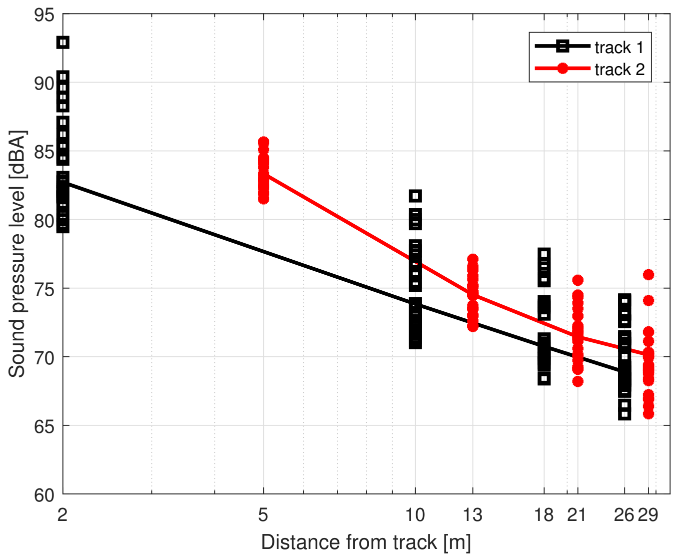

Figure 4.1: The maximal A-weighted SPL for the model M28/M29 at the four microphone positions shown for track one and two.

Table 4.2: Sound attenuation per distance doubling for tram type M31. Level difference taken from Figure 4.2

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
10/5	3.9	-
26/13	3.7	-
13/6.5	-	6
29/14.5	-	4.2

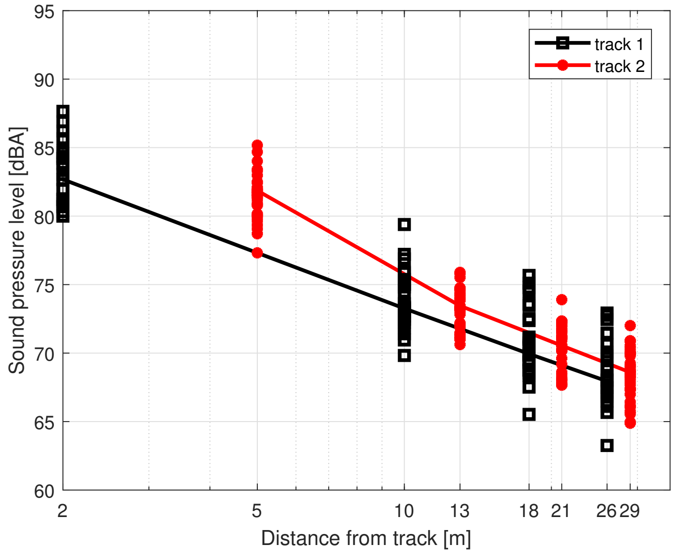

Figure 4.2: The maximal A-weighted SPL for the model M31 at the four microphone positions shown for track one and two.

Table 4.3: Sound attenuation per distance doubling for tram type M32. Level difference taken from Figure 4.3

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
10/5	4.9	-
26/13	4.1	-
13/6.5	-	6.4
29/14.5	-	4.9

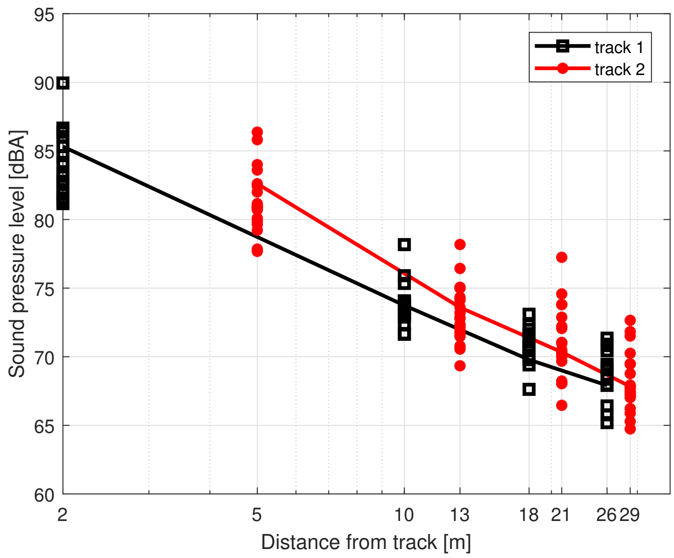

Figure 4.3: The maximal A-weighted SPL for the model M32 at the four microphone positions shown for track one and two.

4.1.2 Oslo

The results from Oslo, presented in Figure 4.4 - 4.6, are obtained from three different measurement sites, and two tram models were measured at each location. The results for the two tram models are presented at each measurement site separately. The rates of the sound attenuation for the various tram types and measurement sites are presented in Table 4.4 - 4.9

Table 4.4: Sound attenuation per distance doubling at Birkelunden west for tram type SL79. Level difference taken from Figure 4.4

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
12/6	4.1	-
28/14	6.4	-
16/8	-	6.3
32/16	-	5.2

Table 4.5: Sound attenuation per distance doubling at Birkelunden west for tram type SL95. Level difference taken from Figure 4.4

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
12/6	5.1	-
28/14	5.7	-
16/8	-	9.7
32/16	-	6.4

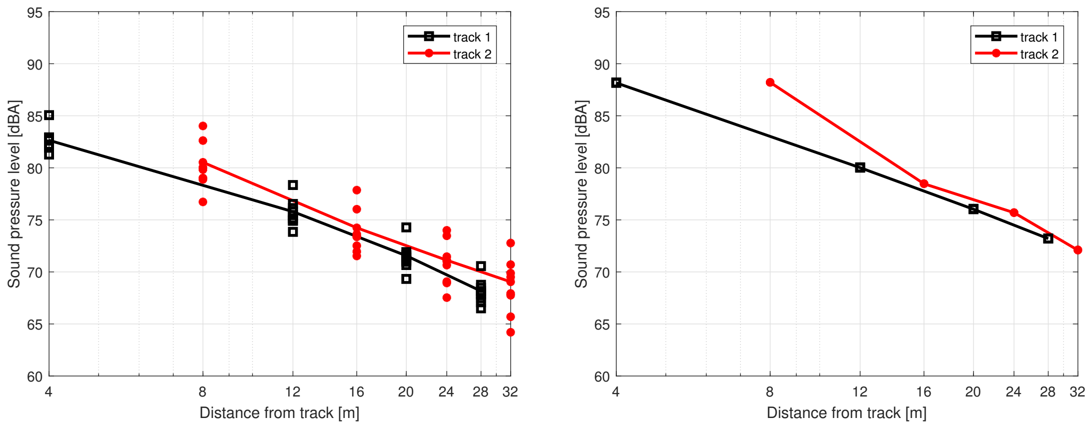

Figure 4.4: The maximal A-weighted SPL for both the models SL79 (left plot) and SL95 (right plot) at the four microphone positions at Birkelunden west for track one and two.

Table 4.6: Sound attenuation per distance doubling at Birkelunden north for tram type SL79. Level difference taken from Figure 4.5

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
12/6	6	-
28/14	3.2	-
16/8	-	4.3
32/16	-	1.4

Table 4.7: Sound attenuation per distance doubling at Birkelunden north for tram type SL95. Level difference taken from Figure 4.5

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
12/6	4.9	-
28/14	4.2	-
16/8	-	4.8
32/16	-	2.2

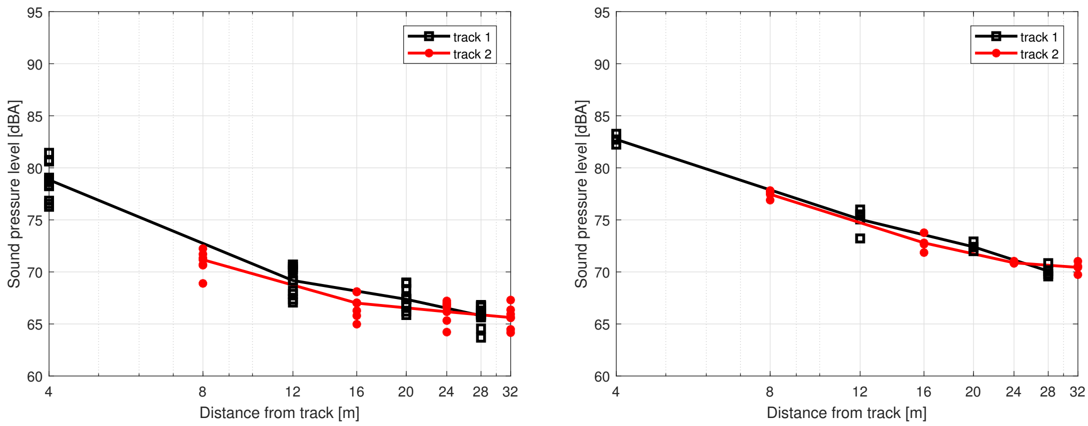

Figure 4.5: The maximal A-weighted SPL for both the models SL79 (left plot) and SL95 (right plot) at the four microphone positions at Birkelunden north for track one and two.

Table 4.8: Sound attenuation per distance doubling at Olaf Ryes Plass for tram type SL79. Level difference taken from Figure 4.6

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
10/5	3.6	-
26/13	6.3	-
14/7	-	3.7
30/15	-	6.6

Table 4.9: Sound attenuation per distance doubling at Olaf Ryes Plass for tram type SL95. Level difference taken from Figure 4.6

Distance to track [m] subtrahend/minuend	Track 1 [dB]	Track 2 [dB]
10/5	3.1	-
26/13	6.2	-
14/7	-	3.8
30/15	-	8

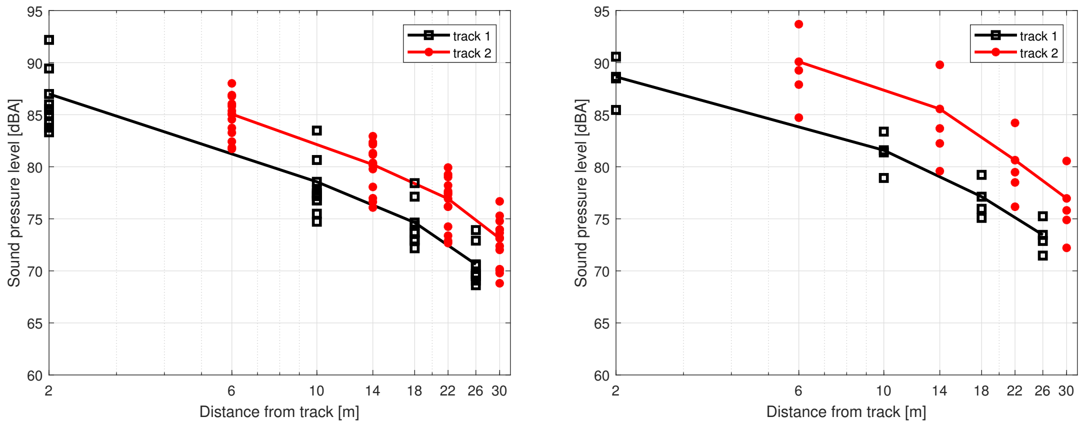

Figure 4.6: The maximal A-weighted SPL for both the models SL79 (left plot) and SL95 (right plot) at the four microphone positions at Olaf Ryes Plass for track one and two.

4.2 Background noise

The background noise is analyzed and presented with the intent to see if the SPL at any microphone position in any case is in the same order as the background noise, and also to see if the background noise is different for any location in such a way that it might affect the results.

4.2.1 Gothenburg

Background noise was measured for both measurement locations in Gothenburg, and presented in Figure 4.7. The SPL of the background noise at the two measurement locations in Gothenburg at each of the four microphone positions is about 10 dB lower than the SPL during a tram pass-by and should hence not effect the results.

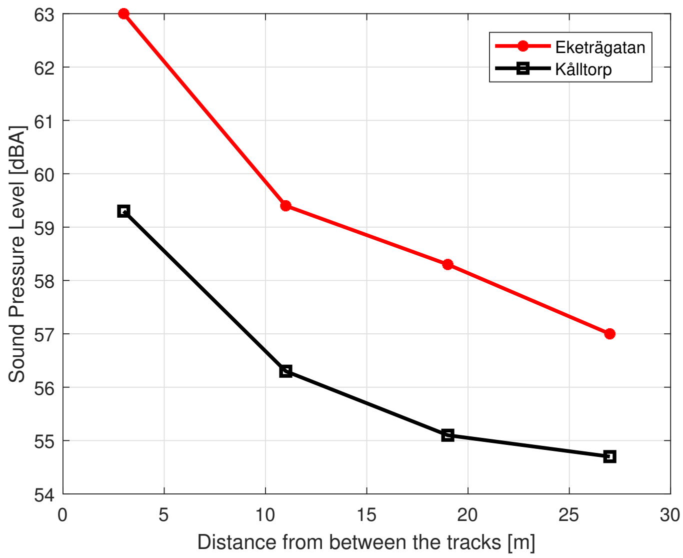

Figure 4.7: Background noise in Gothenburg

4.2.2 Oslo

Background noise was measured for all three measurement locations in Oslo, and presented in Figure 4.8. The SPL of the background noise at the three measurement locations in Oslo at each of the four microphone positions is about 10 dB lower than the SPL during a tram pass-by and should hence not effect the results.

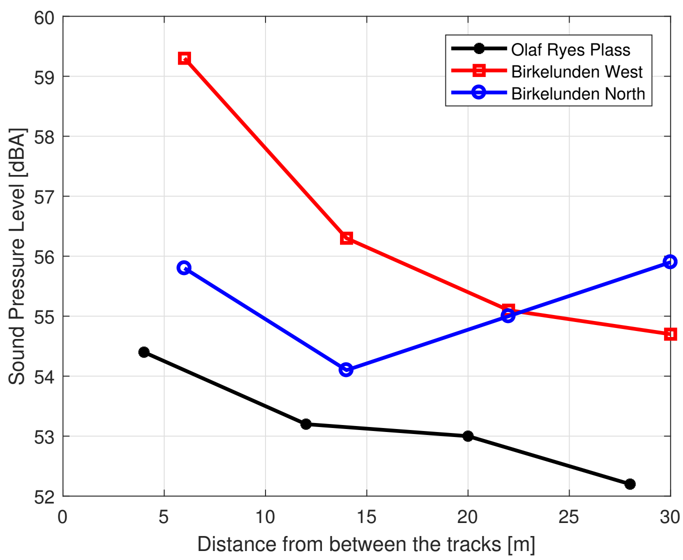

Figure 4.8: Background noise in Oslo

4.3 Tram Velocity

The velocity of each tram was measured in order to observe how the influence of velocity would affect the results.

4.3.1 Gothenburg

In Gothenburg the velocity is averaged for the individual tram models going in to and out of town.

Table 4.10: Average tram velocity in Gothenburg

Tram model	Trams going in to town [m/s]	Trams going out from town [m/s]
M28/M29	7.82	11.40
M31	8.90	11.80
M32	8.34	13.12

4.3.2 Oslo

In Oslo the velocities were measured and averaged for each individual measurement location and tram type as well as for incoming or outgoing trams.

Table 4.11: Average tram velocity in Oslo, Birkelunden west

Tram model	Trams going in to town [m/s]	Trams going out from town [m/s]
SL79	8.12	8.50
SL95	8.24	8.88

Table 4.12: Average tram velocity in Oslo, Birkelunden north

Tram model	Trams going in to town [m/s]	Trams going out from town [m/s]
SL79	4.41	5.29
SL95	5.00	4.89

Table 4.13: Average tram velocity in Oslo, Olaf Ryes Plass

Tram model	Trams going in to town [m/s]	Trams going out from town [m/s]
SL79	7.04	7.96
SL95	6.68	9.02

4.4 Tram pass-by in time domain

A difference can be observed between the results from Oslo and Gothenburg regarding distance sound attenuation. For that reason it was decided to investigate the tram pass-bys in the time domain in order to gain further information about the matter. The results presented in section 4.4 are the total A-weighted maximum SPL in the time domain for one single pass-by of each tram model.

4.4.1 Gothenburg

The M28/M29 model does not create distinctive peaks during the pass-by, as shown in Figure 4.9, though the levels at the first microphone is higher.

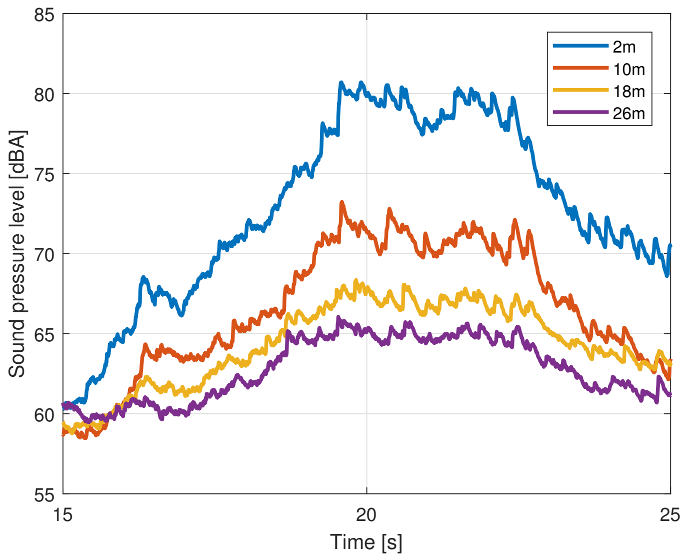

Figure 4.9: The sound pressure level at the various mic positions for the tram passage of a M28/M29 model.

The total SPL during the pass-by of a M31 tram shows distinctive peaks at around 11 and 14 seconds, see Figure 4.10.

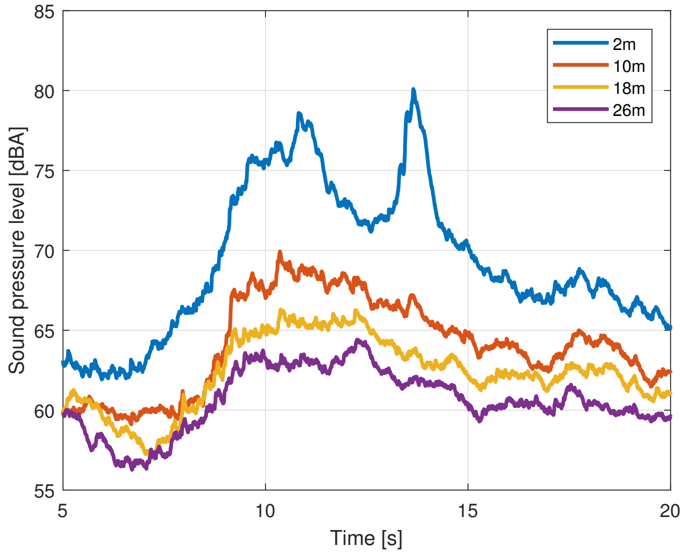

Figure 4.10: The sound pressure level at the various mic positions for the tram passage of a M31 model.

The total SPL during the pass-by of a model M32 tram also shows distinctive peaks at the first microphone position, presented in Figure 4.11. These occur at around 13 and 15.5 seconds. The velocity of this tram during the passage was 8.34 m/s. At this velocity the peaks at the first microphone position occur when the main bogies of the tram pass by the microphone array.

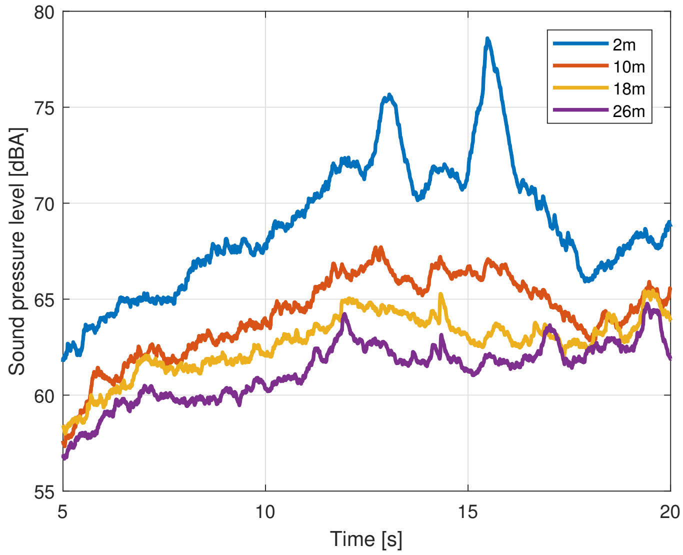

Figure 4.11: The sound pressure level at the various mic positions for the tram passage of a M32 model.

4.4.2 Oslo

The measurements in Birkelunden west and north had to be carried out 2 meters further from the tracks due to the placement of the tracks on the road.

The pass-by of the trams in Birkelunden west, presented in Figure 4.12, does not display any distinctive peaks but rather a smooth increase and decrease during the pass-by.

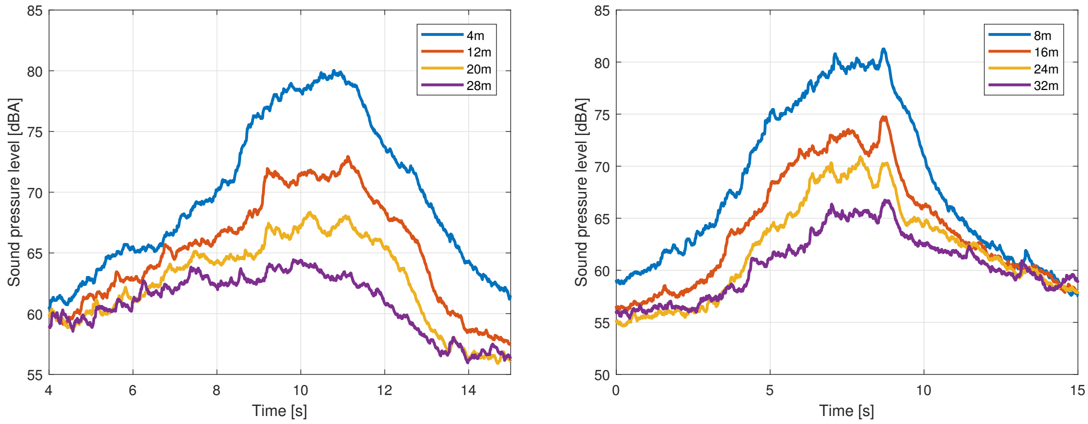

Figure 4.12: Pass-by in Birkelunden west. The left graph displays the SL79 and the right graph displays the SL95.

The velocity of the trams passing by Birkelunden north is lower than the velocity at the other measurements locations. The SL95 display three peaks during the passage, see Figure 4.13.

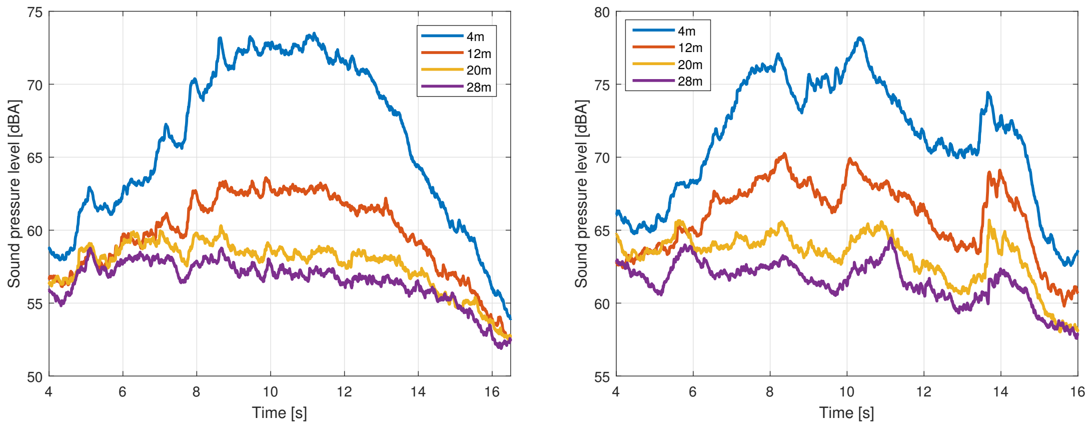

Figure 4.13: Pass-by in Birkelunden north. The left graph displays the SL79 and the right graph displays the SL95.

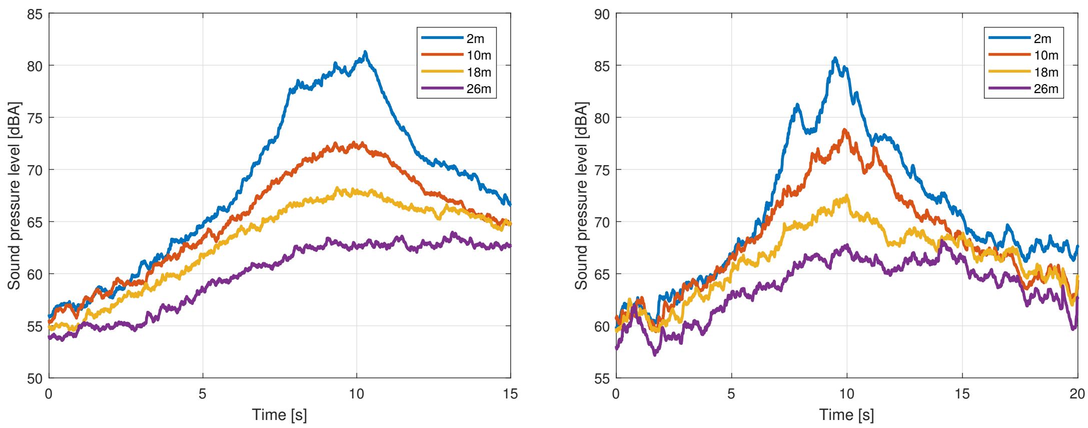

Figure 4.14: Pass-by in Olaf Ryes Plass. The left graph displays the SL79 and the right graph displays the SL95.

4.5 Spectrum analysis

In order to determine the dominating frequency bands of the various tram types a spectral analysis was performed. This could give an idea about the different sound sources on the trams. Looking at the sound attenuation as a function of frequency band, as presented in section 4.6, it would be possible to see if there are any sound sources with point source characteristics present, since the distance attenuation for point sources and line sources differs, as explained in section 2.2.2.

In Gothenburg the resulting spectral plots are averages of all measurements done for a specific tram type on both of the two measurement locations Eketrägatan and Kålltorp. This is because there were quite similar measurement conditions on the two locations regarding microphone distance and surrounding environment. In Oslo this was not the case, and the resulting spectral plots are averages for the measurement for a specific tram type at a specific measurement location.

4.5.1 Gothenburg

Figure 4.15 shows that the SPLs are significantly higher at microphone position one in the frequency range 200Hz to 2000Hz for the tram model M28/M29. Also, the frequency content of the sound at the nearest microphone position is different compared to the other positions.

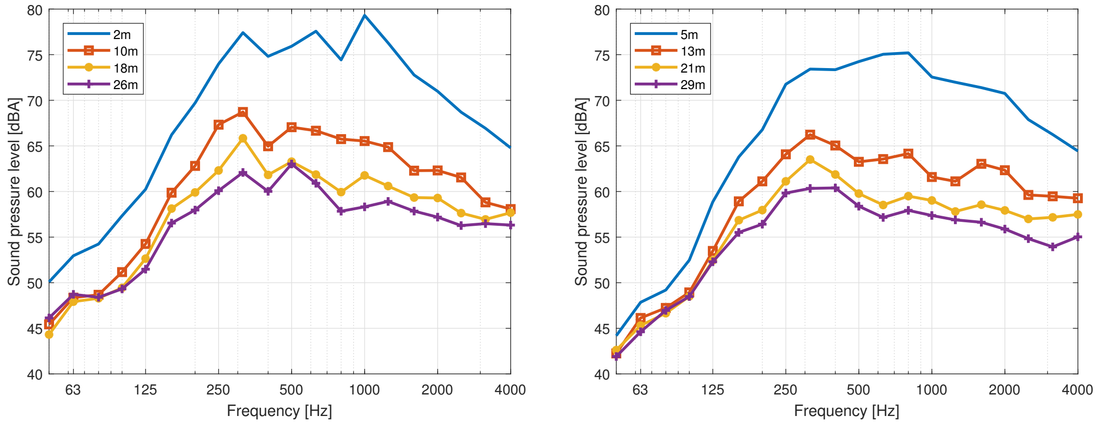

Figure 4.15: The maximal A-weighted SPL for the model M28/M29 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two.

Figure 4.16 shows that the frequency content of the sound at the nearest microphone position differs from the other positions for tram type M31. The spectral curve for the nearest microphone position appears more similar the other positions for trams passing by on track two. For the first microphone position there is a peak in the curve at approximately 630 Hz.

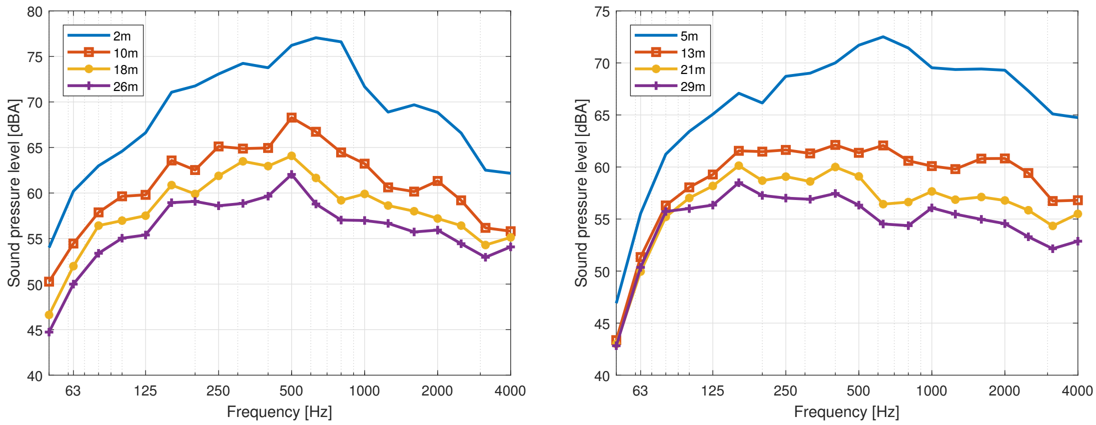

Figure 4.16: The maximal A-weighted SPL for the M31 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two.

Figure 4.17 shows that the frequency spectra at the nearest microphone position differs distinctly compared to the others in the case of track one, while the corresponding curve for track two shows similar characteristics to the other microphone positions but with an increased amplitude.

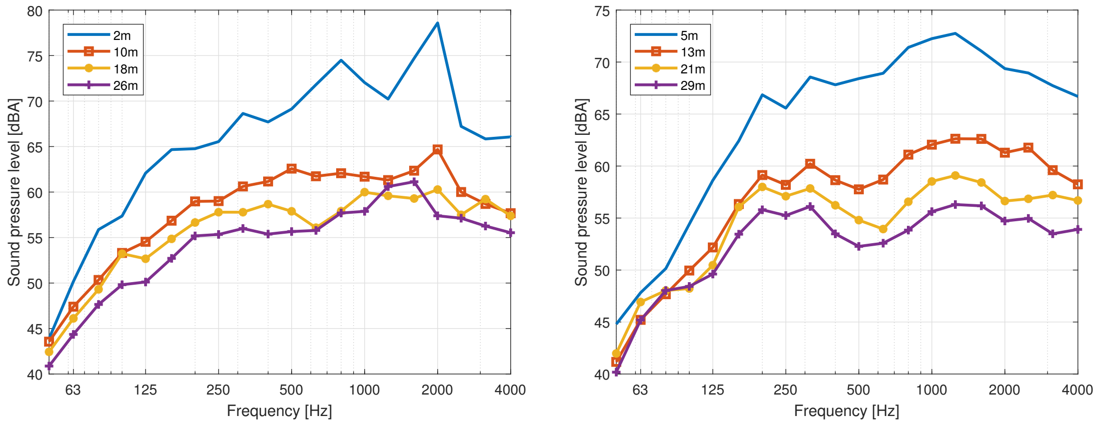

Figure 4.17: The maximal A-weighted SPL for the M32 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two.

4.5.2 Oslo

The dominating frequencies for model SL79 at the location Birkelunden west are in the range 500 Hz to 1500 Hz as can be seen in Figure 4.18.

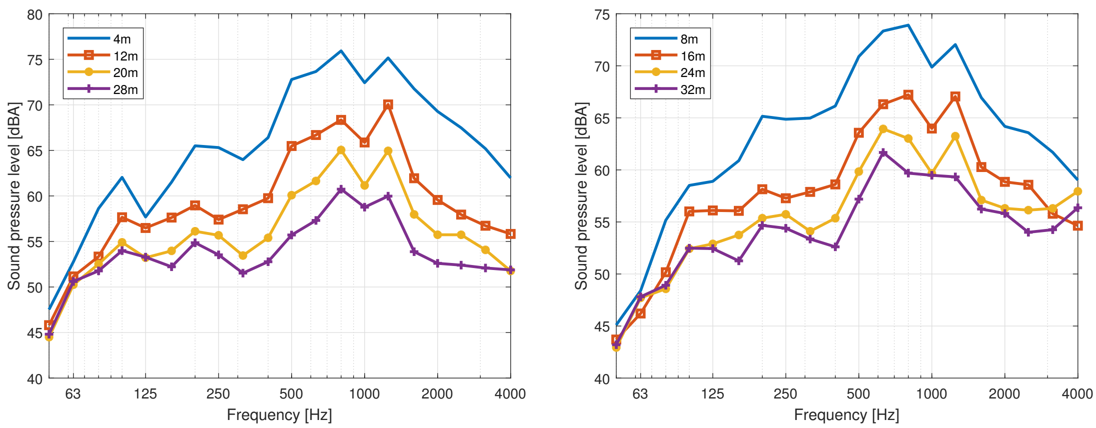

Figure 4.18: The maximal A-weighted SPL for the SL79 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two. Results from Birkelunden west.

Figure 4.19 shows that there is a distinctive peak at 2000 Hz for the tram model SL95 at Birkelunden west. The difference between the top values of the first and second microphone position is greater at track two, which correlates well with the result from Figure 4.4 where the decrease in SPL from mic one to mic two is higher for the trams on track two for the SL95 model.

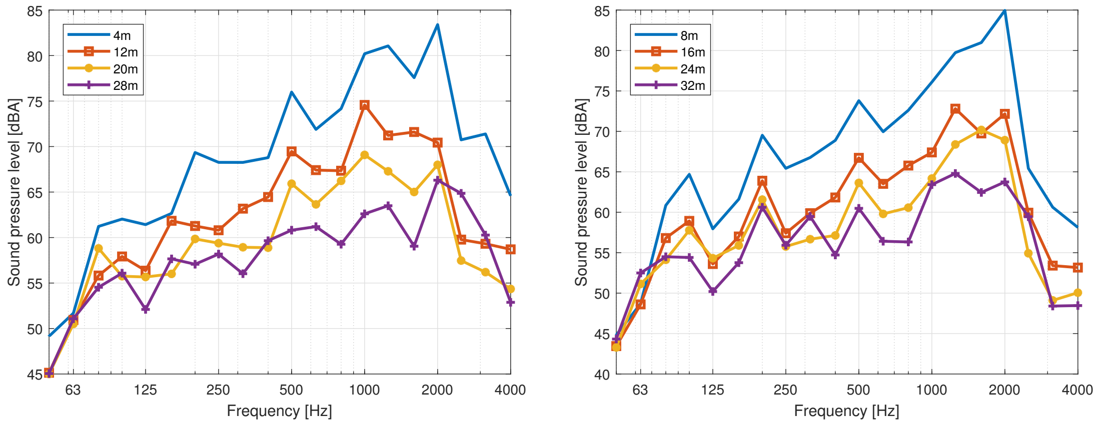

Figure 4.19: The maximal A-weighted SPL for the SL95 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two. Results from Birkelunden west.

The shapes of the curves for the spectral content looks rather similar at the four microphone positions for both track one and two for tram model SL79 at Birkelunden north. The SPL is significantly higher at position one than at the other positions, which corresponds well with Figure 4.5 where it is visible that the sound attenuation is higher close to the tracks.

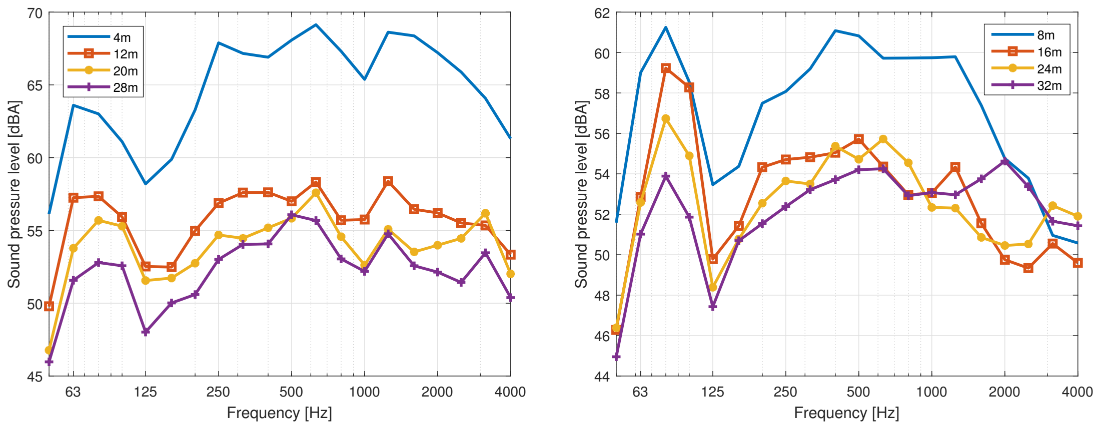

Figure 4.20: The maximal A-weighted SPL for the SL79 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two. Results from Birkelunden north.

The spectral curves look fairly similar throughout the four microphone positions both for track one and track two regarding tram model SL95 at Birkelunden north. See Figure 4.21.

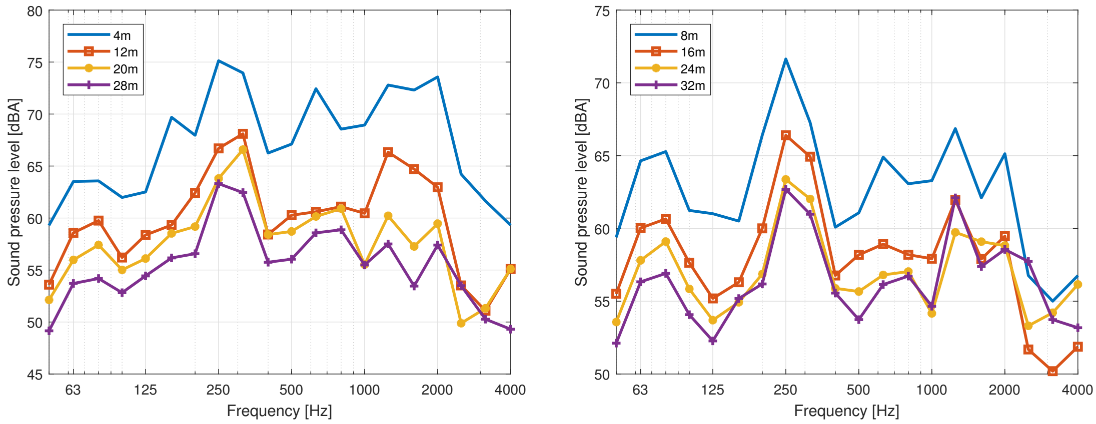

Figure 4.21: The maximal A-weighted SPL for the SL95 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two. Results from Birkelunden north.

In Figure 4.22 the results for the passages of tram model SL79 at Olaf Ryes Plass are presented. It is visible the first mic position on the closest track differs from the rest of the mic positions in the frequency range of 500 Hz to 1500 Hz. On the second track however, the attenuation is about the same for each microphone. It can also be mentioned that difference in SPL is fairly constant between microphone positions two to four, which would mean an increasing sound attenuation with increasing distance. This can be seen in Figure 4.6.

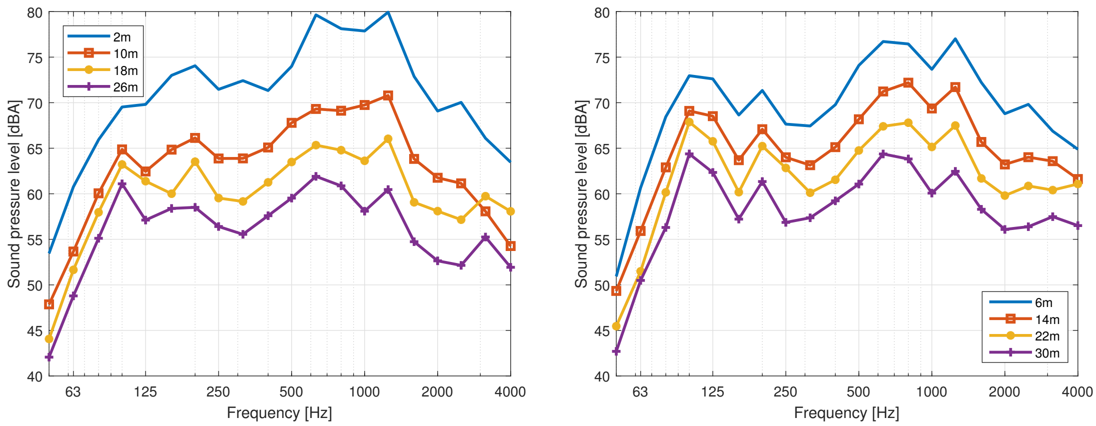

Figure 4.22: The maximal A-weighted SPL for the SL79 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two. Results from Olaf Ryes Plass.

In Figure 4.23 the results for the passages of tram model SL95 at Olaf Ryes Plass are presented. The dominating frequencies are at around 1000 Hz to 2000 Hz. Track two has an additional peak at 630 Hz. Track two, which is the track furthest away, generates slightly higher levels for most frequencies. The trams going on this track have a higher average velocity than the trams on track one.

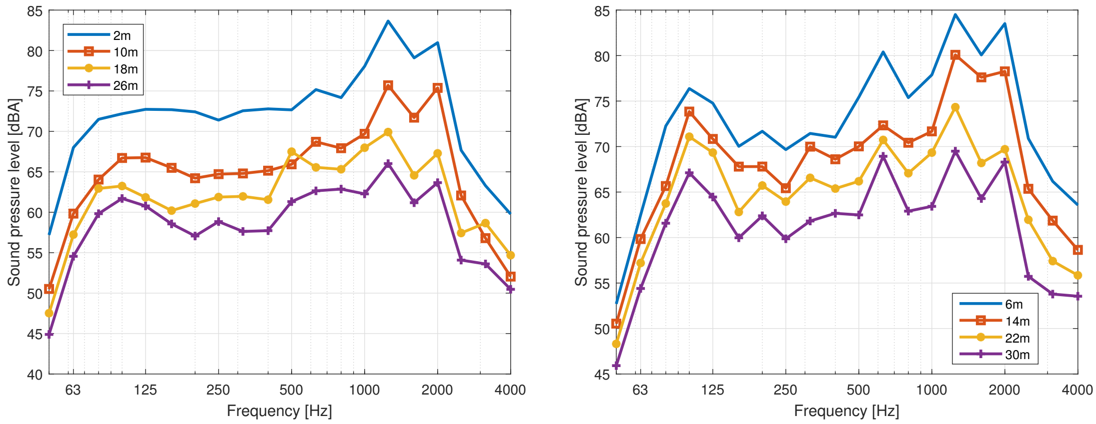

Figure 4.23: The maximal A-weighted SPL for the SL95 shown in 1/3-oct bands for all four mic positions. The left plot represents track one, and the right plot track two. Results from Olaf Ryes Plass.

4.6 Spectrum attenuation

Figure 4.24-4.32 present the distance sound attenuation as a function of 1/3-oct bands, in order to easier display the attenuation of each 1/3-oct band. The results are presented in dB reduction from the microphone position closest to the tracks.

4.6.1 Gothenburg

The spectrum attenuation of the three tram models in Gothenburg are presented in Figure 4.24-4.26. The attenuation is overall highest for frequency range 500 Hz to 1250 Hz.

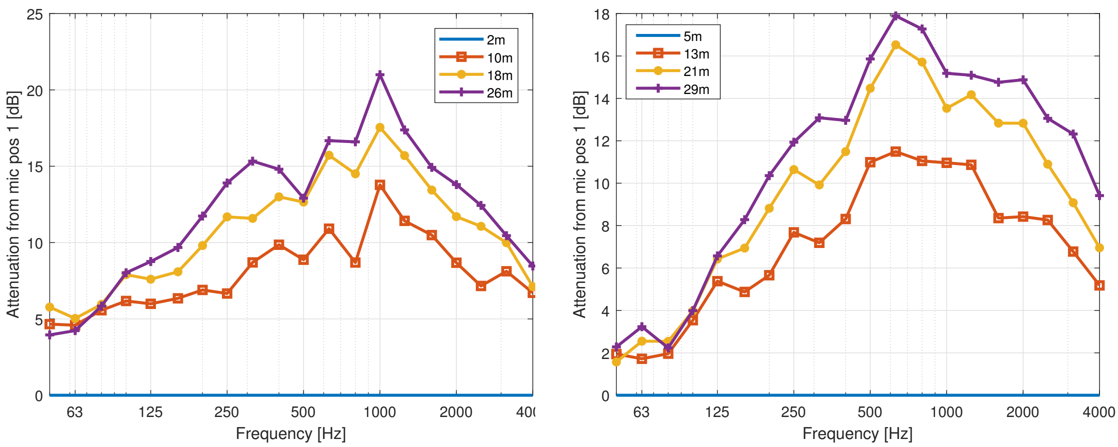

Figure 4.24: The sound attenuation (expressed in dB) for the M28/M29 at the four mic positions relative to mic position 1. The left plot represents track one, and the right plot track two.

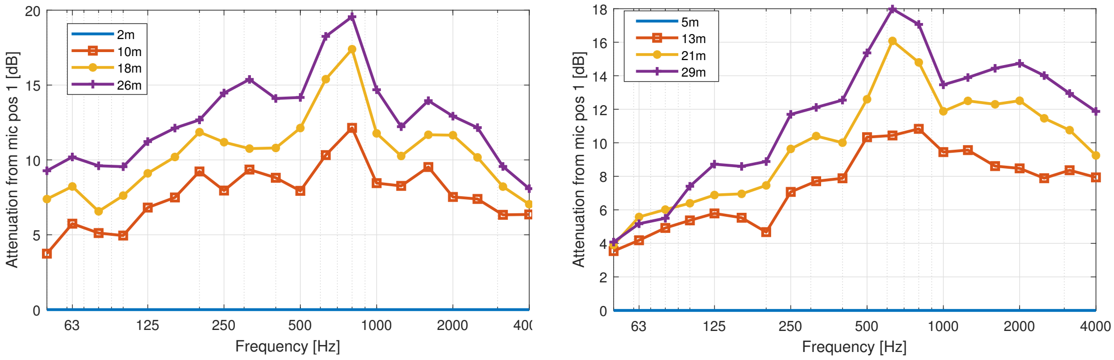

Figure 4.25: The sound attenuation (expressed in dB) for the M31 at the four mic positions relative to mic position 1. The left plot represents track one, and the right plot track two.

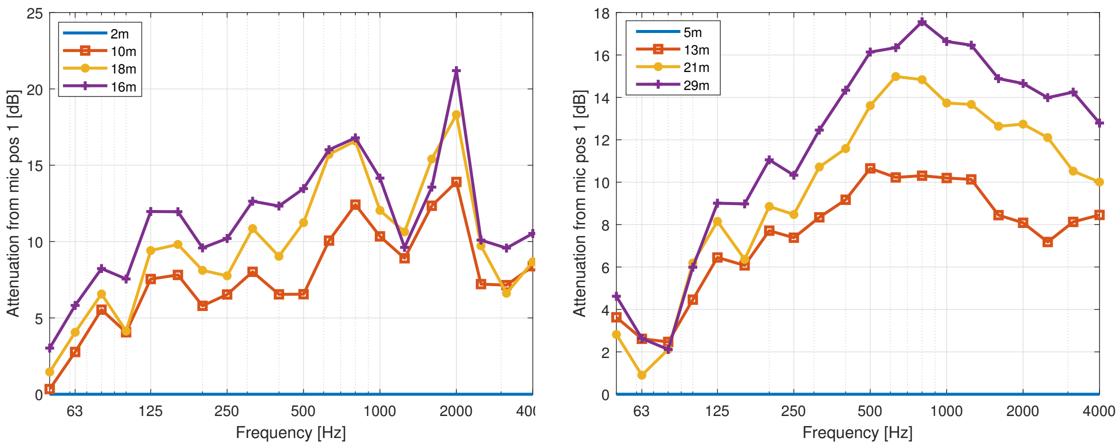

Figure 4.26: The sound attenuation (expressed in dB) for the M32 at the four mic positions relative to mic position 1. The left plot represents track one, and the right plot track two.

4.6.2 Oslo

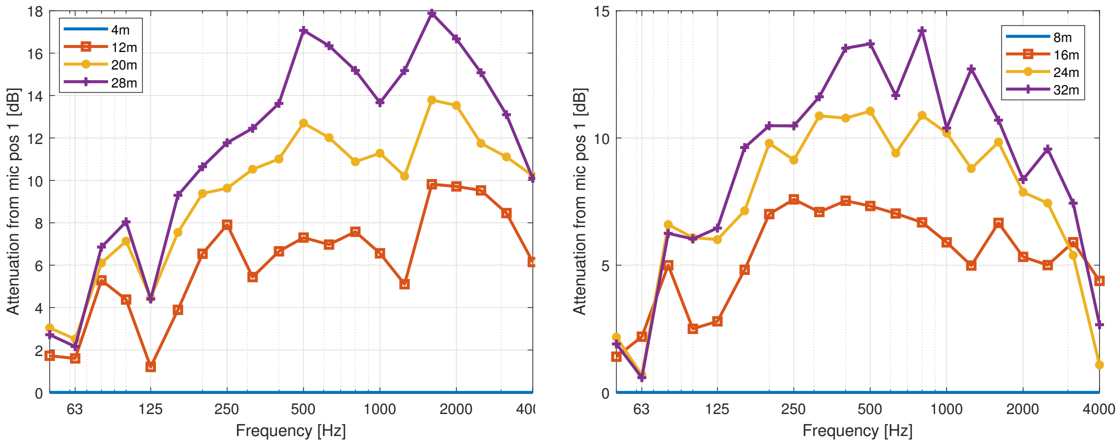

Figure 4.27: The sound attenuation (expressed in dB) for the SL79 at the four mic positions relative to mic position 1. Measurements at Birkelunden west. The left plot represents track one, and the right plot track two.

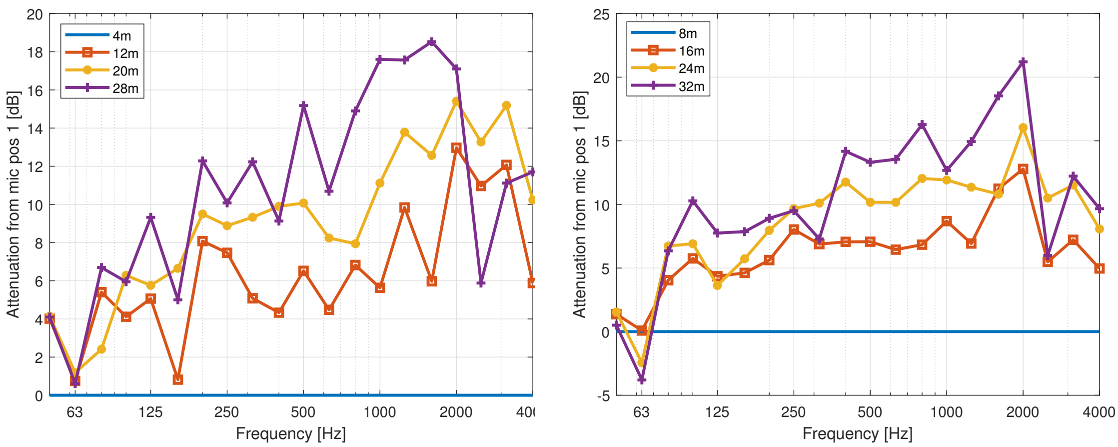

Figure 4.28: The sound attenuation (expressed in dB) for the SL95 at the four mic positions relative to mic position 1. Measurements at Birkelunden west. The left plot represents track one, and the right plot track two.

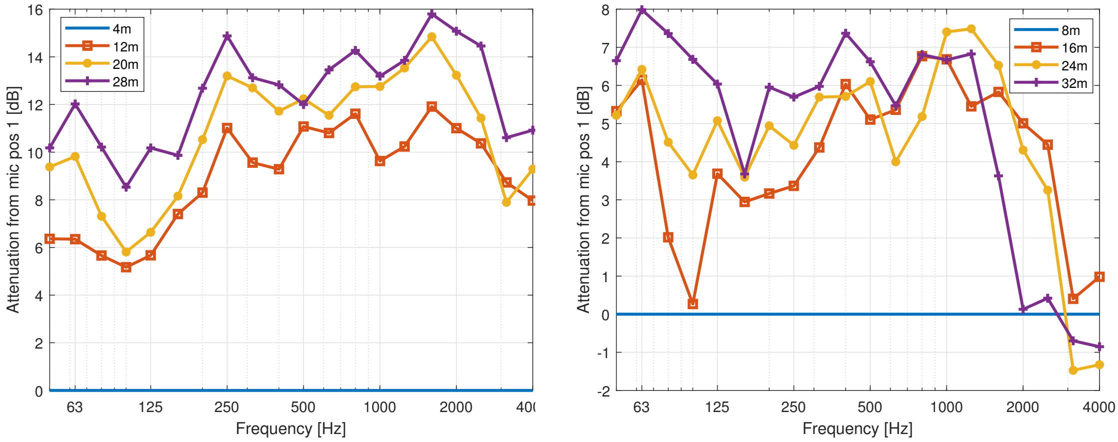

Figure 4.29: The sound attenuation (expressed in dB) for the SL79 at the four mic positions relative to mic position 1. Measurements at Birkelunden north. The left plot represents track one, and the right plot track two.

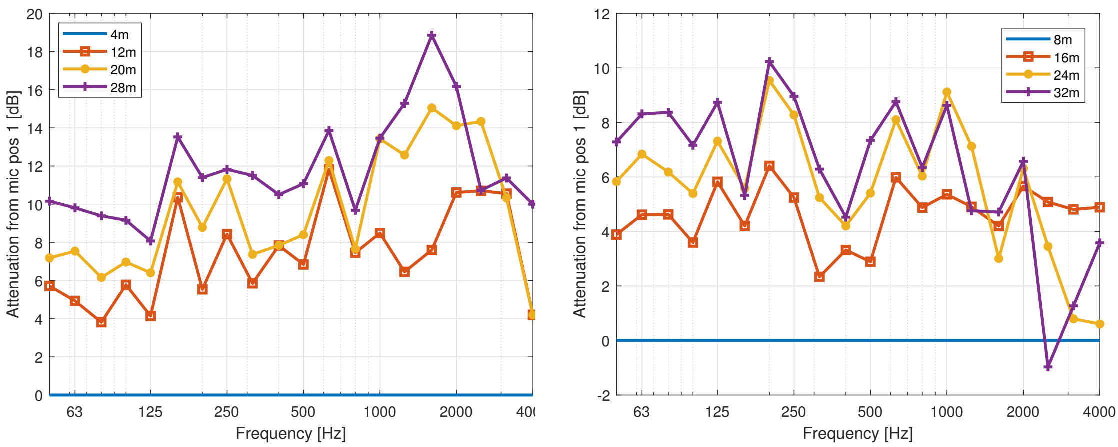

Figure 4.30: The sound attenuation (expressed in dB) for the SL95 at the four mic positions relative to mic position 1. Measurements at Birkelunden north. The left plot represents track one, and the right plot track two.

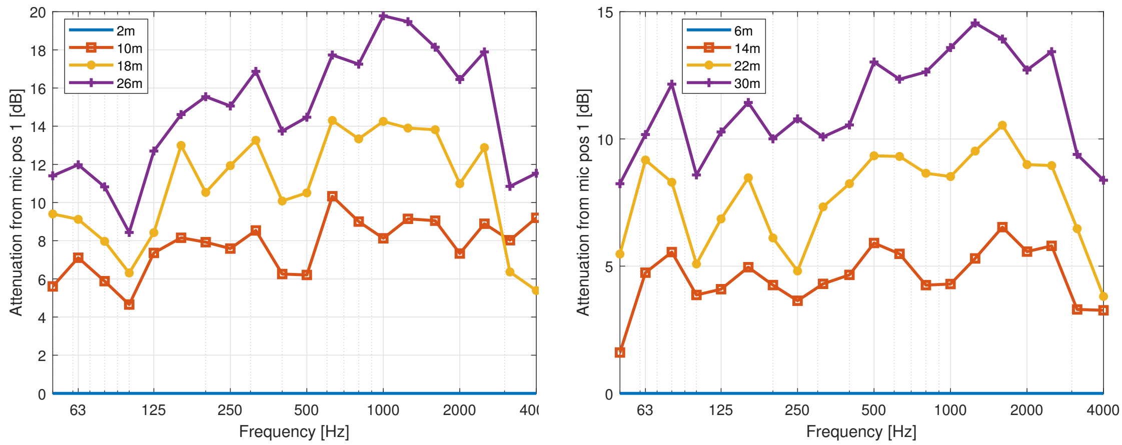

Figure 4.31: The sound attenuation (expressed in dB) for the SL79 at the four mic positions relative to mic position 1. Measurements at Olaf Ryes Plass. The left plot represents track one, and the right plot track two.

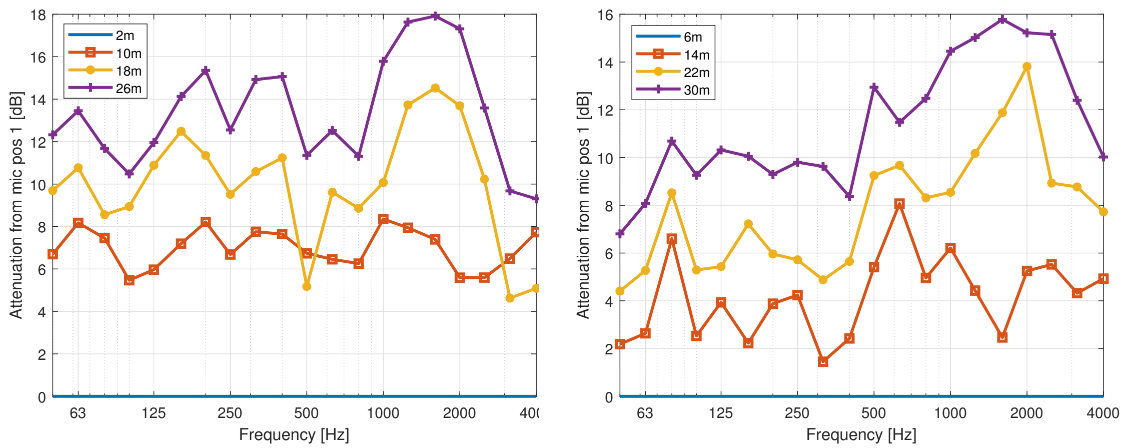

Figure 4.32: The sound attenuation (expressed in dB) for the SL95 at the four mic positions relative to mic position 1. Measurements at Olaf Ryes Plass. The left plot represents track one, and the right plot track two.

4.7 Results from simulation

In order to better understand, and to see if it would be possible to accurately predict the sound attenuation of a passing tram, five simulations were performed using the software Matlab, as is further explained in section 3.5. The results of these simulations are shown in Figure 4.33 - 4.42.

4.7.1 Line- and point source

Figure 4.33 shows the total SPL as a function of time at various distances for the simulated pass-bys of a line source (with the length of a tram M32) and a point source. The strengths of the sound sources in the two cases were tuned so that the sound exposure levels at a distance of 10 meters would match that of a measured pass-by of a tram M32. The corresponding SPL curve for this pass-by can be viewed in Figure 4.11

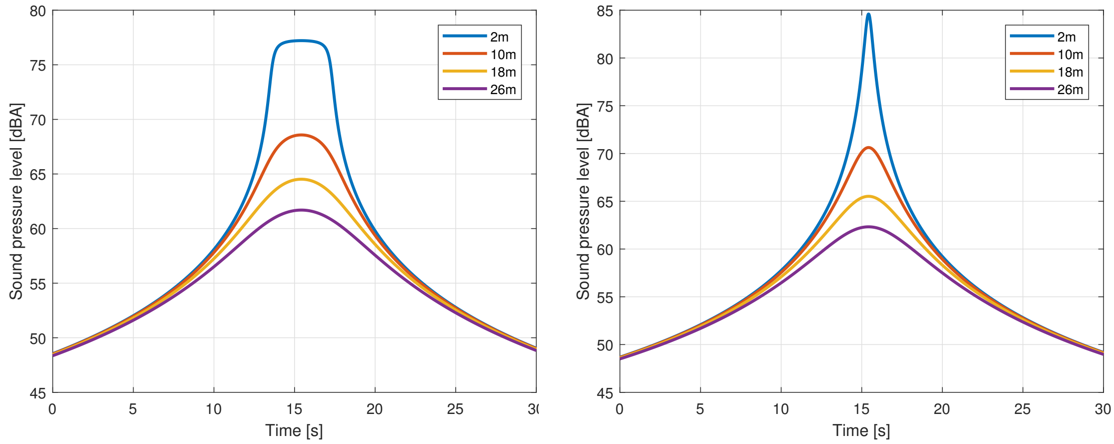

Figure 4.33: The SPL of a simulated pass-by of a line source (left plot) and a point source (right plot) as a function of time at the four microphone positions.

Table 4.14: Sound attenuation per distance doubling for a simulated pass-by of a line source with the length of a tram M32, compared to the measured average SPL for the M32. Level differences are taken from Figure 4.34 and 4.3

Distance to track [m] subtrahend/minuend	Line source [dB]	Measured average [dB]
10/5	3.7	4.9
26/13	5.1	4.1

Table 4.15: Sound attenuation per distance doubling for a simulated pass-by of a point source,compared to the measured average SPL for the M32. Level differences are taken from Figure 4.34 and 4.3

Distance to track [m] subtrahend/minuend	Point source [dB]	Measured average [dB]
10/5	6	4.9
26/13	6	4.1

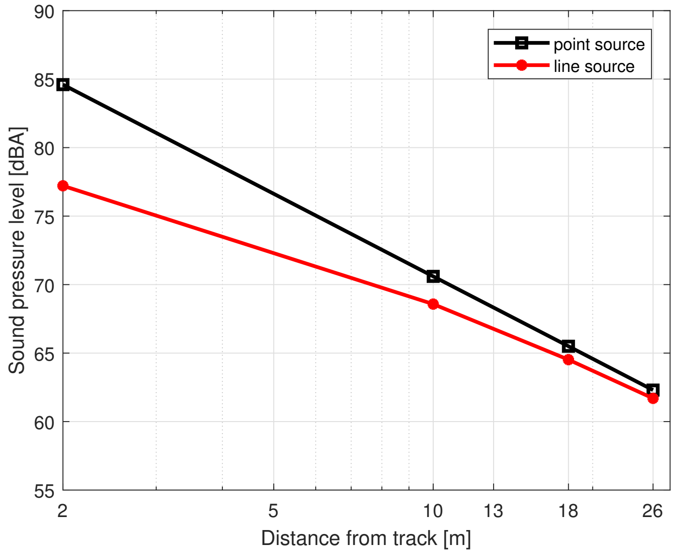

Figure 4.34: The maximal A-weighted SPL for the simulated pass-bys of a line- and a point source.

4.7.2 Exclusively the wheel bogies

Judging by the results from the simulations of the passing line- and point source in Section 4.7.1, it is clear that a more detailed model is needed to accurately predict the sound attenuation of a passing tram. Hence a simulated pass-by using several point sources, with various strengths, placed along the length of the tram was carried out. In Figure 4.35 the maximal SPL of the tram passage of a simulated M32 is shown as a function of time. At the first microphone position at 2 meters, the peaks of the front and rear boogies are visible as well as the slightly less prominent peak of the middle boogie. At the microphone positions further away, these peaks are lower and the total curves more even. This can be compared with the measured passage of a real M32 in Figure 4.11.

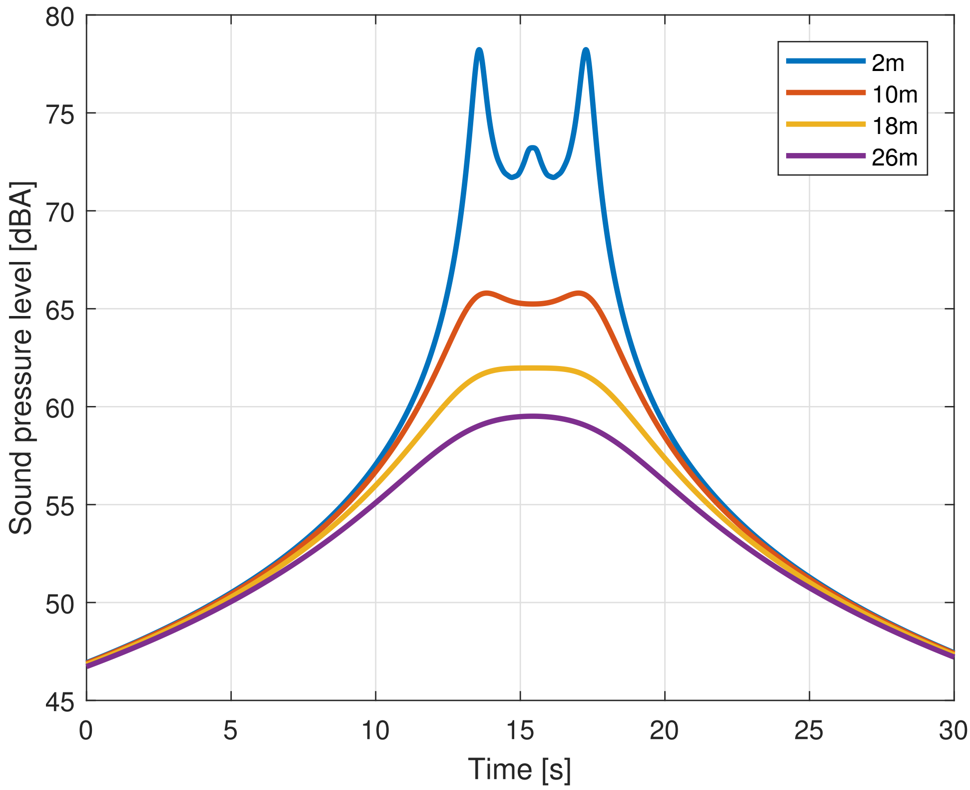

Figure 4.35: The sound pressure level of a simulated pass-by of a tram M32 as a function of time at various distances.

Table 4.16: Sound attenuation per distance doubling for a simulated pass-by of a tram M32, compared to a real pass-by of a single M32 as well as the measured average for the tram type. Level difference taken from Figure 4.36 and 4.3

Distance to track [m] subtrahend/minuend	Simulation [dB]	Real M32 [dB]	Measured average [dB]
10/5	5.4	4.7	4.9
26/13	4.6	2.5	4.1

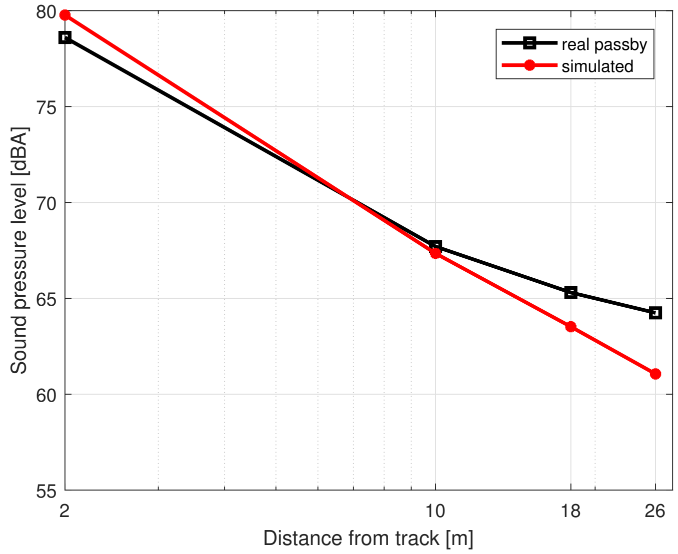

Figure 4.36: The maximal A-weighted SPL for the simulated and real pass-bys of the model M32 at the four microphone positions.

Figure 4.37 shows the sound exposure levels of the simulated pass-by without rail noise, and the sound exposure level of the real pass-by. It is visible that the simulated levels get lower than the real levels with increasing distance from the track.

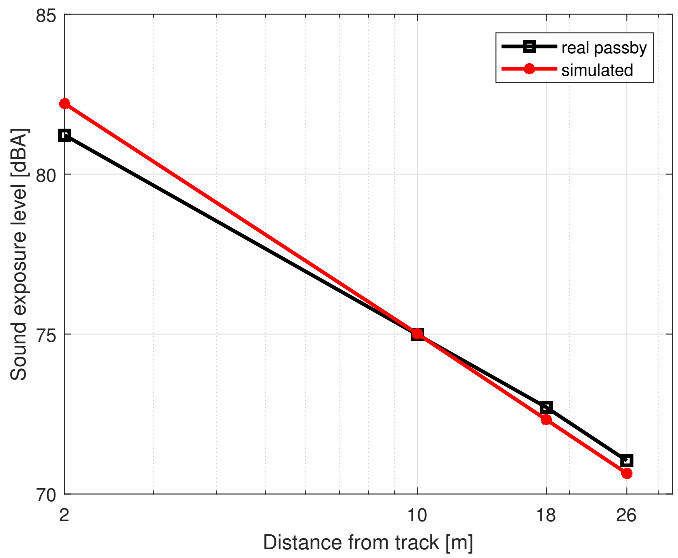

Figure 4.37: The sound exposure levels for the simulated and real pass-bys of the model M32 at the four microphone positions.

4.7.3 Rail and wheel bogies

When looking at the results for the case with only the wheel boogies in Section 4.7.2 it is visible that the rate of the sound attenuation is more similar to the measured average for the tram M32 than for the two cases with the passing line- and point source in Section 4.7.1. However, the curve for the sound exposure level presented in Figure 4.37 is a bit different from that of the measured case. For this reason, and in order to see how it would affect the rate of the sound attenuation, another simulation was performed which included sound coming from the rails. Figure 4.38 shows the maximal SPL of the tram passage of this simulated M32 with the included rail noise (further explained in Section 3.5) as a function of time. It is visible that the added rail noise makes the appearance of the graf more similar to the real pass-by in Figure 4.11.

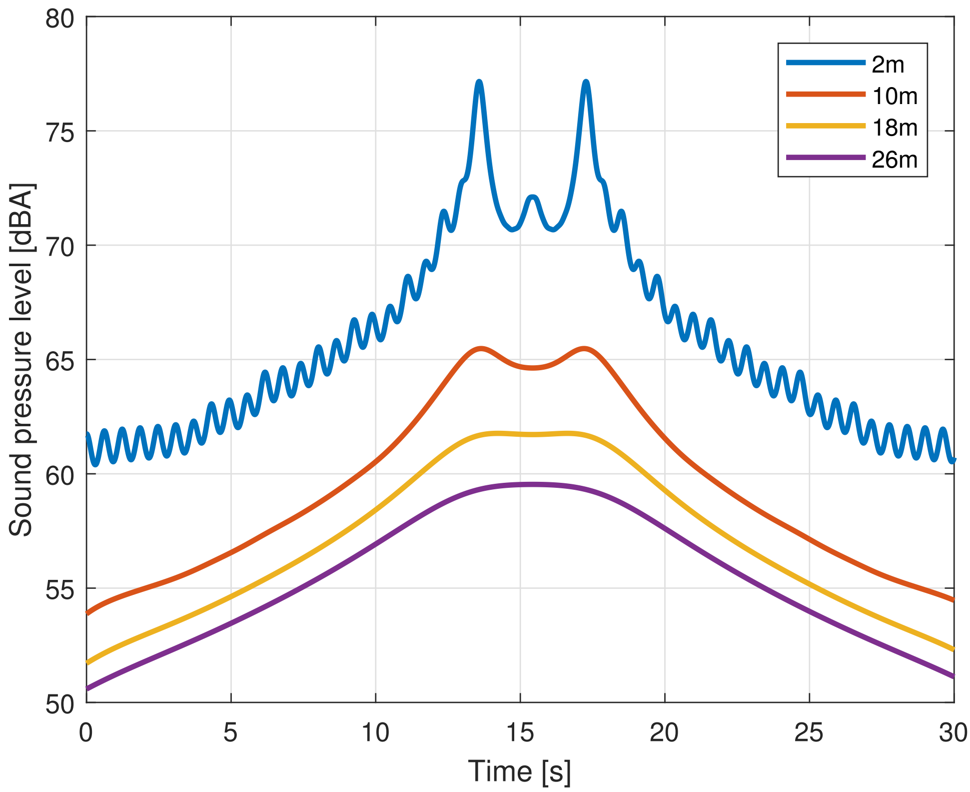

Figure 4.38: The sound pressure level of a simulated pass-by of a tram M32 (including rail noise) as a function of time at various distances.

It is visible in Figure 4.39 that the added noise from the rails lowers the SPL for the simulated pass-by. This is because the source strengths used in the simulation are tuned after the sound exposure level for the microphone at 10 meters from the track. With additional sources, the source strengths need to be lower in order to get the same sound exposure level as for the real pass-by. However, it is also visible that the two curves are a bit more parallel than the case without the rail noise in Figure 4.36.

Table 4.17: Sound attenuation per distance doubling for a simulated pass-by of a tram M32 (including rail noise), compared to a real pass-by of a M32 as well as the measured average for the tram type. Level differences are taken from Figure 4.39 and 4.3

Distance to track [m] subtrahend/minuend	Simulation [dB]	Real M32 [dB]	Measured average [dB]
10/5	5.1	4.7	4.9
26/13	4.3	2.5	4.1

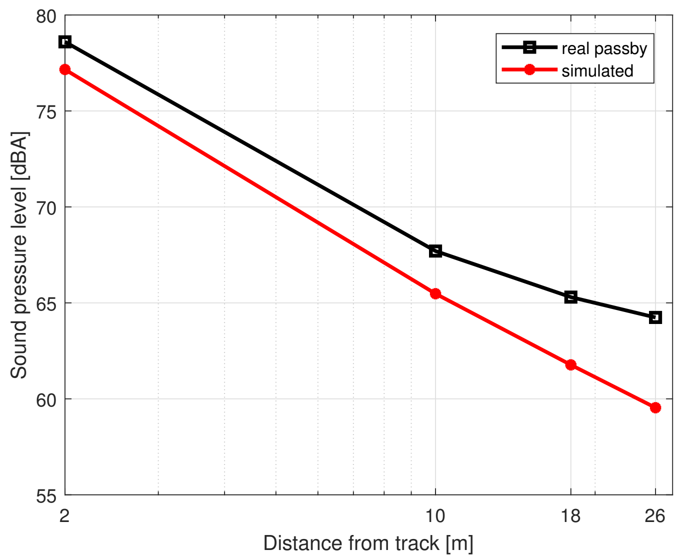

Figure 4.39: The maximal A-weighted SPL for the simulated (including rail noise) and real pass-bys of the model M32 at the four microphone positions.

Figure 4.40 shows that the sound exposure level with the added sound from the rails gets more similar to the sound exposure level of the real pass-by than the case without rail noise shown in Figure 4.37.

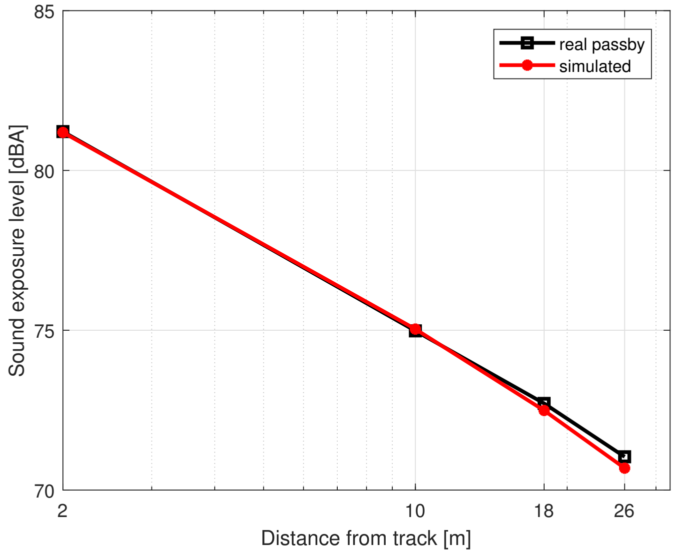

Figure 4.40: The sound exposure levels for the simulated (including rail noise) and real pass-bys of the model M32 at the four microphone positions.

4.7.4 Spectrum

The resulting sound attenuation from the simulations is rather realistic when comparing maximum values or SEL-values to the measured ones, but when looking at 1/3 octave it is not as realistic since the same source spectrum at every source position will undoubtedly lead to equal sound attenuation for every frequency band, as is visible in the left plot of Figure 4.42. For this reason it was investigated in what way a more complex distribution of sound sources with different characteristics would effect the spectral sound attenuation of the simulated pass-by, as explained in Section 3.5. In the right plot of Figure 4.42 the results of a pass-by with low frequent sound sources added along the tram in addition to the original ones is presented. This would represent a low frequent rumbling of the body of the tram. The result shows that there is less sound attenuation for the frequency bands whose sound sources are more evenly distributed along the tram. When the sources are spread out in this way the sound attenuation goes more towards that of a line source as explained in Section 2.2.2. Figure 4.41 shows the max values of the spectral SPL for the two pass-bys.

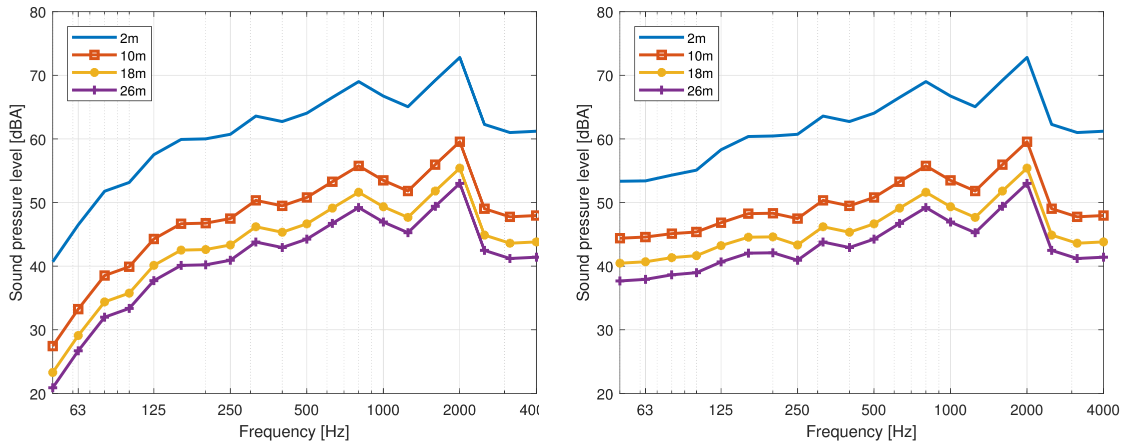

Figure 4.41: The sound pressure level spectra for two simulated pass-bys using sound sources with identical spectrum at all source positions (left), and with low frequency noise added along the tram (right).

4.7.5 Spectrum attenuation

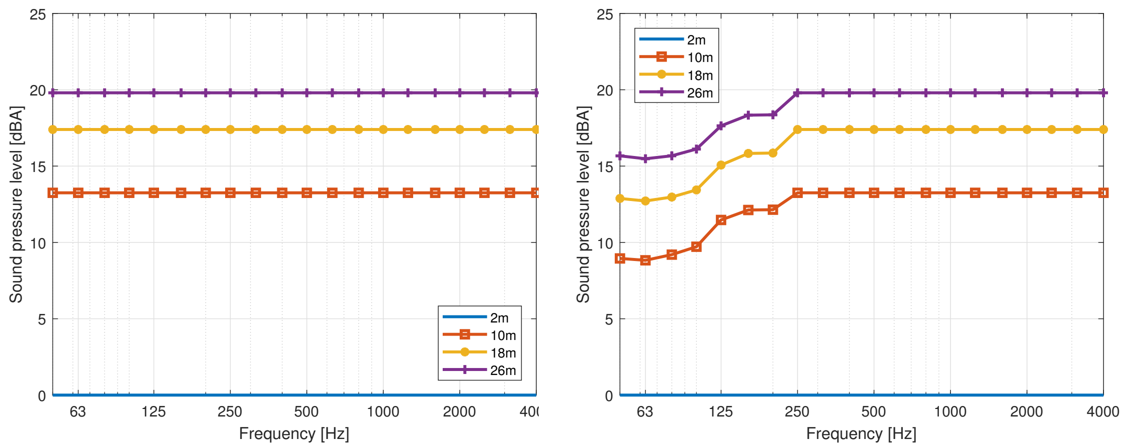

Figure 4.42: The attenuation spectra for two simulated pass-bys using sound sources with identical spectrum at all source positions (left), and with low frequency noise added along the tram (right).

5 Discussion

5.1 Total sound pressure levels

The total SPL attenuation of the various tram types in Gothenburg, presented in section 4.1.1, show a rather consistent behaviour in two ways:

1. The sound attenuation per distance doubling is nearly constant for all tram types passing by on the track closest to the microphone array.

2. The rate of the sound attenuation is the highest, for all cases, between the first and the second microphone for trams passing by on the track furthest away from the microphone array.

Point one indicates that it is not sufficient to model a passage of a tram as merely a line source with the length of a tram since this, as shown in Table 4.16, leads to an increasing rate of the sound attenuation with an increasing distance. This is most likely because the sound source at a larger distance more resemblances a point source with a sound attenuation of 6dB per distance doubling, than a line source with the corresponding attenuation of 3dB. The simulations made in Section 4.7.2 and 4.7.3 indicate that placing the sound sources further out towards the edges of the tram, or including noise coming from the rails in front of and behind the tram, both lower the rate of the sound attenuation at a distance since these operations make the sound source wider. This is probably closer to reality.
The passages of the tram types M28/M29 and M31 both have a rather low rate of sound attenuation close to the tram, quite similar to the case with the simulated line source in fact, which suggests that these tram types have a somewhat balanced distribution of the sound sources along the tram. The tram type M32 has slightly higher rate of sound attenuation close to tram than the other two. This indicates that the sound sources of the M32 are less evenly distributed along the tram, meaning that there are point sources dominating the sound field close to the track. The simulations performed in Section 4.7.2, where the pass-by of a M32 was mimicked, show that the rate of the sound attenuation as expected is higher close to the tram when strong point sources are present. Further away from the track where the sound of a single point source is not as dominant, the sound from the body of the tram overpowers the point source and the sound attenuation behaves more like a line source. The point sources can for instance be the wheels or the engine. This phenomenon can be seen in the plots from the Gothenburg measurements in Section 4.4.1, where there are distinctive peaks in SPL during the pass-by of the M31 and M32 models.

These peaks seem to correlate to the instances when a set of wheels pass by the microphone array. Since the SPL peaks of the pass-bys of the M31 and M32 models, Figure 4.10 and 4.11, do not appear nearly as prominent at the other microphone positions it shows that there is in fact a dominating source close to the tram and that this source is not as influential further away. The M28/M29 model does not seem to have as clear peaks as the other two mentioned Gothenburg tram types, as can be seen in Figure 4.9. However, there is a dip in the SPL curve in the middle of the passage which is probably when the front and rear boogies are as far away from the microphones as possible. The plots of the individual passages for the three tram types in Section 4.4 were selected in order to clearly illustrate the peaks of the wheel boogies, and it can be assumed for the M31 that this is not so often the case since the average rate of the sound attenuation for this tram type is quite low.

The reason for point two, the fact that the rate of the sound attenuation is disproportionately high between microphone one and two for the track further away compared to track one, is a bit unclear. One thing worth taking into consideration is that the trams passing on track two have a higher average speed than the ones passing on track one, which can be seen in Table 4.10. One theory would be that sound coming from the wheels increases with increasing speed, and/or that the sound of the body of the tram becomes less prominent.

The measurements in Oslo were not as consistent regarding SPL attenuation. In Figure 4.4- 4.6 it can be seen that there are inconsistencies between the various measurement sites. At "Birkelunden west" the rate of the sound attenuation is rather constant with increasing distance, at "Birkelunden north" the attenuation is significantly low far away from the track, and at "Olaf Ryes Plass" it is higher far away from the track. These inconsistencies could be due to various reasons such as a too low number of measurements, a less optimal measurement environment regarding ground type, buildings (which were always present on one side of the tracks) and other reflecting objects, acceleration and breaking due to tram stops, a curved tram track, up and downhill conditions, and of course a combination of these.

5.2 spectrum attenuation

When studying the spectrum attenuation in 1/3-oct bands, Section 4.6, one can see that it is a bit more complex than just looking at the total SPL attenuation since the attenuation varies from one frequency band to the other. The plots from the Gothenburg measurements in Section 4.6.1 show a tendency that the attenuation is the most prominent in the frequency range of 500 Hz to 1000 Hz. With a slight simplification, the attenuation for all Gothenburg tram types starts a decline at around 1000 Hz with increasing frequency, except for the case with the M32 tram at the closest track, Figure 4.17 and 4.26, where there is a peak both in SPL and sound attenuation at 2000 Hz. This is quite likely noise from the engine as this tram type has a rather characteristic high pitched engine noise, based on personal observations. The alternative would be squeal from the wheels, which is also a sound this tram type tends to produce, but it makes sense either way that the attenuation is high at these frequencies since the sound originates from an engine or a wheel and should hence behave like a point source. The reason why the attenuation declines above 1000 Hz could be due to that the tram body does not produce a lot of noise at these frequencies, but rather the rails acts as sound sources which would lead to more of a line source behaviour. The sound attenuation for frequencies below approximately 100 Hz is also quite low. It seems as if the trams do not produce much sound in this frequency region which means that the SPL is close to that of the background noise.

The Oslo measurements, presented in Section 4.1.2, are just as for the case regarding total SPL attenuation not as consistent as the Gothenburg measurements and it is not trivial to draw conclusions from the results. One general observation of the attenuation plots in Section 4.6.2 is that the SPL in some cases is higher at the microphone positions further away from the tram than at the ones closer. This could as mentioned be due to reflections on buildings, parked cars etc, or due to inconsistent ground type since it at these sites varied between soft and hard ground. In "Birkelunden north" the track included a turn which also could have effected the SPL at the microphones furthest away.
The most "ideal" pass-by in Oslo, meaning here the straightest and with the most consistent velocity, was the one in "Birkelunden west". When looking at the attenuation plots for "Birkelunden west", Figure 4.27 and 4.28, one can see that the SL79 tram type on the closest track has its maximum attenuation around 2000 Hz, which is higher than all the cases in Gothenburg except for the M32 type at the nearest track where there was a lot of noise coming supposedly from the engine. In this case, with the SL79, 2000 Hz is not a dominating frequency as can be seen in Figure 4.18. When looking at the model SL95 in Figure 4.19 one can draw parallels to the M32 type with the clear peak at 2000 Hz. Also in this case the sound attention is largest around this frequency, and it is likely that it is the engine being the sound source here as well. Apart from that, it is visible in the plots that the curves for the sound attenuation is "spikier", or with other words more unpredictable in Oslo than in Gothenburg. It is possible that this is the case when measuring in a less open environment and that one has to differ between a completely open-, and a semi-open environment when predicting sound attenuation from trams.

5.3 Simulations

Simulations of a pass-by of a tram type M32 were performed in order to better understand the tram as a sound source. Various point sources, in various configurations, were simulated passing by an array of receivers (similar to the measurement setup) and the results were compared to the measurements in order to see connections and to possibly draw some conclusions. The simulations are mainly compared to the measurements done in Gothenburg since the measurement conditions were more optimal in this location, meaning more open, straight, and with less reflecting objects, and hence more similar to the simulation model. The procedure of the simulation is explained further in Section 3.5 and the results are presented in Section 4.7.

The results from the simulations show that it is not sufficient to model a tram passage as simply a point source, nor to model it as a line source with the length of a tram. The appropriate way seem the lay somewhere in between. A passing point source gives as expected simply a sound attenuation of 6dB per distance doubling, and a passing line source gives a too high attenuation far away from the tracks compared to all the tram types in Gothenburg, and a too low attenuation close to the tracks compared to tram M32. The simulations indicate a few parameters which have influence over the total SPL of the tram pass-by. Dominating point sources such as wheel boogies and the engine lead to a higher rate of sound attenuation close to the tracks but do not affect the attenuation substantially at a distance. Far away from the tracks, what really makes a difference for the rate of the sound attenuation is the width of the sound source. Strong sound sources placed at the edges of the tram (front and rear) as well as the influence of rail noise in front of and behind the tram both lead to a lower rate of sound attenuation far away.

As can be seen in Figure 4.35 placing point sources in the front and in the rear of the tram, as well as one with a slightly lower sound power in the middle, it is possible to reasonably well imitate a pass-by of a M32 tram regarding the peaks which originate from the boogies of the tram. Additional sources, Figure 4.38, along the rails further mimics the shape of the SPL curve of the measured pass-by in the time domain. This also makes the sound exposure levels at the various receiver positions more similar to the real case if the source strengths of the original sound sources (the boogies) are tuned so that the sound exposure level matches that of the real pass-by at 10m distance, Figure 4.40. Since different tram types vary regarding source placements and strengths, engine noise, and general condition/quality (rumbling of the body), it seems as one has to model each tram type separately and tune the parameters in order to accurately be able to predict the sound attenuation.

The sound attenuation for a real pass-by vary between frequency bands. It is needed to include sources with different frequency content along the tram in order to predict this, otherwise the attenuation will be the same for all frequency bands. The simulations confirm that adding low frequent sound sources along the tram leads to a lower sound attenuation in those frequency bands. This is due to the fact that this makes the "sound source" wider and hence behave more like a line source.

In order to improve the model regarding spectral attenuation, important sound sources of the tram should be localized and their sound spectra determined. This could for instance be done using an acoustic camera. The strengths of the sources along the tram and the rails should also be investigated further so that the sound attenuation far away from the tram more accurately can be predicted. Other parameters which are relevant and could be examined are how temperature and quality of the rails plays a role, and in what way the speed of the tram affects the strengths of the various sound sources as well as their spectral content.

6 Conclusion

The measurement data as well as the results from the simulations performed in this report show that the sound attenuation varies a great deal between different tram types and measurement locations, and even between individual trams within the same tram type. The rate of the sound attenuation close to the tram is high when point sources such as the engine or the wheel boogies dominate the sound field in this region. These sources do not however affect the sound attenuation far away from the tram significantly since their sound attenuates rapidly. At a distance, what clearly affects the sound attenuation is the width of the sound source. If sound sources with a high sound power are located at the edges of the tram (front and rear), or if the sound coming from the rails in front of and behind the tram is substantial, the rate of the sound attenuation far away gets lower since the source is more similar to a line source. At an even greater distance it can be assumed that the tram once again would behave like a point source, though this could not be confirmed due to that the sound pressure levels of the tram would approach the background noise levels of the measurement locations at such a distance from the tram.

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