INDOOR NOISE FROM URBAN RAILBOUND TRANSPORT

OLAFSEN, SIGMUND

2016

Document Version:
Publisher's PDF, also known as Version of record

Link to publication

Citation for published version (APA):
OLAFSEN, SIGMUND. (2016). *INDOOR NOISE FROM URBAN RAILBOUND TRANSPORT* (1st ed.). [Doctoral Thesis (compilation), Engineering Acoustics]. Engineering Acoustics, LTH, Lund University.

INDOOR NOISE FROM URBAN RAILBOUND TRANSPORT

SIGMUND OLAFSEN

Engineering
Acoustics

Doctoral Thesis

DEPARTMENT OF CONSTRUCTION SCIENCES
DIVISION OF ENGINEERING ACOUSTICS

ISRN LUTVDG/TVBA--16/1014--SE (1-169) | ISSN 0281-8477
ISBN 978-91-7623-717-5 (print) | ISBN 978-91-7623-718-2 (pdf)
DOCTORAL THESIS

INDOOR NOISE FROM URBAN RAILBOUND TRANSPORT

SIGMUND OLAFSEN

Front cover photography by Kjersti Holst.

Printed by Media-Tryck LU, Lund, Sweden, May 2016 *(Pl)*.

For information, address:
Div. of Engineering Acoustics, Faculty of Engineering LTH,
Lund University, Box 118, SE-221 00 Lund, Sweden.
Homepage: http://www.akustik.lth.se

Indoor noise from urban railbound transport

Empirical methods

Sigmund Olafsen

LUND
UNIVERSITY

DOCTORAL DISSERTATION
by due permission of the Faculty of Engineering LTH, Lund University, Sweden.
To be defended at Matematikhusets annex, auditorium MA3
Sølvegatan 22A, Lund.
Tuesday the 14th of June 2016 at 13.00h.

Faculty opponent
Professor Ulf R. Kristiansen
NTNU, Trondheim, Norway

Organization
LUND UNIVERSITY
Faculty of engineering

Document name
DOCTORAL DISSERTATION

Date of issue 2016-04-28

Author: Sigmund Olafsen

Sponsoring organization

Title and subtitle Indoor noise from urban railbond transport

Abstract

Methods for determination of indoor noise and vibrations from urban rail bound transport are presented in this work. Both measurement methods and empirical prediction methods are described. The data and resuls are taken from field measurements of noise and vibrations from the trams and metro trains of Oslo. The methods applied should be universally adaptable.

The general approach is to use empirical modelling based on large measurement series and statistical analysis. A complete model consists of a description of outdoor noise and vibrations as well as transmission through buildings and a correct determination of the physical and perceived immision.

The introduction, chapter 1, gives a description of this type of model. This is followed in chapter 2 by an expansion of the similarities and differences between trams and metro trains on the one hand and ordinary railways on the other hand. Article 1 gives a description of measurements and building of an empirical model for outdoor noise from trams The difference in groundborne noise and vibrations from two types of metro trains is described in article 2. The general principles of empirical modelling as applied to indoor noise and vibrations from trams and metros are described in chapter 3. Articles 3, 4 and 5 deal with different technical aspects of the measurement of transmission of airborne sound through building facades.The concepts behind these measurements are discussed in chapter 4. Chapter 5 and article 6 discuss transmission of vibrations into residential buildings. Chapter 5 decribes weighted physical vibration levels from several metro trains and includes preliminary results from investigations of perceived annoyance from vibrations. Article 6 includes considerations of spectrum shapes and variation between individual train passages. Chapter 6 and article 7 are about field measurement of the noise and vibrations inside residences.

Chapter 7 presents the works that are planned in the near future to extend and complete the models presented.

Key words noise, vibration, trans, metro trains, transmission

Classification system and/or index terms (if any)

Supplementary bibliographical information

Language English

ISSN and key title 0281-8477

ISBN 978-91-7623-717-5

Recipient's notes

Number of pages 184

Price

Security classification

I, the undersigned, being the copyright owner of the abstract of the above-mentioned dissertation, hereby grant to all reference sourcespermission to publish and disseminate the abstract of the above-mentioned dissertation.

Signature Sigmund Olafsen Date 2016-05-02

To Kjersti, the love of my life

Content

Acknowledgements

The work presented in this thesis was conducted at the Department of Construction Sciences, division of Engineering Acoustics, at Lunds Tekniska Högskola (LTH). I would like to express my sincere gratitude to my mentor at LTH, Delphine Bard, who made it possible to combine academic research with my work as a consultant in noise and acoustics.

Data collection and compilation was done during my daily work as a noise consultant at Brekke & Strand Akustikk in Oslo. Those of my colleagues who continuously participated in this project for several years are named explicitly in the following. Many others among my colleagues at Brekke & Strand contributed to distinct parts of the project as reported or were helpful in other ways. In reality, all of my colleagues contributed to the work to some extent. Some participated to such a degree that this work could not have been realized without them. These colleagues will be presented below.

Ingjerd Aaraas, the managing director of Brekke & Strand, wholeheartedly supported the project all the way. The company's resources such as instruments and computers have been available whenever needed. There has never been any question about taking leave for going to lectures or mentor meetings. The company has covered all expenses for necessary books and travels.

Arild Brekke, one of the founding fathers of Brekke & Strand, willingly shared his knowledge of the physics of the transmission of sound and vibration from a train, into the air or the track and ground and into neighboring residences. He was also a continuous source of inspiration during the data collection and the development of the methods presented here.

Atle Stensland was the salesman and project manager who acquired and managed the contracts under which the data collection was performed. He managed to convey to the customer the need for continuous extension of the knowledge about noise and vibration from trams and metros in such a

way that it was been possible to conduct serious research based on regular consultancy assignments.

Maria Kristin Strand provided extremely valuable contributions to the development of the methods for the measurements of sound insulation in facades. She should also be credited with teaching me that reading the old standards before writing new ones is recommended.

Teresa Fernández Espejo and Tore Fodnes Killengreen were of invaluable help in performing the large number of field measurements required to build empirical models. They ran several kilometers of cable, carried tons of instruments, waited for countless hours for the next train and had millions of numbers run through their computers for the preliminary analysis. Teresa also participated in the continuous development of methods for multichannel vibration measurements, while Tore developed into a project manager.

Lars Fredrik Riddervold Nordin went through the draft looking for typos and errors in language usage. This meticulous work substantially improved the quality of the final product.

Thanks are also due to Sporveien, the publicly owned company that commissioned most of the field measurements necessary for the compilation of sufficiently large databases. Much of the contact with Sporveien went through Laila Kristin Dokken Gundersen, but there are also many others at Sporveien who contributed towards the increased knowledge of noise and vibrations from trams and metro trains.

Other obvious contributions should also be mentioned. Some of the illustrations were made for this thesis or obtained from other sources.

My sincere thanks are also in place to the staff at Media-Tryck at Lund University, who in a friendly, efficient and professional way helped to turn my thesis in a book. Gunilla Albertén, Monika Jönsson and Jonas Palm all were a great help to a novice at publishing.

Bo Zadig designed the front and title page and drew the illustrations for the transmission of vibrations from a metro train into buildings, a part of figure 1-3. The front page picture and figure 7-2 are photos captured by my wife, Kjersti Holst. Figure 1-1 was drawn by Randi Matland, a professional drawing artist. Figure 2-1 was taken from finn.no, a Norwegian service of maps and photos among other items. Figure 5-2 was drawn by Oskar Andreas Sivertsen, this drawing also forms the basis for figure 2-2. Figure 6-1 was made by Teresa Fernández Espejo, originally intended for internal education at Brekke & Strand.

My fellow Ph. D. students of acoustics at LTH, Juan Negreira and Anders Sjöström were of invaluable help to a student who had been out of university for 28 years prior to pursuing the Ph.D. There are many practical obstacles in the way of a second time student, and I am very grateful for the help from my fellow students in these matters.

I would also like to thank my other teachers and fellow students of courses at LTH and at the two Norwegian universities where I was allowed to take courses: NMBU at Ås and University of Oslo for their inspiration to acquire new theoretical knowledge and apply it to increase the knowledge on how to determine noise and vibration from urban rail bound transport.

Naturally, last but definitely most important, this work would never have been possible without the never ending faith and belief that my beloved wife, Kjersti Holst, has had in this project. She had an extraordinary patience with a husband who often had his mind far away. In addition to posing questions and challenges, she captured the front cover photograph and one of the other photographs used to illustrate the main thesis.

The responsibility for any errors remains mine.

Preface

The work presented in this thesis was conducted out at the Department of Construction Sciences, Division of Engineering Acoustics. I would like to express my sincere gratitude to my mentor at LTH, Delphine Bard.

Much of the work for this thesis was performed at Brekke & Strand Akustikk as in Oslo, where I worked as a full time consultant in noise and acoustics during the development of this thesis. Most of the data collection was performed as part of consultancy assignments for Sporveien, the publicly owned company that runs the trams and metros of Oslo. The data presented are valid for Oslo, but the methods developed should be applicable anywhere.

The reader is advised to view the present work as a status report. The acquisition of data, formulation of prediction models and development of measurements procedures for indoor noise from urban rail bound transport are a continuous process. Or it could be said in more general terms in Karl Popper's words from "The logic of scientific discovery":

> The empirical basis of objective science has thus nothing "absolute" about it. Science does not rest upon solid bedrock. The bold structure of its theories rises, as it were, above a swamp. It is like a building erected on piles. The piles are driven down from above into the swamp, but not down to any natural or "given" base; and if we stop driving the piles deeper, it is not because we have reached firm ground. We simply stop when we are satisfied that the piles are firm enough to carry the structure, at least for the time being.

This is the nature of observational studies. There will never be a final answer. Hopefully the presented work can be of use to those who battle with noise and vibration problems from urban rail bound transport in their daily lives.

List of appended articles

Article number	Title	Author(s)	Publishing status
Article 1	An empirical method for prediction of tram noise	Sigmund Olafsen, Delphine Bard, Atle G. Stensland, Tore Fodnes Killengreen	Submitted to Acoustics in Practice
Article 2	Difference in levels of groundborne noise and vibrations between the T-1300 and MX-3000 metro trains in Oslo	Sigmund Olafsen	Presented at Baltic-Nordic Acoustics Meeting 2012 Odense
Article 3	Sound insulation measurements of facades with variable microphone positions	Sigmund Olafsen	Presented at Internoise 2011, Osaka
Article 4	Methods of field measurements of façade sound insulation	Sigmund Olafsen, Delphine Bard, Maria Kristin Strand, Teresa Fernández Esepejo	Noise Control Engineering Journal **63** (5), September-October 2015, pp. 467-477
Article 5	Measurements of façade sound insulation using a loudspeaker or rail bound vehicles as sources	Sigmund Olafsen	Presented at Baltic-Nordic Acoustics Meeting 2012 Odense
Article 6	Transfer functions of vibrations from metro trains to houses	Sigmund Olafsen	Presented at Baltic-Nordic Acoustics Meeting 2014 Tallinn
Article 7	Measurements of vibration and noise from metro trains	Sigmund Olafsen, Arild Brekke, Tore Fodnes Killengreen, Delphine Bard	Acoustics in Practice, Vol. 3, No1, January 2015

1. Introduction

Trams and metro lines are increasingly important modes of urban transport because of low energy consumption per passenger and kilometer. This has become increasingly evident and important during the last decades. An overview of energy consumption per passenger kilometer in Norway[1] shows that trams (“sporvogn” or “trikk”) and metro (“T-bane”) have a substantially lower energy consumption than cars. A less sober example is an investigation from transport in Lisboa conducted in 2013[2] , that cites 20 times lower energy consumption per passenger kilometer for local rail bound traffic than for cars. A quote from the American Public Transit Association claims that one person’s switch to public transport can save as much as 20 pounds (approximately 9 kg) of carbon per day.[3] There is also the fact that the consumption of valuable space is much less for trams and metro lines than for cars, again quoting the American Public Transit Association:[3]

> Efficiently run transit moves a lot of people in little space – more than ten times as many people per unit of roadway space than by car. In urban areas, it is often more cost-effective to invest in transit to create roadway capacity than it is to invest in added roadway capacity.

One problem of denser cities is that more people live closer to the transport arteries. The increased frequency of departures by tram or metro is followed by a larger number of complaints about noise and vibrations. Figure 1-1 illustrates an artist’s impression of this problem, with a tram rattling past on the street outside the window.

The first part of this introduction, section 1.1 describes the main concepts and ideas to be used. Section 1.2 provides a brief description of the physical parameters involved and the manner in which they are measured and evaluated.

Figure 1-1,
an impression of a resident having the tram as the nearest neighbor. This figure will be referred to again in the text.

1.1. Concepts and ideas

The present work considers noise and vibrations that originate from conventional urban rail bound traffic, which includes trams and metro lines. The starting point of the thesis is the immission of noise. The central focus is the person exposed to noise, i.e. the person is bothered by airborne noise from the tram that rattles in the street outside the window or from the rumbling of the metro line that passes by the house.

The term “immission” is used for the physical and perceived noise and vibration as measured or perceived in rooms inside a residence.

A basic principle of the analysis is the collection of experience data from measurements. Collected data can be divided into three groups:

- Source data, which includes measured noise and vibration levels outside the building
- Transmission path data, which includes façade insulation of airborne sound and transfer functions of vibrations from the outside of a building into rooms meant for permanent occupancy
- Immission data, which includes measurement of physical and perceived noise and vibration.

Immission can be calculated from source and transmission path data. Sometimes the source and transmission path data from other places can be used to determine immission in a given case. A more thorough description of the construction of an empirical model follows in chapter 3.

The source data presented in this thesis include noise and vibration measurements made from the metros and trams that operate in Oslo. Different types of urban rail bound transport have widely varying characteristics. One example of this can be seen in article 2, which describes the different vibration signatures of two types of metro train in Oslo. Another example is that the trams and metro trains of Oslo have very different properties with regards to noise and vibration. This is due to many differences in operating characteristics. Some systems, such as metros or light railways, operate on grade-separated tracks independently of other traffic. Trams usually run in the streets and have to adapt to other traffic, such as cars, bicyclists and pedestrians. The vehicles also have very different characteristics in other ways. They are of widely varying weight, for example the urban rail bound vehicles of Oslo range in weights from 33 tons for the lightest tram to 180 tons for a six-car metro train. There might be different power supply systems, such as overhead wires or siderails. Even the track construction can vary widely from ballast tracks to city streets and other solutions. This means that the data presented for the sources are only completely valid in Oslo. However the methods based on the compilation of measured data followed by statistical analysis as presented in article 1 are universally valid.

The situation for using transmission path data in a situation different from the one in which such data were originally collected is quite different. Measurements of insulation against ***airborne*** sound have been made for a wide range of Norwegian houses. The collection of these measurements has been made mostly for reasons other than to determine indoor noise levels from trams and metros. Many of the measurements have been made to control indoor road traffic levels in old houses along existing roads and streets in the years since 2000, these houses in towns and in the countryside of southern Norway probably give a good cross section of ordinary residential buildings. Some measurements have been made in order to check compliance with design requirements in recent buildings in the Oslo area. The current database with façade sound insulation measurements in more than 500 cases can be used to estimate indoor levels for any sound source with a known spectrum. The transfer of façade sound insulation data from these Norwegian houses to houses in other countries with different materials available, different climate and different traditions of construction could also be difficult. However in countries with cold winters the data collected might be immediately useful.

The application of immission data from one situation to a different one could be difficult. The challenges of direct measurement of indoor noise are discussed in chapter 4.

The principles of the model to be presented are shown in figure 1-2.

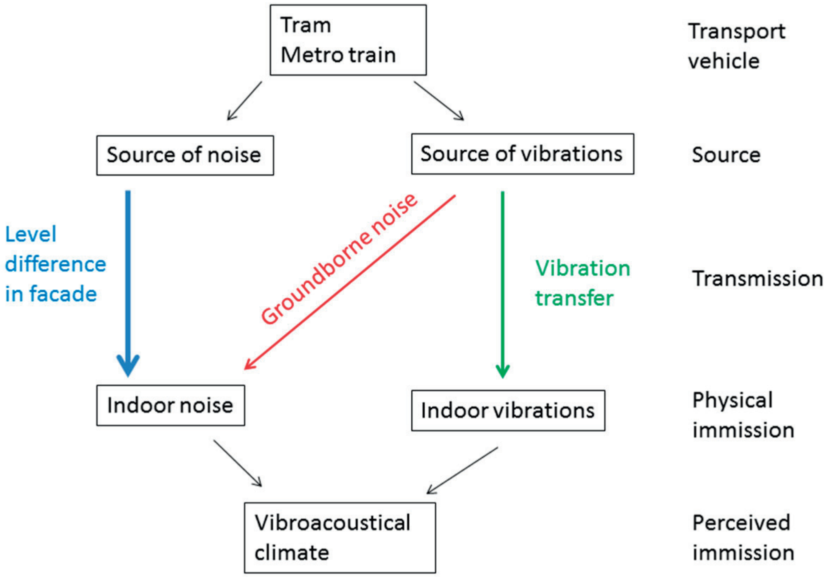


Figure 1-2,
principle of a model for noise and vibrations for trams and metros.

Noise and vibrations from rail bound vehicles raise new challenges for the acoustician. These challenges are sometimes similar to, sometimes different from those that road traffic introduces. The primary emphasis in the following is on the measurement and calculation of indoor noise, transmitted through the air or through the ground. Vibrations from the same vehicles are also discussed, but not to the same level of detail as noise. The purpose is to contribute towards the prevention and control of noise from urban rail bound sources as a nuisance. To achieve better control of the noise there is a need for improved methods for measurement and calculation of indoor noise from these sources. Noise and vibrations from trams and metro lines in the open are discussed.

Measurement and calculation of physical parameters of the noise and vibrations are discussed. A correct determination of the physical parameters of the noise by measurement or calculation is essential for predicting or improving the perceived acoustic comfort as experienced by the resident.

This calculation or measurement should include an estimate of the uncertainty in the result.

To this end some of the challenges for the correct determination of indoor noise from urban rail bound vehicles are presented. The main thesis presents the development of methods for the overall prediction of outdoor and indoor noise at short distances and the concepts and general ideas. The articles show specific examples with the obtained results. In addition the main thesis shows some recent results that have not yet been published elsewhere (to the best of our knowledge).

Throughout the work an empirical approach is developed. The methods are based on a solid base of practical experience in prediction, measurement and control of noise and vibrations. The main report concentrates on theoretical issues. The technical details can be found in the articles.

Chapter 2 discusses the peculiarities of noise and vibrations from urban rail bound transport, and how it differs from mainline railways and road traffic. References are provided to standard methods and their applicability is discussed.

Chapter 3 considers the concept of empirical modelling and describes the method of continuous data collection from field experience followed by statistical analysis. There is always both an airborne and a groundborne component to the indoor noise from rail bound vehicles, although one or the other is usually be completely dominant.

Chapter 4 pertains the methods for measurement and prediction of outdoor noise from urban rail bound vehicles. There are many prediction methods and measurement standards based on theoretical considerations and measurements on mainline railways. These are referenced and described in the chapter. These standard methods are not necessarily transferable to urban rail bound vehicles. Chapter 4 also includes methods for field measurement of the sound insulation of a façade against airborne noise. This is actually a much more involved and complicated task than was previously believed, mostly because of the challenges of taking measurements in the field. Ideally measurements of facade sound insulation should be made either with the microphone directly on the facade or at a distance of 2 m. This cannot always be achieved in actual field measurements.

Chapter 5 pertains the measurement of transfer of vibrations into houses. A main challenge is that the transfer functions of vibrations are three-dimensional, and the most important direction may not be the same on the outside of the house and the inside.

Chapter 6 pertains field measurements of the total immission of noise and vibrations outside and inside a residence. This chapter considers the limitations inherent in making measurements inside a residence. A typical setup of vibration measurements is shown.

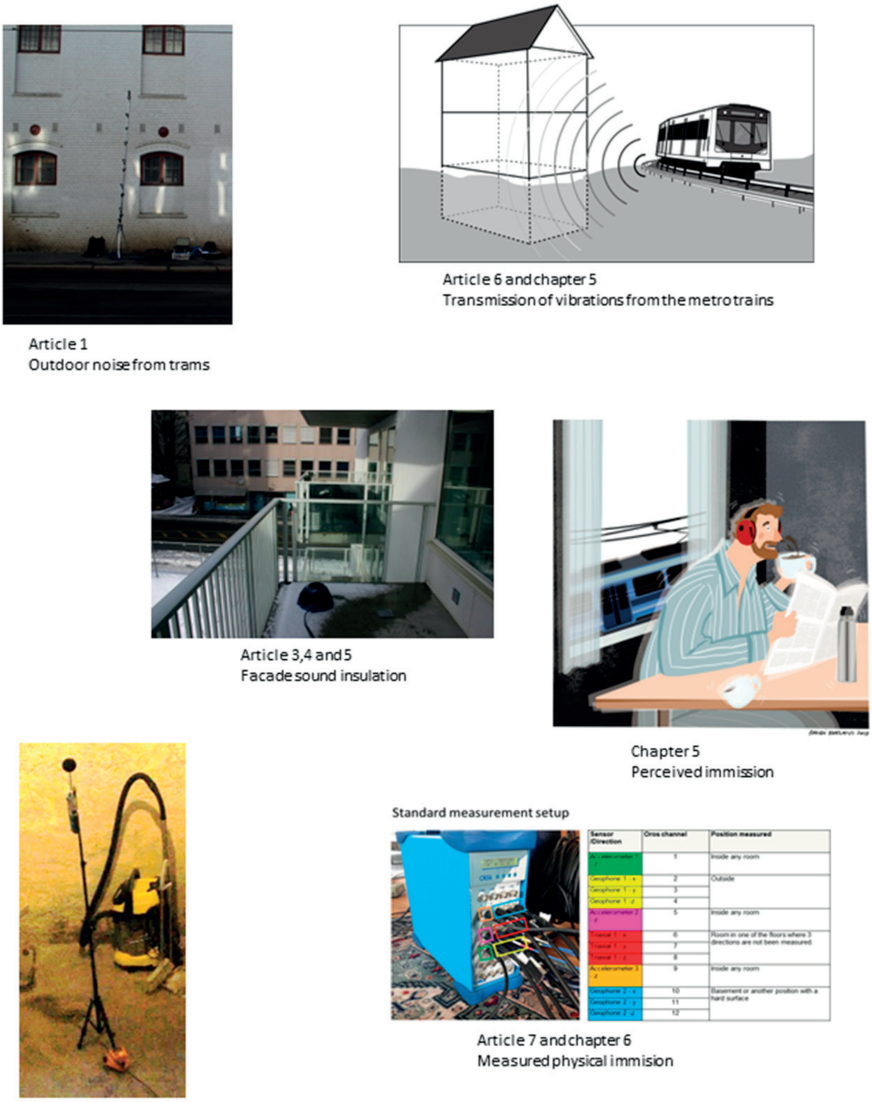
Chapter 7 is a summary of the investigations performed and planned future developments.

The articles included contain more detailed technical information and are introduced briefly below. These articles can be divided into three groups. The first two articles are related to the sources of noise and vibration. Then there are four articles on transfer paths for noise and vibration into the house. Finally the last article pertains immission measurements inside residences. Figure 1-3 provides an overview of the new results presented.

Articles 1 and 2 pertain the description of a source of airborne noise (1) and groundborne noise and vibrations (2).

Article 1 describes the compilation of data and the consequent regression analysis that lead up to a prediction model for outdoor noise levels from the trams of Oslo. The methods used should be universally adaptable.

Article 2 shows the change in spectra of groundborne noise and vibrations that resulted when Oslo changed the type of train to operate on the metro. The change occured in the years 2006 to 2010, and on some lines both types operated during the transition. The dominant feature after the analysis is a change in spectrum. In most cases the vibration levels given as v_{w95} were at the same level or higher when the new MX-3000 trains replaced the older T1300 and T2000 series.



Article 1
Outdoor noise from trams

Article 6 and chapter 5
Transmission of vibrations from the metro trains

Article 3,4 and 5
Facade sound insulation

Chapter 5
Perceived immission

Standard measurement setup

Sensor /Direction	Oros channel	Position measured
Accelerometer 1 - z	1	Inside any room
Geophone 1 - x	2	Outside
Geophone 1 - y	3	
Geophone 1 - z	4	
Accelerometer 2 - z	5	Inside any room
Triaxial 1 - x	6	Room in one of the floors where 3 directions are not been measured.
Triaxial 1 - y	7	
Triaxial 1 - z	8	
Accelerometer 3 - z	9	Inside any room
Geophone 2 - x	10	Basement or another position with a hard surface
Geophone 2 - y	11	
Geophone 2 - z	12	

Article 7 and chapter 6
Measured physical immision

Article 2, groundborne
noise and vibrations

Figure 1-3,
overview of the results shown

Articles 3 to 6 are related to the description of transfer paths. The first three of these, articles 3 to 5, are about the transmission of sound through a façade. Article 3 is a forerunner for later work on methods for façade sound insulation that features a preliminary investigation from one single site.

Article 4 is a continuation of the discussion of façade sound insulation measurements in article 3 based on the measurements from 59 sites. Article 5 discusses the differences between façade sound insulation measured with the rail bound traffic as the source on the one hand and the insulation measured with a loudspeaker on the other hand. Article 6 is an introduction to the problem of measurement of three-dimensional transfer functions for vibrations.

Article 7 presents the results of a measurement campaign in places with complaints about noise and/or vibrations. The measurements include indoor noise and vibrations in residences.

The thesis is also based on previously presented conference papers and other publications by the author and his colleagues. A list of earlier papers is provided in the appendix. These papers are referred to where relevant.This is a status report on the current knowledge of measurement of physical noise and vibrations from the trams and metro trains of Oslo as of early 2016. A small ongoing study of perceived vibrations from metro trains is also introduced. It is the nature of this type of work that continuous updates are required. It is the author's wish that the methods presented can also be of use in other cities and parts of the world.

1.2. Physical parameters

The final part of the introduction is a description of the physical parameters determined in the investigations of noise and vibrations. We start by introducing the physical parameters in terms of the most commonly used single number ratings. Noise is most commonly described in terms of a sound pressure level:

$$L_p = 10 \log (p/p_0)^2 \text{ (expressed in dB)}$$

where:

p is the actual effective sound pressure

p_0 is defined as 20 μPa

Effective sound pressure is a measure of the variations in pressure around static air pressure. There is also the matter of duration of noise. Using the energy equivalent level over time as one parameter, and a probabilistic measure of maximal level as another, is customary. The frequency dependence for noise is managed using the A filter. The A filter is a common method for constructing a single number value for different compositions of noise. The maximal level is not the absolutely highest peak level;- it is defined by the time constant FAST. Most regulations that concern transport noise are provided in terms of single number ratings.

The single number ratings relevant for noise from the metros and trams of Oslo, are as follows:

Parameter	Description
L_{den}	Energy equivalent outdoor A-weighted level, with an extra 5 dB added for noise in the evenings (19-23) and 10 dB added for noise at night (23-07).
L_{AF95}	Maximal A-weighted outdoor or indoor level expected to be exceeded by 5% of the noise *events* caused by the passage of a tram or a metro train
$L_{eq,24h}$	Indoor energy equivalent level for the whole 24-hour period without any special time weighting
SEL,A	A measure of the total A-weighted energy from the passage of a tram or metro train
$L_{A,MAX}$	Highest A-weighted level during a noise event

Sound is usually measured with a microphone, that converts sound waves into electric voltages that can be analyzed.

Vibrations are waves that propagate in a solid medium. They can be described in terms of acceleration, velocity or displacement. There is no universally accepted way of describing vibrations. Thus the conventions used in a given case must be presented along with the values. The sensors most used for measurement of vibrations from transport are accelerometers that provide an electrical charge or voltage as a function of acceleration, and geophones that provide a voltage which is a function of vibration velocity.

Only one parameter is required for evaluating of compliance with Norwegian guidelines for vibrations.

Parameter	Description
$v_{w,95}$	Maximal weighted indoor level expected to be exceeded by 5% of the vibration *events* caused by the passage of a tram or a metro train. The maximal level is evaluated with the time weighting SLOW

However, there is a complication in this apparently simple single number rating. The parameter should be evaluated in the direction with the highest vibration level, which means that simultaneous measurements in three directions are required for vibration measurements.

In many other countries vibration guidelines are based on weighted acceleration levels. There is no simple and consistent conversion of single number values from velocity to acceleration and vice versa. The ratio between acceleration and velocity is frequency dependent. This means that the ratio between weighted acceleration and weighted velocity depends on the frequency spectrum shape.

Both physical noise and vibrations as measured with instruments are frequency dependent. Human sensitivity to noise and vibrations is also frequency dependent. In addition to the method described above for presenting a single number rating, these frequency dependencies can be managed differently, i.e. by presenting the results as a function of frequency. Such a presentation is called a spectrum. An often used way to show spectra is to use so called “third octave bandwidths.” These frequency bands have a relative width of 25 %, which means that the bands increase in width with increasing frequencies. The center frequencies of these bands are standardized. Single number ratings are meant to be used to control compliance with guidelines and regulations. For the design of abatement measures against noise and vibrations an analysis of the frequency spectrum contents is always required.

2. Models of noise from urban rail bound transport

The scope of this thesis is to find suitable methods for measuring or predicting physical indoor noise and vibration levels from urban rail bound traffic such as metro lines and trams.

Urban rail bound transport is defined as the trams, metros or other rail bound vehicles that travel short distances at moderate speed within a built-up area. A typical distance from one end of the network to another could be 30 km. The vehicles can travel on city streets or separate tracks. Because of the limited speed and size of the vehicles, urban rail bound transport is usually only a noise and vibration problem at short range. Urban rail bound transport usually only handles persons, not freight goods. An example from the Norwegian map service finn.no in figure 2-1 shows Lambertseterbanen, one of Oslo’s metro lines, winding its way between houses.

Urban rail bound transport is similar in many respects to intercity or mainline railways, but in other respects urban transport has its own peculiarities, which are important to consider. Intercity or mainline railways usually move on networks of a much larger extension, often spanning continents. Mainline railways might carry local person traffic, but they also carry freight trains and long distance traffic. The speeds are much higher than urban rail bound transport.

There are also differences between modelling rail bound transport in general and modelling road traffic noise.

The difference between urban rail bound transport and mainline railways is considered in section 2.1. The difference between rail bound transport in general and road traffic is considered in section 2.2.

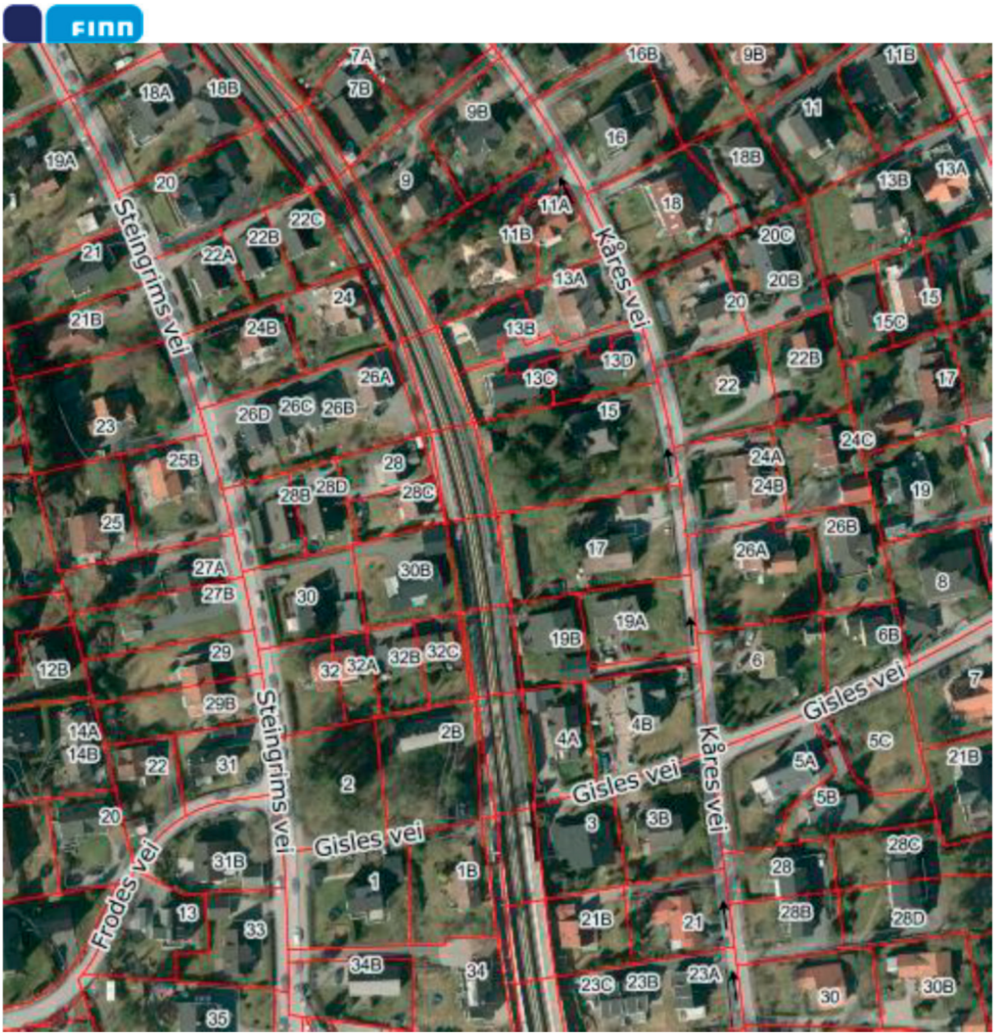


Figure 2-1,
a hybrid of a map and an aerial photo from finn.no showing the metro line Lambertseterbanen between the houses

2.1. Urban rail bound transport versus mainline railway traffic

The main differences are listed below:

- Urban rail bound transport moves very close to neighbouring houses, much closer than mainline railways usually do
- Urban rail bound transport moves at relatively low speed, often less than 70 km/h.
- Urban rail bound transport is a closed system with one or two types of trains moving approximately the same speed, whereas mainline railways can have several different types of passenger and freight trains moving at a range of speeds.
- Local geometry can significantly influence noise and vibration from urban rail bound transport, whereas mainline railways can often be considered to operate on flat, straight tracks.

2.1.1. Proximity to neighbouring houses

The traditional method for modelling noise propagation from mainline railway traffic consists of describing a noise source, a transmission path and a receiver. This modelling method is often difficult to apply when considering noise and vibrations from urban rail bound vehicles such as trams and metro trains. Figure 2-2 shows the train length, L, and the distance from the track centerline to the receiver, d. The length of the train, (L), is often greater than the distance from the train's path to the receiver (d). The short distances imply that the receiver could easily be in the near field of the source. In these cases it may not be possible to assume a point source or a line source. Article 1 describes a different approach to the problem. This approach is to use the distance as one of the predictors of measured noise in a multivariate regression on measurements of many tram passages in many points.

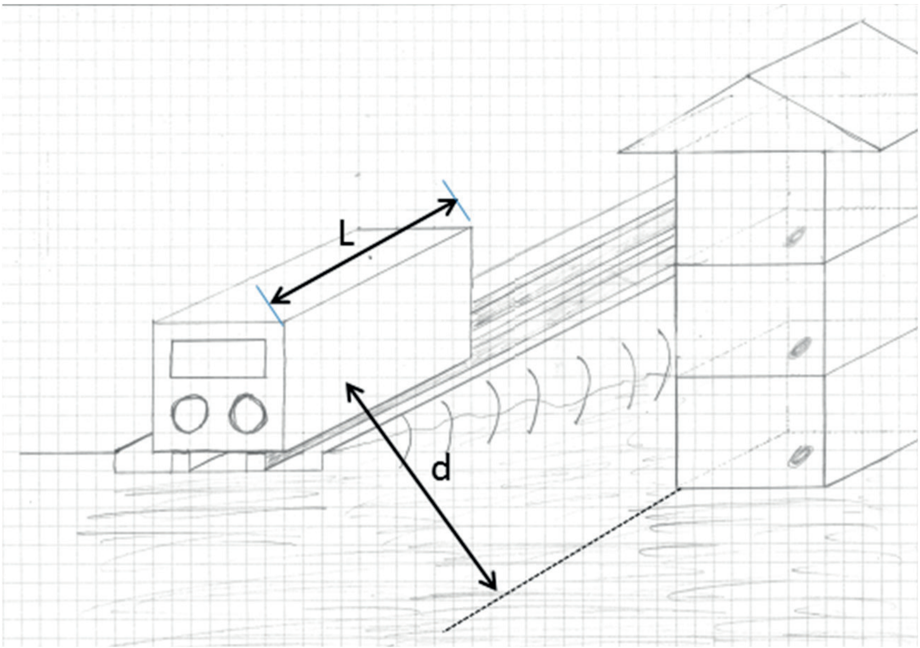


Figure 2-2,
length of the train compared to the distance to the receiver

Figure 2-3 shows the 33 m long tram # 158 driving through Storgata in Oslo. The street is approximately 15 m wide, and the trams are 22 or 33 m long.[4] In some places, the body of the tram is no more than 1m to 2 m away from the house wall. Through this canyon at peak traffic there are 36 trams per hour. In this street the reflections from the facades on both sides also have to be taken into account. The situation in Storgata is probably one of those in Oslo with the shortest distance between the tram and the facades, but there are many places which are not very different.

Figure 2-3,
tram in Storgata

In this thesis, the *source* of noise and vibrations is defined to as going as far as the house wall including the source and early propagation. This source is given as a sound pressure level at the actual location. This is different from the traditional approaches of defining a sound power level or a sound pressure level at a fixed distance from the center of the noise source. The façade sound insulation and the vibration transfer function are taken to be the *transmission path* of sound and vibration respectively. *Immission* is taken to mean the physical noise and vibration in areas intended for permanent occupancy, such as living rooms, bedrooms and gardens. These definitions are chosen because traditional models based on point or line sources are not suitable to describe noise and vibrations from trams and metros.

2.1.2. Urban transport moves at relatively low speed

The highest permitted speed in Oslo's tram and metro network is 70 km/h[5]. Traditional models for noise from mainline railways[6,7] assume that the train as a noise source can be described as a constant level in dB per octave or dB(A), a speed dependent level or spectrum and corrections for track construction. At the tram or metro train speeds this may not be relevant. Dependence of noise on vehicle speed is discussed in article 1 for Oslo's trams. For Oslo's metro trains a separate investigation was performed for low speeds, showing that different input values should be used for the prediction of noise up to 30 km/h and above 30 km/h.[8] Since then, two separate sets of input data for the prediction of noise from metro trains are used for speeds up to 30 km/h and above 30 km/h. Similar considerations should apply in other cities.

This is different from mainline railways where the speeds are much higher, and the rolling noise is dominant until speeds are reached where aerodynamic noise takes over.

2.1.3. Few types of train moving at roughly the same speed

The fact that urban rail bound transport usually operates on closed systems separated from mainline railways means that all the trains are similar and move at the same speed. This leads to a different situation than a mainline railway where different types of train run at different speeds. There are two consequences of this:

- Firstly it would seem easier to acquire complete input data for prediction of noise since only one or two types of train and a modest range of speeds are relevant.
- Another consequence, however, is more difficult to handle. The track is mostly trafficked by the same type of vehicle at about the same speed. Due to this, corrugation of the rails is much more prone to settle into regular patterns, looking like a wave on water which may in turn give rise to noise or vibration in narrow frequency bands. Figures 16 and 17 in

article 7 show an overview of a particularly bad case of this type of wear on the rail. A detail is shown in figure 2-4.

Figure 2-4,
example of a rail after many years of wear by one type of metro train at nearly the same speed

Article 2 shows another consequence of there being only a few types of vehicles on the track. During the change from the older T-1300 to the newer MX-3000 type of metro train in Oslo, a change in the signature of noise and vibration from the trains could be observed. This was mostly a shift in which frequencies were dominant, in some places also an increase in the weighted vibration level as described in the article. However, the new trains appeared to generate less airborne noise when introduced.[9] Unfortunately, all the type T-1300 trains have been recycled, and thus further investigation into this case is not possible. It is hoped that this type of investigation can be conducted when new trams enter the streets of Oslo in a few years' time. It is characteristic of urban rail bound traffic that noise and vibration emission changes in discrete steps when a new type of vehicle is introduced.

2.1.4. Effect of local geometry

Most prediction models for rail bound traffic do not consider local geometry of the rail. Some official models have provisions for sharp horizontal curves. The German method Schall 03[10] adds a correction of 8 dB for horizontal curve radius that is less than 300 meters, 3 dB for a horizontal curve radius of between 300 and 500 meters. The phenomenon of curve squeal has been investigated by field measurements[11] and it is known to happen occasionally, but it is not considered in ordinary prediction models. No official prediction method has been found that considers the vertical gradient. In article 1, the vertical gradient is considered, but not the horizontal curves. Vertical gradient has been investigated earlier,[12] although no evidence has been found (to the best of our knowledge) that these investigations have led to inclusion into official models. Urban rail bound transport has much sharper horizontal curves and much steeper vertical gradients than ordinary mainline railways because the trains are smaller and move at lower speeds. This means that these effects could become significant for urban rail bound transport.

2.2. Difference between noise from rail bound transport and road traffic

The main differences are as follows:
Road traffic usually consists of a much larger number of vehicles than rail bound traffic. There are also much fewer problems with vibrations from road traffic.

2.2.1. Number of vehicles

Road traffic usually consists of much smaller vehicles than rail bound traffic. This leads to road traffic normally being a problem only in places with heavy traffic. Thus there are many more cars that pass per time unit on a road than there are trains on a rail.

2.2.2. Vibrations

In our experience problems with vibrations from road traffic are much rarer than problems with vibrations from rail bound traffic. This may be the case because most road vehicles are lighter than rail bound vehicles. One case that occasionally gives rise to significant vibrations from road traffic is buses that travel over speed humps close to buildings with timber foundations in soft clay.

3. Prediction model

The construction of a prediction model is based on ordinary principles of empirical modelling. In this chapter we first develop the general concepts of empirical modelling in section 3.1. In section 3.2 we also discuss the components of the indoor noise to which a resident is exposed. In addition, in section 3.3 the development of a model for indoor noise from trams is described. At the end of the chapter, some guidelines for future development are given.

3.1. Empirical modelling

Popper[13] defines empirical science in general as falsifiable science. The present investigations have the more limited aim of finding reasonable models to predict indoor noise from urban rail bound transport. The goal is not defined as giving complete answers to the mechanisms of the generation and propagation of sound. A more modest approach appears more suitable. Therefore, it seems more appropriate to give a quote on empirical modelling:

> In the above, we note one of the primary values of a mathematical model – namely, as a framework in which to view data. The model gives us a benchmark by which to gauge our observations. It forces us to ask questions about the implications of the data in the light of our “best guess” made prior to the data analysis itself. This will generally lead to modifications of the original model, which will give us a new framework requiring that other data be collected, and so on.[14] – James R. Thompson

An ideal theoretical model of physical phenomena is built on a complete description of the mechanisms involved. For indoor noise, this would include the noise source emission, propagation path and immission conditions. In many cases it is difficult to determine all relevant input parameters with a sufficient accuracy from theoretical considerations. The entire concept of empirical modelling is well adapted to this type of situations where an exact description of the physical situation is not yet realistically possible. Several examples of empirical modelling are parts of the research that lead up to this thesis.

Figure 3-1 shows a presentation of the process of building an empirical model. The initial guess might be based on a limited number of pilot field measurements or standard prediction models. As an example, the starting point of the model for Oslo’s trams discussed in article 1 was with measurements of noise from a single tram at a single site combined with the Nordic Prediction method for Railway traffic.[6]

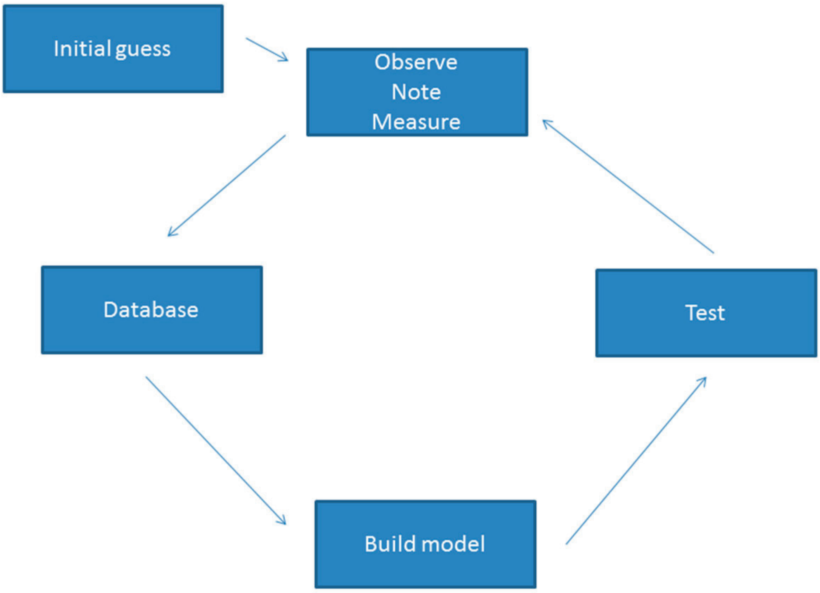


Figure 3-1,
building an empirical model

Empirical models can be made for outdoor or indoor noise. The principles of building the models have been presented earlier.[15]

- Field measurements form the basis of the models (no laboratory facilities required)
- All field measurements are stored for possible future use (open and extensible)
- Models are built on a continuously updated measurement database (heuristic)
- Expected uncertainty is computed along with the result (stochastic)
- Transfer functions are obtained from field measurements, theoretical refinements are only added if they provide significantly increased accuracy (mathematically minimalistic)

This type of model has never been "falsified" to use Popper's term[13], as new data have so far been used to add to the completeness of the model. Therefore, new data supplement this type of model.

There are some limitations to these types of empirical models. Such models cannot manage vehicles or constructions not yet taken into use. Another limitation is that such an empirical model requires a large amount of field measurements in order to provide reliable results.[16]

In the following, a description of an empirical model for outdoor noise from trams is presented as an example followed by a summary of previous empirical models of the difference between outdoor and indoor levels. The final goal of an empirical model is the same as for other types of model. However, the starting point of the empirical models is always the observed result. Complexity is added to the model as required. During the development of an empirical model the end result is always given. It is the formulation of the way to reach the end result that is under continuous development. The uncertainty should be kept under control and monitored closely in the process of developing an empirical model.

3.2. Components of indoor noise and vibrations

There are two components of indoor noise: airborne and groundborne. The sum of indoor noise is often difficult to measure because of problems with background noise. Separating the two components can be even more difficult. However, it is very important to be able to distinguish between these two components. There is not much use in putting up a noise barrier if the noise comes from the ground.

Vibrations are transmitted through the ground. There are no significant indoor vibrations induced by outdoor noise from metros or trams. An overview of the physical and perceived noise and vibrations as seen from the resident's point of view are shown in figure 3-2.

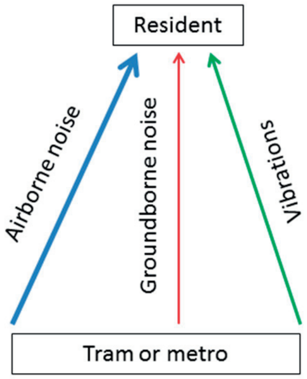


Figure 3-3,
noise and vibrations as seen from the perspective of the resident

Airborne and groundborne noise are perceived differently. One reason for this is the spectrum shape. Airborne indoor noise often has a more or less flat spectrum in the range of 125 Hz to 2000 Hz, whereas groundborne noise often has a peak below 200 Hz. Sometimes it is a sharp peak, similar to a resonance, in other cases the peak can be wider and smoother.

For this reason, airborne noise would seem to be perceived as less annoying than groundborne noise. In addition, the source of airborne noise is usually visible to the receiver. Further analysis of the different perception of airborne and groundborne noise is beyond the scope of the present work. Local and national guidelines and regulations have consequences for the need for prediction and measurement of these noise levels and should be considered. In the current Norwegian regulations,[17] the permitted maximal indoor level from outdoor sources given as L_{5AF} in bedrooms at night is 45 dB. From tunnels and other underground constructions, the limit is set to 32 dB.

In our case this means that there is hardly any control of indoor groundborne noise from trams and metros running in daylight, as the regulations only deal with total noise level. In a well isolated modern house behind a noise barrier, this might lead to an indoor level of groundborne noise of $L_{5AF} = 45$ dB could pass as acceptable if the airborne contribution is negligible. For the most recent parts of Kolsåsbanen, a metro extension outside Oslo, a recommended maximal value for groundborne noise was set to $L_{5AF} = 37$ dB based on unpublished listening tests in a house with limited airborne noise contribution.[18] It is hoped that this lower level could be set as precedent.

Vibrations give rise to a different kind of sensation than either airborne or groundborne noise. Vibrations have travelled through the ground and the building structure. For a resident, it could be difficult to distinguish between vibrations and groundborne noise. The experience may be something like that shown in figure 1-1 in the introduction.

3.3. Empirical model of outdoor tram noise

Article 1 describes the development of an empirical model of outdoor noise from single tram passages. The model has been developed based on noise measurements from the trams in Oslo. Full details of the measurement method and the development of the empirical prediction method are given in article 1. A brief summary of the parameters noted during the measurement of individual trams is given below.

For each passage of a tram the following parameters are noted:

- SEL, A-weighted and in 1/3-octave bands
- $L_{A(F)max}$ and $L_{(F)max}$ in 1/3-octave bands

For each tram passage, the identity of the tram is noted. The identity of the tram is clearly marked with a three-digit number in front, in the rear and on both sides of the tram. The trams in Oslo are of two main types: SL-79 and SL-95.[4]

Vehicle speed is measured, usually with a laser.

The direction of the tram is noted. By convention “inbound” means towards Oslo city center, “outbound” means away from city center. Special noteworthy details from each measurement are also noted.

On every measurement day on a given site the non-acoustical parameters have been noted as follows:

- Weather conditions are noted, temperature, wind speed and wind direction. The measurements are made at close distances, so that the meteorological conditions have minimal influence on the results. It is noted whether background noise is a potential problem.

Rail corrugation measurements are made within three months of the noise measurement. A general description of the geometry of the site is included in the analysis. One typical example of a setup for outdoor tram measurements is shown in figure 3-4.

The model has been developed for the passage of individual vehicles, and it can easily be extended to aggregated levels over time, such as L_{den}, $L_{eq,24h}$ or L_{5AF}. The entire concept of empirical modeling is based on the idea that it is possible to start with measurements of the immission and work backwards to a description of the emission. This is clearly an attractive idea because the predicted values from such a model can be immediately controlled against the observed answer. The problem with empirical models is that they require large amounts of data to become reliable. Article 1 presents an empirical model of an apparently simple problem: to describe the outdoor sound levels from trams given as SEL and MAX, FAST, A-weighted. Trams are not very powerful sources of noise, and thus their zone of influence is limited to some 30 meters from the track. In addition, the ground between the track and the receiver is usually hard. This means that there is not much ground effect and negligible influence of meteorological conditions.

For trams there are other factors that might appear to simplify matters even more when compared with a mainline railway. Usually in a given city there are only a very limited number of types of tram. One example is Oslo, which only has two types of tram. Therefore, there are a limited number of individual vehicles, and the distance attenuation is not disturbed by the effects that can produce large uncertainties in predicting noise at a larger distance. However another problem appears at these short distances. The dimensions of the tram are not small compared with the distance from the tram to the receiver. This means the measurements that form the basis of empirical modelling must be made within the near field of the tram.

Figur 4. Situasjonsplan for målepunkt i Kirkeveien ved Frognerparken.

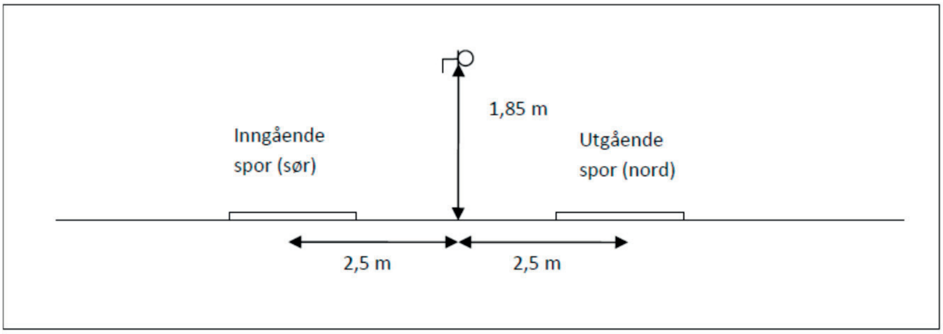


Figure 3-4,
outdoor tram measurement as reported

There are three distinctive types of track in Oslo. There are also other complications in using empirical modelling. The wear of the rails may vary from place to place. The measured noise level from the tram is not necessarily a simple function of the speed of the tram, indeed article 1 shows that it is not. There are also other complications. A tram can have a mechanical problem on a given day. The condition of the rail may have consequences for the noise emitted. The local geometry of the track may have a significant influence. There may be significant differences in emitted noise from trams of the same type produced in the same series.

The model presented in article 1 is based on measurements of noise from 960 tram passages through 5 years. The model now predicts noise given as A-weighted maximal level or SEL from individual trams within ± 5 dB in 85% of the cases.

3.4. Empirical models of the level difference in façades

Norwegian regulations for indoor noise from any source, even in existing situations where both the residence and the noise source had been present for a long time, were introduced in 1997.[19] These regulations stipulate that it is the responsibility of the owner of the noise source to ensure that nobody is exposed to an $L_{Aeq,24h}$ of 42 dB or more, indoors with closed windows and closed ventilation devices. This requirement was formulated as an objective responsibility regardless of whether the noise source or the residence came first. The law quickly introduced a large need for determination of indoor noise levels. The official prediction method[20] did not cover all cases, and anyway it is not always possible to determine the sound insulation properties of a façade simply by inspection of the outside and inside of a wall. This led to a need for measurements and other methods of determining the level difference between the outdoor and indoor of a house. The measurements of level differences between outdoor and indoor were first described in 2002.[21] The method for measuring level difference in a façade is described in more detail in section 4.2. In this section we assume that the measurement has been made. An empirical method for calculating indoor noise from road traffic was first presented in 2003.[22] A basic assumption for this type of model is that it is the difference in A-weighted level between the outdoor and indoor that is critical. This model consists of selecting outdoor spectra that match the criteria of speed limit, distance to the road, and degree of protection by natural or artificial barriers, and then selecting level differences matching criteria of type of house construction, window, ventilation opening and insulation. Figure 3-5 illustrates the procedure.

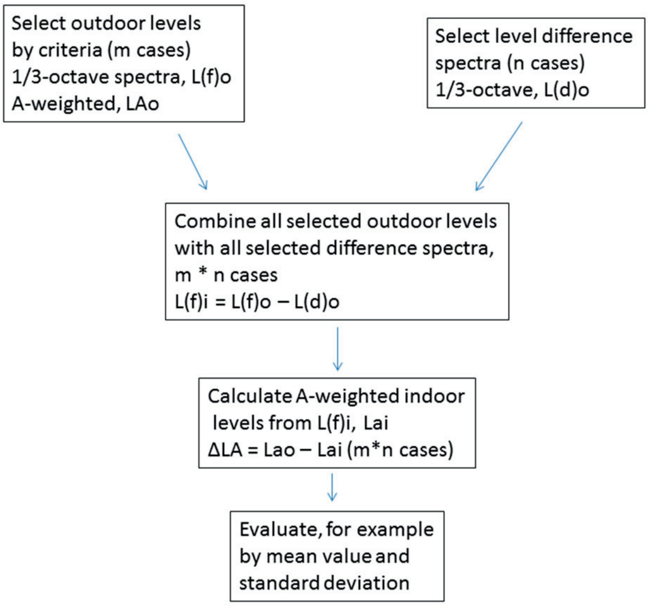


Figure 3-5,
empirical calculation of level difference between outdoor and indoor noise

The first presentation of an empirical method for indoor road traffic noise is based on the A-weighted level difference between outdoor and indoor levels as obtained from the procedure described in figure 3-5. Later investigation into whether room acoustics and geometry needed to be included in such an empirical model concluded that they are not required.[23,24] Thus the term level difference is used for the actual difference between outdoor and indoor levels in a given case. Façade insulation measurements strictly according to current standards[25,26] are not required. The use of empirical modelling for indoor levels has its advantages and disadvantages when compared with more traditional methods of calculating indoor level.

The most important properties of the results from experience with empirical methods are listed below[16]:

- Best suited for older houses with unknown details
- Provides an estimate for the expected value for and uncertainty of facade sound insulation
- Experience shows much better results than originally expected. Achieved accuracy compared with measurements is a standard deviation of 2 dB to 4 dB
- Requires, an absolute minimum of 50 field measurements of insulation spectra; 200 such measurements are recommended
- Empirical methods cannot be applied to new and unknown types of construction

An extrapolation of the methods applied for road traffic noise encounters two problems[27] when also applied to tram noise. Firstly, groundborne noise may influence the indoor level from trams, which is not a frequent problem when considering with road traffic. This problem is discussed in section 4.1. Another problem is that the maximal level occurs at different times in different frequency bands. This problem is also discussed in section 4.1. In addition the current state of knowledge about noise from trams presented in article 1 is based on a much more comprehensive model than the one presented in the earlier publication.

3.5. Prediction of indoor noise

The traditional methods for the prediction of indoor noise start from a predicted outdoor level. Then a reduction factor for the façade is calculated based on laboratory tests of building components. This could be in the form of single number reduction ratings with spectrum corrections for different sources similar to the official Norwegian method,[20] or it could be based on spectrum values from the laboratory tests. The general problem of transferring data from a laboratory measurement to an actual house is similar. The consequences of using a single number rating for spectrum corrections have been discussed for road traffic noise[28] and later for tram noise.[27]

Another problem of a more formal type is that in some countries there are different metrics for outdoor and indoor noise[17,29,30]. For time integrated metrics of noise such as L_{eq}, L_{night} or $L_{den,}$this is not a significant problem, because the total energy of an event is taken into account anyway. For the maximal noise from a passage the problem is much more difficult. As an example, in Norway, the outdoor level should be calculated according to the Nordic Prediction model for railway traffic.[5] This model provides as a result a so called middle max level, defined as a stable level during the passage of the train. However, the Norwegian requirements for indoor noise from outdoor sources[23] has the maximal level defined by the parameter L_{5AF}, which is defined such that the probability of a passing train giving a higher A-weighted FAST, max level compared with L_{5AF} is 5%. In theory the parameters of outdoor and indoor maximal levels are not compatible.

An early attempt at an empirical prediction method for indoor tram noise has been presented[27]. The model was not satisfactory at the time because of its lack of completeness. The handling of maximal levels was also unsatisfactory as this part of the model was obtained directly from an empirical model for road traffic. As shown in section 4.1, this leads to an overestimation of the indoor maximal level unless corrected.

3.6. Further development of empirical models for outdoor noise from trams and metro trains

A systematic development of an empirical model for environmental noise and vibrations from the metro trains in Oslo is expected to start during 2016. The program is planned to include local geometry represented by a vertical gradient and horizontal curvature from its inception. The metro trains in Oslo are different from the trams in Oslo in several ways:

- The metro trains are much heavier than the trams.[4] The metro train with three cars have a weight of 90 tons, and normally two trains operate together making a total of 180 tons versus 30 to 60 tons for the trams
- The metro runs on separate tracks independent of other traffic
- There is only one type of track and one type of train, as compared with the tram that has three types of track and two types of vehicle

The standard metro train is a six-car train that consists of two three-car trains linked together. Usually the two trains that operate together are not the same from day to day. This means that there are more than 6500 possible six-car trains running. Because they consist of two independent trains, there is remote possibility that especially noisy or exceptionally quiet trains can be identified.

In contrast to the large number of different metro trains, there are only 72 trams in Oslo, making the identification of noisy or quiet vehicles possible for the trams. Our expectation is for the results from trams and metro trains in Oslo to be useful for the design of similar programs in other cities. Possibly the acquired knowledge can be applied during the acquisition of new trams in Oslo.

Some factors are difficult to include in empirical models. In some cases there are periods with more noise. In some places on metro lines this is in the form of a curve squeal in a very limited frequency band (3150 Hz 1/3-octave band) as mentioned in section 1.1.4.[11] On the tram lines in Oslo we have observed another phenomenon; occasional periods of high noise levels in the frequency range of 2000 Hz to 5000 Hz, as yet unpublished.

An attempt at noise abatement that has not yet been included in the empirical modelling of outdoor tram noise is attenuation by means of rail dampers. The first test in Oslo was extremely successful.[31] At this first attempt only noise was measured, but the results were excellent: 6 dB to 7 dB on the SEL,A value of passing trams.

Rail corrugation is not the only possible measure of rail quality. Another measure of rail quality that has been connected to noise emission is track decay rate (TDR). Normally there is no time to measure TDR according to ISO 3095[32] on Oslo’s tram and metro tracks because it is usually only possible to gain access to the tracks between 01:00 and 05:00. When TDR has been measured, a much simpler procedure was performed. The knowledge of the TDR of the tracks of metro and tram lines of Oslo is too limited to be included in prediction models.

Article 2, as mentioned in section 1.1.3, describes what occured with groundborne noise and vibrations when the metro trains in Oslo were replaced between 2005 and 2010. For some time both types of metro trains operated on the same lines, thus allowing measurements of both types of trains in the same immission point and under the same conditions. One very clear observation is easy to make from article 2; the vibration signature of the trains changed in an easily measurable way. For the most part the new MX 3000 trains produced more vibrations and groundborne noise than the older T1300 trains, but the shift in which frequencies were dominant was the really distinguishing feature. This means that when new types of train are introduced, the empirical model has to be rebuilt for the new type of train.

4. Measurement of indoor noise

Measurement of outdoor noise from rail bound traffic is described in section 3.3 and article 1. This chapter considers indoor noise. The goal is to determine as accurately as possible the indoor noise from an existing or new rail line into an existing or new house. Measuring indoor noise directly would be an attractive solution if both the rail line and house are already there, so in section 4.1 the challenges of measurements is discussed.

4.1. Direct measurement of indoor noise

As already stated measuring indoor noise directly is difficult in many cases. The method that consists of measuring outdoor spectrum and airborne sound level difference has a long history for road traffic noise.[25] This method can be used for equivalent levels from rail bound traffic. Measurement of maximal levels in this manner introduces difficulties, however. In theory the maximal A-weighted level is not the same as the energy sum of A-weighted 1/3-octave band levels. For road traffic this is not much of a practical problem. The highest level in all frequency bands occurs when the noisiest vehicle is at the point where noise attenuation is least. For rail bound traffic, however, it is not that simple. It is quite normal for the sum of A-weighted maximal levels in 1/3-octave bands to exceed the A-weighted maximal level by 1, 2 or even 3 dB This is because the maximal levels in different bands occur at different times. Figure 4-1 shows a histogram of the distribution of this difference calculated from 1842 measurements of outdoor spectra. The maximal A-weighted indoor level does not necessarily occur at the same time as the outdoor maximal A-weighted level.

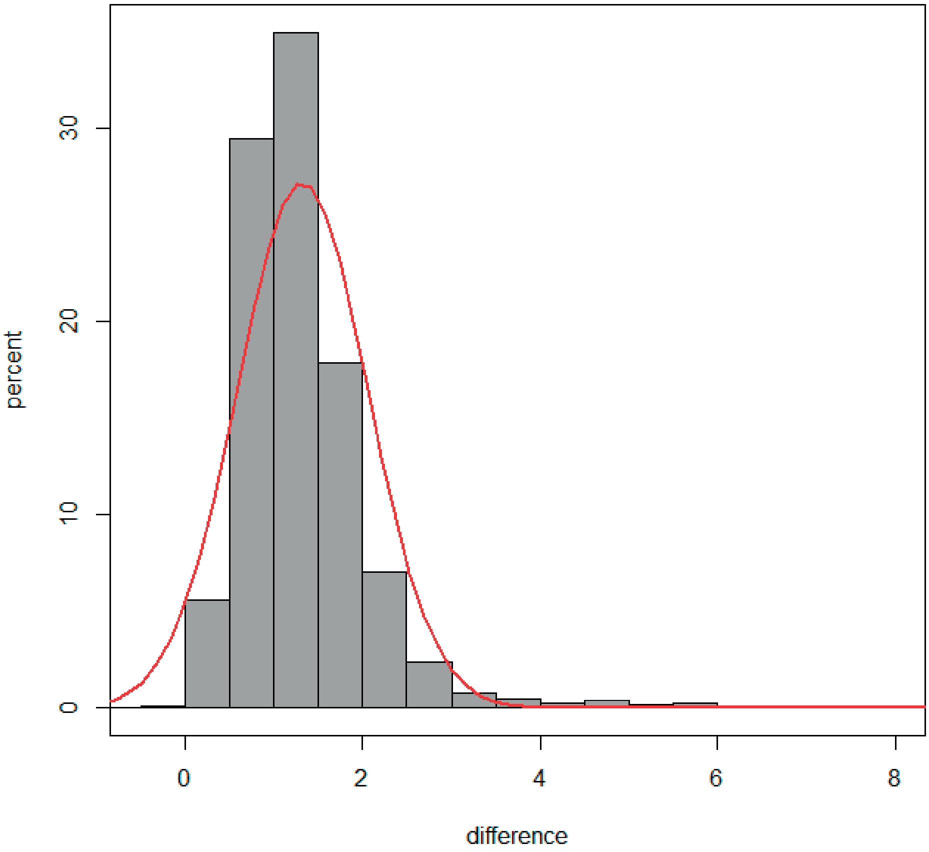


Figure 4-1,
Difference between A-weighted maximal level and the energy sum of 1/3-octave A-weighted maximal levels, 1842 measurements of tram passages. The difference in dB is on the X-axis. The percentage of cases within each 0,5 dB bin is on the Y-axis.

The mean difference is 1.3 dB and the median is 1.2 dB, in most cases the difference is not too far from 1 dB. However, this could become larger if there are several different noisy events during the passage of the train.

There is also a problem that indoor level varies with the position in a room. The current Norwegian standard[29] requires for measurements to be made in three points inside. This requirement stems from the need to control the variation of noise inside the room. Ideally the same trains should be measured for each indoor immission point. This could be difficult to perform in practice because of the number of train passages required, or alternatively, the amount of instruments required to perform the measurements.

In addition there is the problem of groundborne noise. One possible method for to estimation of groundborne noise is to find a room well shielded from airborne noise and measure noise directly in that room. A major setback to this approach is that such rooms can usually be found in the basement at the back of the house, which are not intended for permanent occupancy and thus the noise level is not critical. The measurements in such rooms can give relevant information because the results may be used in the evaluation of groundborne levels in other rooms. Another possible method is to measure vibrations on a floor and use that information to estimate the groundborne component. The radiated sound can then be calculated by:[33]

$$W_{rad} = \sigma \rho c S \langle v^2 \rangle$$

where:

- W_{rad} is the radiated power
- S is the area of the radiating surface
- $\langle v^2 \rangle$ is the average of the square of the velocity amplitude
- σ is the radiation efficiency
- ρ is the density of the surrounding medium
- c is the speed of sound

However, estimation of the radiation efficiency is quite uncertain, especially at low frequencies. This leaves the prediction of radiated noise from vibrations in the structure quite uncertain.

The final method would be to measure the sound insulation of the façade using both a loudspeaker and a train as sources. Article 5 describes some results from using this method. The train gives a lower apparent façade sound isolation than the loudspeaker. The results are not sufficiently clear to conclude that the difference in apparent sound insulation is due to the groundborne component.

4.2. Methods for field measurement of façade insulation against airborne noise

The possibility of measuring the sound insulation of a façade is essential. Calculations of indoor levels can be performed using existing methods,[20] but these methods assume that the constructions are similar to those tested in a laboratory. There are also empirical methods for calculation of indoor levels.[22,27] Such empirical methods depend on large numbers of field measurements of façade sound insulation in order to provide satisfactory results. The advantages and disadvantages of using empirical methods are presented in section 3.1.[16] There are two primary decisions that need to be made with regards to field measurements of façade sound insulation:

1. Choice of microphone position
2. Choice of source signal

Article 3 discusses a simplified theory of the effects of microphone positions. Article 4 shows a detailed investigation based on thorough measurements on 59 locations in the field. It is taken for granted that measurements must be made with the sound source on the outside of the façade that is to be measured. Article 5 shows the results of using both the traffic and a loudspeaker as source.

4.2.1. Choice of microphone position

Article 3 introduces the problems of choice of microphone positions. The previous and current standard[25,26] recommend that microphone positions be either directly on the façade or 2 m in front of the façade. Article 3 describes a simple theory on the reflections from the wall. With a point source of sound that emits noise onto a perfectly reflecting façade and no other reflections present there is indeed a problem according to these calculations. As soon as the distance between the wall and the microphone exceeds, for example, 2 cm, destructive interference starts to go into the building acoustics frequency range.[34] At a distance of 2 meters the problem of destructive interference is still a problem according to these calculations. However the test measurement presented in article 3 shows much less problems than the simplified calculations indicate. This is probably due to the presence of other reflections on the balcony where the measurement was made.

The work of article 3 was extended into article 4, where a similar analysis of measurements from 59 sites is included. This analysis shows that microphone positions directly on the façade are always preferable. However, in cases with other reflections present the measurements in front of the façade can be used without any great loss in accuracy. A sweep at 25 cm distance in front of the façade can usually be taken when there are other reflections present. A problem is that the procedure for placing a microphone directly onto the façade is that it is originally designed for situations where one component has a much weaker sound insulation than the rest of the façade. This is normally the case in many countries where a concrete wall and single glass window compose the façade of the building. However, in countries with a tradition for wooden houses and heat insulating windows such as Norway, it is not uncommon for a window to have the same, or even better, sound insulation than the wall. In other cases, it is not possible to reach a distance of 2 meters away from the façade. This means that in many cases the microphone must be placed at a distance between 0 and 2 m away from the façade. Article 4 shows the practical consequences of measuring with the microphone at a distance of 0.25 m in front of the façade. This is not an ideal choice, but in cases with other reflections, the performance is not significantly worse than with the microphone directly onto the façade. Nevertheless, the recommendation is clear: if it is possible to mount the microphone directly onto the wall, this position should be preferred. Otherwise a sufficient number of microphone positions or a sweep in front of the façade can be used. If there are other reflections present, there is not too much of a problem. The investigations leading up to article 4 uncovered another interesting feature of different microphone positions. At frequencies below 200 Hz roughly the same level is measured whether the microphone is on or in front of the façade. Direct measurements of the reflection from a façade have not yet provided usable results at frequencies below 200 Hz.

4.2.2. Choice of source signal

There are two types of signal that can be considered for the test: rail traffic itself or loudspeaker. The results obtained using these two different types of test signals are described in article 5. Before examining the results in more detail, an introduction is warranted. Rail traffic is theoretically attractive as a test signal because the indoor level then becomes real. However there are other conceptual problems with rail traffic. It is necessary to measure the indoor and outdoor level in several points, because there is some variability in the indoor level at different points even with an identical source. The consequence of this is that in order to achieve a really good measure of sound insulation, it will be required either to make a large number of measurements or measure the signal from several microphones at the same time for each passage of a tram or metro train as mentioned in section 4.1.

The use of a loudspeaker eases considerably the measurement of sound insulation in many points, because only a few seconds of measurement time is required for each point. Figure 4-2 shows an example of a loudspeaker ready to measure sound insulation through a façade.

Figure 4-2,
a house where sound insulation in the façade was measured

The real test of these source signals is in the results of field trials. Article 5 shows five cases of measurements of façade sound insulation that use both a loudspeaker and rail traffic as sources. The speaker used provides a usable signal in the frequency range of 50 Hz to 5000 Hz. The cases included in article 5 are one case of train traffic, one case of tram traffic and three cases of metro traffic. The two types of measurement signal give closely matching results in the most critical frequency range from 125Hz to 1000 Hz. The sound insulation measured using the traffic itself appears poorer at the lowest and highest frequencies, the range varies slightly from case to case. At the high end of the frequency range considered this is not a problem, because at frequencies above 1000 Hz the traffic simply does not have sufficient energy to overcome background noise levels. Therefore, at high frequencies the traffic does not provide a true sound insulation value, but that does not lead to any wrong decisions with regard to whether indoor noise level requirements are satisfied because these levels are low.

However, at low frequencies, a larger problem might occur. The lack of information from sound insulation measurements using loudspeakers as a signal source introduces uncertainty with regard to whether the low measured insulation values are truly a problem. Unfortunately, obtaining field measurements of sound insulation at frequencies lower than 50 Hz with a loudspeaker is not an easy task for two reasons: First, the loudspeaker has to be big in order to produce sufficient sound at such low frequencies, second, the response of the room is hard to measure because the wavelength at these frequencies is often longer than the largest dimension of the room.

The challenges of measuring the groundborne component of noise are presented in some detail in section 4.1.

5. Transmission of vibrations to buildings

The measurement of vibration transmission is performed in order to investigate the propagation path of vibrations from the ground outside the house and into the building. The Norwegian measurement standard[30] for vibrations provides guidelines for how to measure and evaluate indoor vibrations from transport. The generation and transmission of outdoor vibrations have been reasonably well described previously.[35,36,37] However, there appears to be a need for more knowledge on indoor vibrations. Article 6 provides information about the transfer of vibrations form the ground into houses, while article 7 gives a report from a measurement campaign.

5.1. Introduction

There are three main reasons that vibrations are annoying:

1. Those vibrations perceived as motion of the floor are uncomfortable and give rise to fear of damage to the building.
2. Vibrations lead to sound radiated from the surfaces of the room. This sound has mainly low frequency content and is perceived as disturbing.
3. Vibrations lead to rattling of glass and movement of paintings hanging on the walls.

The drawing in figure 1-1 illustrates these points. For all these mechanisms reduced vibration intensity will lead to improved perceived comfort for the resident.

There are different frequency ranges and different methods of considering vibrations. In this work the following conventions are used:

The immission levels from single events are measured as RMS acceleration spectra in dB rel. 10^{-12} m/s^2, in other words 1 g is equal to 140 dB. For evaluation of vibrations from a series of measurements RMS velocity as given by the term $v_{w,95}$ in mm/s is used.[34] v_w is a single number rating for vibration velocity amplitude weighted by a standard filter. $v_{w,95}$ is a statistical value expected to be exceeded by 5% of the vibration events.

Integration times are used as standard FAST or SLOW. FAST (125 ms integration time) is best suited for noise evaluation, whereas SLOW (1 s integration time) is best suited for vibration evaluation.

A coordinate system for the vibrations from rail bound traffic is used as follows, see figure 5-1:

The x direction is horizontal, normal to the track
The y direction is horizontal, parallel to the track
The z direction is vertical

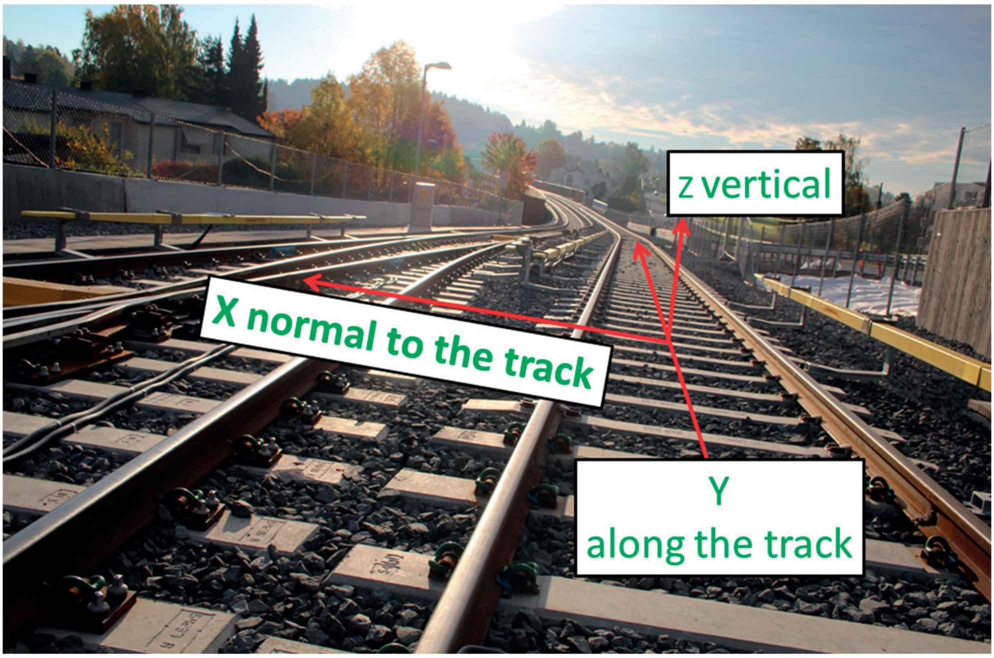


Figure 5-1,
the coordinate system used for vibrations

5.2. Measurement of vibration transmission

Vibration transmission can be determined by measuring vibrations simultaneously in several points during the passage of a train. Earlier Japanese investigations[38] indicated that different houses exposed to different vibration sources had very similar transmission factors in three orthogonal directions. The need for deeper investigations into the transmission of vibrations into homes originated from the changed and often increased vibration levels from the new MX-3000 metro trains as described in article 2. As a result, an increased program of vibration measurements was started up. Article 7 describes the first attempts at measuring vibrations in houses. It soon became clear that further analysis was required. It was hoped that the Japanese experience[38] of well-behaved transfer functions could be replicated on Oslo's metro trains. Article 6 is a status report after the first 18 houses had been investigated. It has transpired that Norwegian houses are not as similar to each other as Japanese houses.

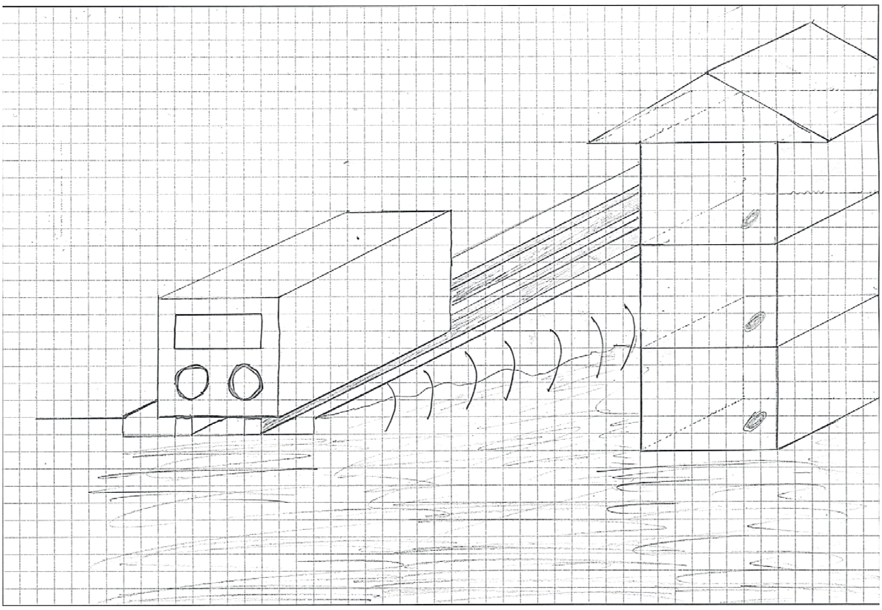


Figure 5-2,
an illustration of the floor levels investigated; basement one level below the ground facing the metro line, ground floor on ground level and first floor above ground level

Because article 6 does not yet provide a clear picture, another type of analysis has been made based on a larger and updated sample of 44 houses including the original 18 houses. Figure 5-2 shows the floor levels of the house in principle in an artist's version.

This analysis has so far been completed for v_{w95}^{30} for all three directions outside the house and on three levels inside the house. The vibration level on the ground outside the house is denoted x, y and z.

Level B: basement, measurements made on a basement floor one level below the ground on the side of the house that face the metro line. Vibration levels are denoted xb, yb and zb, respectively. A total of 23 cases of outdoor vs. basement levels have been analyzed.

Level 0: ground level, measurements made on a floor on the same level as the ground, denoted x0, y0 and z0. A total of 27 cases of outdoor vs. ground level have been analyzed

Level 1: upper level, measurements made on a floor one level higher than the ground facing the metro line, denoted x1, y1 and z1. A total of 25 cases of outdoor level vs. first floor level have been analyzed.

The definitions are used as stated above because many Norwegian houses are built on sloping terrain, and thus the ground may be on different levels on two sides of the house. Use of the outdoor surface vibration levels as reference is made because the outside of the house is always accessible for measurements. Thus it would be of great practical value to gather sufficient knowledge of the transfer of vibrations from outside to inside in order to calculate indoor vibration levels from outdoor levels.

There are problems with the approach used in this first analysis. The most immediately obvious one is that the surface vibration levels might not necessarily be the driving forces behind the vibration on the floors of the building. Another problem is that neither the mechanical properties of the ground nor of the building structure are considered.

In the following the analysis is presented for the three levels separately.

5.2.1. Vibration transmission from outside the house to the basement

A correlation matrix of vibration transmission from the outdoor to the basement floor is presented in table 5-1.

Table 5-1,
correlation between outdoor and basement floor triaxial vibrations

	x	xb	y	yb	z	zb
x	1.000000	0.725603	0.977965	0.862697	0.955446	0.761532
xb	0.725603	1.000000	0.690939	0.923317	0.756724	0.929771
y	0.977965	0.690939	1.000000	0.837781	0.955112	0.713473
yb	0.862697	0.923317	0.837781	1.000000	0.842994	0.915513
z	0.955446	0.756724	0.955112	0.842994	1.000000	0.778707
zb	0.761532	0.929771	0.713473	0.915513	0.778707	1.000000

The outdoor vibrations are best correlated with the indoor vibrations in the y direction on the basement floor. A plot of the measured actual levels is shown in figure 5-3.

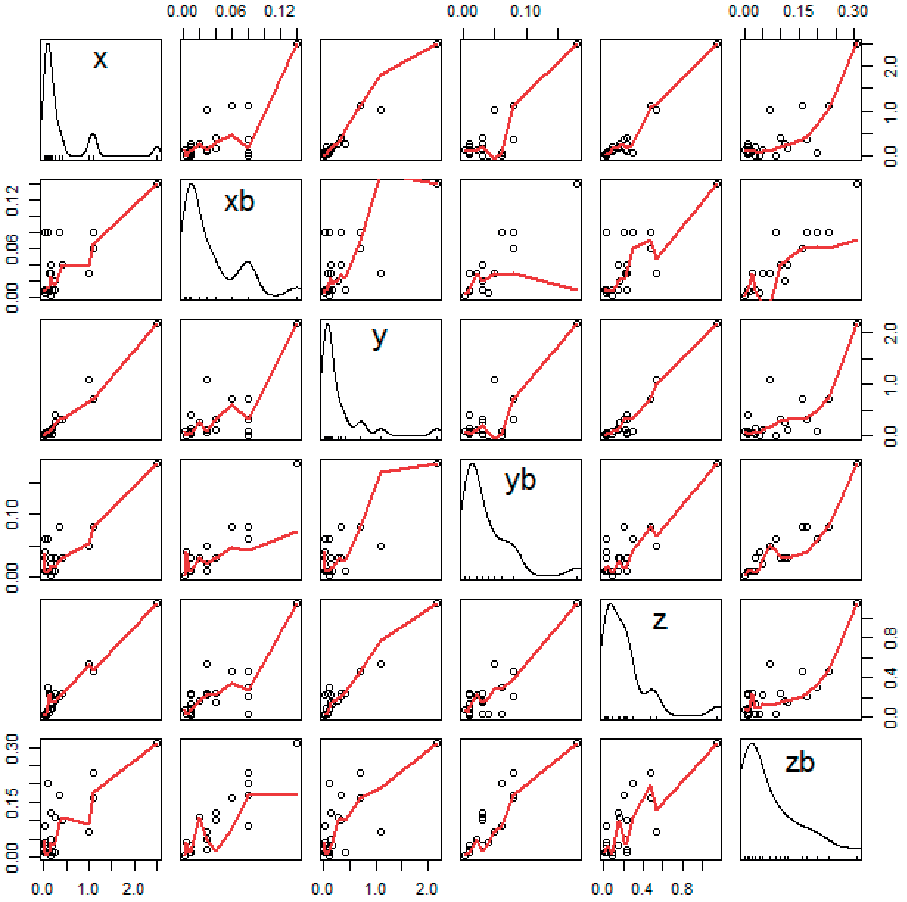


Figure 5-3,
plot of measured vibration levels outdoors and on basement floors

The results show a clear positive correlation between all directions outdoors and indoors. Therefore, achieving a reasonable prediction of indoor vibration levels on the basement floor based on measurements of outdoor surface vibrations appears possible. However, this is not yet possible based on the current data. Nevertheless, pending more data and a deeper investigation, some practical guidelines are possible. The average of the outdoor and indoor vibration levels is listed in table 5-2.

Table 5-2,
Vibration level outdoors and on basement floor, average of 25 cases, vw95

	x	y	z	xb	yb	zb
Average vw95, mm/s	0,344	0,286	0,208	0,033	0,035	0,073

This table indicates that the indoor level on the basement floor is almost always lower than on the surface outside. The cases with higher vibration levels indoors than outdoors occur only at very low vibration levels. Based on the data acquired so far, it is safe to assume that indoor levels on a basement floor can be evaluated on the based on outdoor vibration measurements. No high vibration levels in any direction on the basement floor occurs indoors if the levels on the outside are below v_{w95} = 0.3 mm/s in the vertical direction.

5.2.2. Vibration transmission from the outside to the ground level

A correlation matrix between the vibration levels on the outside and the ground floor is indicated in table 5-3. The results are not sufficient to establish any connection between the outdoor and ground floor vibration levels.

Table 5-3,
correlation between outdoor and ground floor triaxial vibrations

	x	x0	y	y0	z	z0
x	1.000000	0.488472	0.817579	0.467173	0.785745	0.424008
x0	0.488472	1.000000	0.718521	0.963054	0.791227	0.869967
y	0.817579	0.718521	1.000000	0.730803	0.960761	0.634141
y0	0.467173	0.963054	0.730803	1.000000	0.755765	0.800189
z	0.785745	0.791227	0.960761	0.755765	1.000000	0.766401
z0	0.424008	0.869967	0.634141	0.800189	0.766401	1.000000

Figure 5-4 shows a plot of measured values. The results are inconclusive. Further analysis and a several more measurements will be required before any guidelines can be provided.

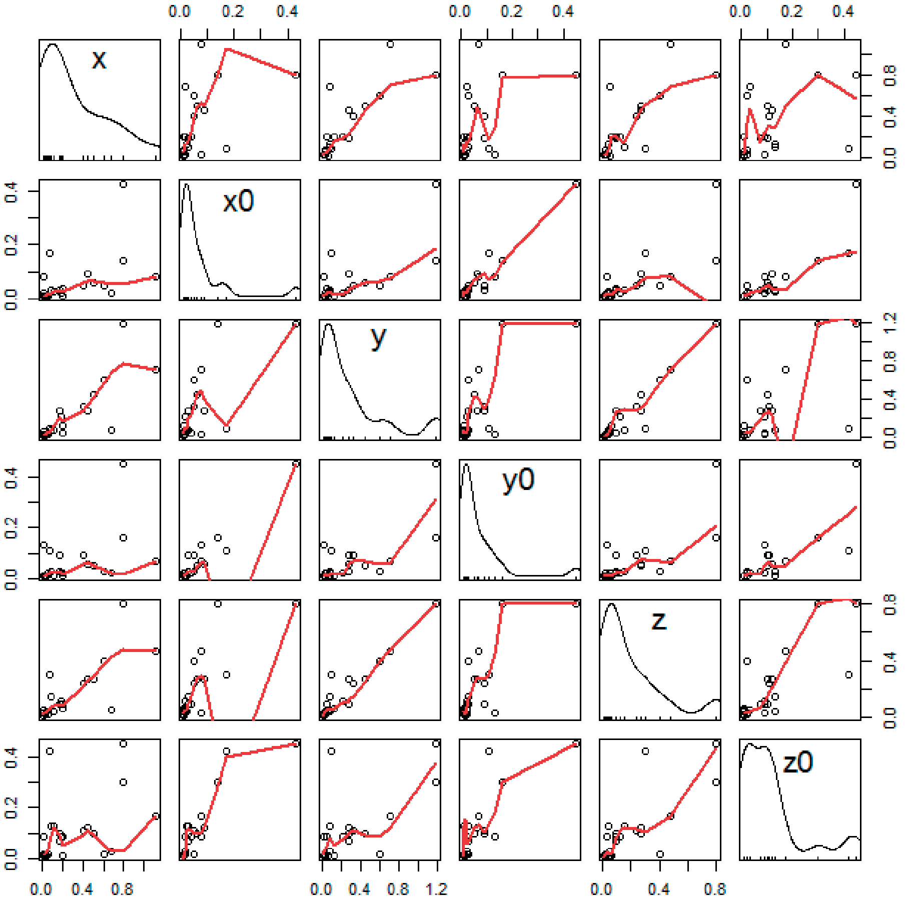


Figure 5-4,
plot of measured values outdoors versus ground floor

5.2.3. Vibration transmission from outdoors to first floor

Table 5-4 lists the correlation between the different axes of outdoor vibrations versus first floor levels.

Table 5-4,
correlation between outdoor and first floor triaxial vibrations

	X	x1	y	y1	z	z1
x	1.000000	0.492021	0.925473	0.419172	0.923778	0.830007
x1	0.492021	1.000000	0.439824	0.880035	0.573548	0.669362
y	0.925473	0.439824	1.000000	0.353728	0.950984	0.830018
y1	0.419172	0.880035	0.353728	1.000000	0.468461	0.594519
z	0.923778	0.573548	0.950984	0.468461	1.000000	0.851115
z1	0.830007	0.669362	0.830018	0.594519	0.851115	1.000000

The measured values are plotted in figure 5-5. The z1 values, vertical vibrations on the first floor, are reasonably correlated with all three directions of outdoor vibrations. The horizontal vibrations in the x and y directions on the first floor do not show any clear correlation with any of the directions outdoors. This is not critical because the vertical component on the first floor is usually higher than the horizontal components.

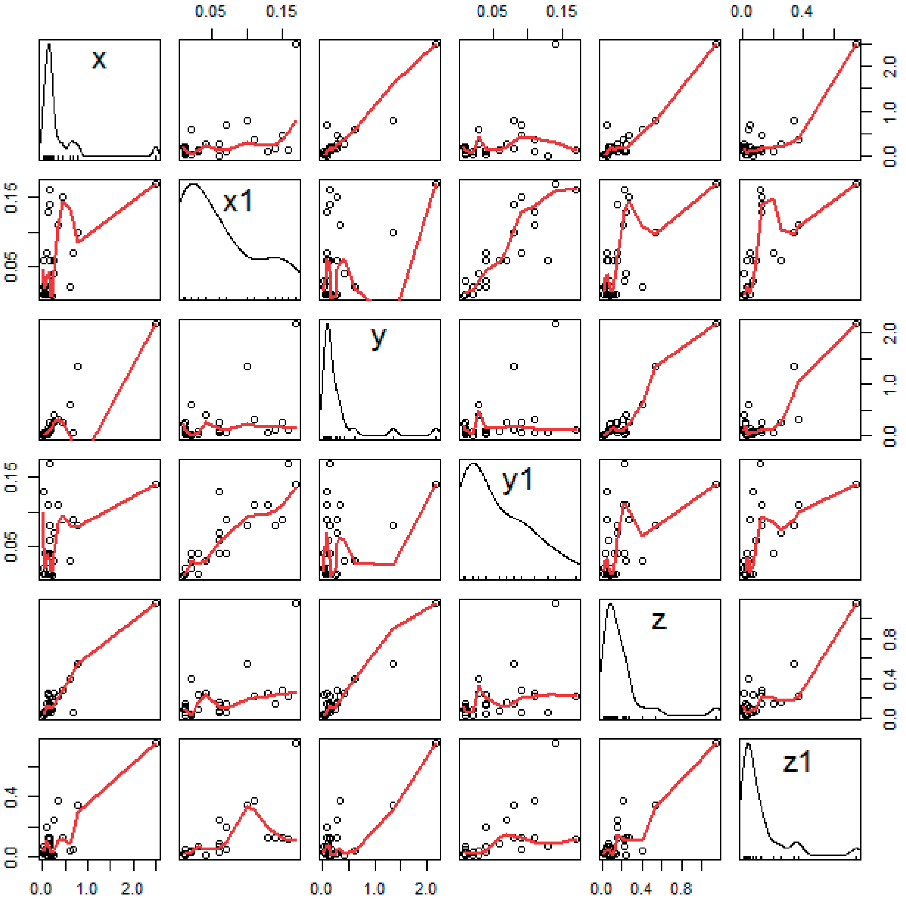


Figure 5-5,
plot of measured values outdoors versus first floor

On average there are less vibrations in the vertical direction on the first floor than in any direction on the ground surface by the house. The ratio between the vertical vibrations on the first floor and the direction with the strongest vibrations outside the house among the 27 measured cases is as follows:
v_{wz} (1stfloor) / $v_{wmax(x,y,z)}$(outside) = 0.46 mean value, 1.33 highest measured value.

5.2.4. Summary of transmission analysis

The transmission analysis indicates that outdoor vibrations can be used to provide a reasonable prediction of weighted vibration levels on the basement level. Outdoor vibrations can be used for a reasonable prediction of vertical vibration levels on the first floor. Further investigations including evaluation of the spectra from each passage, the ground conditions and the structure of the house are required in order to achieve a sufficiently good prediction. For the time being, the best practical guide is to rely on the ratio between outdoor vibration level and indoor vibration level. Figure 5-6 shows an overview of this ratio for 44 cases.

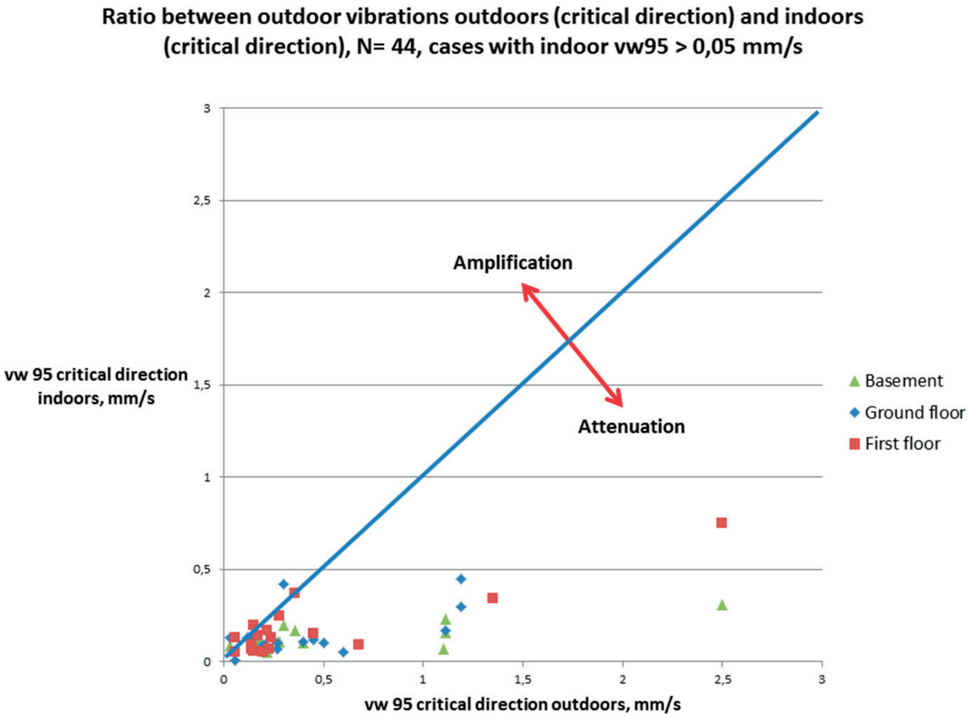


Figure 5-6,
ratio between outdoor vibration (critical direction) and indoor vibration (critical direction).

Figure 5-6 provides a good impression of the general tendency that most houses attenuate vibrations, and thus indoor vibration levels are usually lower than outdoor vibration levels. The range of vibration levels makes it difficult to see details at low vibration levels.

A finer resolution of the vibration transmission at low levels is offered in figure 5-7. Figure 5-7 does not give an intuitive feeling of the ratio between outdoor and indoor vibration, but it shows more detail of the ratio.

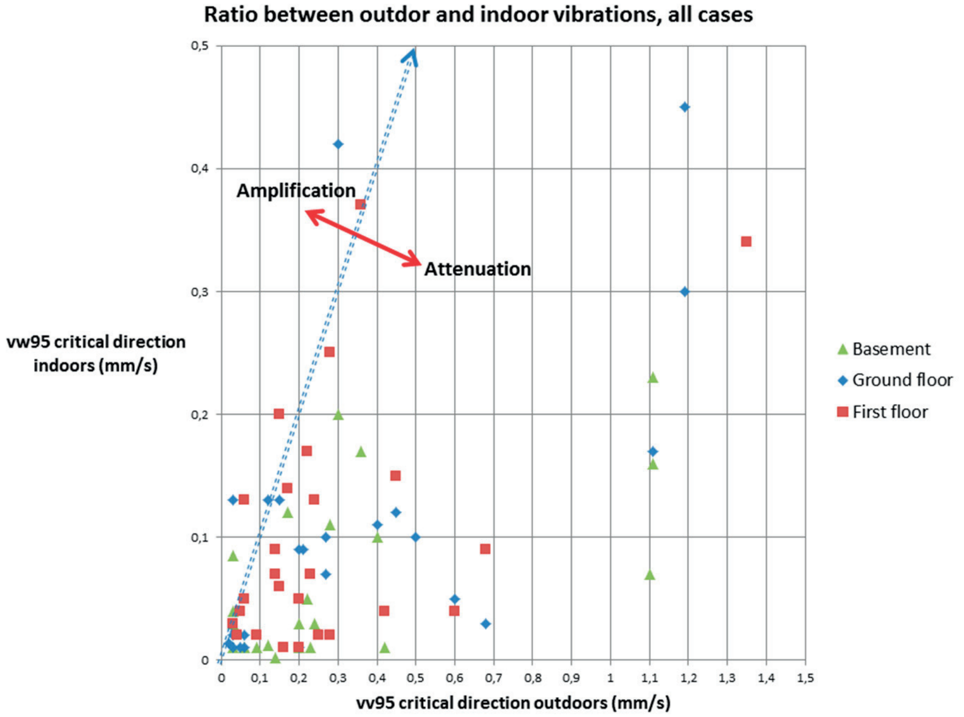


Figure 5-7,
ratio between outdoor vibration and indoor vibration in a different scale than figure 5-6

The practical use of the results shown in figures 5-6 and 5-7 is to evaluate the expected indoor level based on measured outdoor level. In our experience this ratio has never exceeded 1.4. This knowledge can be used to estimate the indoor level in a house based on measurements of vibrations on the site before building the house. It should be noted that the presented results are only valid for small houses exposed to vibrations from metro trains. The houses where the measurements were made are normally concrete structures below ground and wooden structures above ground.

5.3. Subjective evaluation of vibration levels

The current Norwegian guidelines for acceptable vibration levels in residences[30] were based on telephone interviews with 1000 residents exposed to vibrations from rail bound traffic.[39] Out of these, 53 lived alongside metro lines, only along one metro line and in one neighborhood. The results of the enquiry were analyzed against calculated vibration levels on the same sites. This enquiry led to the recommended value for protecting the majority against being annoyed by vibrations being set at $v_{w95} = 0.3$ mm/s.

A more recent, but much smaller, enquiry analyzed a written questionnaire sent by e-mail to recipients where a comprehensive measurement of vibrations was made, indicates a different sensitivity to vibrations.[40] This enquiry indicates that some residents are bothered by vibrations even at levels below $v_{w95} = 0.1$ mm/s.

There are many possible explanations for this discrepancy. The most natural explanation is that the latter investigation is based on measured values, whereas the former is based on extrapolations from a few measurements. It is quite likely that the current prediction models are conservative with regards to indoor vibration levels. This means that the measured values are lower than the predicted values, which is consistent with residents being bothered at lower vibration levels. Another possible explanation is that the latter investigation was performed with people who had seen engineers set up a large rig to measure vibrations in their home, indicating a serious problem.

The results from the last investigation are shown in detail in figure 5-7. At vibration levels above $v_{w95} = 0.3$ mm/s all the respondents were annoyed or highly annoyed.

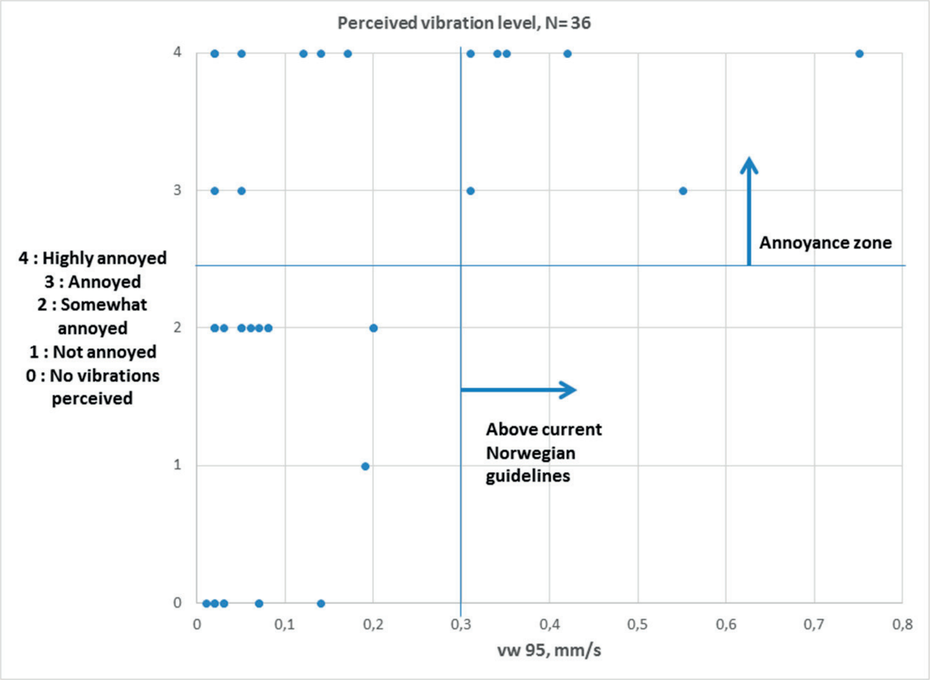


Figure 5-7,
annoyance due to vibrations

The investigation should be continued with more measurements of physical vibrations and a continued enquiry. The results so far indicate that a guideline of v_{w95} = 0.3 mm/s is too high to avoid complaints. In reality, all respondents exposed to a vibration level above v_{w95} = 0.3 mm/s were annoyed or highly annoyed. Another interesting feature is that there is no safe vibration level below which no one feels annoyed. It should be kept in mind that there is no control of whether these respondents were also annoyed by noise from the metro.

6. Measurement of total immission of noise and vibration into houses

Residences close to a tram or metro line are exposed to noise and vibrations. Sometimes annoyed residents complain about excessive noise and vibrations. At the current state of knowledge, measurements are often required to determine whether the complaints are justified. The immission of noise and vibration should be determined as well as possible in all areas designed for permanent occupancy, outdoors and indoors. Some areas are more exposed than others, and it might not always be obvious which areas are most critical. This section considers which parameters to measure: outdoor sound, indoor sound, outdoor vibrations and indoor vibrations. It is rarely possible to measure all the desired parameters simultaneously, and thus, in practice, those that are the most critical ones must be selected.

6.1. General considerations

The data behind the present work have been gathered through field measurements inside private residences. This places a practical limit to how extensive the measurements can be. The limitations apply to both the amount of instruments to be used and the time required to take the measurements. Measurements inside residences are taken either because of complaints from the residents or as a routine control after a new metro line opens.

The recommendations of current standards[25,26,29,30] require a number of train passages to be measured. For a metro line in the Oslo area there are four trains in each direction per hour. In places where only one line operates, this means that measurements of 20 trains will require two and a half hours after the rig has been set up and calibrated. In our experience four hours is the maximum time that most residents accept for completing the measurements. In practical cases this is approximately the same time required to make the recommended measurements.

It is not recommended to retain the time signal for all measured channels. This is partly because of to the amount of data collected, and partly because the data is not used. In the measurements that form the basis of our presented data only the MAX and/or SEL spectra for individual train passages have been retained. For the MAX spectra only the appropriate meter damping, FAST or SLOW, have been retained.

If possible the vehicle speed should be recorded. This can be performed with sufficient accuracy with a stopwatch that measures the average speed past the measurement site. Another useful fact to note is sometimes the identity of the train. For Oslo’ s trams this has proved useful, but not for the metro lines because there are a large number of possible train combinations.

6.2. Sound measurements

Outdoor sound level should, if possible, be measured at an outdoor area of the resident’s choice. The outdoor area can be selected by observing where the outdoor furniture is located. It is usually also obvious from the orientation of the areas and whether there is a view.

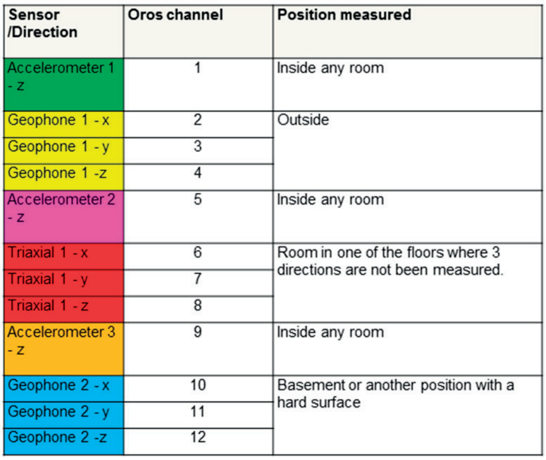
In addition, outdoor sound level should be measured in some way so that indoor level can be determined. If possible this should include separate measurements of airborne and groundborne noise. Indoor airborne noise can sometimes be measured directly, but most often it must be measured by means of outdoor noise and sound insulation. Groundborne noise should be measured in a room at the back of the house or below ground in a room without windows towards the metro line.

6.3. Vibration measurements

Ideally, vibrations should be measured in three orthogonal directions outside, on the building foundation and a few places on each level in a building. However, this may be impossible due to the large number of channels required. The data presented in article 7 were collected using an 8-channel analyzer, the data presented in article 6 were collected using a 12-channel analyzer, enabling the use of three triaxial and three single-axis vibration transducers.

Presently only the MAX, SLOW spectrum has been stored in the measurements analyzed. This provides only the magnitude information to be used in an analysis. The setup for measurements in 12 channels is illustrated in figure 6-1.

Standard measurement setup



Sensor /Direction	Oros channel	Position measured
Accelerometer 1 - z	1	Inside any room
Geophone 1 - x	2	Outside
Geophone 1 - y	3	
Geophone 1 -z	4	
Accelerometer 2 - z	5	Inside any room
Triaxial 1 - x	6	Room in one of the floors where 3 directions are not been measured.
Triaxial 1 - y	7	
Triaxial 1 - z	8	
Accelerometer 3 - z	9	Inside any room
Geophone 2 - x	10	Basement or another position with a hard surface
Geophone 2 - y	11	
Geophone 2 -z	12	

Figure 6-1,
standard setup for 12-channel vibration measurement. Photo and text by Teresa Fernández Espejo

6.4. Considerations about empirical modelling of sound and vibration levels

The acquisition of data for empirical prediction models for sound levels outdoors and indoors has been shown to be successful. At the short ranges involved it is also possible to acquire good data for outdoor spectra. The spectra of level difference between outdoor and indoor levels are well known and have a large and continuously growing database.

The acquisition of data could possibly also lead to future empirical prediction models for vibration levels in houses. However, this is more difficult than the acquisition of data for sound transmission. The main challenges are as follows:

- Data collection is based on surface vibrations. It is not certain that there is any clear correlation between surface vibrations and vibrations inside the house. If the building foundation is set deep into the ground, it is likely that vibration level found deeper in the ground are better correlated with the vibrations inside the house
- The transfer functions from point to point vary from train to train. This variation is frequency dependent, and it is not a case of simple parallel lines. Sometimes the transfer function can vary by a factor of four in some 1/3-octave bands between nominally identical trains. The example in article 6 is well-behaved, with the transfer functions for individual trains having reasonably similar shapes. This is not always the case, which means that much more data should be analyzed.
- Vibration transfer is a three-dimensional problem, and it cannot be resolved by simply analyzing the transfer of vibrations in one direction at one point to vibrations in the same direction in another point.[38]
- A final difficulty is that the senses are not of much help in experiencing vibrations. The transmission path is usually underground and inside building structures, thus it cannot be observed visually during a measurement. Our senses tell us if vibrations are excessive, but provide slight information about the spectrum shape or the direction of the vibration.

Therefore, one might ask whether these difficulties are so great that an attempt to create an empirical model that can translate from a simple three-dimensional vibration measurement outside the house to expected vibration levels inside the house is in vain? The alternative would be an analytical solution by FEM or other methods to manage the problem of predicting indoor vibration levels. This approach also has severe limitations. Acquiring sufficient input data about the mechanical properties of the ground is very difficult and expensive.

7. Discussion and the way forward

The target of the investigations is to minimize annoyance due to noise and vibrations from urban rail bound transport. The presented investigations are observational studies based on compilations of investigations of parts of the problem. The data acquired in Oslo are only applicable in that city, but the methods should be applicable anywhere.

The data are divided into source description, transfer path and immission. An overview of the presented data is shown in figure 7-1 along with planned extensions.

The investigations included in the thesis are marked with a thick blue border in figure 7-1. Planned future investigations are also shown in *italics* with a thinner border.

All the presented and planned investigations are observational studies that are still open. This means that the databases are continuously updated as more measurements are performed. The knowledge acquired from the environmental tram noise program provides a good basis for the coming program for the metro trains. The façade sound insulation measurements in special cases can be performed confidently based on the knowledge built behind articles 3, 4 and 5. Calculations of indoor levels of airborne noise from trams can be based on earlier work on this theme. A summary of the status for trams is provided in section 7.1, and for metro trains in section 7.2.

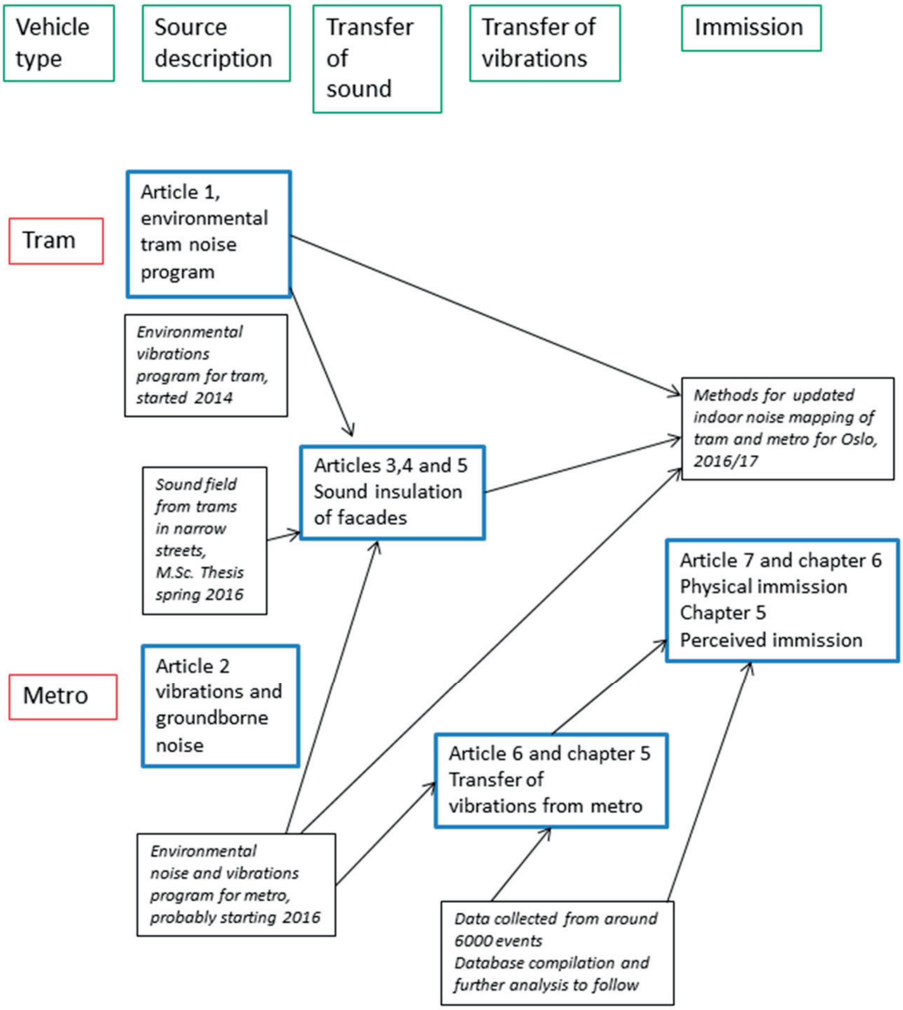


Figure 7-1,
Overview of work presented and planned

7.1. Prediction and measurement of noise and vibrations from trams

The main source of knowledge about noise and vibrations from trams is the environmental noise program started in 2007. Since 2010 the rail corrugation has also been included in this program, and the first vibration measurements were started in 2012. Triaxial vibration measurements were introduced in 2015.

The measurements of 2012[41] were controlled against the maintenance database, and approximately half of the noisy events could be explained by a match with the records from the maintenance database. In 2013 there were much fewer noisy events, and the investigation of noisy tram passages was discontinued.

An investigation into the sound field from trams in a narrow street is under way, currently as an M.Sc. assignment, and it uses multichannel noise measurements and room acoustics simulation. Other pending investigations include analysis of the vibration measurements already performed, and a new prediction method for the 2017 noise mapping. This new prediction method is planned to be compatible with the standard method for outdoor rail bound sources,[6] results from the environmental noise monitoring program[41] and earlier works on calculation of indoor noise.[22,27]

The pieces that still need to be addressed with regard to noise and vibrations from trams are:

- Vibration transfer into houses
- Groundborne noise

Figure 7-2,
there are still many things to consider about noise and vibrations from trams

7.2. Prediction and measurement of noise and vibrations from metro trains

The knowledge of noise and vibrations from metro trains stem mostly from control measurements on newly constructed or rehabilitated metro lines. In addition, some measurements have been made due to complaints from residents. The metro trains are much newer than the trams. Actually the metro trains running in Oslo now are all of the same type, Siemens MX 3000, and they were delivered between 2006 and 2010. The tracks are also of the same type, a ballast track similar to the one used on trams running on suburban lines. There are two varieties of rail, however. The collected knowledge about metro trains is somewhat different from the knowledge about trams.

The investigations into noise and vibrations from metro trains thus stems from measurements on the properties of neighboring residents. The environmental monitoring program for noise and vibrations is intended to fill in the gaps when it starts. The investigation into perceived annoyance from vibrations is open and ongoing, and is expected to bring in more knowledge. The response from residents along the metro lines so far has been exceptional, 75% have responded to the questionnaire.

Figure 7-3,
a metro train showing the way to new discoveries

8. References

1. http://ssb.no/energi-og-industri/artikler-og-publikasjoner/fly-bruker-4-ganger-saa-mye-energi-som-tog
2. http://www.veraveritas.eu/2013/02/carro-ou-comboio.html
3. Sustainable Transportation. Tools for creating vibrant, healthy and resilient communities, Jeffrey Tumlin, Wiley 2012, ISBN 978-1-118-12762-9, from chapter 8 by Tara Krueger Gallen
4. Norske lok og motorvogner 1.1.2008. Norsk Jernbaneklubb, Forskningsavdelingen.
   A wealth of information about the rolling stock on Norwegian regular railways, museum railways, tram and metro lines up to 2008, collected by a private organization on volunteer basis, unfortunately only with Norwegian text.
5. Speeds of Oslo's trams and metros as taken from the charts of the lines
6. Railway traffic noise - Nordic Prediction Model. The Nordic Council of ministers, 1996.
7. Noise and vibrations from high speed trains, Edited by Victor V. Krylov, ISBN 0 72772963 2, 2001, chapter 4.6
8. AKU-02 Avløs base vurdering av a- og b-verdier for lave hastigheter, revised 1. november 2010.

   In Norwegian, giving input values for calculation of noise from metro trains at speeds below 30 km/h, constant speed, acceleration and deceleration, used for calculations of noise from a maintenance base for metro trains at Avløs outside Oslo
9. «MX-3000 og andre T-bane tog, testmålinger». Brekke & Strand akustikk as, report dated august 25th, 2008.

   In Norwegian, report from the reference measurements made to produce input values required for calculation of noise from the MX-3000 trains.
10. Schall 03: Richtlinie zur Berechnung der Schallimmissionen von Schienenwegen. Ausgabe 1990, bekannt gemacht im Amtsblatt der Deutschen Bundesbahn Nr. 14 vom 4. April 1990
11. Tore Killengreen & Sigmund Olafsen "Measurements of curve squeal from Oslo's subway", Acoustics '08, Paris

12. “Prediction of noise from trams” - Ján Mandula, Brigita Salaiová, Mária Koval’akova´ - Applied Acoustics 63(4), 2002, pp. 373-389
13. Karl Popper, “The logic of scientific discovery”, original edition 1934, I have used the Routledge edition for Kindle, ref. to section 21
14. James R. Thompson, “Empirical model building. Data, models and reality.” Wiley, second edition 2011, page 27
15. Sigmund Olafsen “StairWay – a new approach to modelling of physical or perceived noise”, EuroNoise 2006, Tampere
16. Sigmund Olafsen “Accuracy of indoor traffic noise determination, part I, calculations, part II, measurements”, Uncertainty Noise Symposium, Le Mans 2005
17. NS 8175, Lydforhold i bygninger.

    In practice this standard sets the building code requirements for new and improved buildings in Norway
18. Kolsåsbanen, design guidelines for noise and vibrations
19. Forskrift om begrensning av forurensning - §§ 5.4 – 5.10.

    Norwegian pollution control act, 1997. §§5.4 – 5.10 deal with indoor noise in residences
20. Homb, Anders, Hveem, Sigurd, “Isolering mot utendørs støy Håndbok 47”, 1999 (in Norwegian).

    The official Norwegian prediction method and database of laboratory measurements for calculation of indoor noise form outdoor sources
21. Sigmund Olafsen “Sound insulation against traffic noise in wooden houses”, Baltic Nordic acoustical meeting 2002, Lyngby
22. Sigmund Olafsen “An empirical way to calculate indoor noise from road traffic”, EuroNoise 2003, Napoli
23. Sigmund Olafsen & Lars B. Hov “An improved empirical model for indoor traffic noise prediction”, Baltic Nordic Acoustical Meeting 2004, Mariehamn
24. Sigmund Olafsen & Lars B. Hov “Considerations of room acoustics for traffic noise evaluation”, Baltic Nordic Acoustical Meeting 2004 Mariehamn
25. Acoustics, field measurement of sound insulation in buildings and of building elements, part 5: Field measurements of airborne sound insulation of façade elements and facades, ISO 140/5, 1998
26. Acoustics, field measurement of sound insulation in buildings and of building elements, part 3: Façade sound insulation ISO 16283-3, 2014
27. Sigmund Olafsen “Towards an empirical model for sound insulation against tram noise”, Baltic Nordic Acoustical Meeting, 2006, Göteborg
28. Tore Killengreen & Sigmund Olafsen, “The spectrum shape of outdoor and indoor road traffic noise”. Proceeding of Interrnoise 2007, Istanbul

29. NS 8177. Acoustics – Measurement of sound pressure level from rail traffic. This standard from 2010 describes a measurement procedure for rail traffic noise.
30. NS 8176,Vibrasjoner og støt – Måling i bygninger av vibrasjoner fra landbasert samferdsel og bedømmelse av vibrasjonspåvirkning på mennesker. « Vibration and shock. Measurement of vibration in buildings from landbased transport and guidance to evaluation of its effect on human beings»

    The Norwegian standard for measurement and evaluation of vibrations from transport
31. Atle Stensland, "Project with tuned rail dampers on tramway in Oslo", proceedings Internoise 2011, Osaka
32. ISO 3095 – 2005, Railway applications -- Acoustics -- Measurement of noise emitted by rail bound vehicles
33. Tor Erik Vigran: Lydisolasjon I bygninger. Et teoretisk grunnlag med eksempler, TAPIR 1979.

    An excellent book in Norwegian giving the theoretical basis in sound insulation and building acoustics
34. Carl Hopkins, Sound Insulation, Butterworth-Heinemann, ISBN 978-0-7506-6526-1, Chapter 5.1.3.

    In the introduction to this book the building acoustics frequency range is defined as 50 Hz – 5000 Hz.
35. Madshus,C, Bessason, B, Hårvik, L, "Prediction model for low frequency vibrations from high speed railways on soft ground." International workshop on Railway and Tracked Transit System Noise, 5. (5. IWRN). Voss, Norway, June 1995. Proceedings pp. 3.3.1 – 3.3.10. Also published in Journal of Sound and Vibration.
36. ISO 14837 – Part 3 – Measurement "Ground-borne noise and vibration arising from rail systems, 2012, Christian Madshus
37. Teresa Fernández Espejo, Sigmund Olafsen, Arild Brekke "Measurement procedures for vibration propagation from railway tracks", Internoise 2013, Innsbruck
38. Yoshihiro Hirao, Sunao Kunimatsu, Takuji Hamamoto, "Development of wireless measurement system for ground-borne vibration in buildings and measurements for vibration amplifications of detached houses", Internoise 2011, Osaka
39. Klæboe, R. & Fyhri, A. (1999). Opplevelse av vibrasjoner i bolig fra veg- og skinnegående trafikk. Sammendrag. TØI rapport 443/1999. 56 sider. Transportøkonomisk institutt. Oslo In Norwegian, the enquiry was the basis for the NS 8176

40. Innsendingsoppgave i AOS 240, Samfunnsvitenskapelig metode for Erik Leifssøn og Sigmund Olafsen. «Vibrasjoner fra T-Bane”

    A student assignment in “Method in social science”, a course at University of Ås, 2014.

41. “Målinger av støy iht. Måleprogram for trikken – Måleresultater 2012”, Tore Fodnes Killengreen, Sigmund Olafsen, Atle Stensland (in Norwegian only) Reports of measurements up to and including 2012. The 2012 report was the most comprehensive one. Yearly reports have been produced every year since 2007.

APPENDIX

EARLIER PUBLICATIONS BY THE AUTHOR & COLLEAGUES

Sigmund Olafsen "Sound insulation against traffic noise in wooden houses", Baltic Nordic Acoustical Meeting 2002, Lyngby

Sigmund Olafsen "An empirical way to calculate indoor noise from road traffic", EuroNoise 2003, Napoli

Sigmund Olafsen & Lars B. Hov "An improved empirical model for indoor traffic noise prediction", Baltic Nordic Acoustical Meeting 2004, Mariehamn

Sigmund Olafsen & Lars B. Hov "Considerations of room acoustics for traffic noise evaluation", Baltic Nordic Acoustical Meeting 2004, Mariehamn

Sigmund Olafsen "Accuracy of indoor traffic noise determination", part I, calculations, part II, measurements, Uncertainty Noise Symposium, Le Mans 2005

Sigmund Olafsen "StairWay – a new approach to modelling of physical or perceived noise", EuroNoise 2006, Tampere

Tore Killengreen & Sigmund Olafsen "Measurements of curve squeal from Oslo's subway", Acoustics '08, Paris

Knut Haugen & Sigmund Olafsen "Analysis of low-frequency resonances in façade sound insulation spectra", Internoise 2008, Shanghai

Sigmund Olafsen & Maria Kristin Strand "Field versus laboratory sound insulation of windows", Internoise 2009, Ottawa

Sigmund Olafsen "Open versus closed ventilation devices – what is the impact on indoor sound pressure levels?", Baltic Nordic Acoustical Meeting 2010, Bergen

Per Kåre Limmesand & Sigmund Olafsen "Control of sound insulation in glass façades at Oslo's new opera house", ICA 2010, Sydney

Atle Stensland, Tore Fodnes Killengreen & Sigmund Olafsen "Noise measurements on the Oslo tram", Internoise 2012, New York

Arild Brekke, Lars R. Nordin, Trond Norén & Sigmund Olafsen "The Norwegian high speed rail study", Baltic Nordic Acoustical Meeting 2012, Odense

Teresa Fernandez Espejo, Sigmund Olafsen, Arild Brekke "Measurement procedures for vibration propagation from railway tracks", Internoise 2013, Innsbruck

Sigmund Olafsen "The contribution of low (50 – 80 Hz) and high (4000 – 5000 Hz) frequencies on indoor noise from road traffic", Baltic Nordic Acoustical Meeting 2014, Tallinn

Article I

An empirical method for prediction of tram noise

Sigmund Olafsen, Delphine Bard, Atle G. Stensland, Tore F. Killengreen

LUND UNIVERSITY

Abstract

An empirical method for prediction of tram noise has been developed based on an environmental noise monitoring program for Oslo’s trams. The model is designed to predict noise from individual tram passages. A multivariate regression has been performed based on measurements of acoustical and other parameters for 960 tram passages during 5 years. The estimated SEL and MAX, A-weighted levels from the overall regression have been compared to the measured levels from each passage. Three other investigations have also been made based on the data collected. The first one is an analysis of whether the measurement point has an effect beyond the parameters included in the overall analysis. The second one is an analysis of whether there was any difference between vehicles of the same series. The third one is a control of trams with special spectra against the maintenance records.

Acknowledgements

First of all, my sincere thanks to Sporveien, the publicly owned company that runs Oslo’s metros and trams. This company has commissioned the measurements and allowed the publication of the results. In addition, Sporveien’s employees Johnny Vaaga and Haagen Hølaas have taken part in the field work of the measurements. We would also like to thank Eivind Hoel, Håkan Lund and Laila Kristin Dokken Gundersen of Sporveien for the permissions to publish the results and cooperation with regards to access to the maintenance database.

Statistical analysis has been performed with the program package R, which is available for free and widely used in many fields of research. The user interface R Commander from NMBU (The Norwegian University of Bioscience, at Ås) has also been applied. This user interface is also available for free.

1.Introduction

The trend towards denser and bigger urban areas on the one hand and the desire to avoid modes of transport using fossile fuel on the other will increase the demand for electrically powered mass transport like trams. This leads to more people being exposed to noise from trams, but good results with quiet trams have been reported[1].

The noise monitoring program for the trams of Oslo was originally started in 2007 as part of ISO 14000 certification for Sporveien, the publicly owned company that runs the trams and metros of Oslo. Initially in 2007 the measurements were made in 8 points with at least 10 tram passages in each of the points. The program was designed to uncover longterm trends in the noise emission from the trams of Oslo through yearly measurements. Later, in 2010, the measurements of rail quality were introduced. In 2012 the first prediction method for SEL and MAX, A-weighted sound level from individual tram passages, was presented.[2] There are two main types of tram in Oslo. There are 40 of the older type SL-79, and 32 of the more recent type SL-95.

Different types of track would be expected to results in different noise emission.[3] There are three types of track in Oslo:

Rails embedded in city streets

Ordinary ballast track

“Green track”, which is a concrete structure carrying the rails with soil and grass between the rails.

As the data set accumulated over the years, it was decided to investigate whether it could be used for more than an evaluation of a trend in noise emission from Oslo’s trams. This article deals with the development of an empirical model for tram noise based on the data set already collected.

Section 2 gives a description of the measurements, how they were performed and which data were collected. Section 3 gives a description of the analysis methods applied for overall statistics. Section 4 gives a description of other types of more detailed analysis. Two types of detailed analysis were made on the A-weighted levels. The first one was made in order to investigate whether some of the measurement points gave different results than would be expected from the overall analysis. The other one was made in order to investigate whether there were especially noisy or especially quiet trams. Finally an investigation was made of whether trams that had a deviant spectrum had a mechanical problem on the given day the noise from it was measured. Section 5 gives a description of the results of comparing the estimated noise from trams with the actually measured values. In Section 6 follows a discussion of results, while finally Section 7 gives suggestions for further research.

2. Method of measurement

The method consists of noting all parameters expected to be relevant for the measurements.[4] The measurement series has been repeated every autumn since 2007. A total of 16 points have been used during the years and included in the overall analysis. Table 1 shows a list of the points and the years in which measurements have been made in each point.

Table 1

Measurement points

#	Point	2010	2011	2012	2013	2014
1	Toftes gate	X	-	-	X	X
2	Grensen	X	-	-	-	-
3	Drammensveien 53	-	X	X	X	X
4	Cort Adelers gate 17	X	X	-	-	-
5	Kirkeveien at Frognerparken	X	X	X	X	X
6	Lilleakerbanen at Hoff	X	X	X	X	X
7	Grefsenplatået	X	X	X	X	X
8	Kirkeveien at Arboes gt	X	X	-	-	-
9	Nygata	X	X	-	-	-
10	Storgata 36 B	X	X	X	X	X
14	Nils Henrik Abels vei	X	-	-	-	-
15	Abbediengveien 5	X	-	-	-	-
16	Thorvald Meyers gt	X	X	-	-	-
17	Forskningsparken	-	X	X	X	X
20	Ekebergbanen	-	-	X	X	X
21	Grefsenveien at Brettevilles gate	-	-	-	-	X

In each point a series of measurements are made on one day per year. For each day at least 10 tram passages have been measured. The data acquired could be put into three groups:

- Acoustical parameters
- Non – acoustical parameters
- Rail surface corrugation

This information is required in order to develop an empirical model for noise from trams.

2.1 Acoustical parameters

For each passage of a tram the following parameters are noted:

- SEL, A-weighted and in 1/3-oktave bands
- $L_{A(F)max}$ and $L_{(F)max}$ in 1/3-oktave bands

Table 2 shows an example of a part of a measurement log as recorded.

Table 2

Example of part of measurement log

Temperature	**13 °C**			
Wind speed	**1,5 m/s**			
Wind direction	**-**			
Measurement date	**27.oct.14**		**Background noise**	**-**
Vehicle tyep/id	**Direction**	**Vehicle speed(km/h)**	**LAF(max)(dB)**	**SEL (dB)**
79/108	**Inbound**	**37**	**90**	**93**
79/125	**Inbound**	**26**	**87**	**91**
79/127	**Inbound**	**28**	**84**	**89**
79/120	**Inbound**	**28**	**86**	**90**
79/116	**Inbound**	**23**	**85**	**89**
79/136	**Inbound**	**35**	**88**	**92**
79/124	**Inbound**	**31**	**88**	**91**
79/126	**Inbound**	**35**	**85**	**89**
79/119	**Inbound**	**27**	**84**	**89**
95/152	**Inbound**	**28**	**85**	**91**
95/161	**Inbound**	**26**	**84**	**90**
95/144	**Inbound**	**35**	**89**	**94**
Average				
SL 79		**30**	**87**	**91**
SL 95		**30**	**87**	**92**

2.2 Non-acoustical parameters

For every site the local geometry is measured once for the site, see figure 1 for an example of the documentation. Most of the immission points have been used every year. Some points have been changed over the years, or they have been suspended for a year or two during construction works on or close to the track. Table 1 gives an overview of the points used each year. In the present article the vertical gradient of the track has been included in our analysis in addition to the parameters previously reported[2].

Every measurement day on a given site the non-acoustical parameters have been noted as follows:

Weather conditions are noted, temperature, wind speed and wind direction. The measurements are made at close distances, so that the meteorological conditions have minimal influence on the results. It is noted whether background noise is a potential problem.

For each tram passage the identity of the tram is noted. The identity of the tram is marked with a three-digit number clearly marked in front, in the rear and on both sides of the tram. The trams of Oslo are of two main types, SL-79 and SL-95[5]. Table 3 shows the main technical data of each type of tram.

Vehicle speed is usually measured with a laser.

The direction of the tram is noted. By convention “inbound” means towards Oslo city centre, “outbound” means away from city centre. Special noteworthy details from each measurement are also noted.

Table 3, technical data of Oslo’s tram types SL-79 andSL-95

Property	SL-79	SL-95
Length	22,4 m	33,1 m
Width	2,6 m	2,5 m
Bogie wheel distance	1,8 m	1,8 m
Wheel diameter	680 mm	680 mm
Weight empty	32,8 tonnes	65,0 tonnes
Highest speed	80 km/h	80 km/h
Seats	71	88
Room for standing persons	66	108
Year built	1982-83 & 1989-90	1998-2000

2.3 Rail corrugation measurements

Since 2010 measurements of rail corrugation were included in the noise monitoring program. These measurements have been made according to ISO3095-2005[6]. Figure 2 shows an example of the measurements of the rail corrugation.

Figure 2, example of rail corrugation measurement

Rail corrugation measurements are made with an ATP-RSA for both rails in both directions past the measurement point. The idea that rail corrugation has an influence on noise from rails and wheels is not new. One author states that: "The roughness of the rail is the main source of the noise emission of the tramcar".[7] A more recent source talking about the effect of rail grindings on railways indicates that the effect is much more pronounced on new and modern rolling stock than on older vehicles.[8] The instrument used for the measurement is suitable for this type of measurement.[9] Danish railway authorities use rail corrugation measurements for maintenance programs as well as for noise control. [10]

3. Method of analysis

The analysis of the results has been divided into three parts:

- A main overall analysis using linear regression with 8 predictors onto two different outcome parameters, SEL A and $L_{A(F)max}$.
- Factor analysis to determine: a) whether the individual measurement point gave any significant contribution beyond that predicted by the overall analysis and b) whether each individual tram gave any significant contribution beyond that predicted by the overall analysis.
- Spectrum analysis from each measurement day to see whether there was an anomaly in the noise from any individual tram

The main overall analysis is described in section 3.1. The other types of analysis are described in section 4.

3.1 Main overall analysis

The parameters, the method of acquisition and the representation in the statistical analysis of parameters are shown in table 4. The principle of the regression is to find the contributing factors to the noise measured. The noise level as SEL or MAX, A-weighted, free field, has been defined as an outcome. Other factors have been defined as predictors of the noise. Some of the predictors have been transformed before the run of the regression as described in the following text and in table 4.

Table 4

Parameters included in the regression

Predictor /factor	Data gathered	Used in analysis after data reduction/conditioning
Speed (km/h)	Measured with laser	Log_{10} (speed) past the mic
Distance (m)	Distance from track to microphone	Log_{10} (distance)
Year measured	Date	Year, two digits
Tram type (SL 79/SL 95)	Vehicle # (72 trams)	Vehicle type (two types)
Track type	Three types	0,1,2
Rail quality, given as equivalent corrugation spectrum in dB rel. 1 µm	≈ 100 parameters per rail	One number per track
Time since grinding	Number of years	Number of years
Gradient	Approximate vertical height difference per traversed meter horizontally	Gradient in ‰
Outcome / response		
Noise	≈ 60 parameters per passage of vehicle	Single number rating, corrected for influence of buildings, in SEL or MAX A-weighted

The assumption has been that the following parameters contribute to the noise level actually measured:

Speed of the vehicle, represented as the base 10 logarithm of the measured speed in km/h. The speed has usually been measured with a laser, and care has been taken to ensure that the speed is measured as the tram is on its way past the microphone. Drivers have been instructed to drive as they would normally do during our measurements. The range of speeds have been between 10 and 70 km/h. The regression factor is termed p_v.

Distance from the track centerline to the microphone. This parameter is only measured once for each measurement point. The distance is represented in the regression by the base 10 logarithm of the distance in meters. The range of distances in the measurements presented is 2 to 13 meters. The regression factor is termed p_d.

The year has been entered as a two-digit number omitting the preceding 2-0. The regression factor is termed p_y.

Tram type has been entered as 0 for SL95, 1 for SL79. With only two alternatives a linear regression is equivalent to a factor analysis. The regression factor is termed p_s.

Track type has been entered as 0 for city street, 1 for ballast track and 2 for green track. It was originally assumed that the green track would be the quietest and the city street would be the noisiest. The regression factor is termed p_t.

Rail quality has been entered as the single number rating for the most corrugated one of the two rails on a track. The value ranges from around 15 for the best new track to over 30 for the most worn tracks investigated. The regression factor is termed p_c.

Time since grinding has been entered as an integer number of years since the last grinding, this is normally in the range 0 to 5. Some tracks were ground during the summer before the autumn measurements, sometimes the track was new. For lines with little traffic there may be a 5 year interval between grindings. The regression factor is termed p_g.

Gradient is given in ‰ average vertical height difference per unit of horizontally traversed distance during the measurements. The number ranges from 0, flat, to 75, the steepest descent investigated. The regression factor is termed p_h.

Noise is given as SEL and MAX, FAST, free field, for each immission point. The correction for reflections from building facades has been entered as 3 dB if there are buildings on one side of the track, 6 dB if there are buildings on both sides of the track.

The main analysis of the contribution of each predictor has been performed for both SELA and MAX, FAST AS for three cases:

All measurements
All measurements with vehicle speed ≤ 30 km/h
All measurements with vehicle speed ≥ 30 km/h

Noise from railbound traffic is dominated by different sources at different speeds. There is a minimum noise at standstill, and the contribution of this basic noise is reduced as rolling noise takes over at increasing speed. This means it seems reasonable to split the analysis between different speed ranges. The choice of 30 km/h as a dividing line is made because this is an established convention in the Oslo area. For the Oslo metro, different parameters are already used for noise calculations at speed above 30 km/h and below 30 km/h. It is also part of the consideration that the speed limit for road traffic in purely residential areas in Oslo is often 30 km/h, which is the kind of area where the tram would be expected to be a problem at short range.

The measurement points as distinct entities are not directly included in the overall analysis, only the distance and the parameters of the track (track type, rail corrugation and years since last grind). The overall analysis does not include detailed investigation of the spectrum.

The use of a continuous variable for tram type is not problematic. As long as there are only two distinct values, a linear regression using a continuous variable is equivalent to defining it as a categorical variable. For the track type, however, the situation is a bit more problematic. It seemed natural to assume that city street would be the noisiest type of track, green track the quietest with the ballast track somewhere in the middle. Investigations into this problem using different type of analysis have given inconclusive results. One possible reason is that there are no measurement points with green track where both types of tram run. This may lead to confounding of the results.

4. Other analysis

4.1 Factor analysis

The term factor analysis is used about further analysis focusing on a smaller detail of the overall picture. This type of statistical analysis has been made in order to look for explanations to the uncertainties in the overall analysis. Two possible contributors have been singled out for investigations: measurement points and the individual trams.

4.1.1 Measurement point

This analysis was made in order to investigate whether the measurement points had some distinct influence beyond that included in the parameters given above. This was done by including the measurement point as a categorical variable (called factor in the statistics program R) in the overall regression analysis.

4.1.2 Tram identity

There are only 72 trams in Oslo, and there have been measured 960 passages. All the trams have been measured more than once, some vehicles more than 30 times. This means that running the statistical analysis with the tram identity as a categorical variable (called factor in the statistics program R) might reveal more new information as to whether there is a difference between the vehicles.

4.1.3 Detail analysis of individual measurement series 2012

It was decided in 2012 to investigate whether there was any clear connection between the spectrum of particularly noisy trams and the state of maintenance. Spectrum analysis has not been included in the overall analysis. The spectrum analysis has been performed for each individual measurement point individually. The purpose of this analysis was to see whether there was any way to reduce noise complaints by adjusting maintenance routines. For each measurement day in a given point the average spectrum was plotted together with the spectrum for particularly noise vehicles. The results were checked against the maintenance records of the trams. Roughly half the cases of a special spectrum could be explained by the maintenance records. One case is shown in figure 3, another in figure 4.

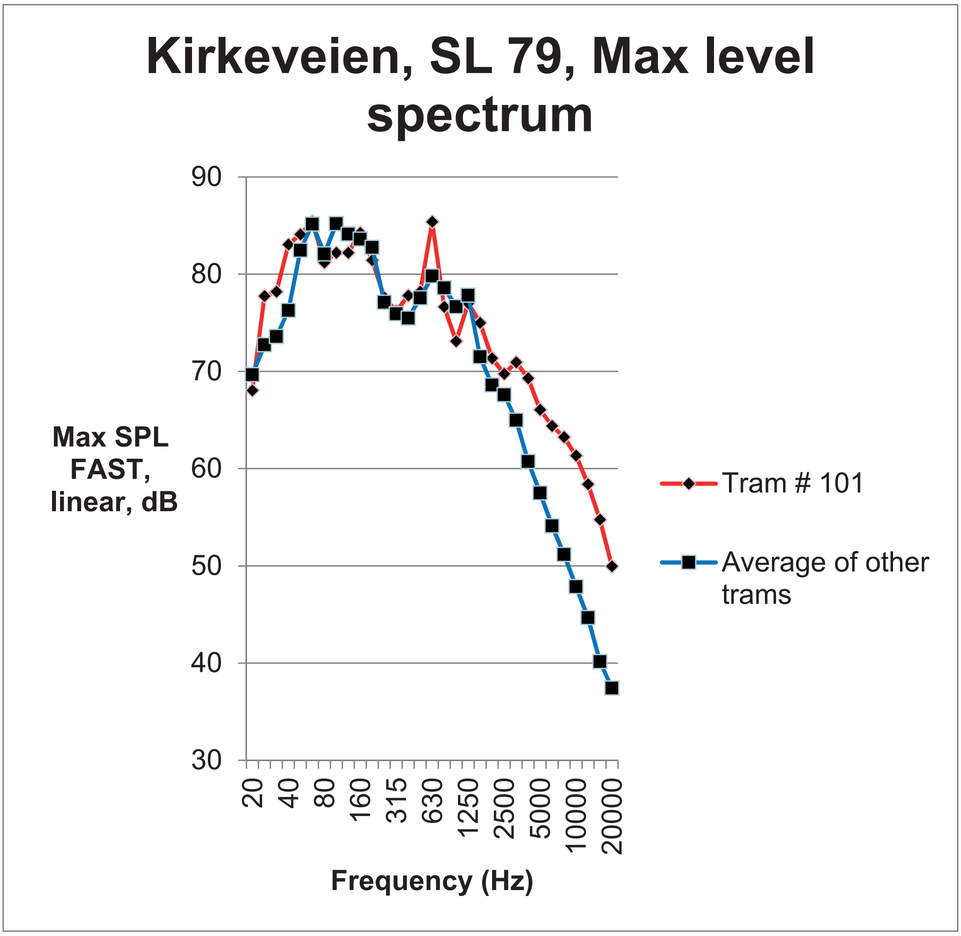


Figure 3, example of a noisy tram

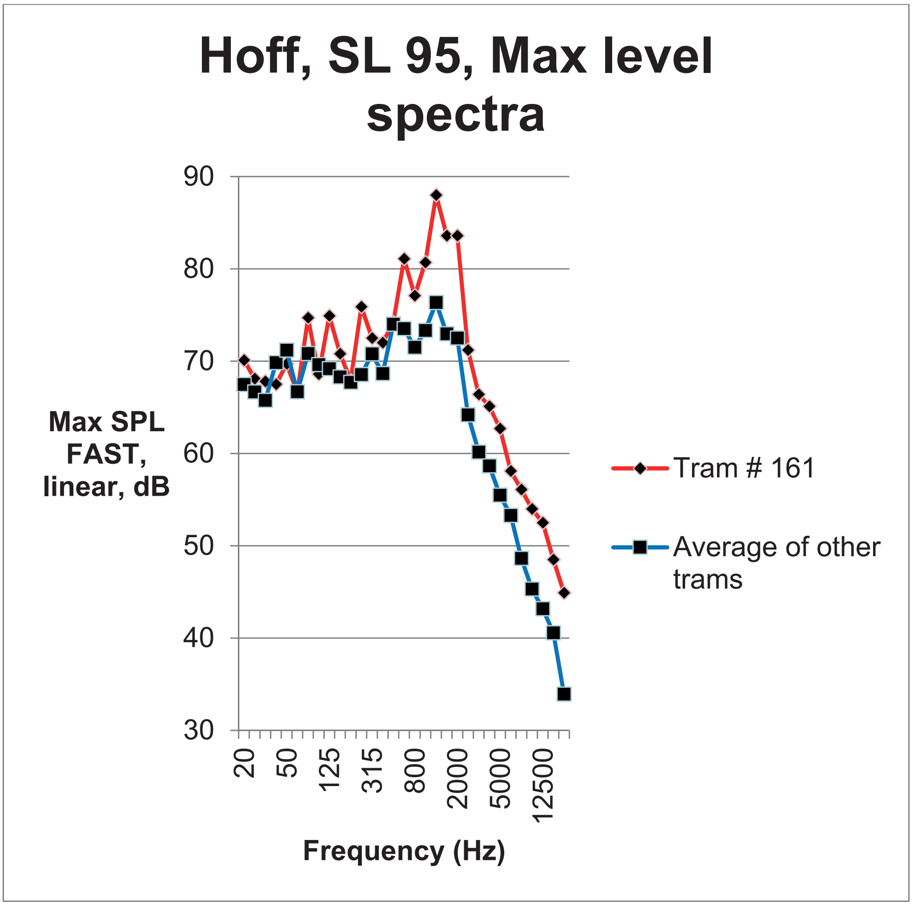


Figure 4, another example of a noisy tram

The case in figure 3 was found to be due to a leak in a hydraulic system on that measurement day, leading to a compressor running continuously on tram # 101. This compressor normally runs at short intervals only. And thus this tram emitted much more high frequency noise on that day than the other trams operating on that line. The case in figure 4 was not explained by the maintenance records. However the driver complained about noise while braking, so something was most likely wrong with the vehicle.

In 2013 a similar type of analysis yielded no results. No special spectra were found that could be matched with the maintenance data base. A probable explanation could be that the noisy events found in 2012 changed the attitude of the people working in maintenance at the tram garage, so that the trams were generally kept in a better state.

5 Development of empirical prediction method

The concept of developing a prediction method based on field measurements only is not new.[11] This is an alternative to developing theoretical models especially suited for trams. [12,13] The main purpose of the present article is to show the results of developing a local empirical prediction method. The resulting formula for the estimated noise level is as follows:

$L = L_0 + p_v(\log(10)\text{speed}) + p_d(\log(10)\text{distance}) + p_y * \text{year} + p_s * \text{tram type} + p_t * \text{track type} + p_c * \text{rail quality} + p_g * \text{time since grinding} + p_h * \text{gradient}$

Where:

- L_0 is the estimated intercept from the regression analysis
- P_v is the regression factor for the log (base 10) of the tram sped
- P_d is the regression factor for the log (base 10) of the distance from the track to the microphone
- P_y is the regression factor for the year the measurement was made
- P_s is the regression factor for the tram type
- P_t is the regression factor for the track type
- P_c is the regression factor for the rail quality given as corrugation in dB rel. 1 µm
- P_g is the regression factor for the time since last grinding of the track
- P_h is the regression factor for the vertical gradient

The other parameters have been described in detail in section 3.1.

It should be noted that the model actually predicts the noise from each individual tram passage. The accuracy to be expected from a calculation of an aggregated level like L_{den} or $L_{eq,24h}$ should be much better than the accuracy for an individual passage of trams. The same goes for the prediction of $L_{5AF,}$ which is meant to be the expected second highest maximal level from 20 passages of trams.

The development of a method consisted in finding which parameters to include in the regression model. In principle this can be done by including more parameters in the regression as long as the r^2 continues to increase[2]. These first attempts at a regression used the first 7 parameters described in section 3.1: Speed, distance, tram type, corrugation, year of measurement, track type and time since grinding. Later the vertical gradient has also been included, as this has been shown to be of importance in the development of an empirical prediction method for another city, Kosiçe, Slovakia.[11]

The results from the regressions at speeds up to 30 km/h and at speeds from 30 km/h upwards were compared with the actually measured noise level in each individual case for both SEL A and $L_{A(F)max}$. The residue has been plotted for each tram passage. The residue is defined as measured level minus estimated level.

6. Results and discussion

The results of the analysis are discussed below. The results are divided into overall linear regression, factor analysis and empirical prediction.

6.1 Overall linear regression

The results of the overall linear regression are shown in table 5.

Table 5
Results of overall regression

Parameter	All	Up to 30 km/h	30 km/h and faster	All	Up to 30 km/h	30 km/h and faster
Intercept, p_0	67,18708	76,53855	59,46154	60,23574	73,35935	50,80419
Logspeed , p_v	13,31078	8,929057	15,31816	18,41583	12,12481	20,92607
Logdist, p_d	-4,79454	-4,661183	-4,218583	-7,091294	-6,303489	-6,645283
Year, p_y	-0,037599	-0,283036	0,253725	-0,067452	-0,410346	0,28885
Train, p_s	-2,262893	-1,510515	-2,973198	-2,559884	-1,22345	-3,640547
Track, p_t	0,76528	0,84514	0,690741	0,830644	0,911343	0,78178
RSA, p_c	0,144813	0,099541	0,198706	0,050191	-0,022064	0,119541
Lastgrind, p_g	-0,372942	-0,11018	-0,614146	-0,494909	-0,234422	-0,744633
Gradient, p_h	0,015315	0,019999	0,015661	0,021583	0,029522	0,020704
r^2	0,531	0,4241	0,4663	0,5708	0,3935	0,5234

The regression factors have been calculated for all the 6 investigated cases from section 3.1, SEL and MAX, A , FAST. Some characteristics of the regression coefficients are reasonable. For both SEL and MAX the overall correlation is higher at speeds from 30 km/h upwards than at lower speeds. The speed dependence is steeper at higher speeds. This agrees with intuition, since some noise from the tram is present even at standstill. The faster the tram goes, the smaller the contribution of noise from machinery that is independent of driving speed becomes. The distance attenuation is essentially the same independent of speed. Distance attenuation will not necessarily be attributable to a line source or point source, since all the measurements have been made at a distance shorter than the greatest dimensions of the tram. The greatest measurement distance is 13 meters, and the smallest of the trams has a length of 22 meters. This is a limitation regarding the theoretical description of the sound field, since all measurements have been made in the near field of the source. It also seems clear that the difference in noise between the two types of tram is greater at higher speeds.

There is a theoretical problem in running the analysis on MAX, A –weighted level. Normally with railbound noise sources like trams the maximal levels in different frequency ranges will occur at different times. For example noise from braking or curve squeal could easily come at different times than noise from bogie resonances. This means that the maximal A-weighted level is usually slightly lower than the A-weighted sum of maximal 1/3-octave band levels. In our as yet unpublished experience this discrepancy usually amounts to 2-3 dB.

6.2 Factor analysis

The results of the two types of factor analysis made on the whole data set will be described below.

6.2.1 Measurement points

The factor analysis of measurement points showed that some of the measurement points had a statistically significant effect on the noise beyond that which could be explained by the overall statistical analysis. The presented difference is the difference left after correction for all other parameters that change from immision point to immision point, distance, track type, rail corrugation and gradient. A full printout of these results is shown in table 6. Points 7 and 9 are slightly noisier than the others, points 5, 6 and 10 are slightly quieter. Further investigation will include horizontal curvature in the statistical analysis which may help to explain these local differences.

Table 6
Estimated influence of the measurement point

	Estimate	Std. Error	t value	Pr(>|t|)
MP(MP01)	0.10710	0.55643	0.192	0.847413
MP(MP02)	0.06366	0.82141	0.078	0.938240
MP(MP03)	-0.16124	0.60002	-0.269	0.788201
MP(MP04)	-1.11884	0.71385	-1.567	0.117376
MP(MP05)	-2.64880	0.64395	-4.113	4.24e-05 ***
MP(MP06)	-2.46146	0.50404	-4.883	1.23e-06 ***
MP(MP07)	1.85212	0.50156	3.693	0.000235 ***
MP(MP08)	-1.25658	1.07513	-1.169	0.242796
MP(MP09)	2.95450	0.81764	3.613	0.000318 ***
MP(MP10)	-1.34858	0.38285	-3.522	0.000448 ***
MP(MP14)	1.60001	1.10588	1.447	0.148281
MP(MP15)	-1.80250	1.00982	-1.785	0.074589 .
MP(MP16)	-0.89565	0.71667	-1.250	0.211707
MP(MP17)	1.03587	0.53955	1.920	0.055177 .
MP(MP20)	1.08895	0.61228	1.779	0.075644 .
MP(MP21)	2.99	Not yet valid data		

6.2.2 Individual vehicles

There are 960 passages of 72 vehicles included in the database of this investigation. It was decided to look for whether any of the trams were particularly quiet or noise even when corrected for all other factors included in the analysis. Factor analysis using the tram identity gave as a result that the trams 110, 131, 132 and 138 have been quieter than predicted from the overall analysis. Trams 153, 163, 164 and 166 have been noisier. All the apparently quiet trams are of the SL-79 series, and all the apparently noisy trams are of the SL-95 series. A possible explanation is that the SL-95 series is generally of a poorer mechanical quality than the SL-79 series, even though the trams of the SL-79 series are older.

6.3 Empirical prediction

One possible way of determining the practical applicability of the work is determined by how well the models actually can predict noise from an individual tram passing. In figure 5 through 8 are shown the differences between the estimated and measured level for each passing tram. The estimate is based on the overall regression for the 4 selected subcases:

- Measured vs. estimated noise – SEL A, v ≤ 30 km/h, shown in figure 5
- Measured vs. estimated noise – SEL A, v ≥ 30 km/h, shown in figure 6
- Measured vs. estimated noise – MAX A, v ≤ 30 km/h, shown in figure 7
- Measured vs. estimated noise – MAX A, v ≥ 30 km/h, shown in figure 8

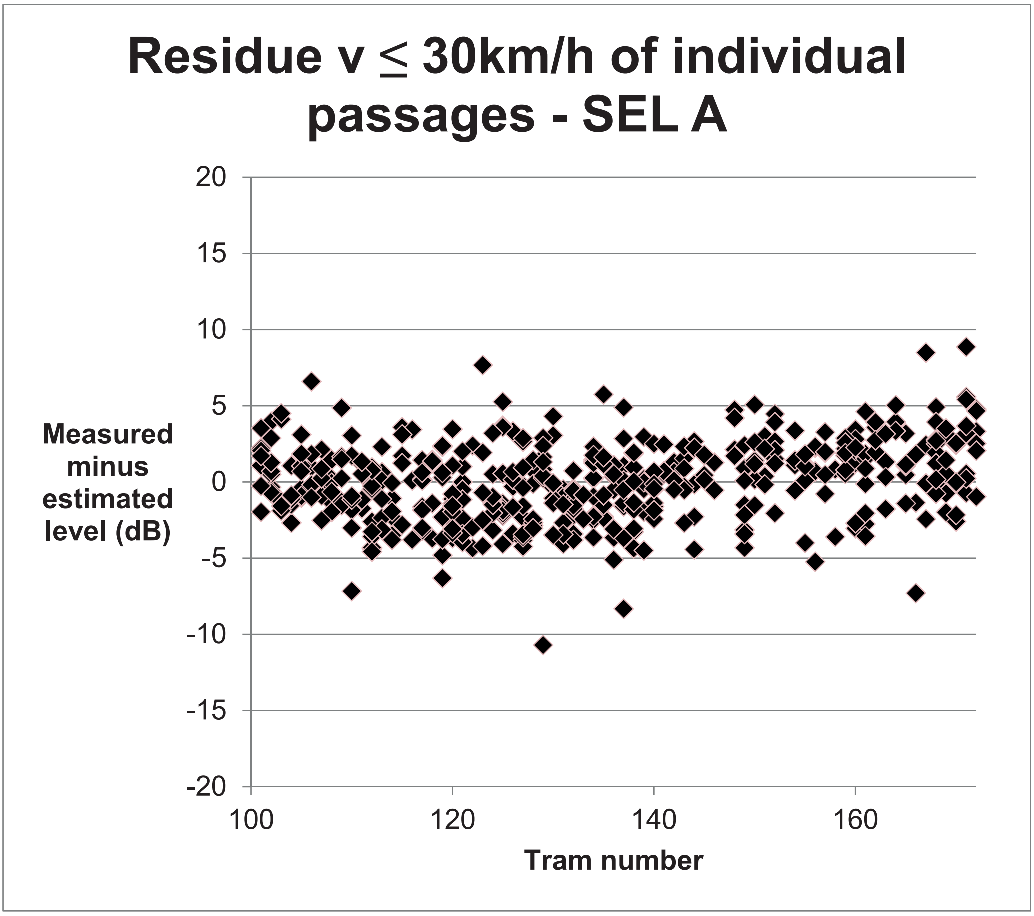


Figure 5, measured vs. estimated noise, SELA, v ≤ 30 km/h

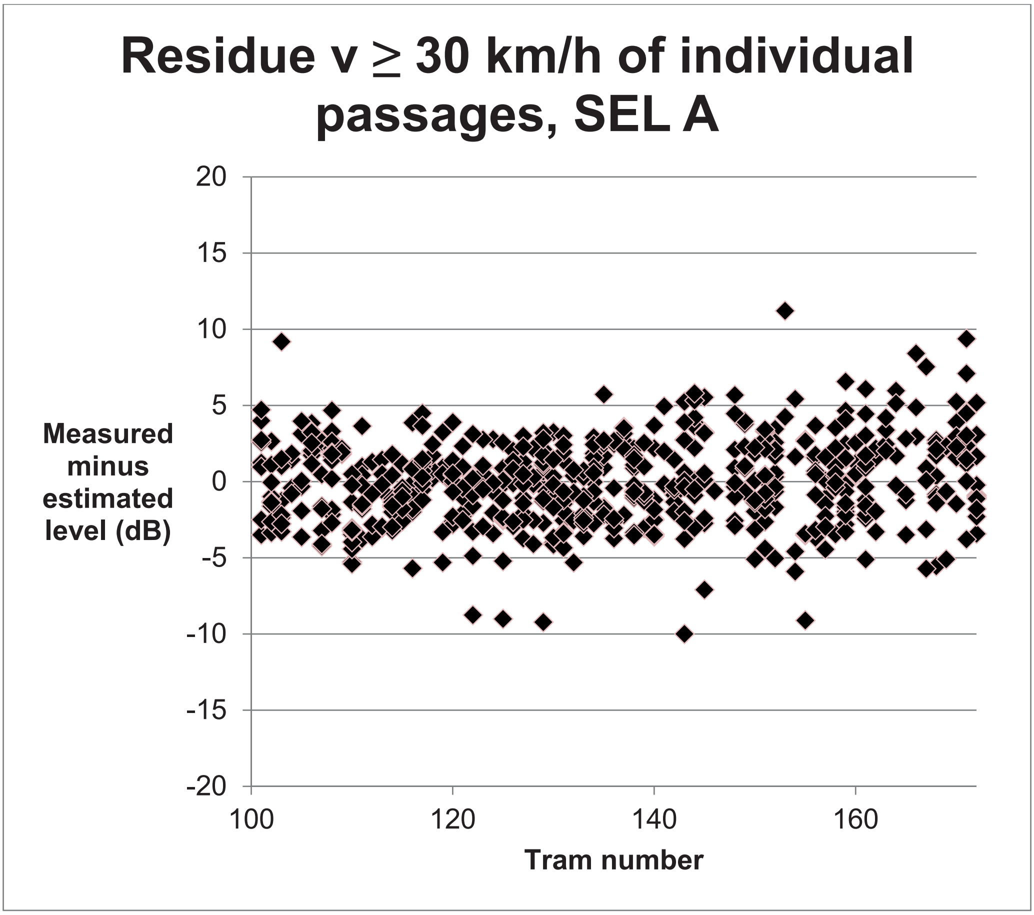


Figure 6, measured vs. estimated noise, SEL A, v ≥ 30 km/h

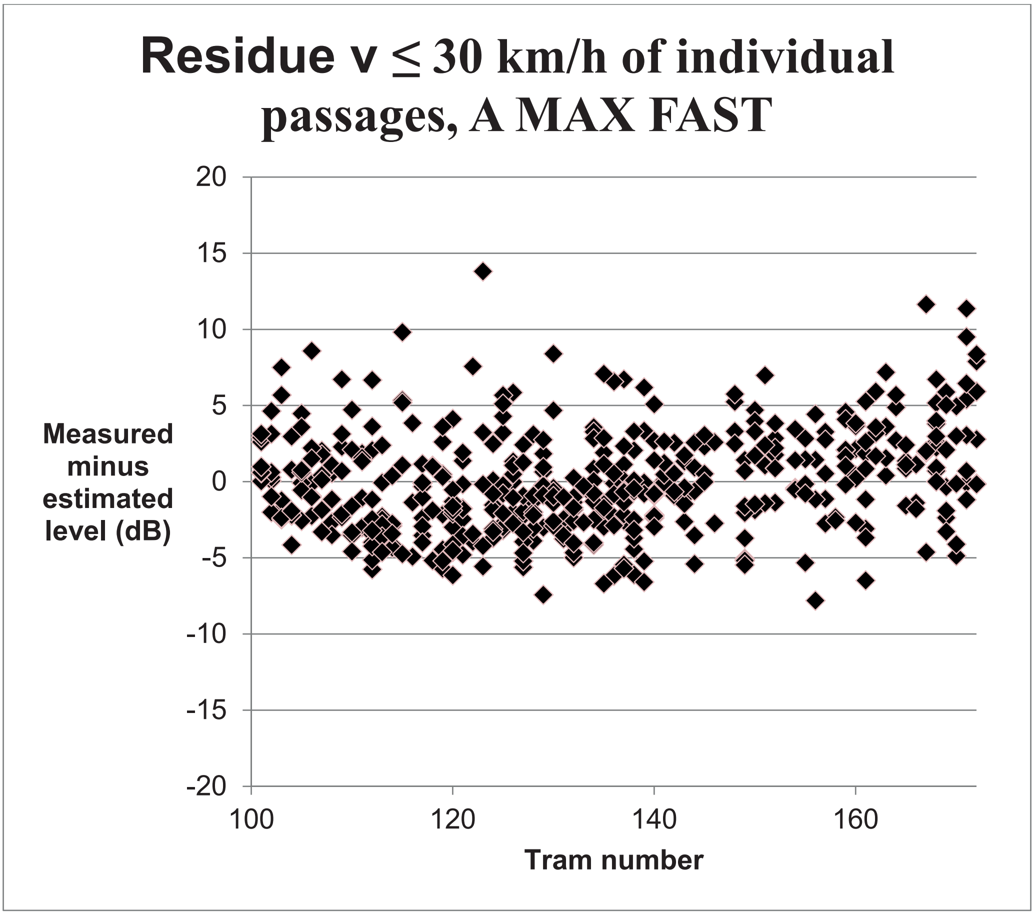


Figure 7, measured vs. estimated noise, v ≤ 30 km/h, MAX A

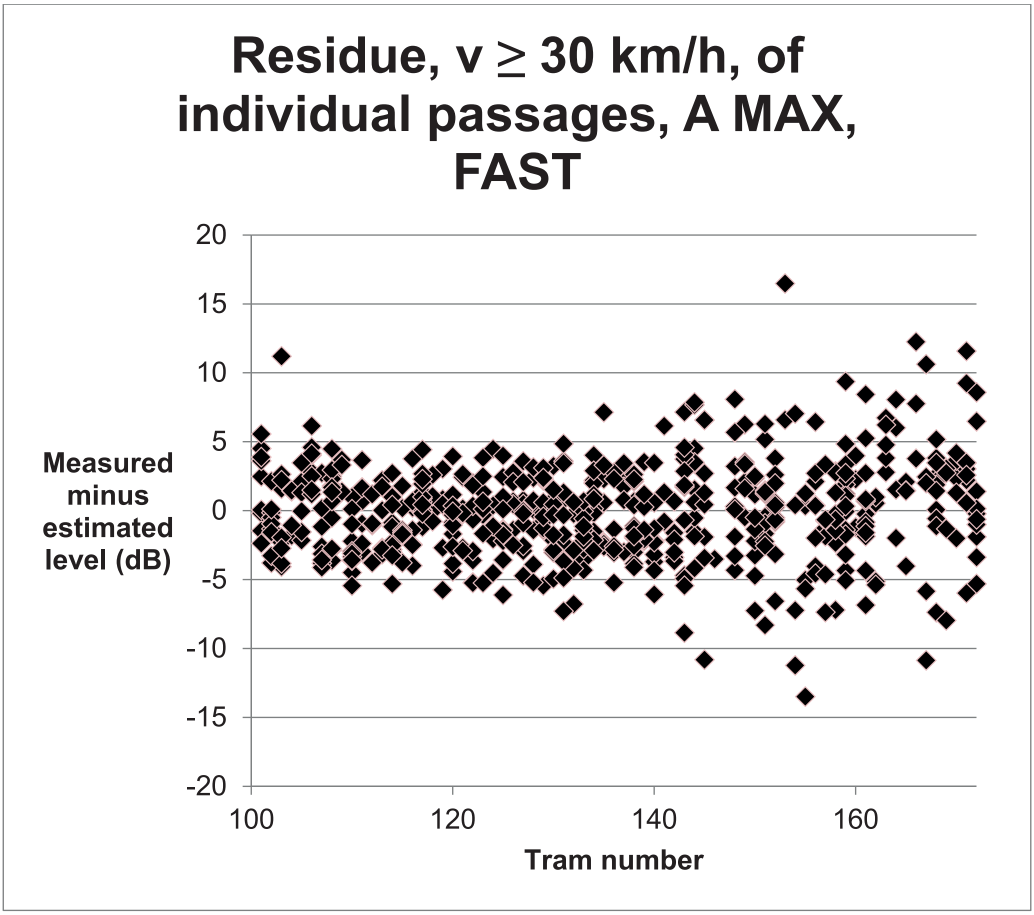


Figure 8, measured vs. estimated noise, v ≥ 30 km/h, MAX A

The figures show that the estimated level lies within ± 5 dB for about 85% of the individual passages. The passages where the measured maximal level exceeds the estimated level by 10 dB or more are exceptional cases. This means the formulas obtained can be used for prediction of aggregate measures of equivalent levels like L_{eq} or L_{den} . They can also be used for estimates of L_{max} or L_{5AF} as long as all the parameters are inside the range that has been in use.

It is generally not advisable to remove especially noisy or escpecially quiet tram passages (outliers) from a multivariate statistical analysis unless there is something clearly wrong in the measurement in question. The largest difference between estimated and measured SEL is 11,2 dB. The largest difference between estimated and measured MAX is 16,5 dB. Both these are from the same passage of tram # 153, which has been identified as a noisy tram.

7. Further research

The results as given are only applicable to the trams of Oslo. However the methods described are applicable to any urban railbound transport system. It would be of great interest to try the methods in other cities. A program for noise monitoring of the metro trains of Oslo is under planning and expected to start in the spring of 2016.

8. Conclusions

An environmental noise monitoring program has been described. It has been shown that this environmental noise monitoring could be developed into an empirical model for noise prediction using multivariate statistics.

References

1. A study of the noise of Sheffield supertram - R B W Heng - Internoise 1996 Liverpool, pp. 427-432

2. Noise measurements on the Oslo Tram. – Atle Stensland, Tore Fodnes Killengreen, Sigmund Olafsen, proceedings Internoise 2012, New York.

3. Noise comparison of Helsinki street car rail structures - Henrik Möller & Mats Backholm – Baltic Nordic Acoustical Meeting 1988 Tampere, pp 247 - 250

4.Målinger av støy iht. måleprogram for trikken – Måleresultater 2012, Tore Fodnes Killengreen, Sigmund Olafsen, Atle Stenslad (in Norwegian only). Report of measurements up to and including 2012. The 2012 report was the most comprehensive one. Yearly reports have been produced every year in the range 2007 – 2014.

5. Norske lok og motorvogner 1.1.2008. Norsk Jernbaneklubb, Forskningsavdelingen. A wealth of information about the rolling stock on Norwegian regular railways, museum railways, tram and metro lines up to 2008, collected by a private organization on volunteer basis, unfortunately only with Norwegian text.

6.ISO 3095 – 2005, Railway applications -- Acoustics -- Measurement of noise emitted by railbound vehicles

7. Noise control of tramcar noise by grinding the rails - Siegfried Riemens - Internoise 1993 Leuven, pp. 1451 – 1454

8. Rail grinding as a noise control measure - Frank Rysgaard Mortensen, Per Finne, Lars Deigaard - Internoise 2001, den Haag, pp. 147-150

9. Development and validation of a rail surface analyser for accurate quantification and evaluation of rail corrugation and track work acceptance after acoustic grinding - Geert Desanghere, Tom Vanhonacker - Internoise 2007

10. Noise and vibrations from railways depending on wheel/rail conditions - S. Junge, J.T. Christensen, I. Brinchmann – Baltic Nordic Acoustical Meeting 1994 Aarhus, pp. 357-362

11. Prediction of noise from trams - Ján Mandula, Brigita Salaiová, Mária Koval’akova´ - Applied Acoustics 63(4), 2002, pp. 373-389

12. Noise emitted by trams- Part I – investigations on emitted noise power, vertical directivity and localization of noise sources - Joël Lelong, marie-Agnès Pallas, Roger Chatagnon – Internoise 2007, Istanbul

13. Noise emitted by trams – part II: development of a tram noise emission model - Marie-Agnès Pallas, Joël Legnon, Roger Chatagnan – Internoise 2007, Istanbul

Article II

BNAM2012
Joint Baltic-Nordic Acoustics Meeting
June 18th - 20th 2012 Odense, Denmark

Difference in levels of groundborne noise and vibrations between the T-1300 and MX-3000 metro trains in Oslo

Sigmund Olafsen
Brekke & Strand akustikk, P.O.Box 1024 Hoff, NO-0218 Norway, sigmund.olafsen@brekkestrand.no

Lunds Tekniska Högskola, Box 218, SE-22100 Lund, Sweden

The introduction of the new MX 3000 metro trains in Oslo led to complaints about increased vibrations. Measurements of groundborne noise and vibrations in three sites during the transition period confirm that these spectra had indeed changed. The values measured at the three sites in question were as follows:
Site A: Vertical vibrations in two separate points on the ground outside the house
Site B: Vertical vibrations on a floor inside the house, groundborne noise in a bedroom
Site C: Vertical vibrations on the ground. In all the points there was a significant difference between the T-1300 and the MX 3000 trains. The difference in the weighted overall levels given as A-weighted sound level and vibrations given as weighted vibration velocity showed a clear increase in all cases. However, the spectra also exhibit a clear change in spectral content. The peak frequencies show a shift. The three cases clearly show that change of train type may introduce new sound and vibration problems in urban transport. These changes in perceived noise and vibration may not be obvious from the quoted noise and vibration data for new types of trains.

1 Introduction

Oslo has had a regular metro service since the 1960's. Many of the original "red" trains in slightly varying editions had been in service for 40 years when the new Siemens MX-3000 trains were introduced in 2006. The measurements of the noise and vibrations from the older types presented in this paper are from the T-1300 series, the last type of the "red" trains. Shortly after the introduction of the new MX 3000 trains complaints were heard about increased noise and vibrations from the new trains. Some measurements were made along lines where both types of metro trains were in use during the transition period. The main purpose of this paper is to show the potential consequences in terms of increased noise and vibrations, even though one of the intentions of introducing a new type of metro train was to achieve a reduced environmental impact on the surroundings of the line. Fortunately the airborne noise contribution from the new metro trains appears to be reduced [1,2].

Figure 1 MX 3000 train

Figure 2 – T1300 series metro train

Taken from Wikipedia

© 2005 J. P. Fagerback

2 Measurement sites

There were three sites which have been designated A, B and C. The vibration levels shown are RMS velocities, averaged and weighted according to NS 8176 [3]. Sound levels are presented as A-weighted 1/3-octave levels measured with the time constant FAST. The terms inbound and outbound are customarily used for Oslo's metros and trams. Inbound simply means the direction toward the city centre, outbound means the direction away from the city centre. Measurements on all the sites were made due to inhabitants being annoyed by groundborne noise or vibrations from the metro lines.

2.1 Site A

Site A

Site A is a detached house on flat ground, 20 meters away from the outbound track, 24 meters away from the inbound track. The maximal vibration levels arise as the outbound tracks cross a track exchange. The measurements have been made in the vertical direction using an accelerometer mounted on the ground. Acceleration was measured in two points. The measured values were converted into weighted vibration velocities in 1/3-octave bands according to NS 8176 [3].

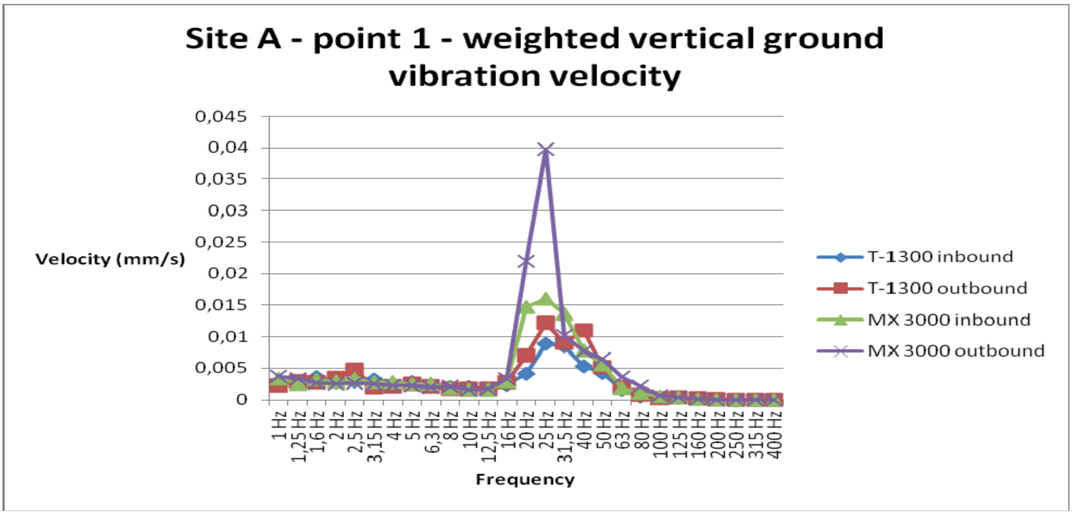


Figure 3 Site A point 1 vertical ground vibrations

Figure 3 shows the vibration spectrum from point 1 on site A. In this measurement a marked increase in vibration levels from outbound trains is clearly visible. In this case the highest levels occur at the same frequency, 25Hz. Thus it would be reasonable to assume that the same excitation mechanism is present. In this measurement point the change is an amplification of a similar phenomenon.

In the figure 4, a different point on the same site, a somewhat different picture emerges. The earlier T-1300 trains give the highest contribution to the vibration velocity at 40 Hz outbound, 31,5 Hz inbound. The recent MX-3000 trains give the highest vibration level at 25 Hz outbound, 20 Hz inbound. In addition to a higher vibration level, a downward shift of the dominant frequency can also be observed.

It should be noted that all the measured values at site A were made on the same day with the same accelerometers mounted in the same position. At that time, there was mixed traffic with both types of trains. So the explanation for the change should be sought in the dynamics of the trains or in the interaction between the train and the ground.

A track interchange is the suspected reason for the difference between outbound and inbound trains.

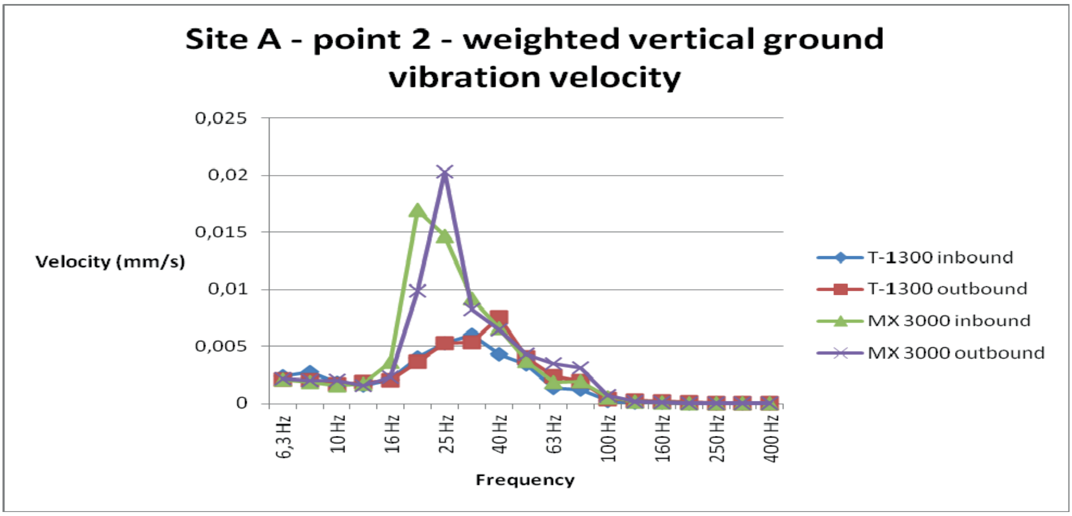


Figure 4 Site A point 2 vertical ground vibrations

2.2 Site B

Site B is a detached house situated 10 meters away from the inbound track, 14 meters away from the outbound track. It was a new house which was actually built on an insulated foundation due to the proximity to the metro line. There was a high noise barrier close to the metro line. In combination with a modern, well insulated house, this virtually eliminated airborne noise inside the house. The house had been designed to comply with applicable Norwegian regulations [4] that permit indoor maximal levels (L_{PAmax},FAST) of up to 45 dB from groundborne noise as long as the sound source is above ground. Figure 5 shows two peaks in the vibration spectrum, one at 16 Hz and one at 50-80 Hz. In this case it is no longer obvious that the MX-3000 gives a higher vibration level than the T-1300. The MX-3000 gives lower vibrations than T-1300 at 16 Hz, but higher at 50-80 Hz.

The groundborne noise measurements in figure 6 shows a slight increase in the noise level at 50 – 80 Hz from the MX-3000 as compared to the T-1300. For this site, there is clearly a change in the noise and vibration pattern from the new metro trains. For site B, this change in pattern is more important than the increase in overall level.

In this case residents perceived the noise and vibrations from the MX-3000 as more annoying than those from the T-1300.

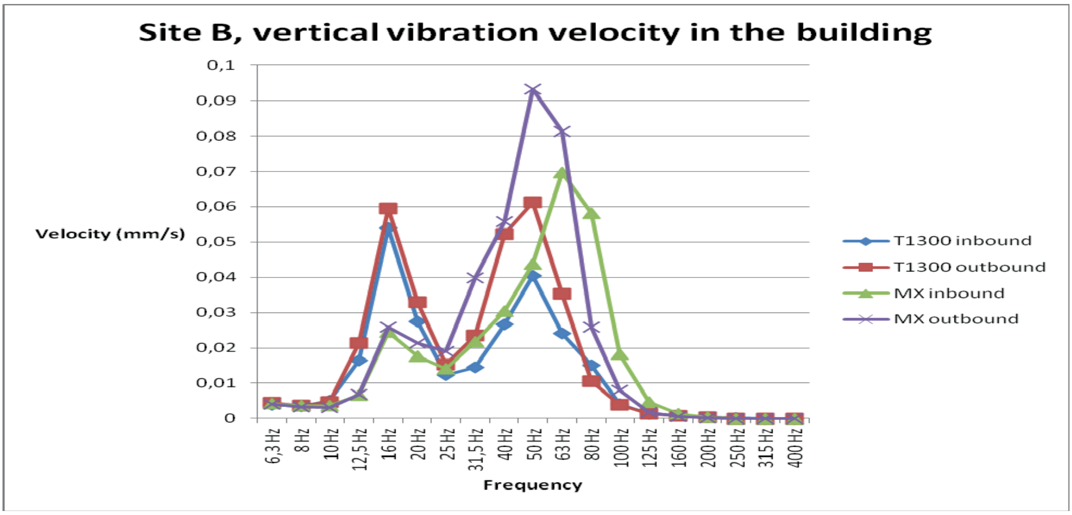


Figure 5, vertical vibrations on a floor in the building, site B

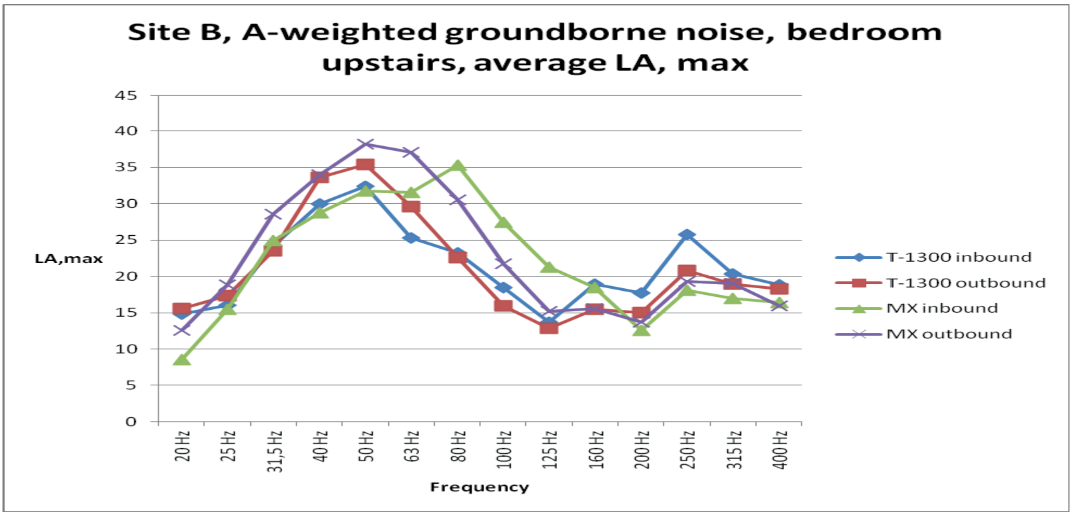


Figure 6, site B, groundborne noise in an upstairs bedroom.

2.3 Site C

Site C is a four-story multifamily block 25 meters away from the metro line. The vibration measurements were made on the ground outside the house. The measured values are shown in figure 7 below.

In this case, there are three spectrum peaks, at 16 Hz, 25 Hz and 63 Hz. The peak at 16 Hz is clearly lower with the new MX 3000 trains than with the older T 1300 type. At 25 Hz the picture is different; the inbound trains give more vibrations, it seems the difference is more due to some difference between the tracks than between the train types. The peak at 63 Hz only shows up with MX trains outbound.

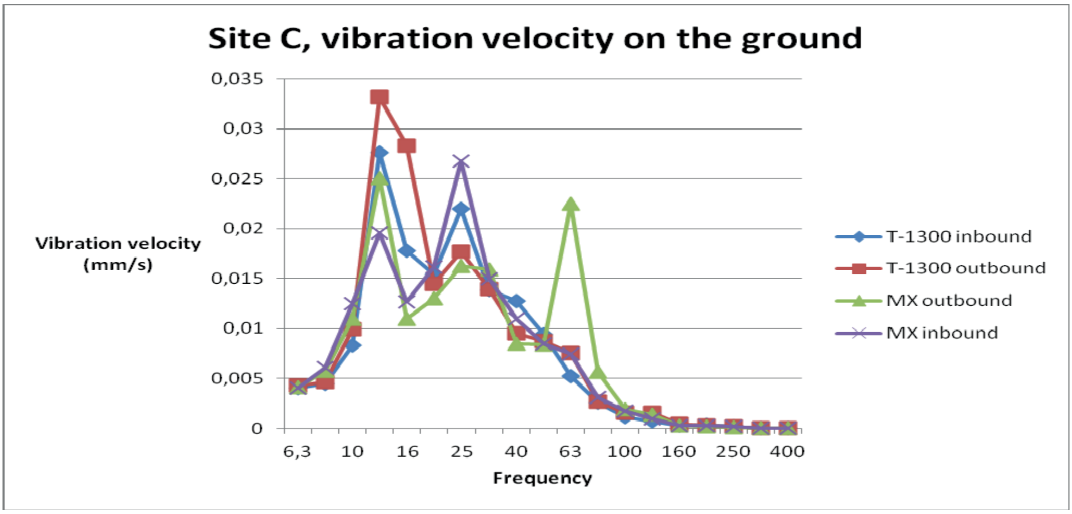


Figure 7 Vertical vibrations on the ground, site C

3 Discussion of results

The clearest result is that the new MX 3000 trains give a different spectrum of vibration and groundborne noise than the earlier T-1300 trains. It would seem that there are two or three distinct peaks in the spectrum. There are one or two peaks at 16 Hz to 25 Hz and a peak at 50 – 80 Hz.

At site A, there was clearly an increase in vibrations with the introduction of the MX 3000 trains. At site B, there was an increase at some frequencies and a reduction at other frequencies which significantly alters the perception of annoyance from vibrations. At site C, the MX 3000 clearly gives lower vibration levels at 16 Hz, there's a mixed picture at 25 Hz, and there's a marked increase in vibration levels from one of the tracks with the MX 3000 train as compared to the T 1300.

The only consistent result is that the MX 3000 trains give different patterns of vibrations and groundborne noise than the T1300 trains.

4 Further research

Urban railbound transport lines are often located very close to residences. Our results show that it is very difficult to predict the consequences for nearby residences when a change of train or tram type is considered. This situation needs to be improved. Railbound vehicles are a very energy efficient means of transport, and lack of space will force residences to be located close to transport lines.

This means that reliable methods to predict vibration transmission at very short distances will be required. A deeper understanding of how to predict vibrations from trains to the ground at the design stage seems to be important. Hopefully it will be possible to investigate the dynamic properties of the bogies and wheels of the MX 3000.

Another challenge that needs to be investigated further, is that the metro lines often run very close to residences. In these cases a traditional model of a vibration source, a transmission path and a receiver is not always applicable. A substantial number of measurements of vibration along three axes in several points on the ground, on the building foundation and on the floors or rooms in residences should be made. This could possibly provide a database of transmission into the building. Different types of ground conditions have different transmission properties, and so a train that gives modest vibrations in one city or on a test track could give more severe vibration problems at another site. The same applies for buildings. Different construction practices could give rise to different vibration problems.

5 Acknowledgements

My sincere thanks go to my Ph. D. Mentor Delphine Bard at LTH and my colleagues at Brekke & Strand akustikk, in particular Arild Brekke, Atle Stensland and Tore F. Killengreen.

6 Conclusions

The transition from the old T1300 type trains to the new MX 3000 trains on Oslo's metro lines gave rise to a changed pattern of vibrations and groundborne noise. Further research into vibration generation and transmission is recommended.

References

[1] MX 3000 og andre tog. (In Norwegian only). *A report from test measurements performed in order to acquire input data for calculation of noise from the MX-3000 trains*, Brekke & Strand akustikk as, May 26th 2006.

[2] S. Olafsen, T. Killengreen, Measurements of curve squeal from Oslo's subway. Proceedings Acoustics '08, Paris 2008

[3] NS 8176, Vibration and shock - Measurement of vibration in buildings from landbased transport and guidance to evaluation of effects on human beings (august 2006)

[4] NS 8175, Acoustic conditions in buildings. Sound classification of various types of buildings, 2008

Article III

大阪
inter.noise 2011
Osaka Japan September 4-7

Sound insulation measurements of facades with variable microphone positions

Sigmund Olafsen[1,2]

[1] Brekke & Strand akustikk as

P. O. Box 1024 Hoff, NO-0218 Oslo, NORWAY

[2] Lunds Tekniska Högskola

P.O. Box 118, SE-22100 Lund, SWEDEN

ABSTRACT

The ISO standard 140/5 specifies measurement methods for facade sound insulation using microphones positioned on the facade or at a distance of 2 meters. The reason for the latter variant is that interferences can take place between the direct and the reflected sound when the microphone is placed in front of the facade at a close distance. Unfortunately, it is not always relevant or practically possible to determine the sound insulation of the whole or a part of a facade using the specified microphone positions. The practical consequences of interference effects are investigated for two suggested techniques for sound insulation measurements. The first type of measurement uses various combinations of loudspeaker and microphone positions. For these measurements the accuracy will be discussed in terms of the statistical properties in third octave bands. The second type of measurement uses microphone sweeps in front of the facade. For the sweep measurement technique the difference between the measured values using sweeps and the measured values using microphone positions on the facade have been investigated. In addition the statistical properties of the measured values obtained with the sweep technique are investigated.

Keywords: Façade, Measurement, Insulation

1. INTRODUCTION

There are two major reasons for performing measurements of sound insulation of facades:

- To determine the indoor noise level from outdoor sources.
- To check compliance with sound insulation specifications for building components.

The current international standard ISO 140/5 [1] gives a description of how to perform the measurement of the sound insulation of the façade or the building component in question. The requirements of mounting the microphone either on the façade or 2 meters in front of the façade are often difficult to fulfill during field measurements, however. As there's a growing awareness of the need to secure a quiet indoor environment, there's also a growing demand for control measurements of façade sound insulation. The challenge of measuring the sound insulation even if the requirements of ISO 140/5 cannot be met in the practice has been addressed through research and field studies [2,3,4,5]. The main difficulty encountered when placing the microphone in front of the façade is interference between the direct sound and the reflected sound from the façade. In this paper an example of a field measurement shall be presented where the sound level was measured using a loudspeaker at a short distance. The different microphone positions are compared both in terms of measured level and uncertainty.

The purpose of investigations of façade sound insulation is to ascertain acceptable indoor noise levels. The frequency range under consideration is limited to 50 Hz to 5000 Hz, as this range is most relevant for indoor noise from outdoor sources. The uncertainty in measurements of façade sound insulation lies in the determination of the outdoor level. The sound field indoors is more easily described correctly and with known uncertainty [1,3,6] and is not analyzed further in this paper.

---

[1] Sigmund.olafsen@brekkestrand.no

2. THEORETICAL CONSIDERATIONS OF INTERFERENCE EFFECTS

The potential problems of interference between direct and reflected sound can be illustrated by a simple calculation. The situation shown in figure 1, slightly modified from an earlier presentation [5] can serve as an example.

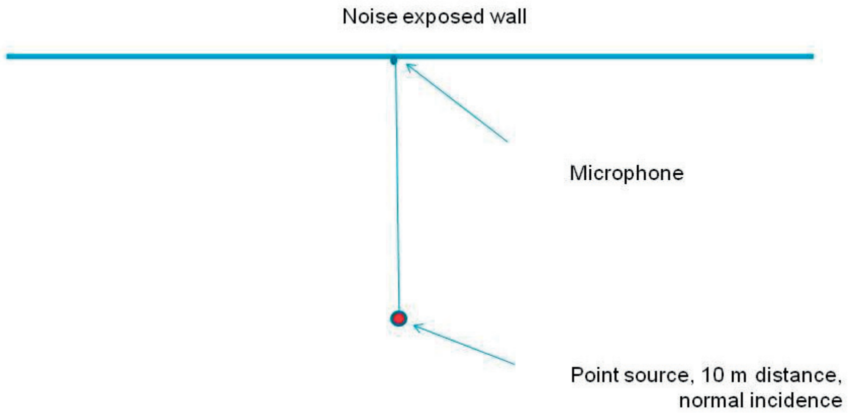


Figure 1 Illustration of the problem of interference between direct and reflected sound

The calculated value is the sound pressure level relative to the free field value. In the calculations the following assumptions are made:

- The wall acts like a mirror reflector of sound
- The sound comes from an ideal monopole source giving free hemispherical propagation over hard ground
- Only direct sound and one reflection from the wall is included
- Only geometric attenuation is considered
- The calculations are made only for pure tones at the standardized 1/3-octave band centre frequencies in the frequency range 50 Hz - 5000 Hz

These assumptions lead to a pronounced comb filter effect when the microphone is placed in front of the façade. There will be a clear destructive interference at frequencies where the difference in path length between direct and reflected sound is close to half the wavelength at that frequency. Similarly, a 6 dB reinforcement should be expected at frequencies well below the first frequency giving destructive interference.

The presented results are shown as a theoretical example in order to investigate the properties of the comb filter under the given assumptions. More extensive calculations using multiple sources or multiple frequencies in each 1/3-octave band give similar results, indicating that the results might also be valid for a broadband line source like real traffic noise or white noise from several loudspeakers.

The calculated values are shown for a distance from the wall of 0,01m, 0,015m, 0,02m, 0,03m and 0,1m (figure 2) and 0,2m, 0,5m, 1m and 2m (figure 3).

These curves show that measurements in front of a façade, especially at distances between 0,1 meter and 0,5 meter, may be disturbed by irregular interference. The calculations presented are valid for a point source and a single microphone position. Research is already going on to analyze the consequences of including multiple reflections [2]. In the following a different approach will be applied, to look at a field measurement and indicate possible solutions to the problem of interference.

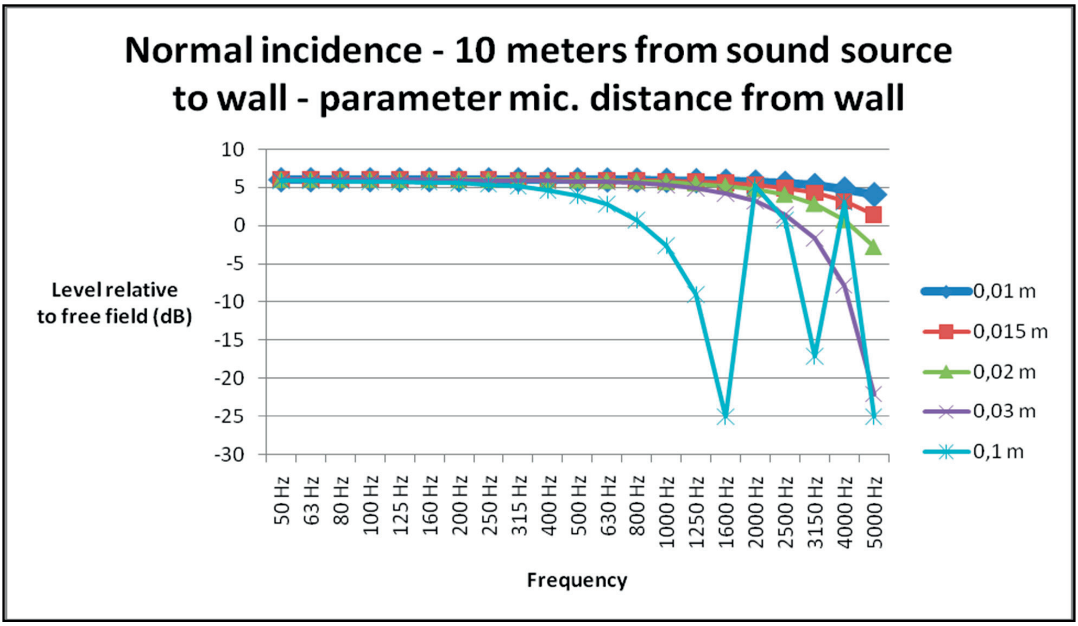


Figure 2 Calculated sound levels at microphone positions at various distances from the wall, 0,01 to 0,1 m

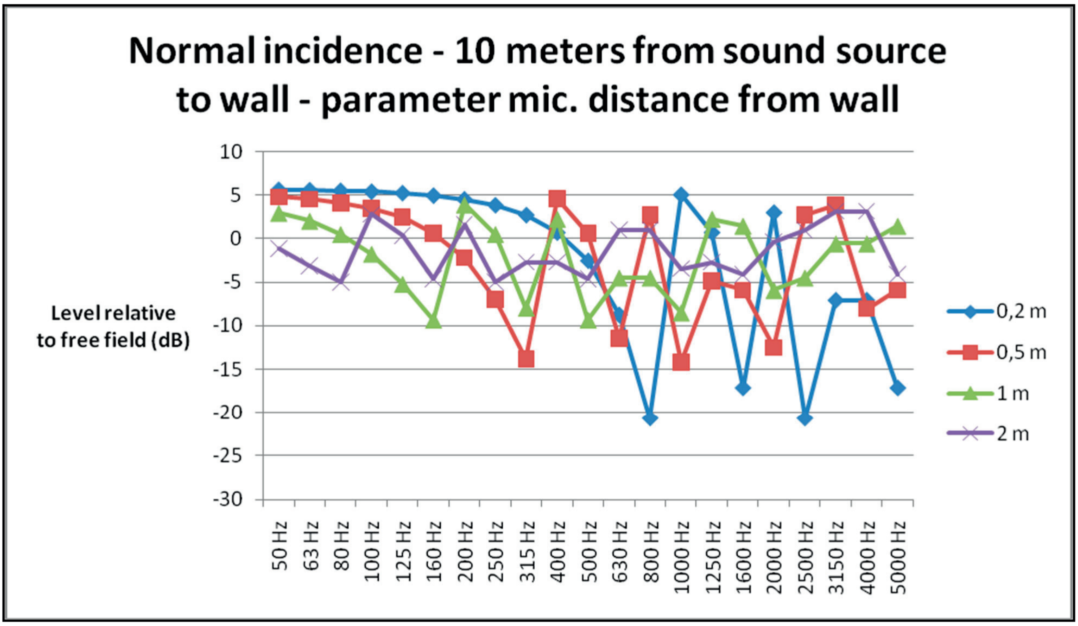


Figure 3 Calculated sound levels at microphone positions at various distances from the wall, 0,2 to 2 m

3. AN EXAMPLE TO SHOW THE CHALLENGES OF FIELD MEASUREMENTS

In the following is shown an example that demonstrates some of the challenges encountered when trying to measure the sound insulation of a façade in the field. Figure 4 shows a balcony of a 4th floor apartment where the resident was not satisfied with the sound insulation from the street to the bedroom inside the balcony. The measurements in this example of a field study were made with the loudspeaker on the balcony, and the frequencies where interference occurs are different from the ones in our theoretical example.

Figure 4, a typical case where the sound insulation of the façade was to be measured

The traffic noise does not give a sufficient signal to use it for sound insulation measurements, so the loudspeaker had to be put on the balcony itself. Two loudspeaker positions were used. Three different methods were used in order to investigate the sound field on the balcony:

- Microphone mounted on the window, N = 10 fixed positions, 5 for each loudspeaker position
- Microphone in front of the façade at points on a tripod, at 0,25 meters distance in front of the façade, N = 11 fixed positions total for the two loudspeaker positions
- Microphone swept in front of the façade, at 0,25 meters and 0,50 meters distance, one sweep for each loudspeaker position. The sweep was made at an even speed moving the microphone continuously, the four performed sweeps lasted between 39 and 48 seconds.

The distance from the loudspeaker to the façade was 1,6 meters. A Norsonic 280 power amplifier/noise generator was used to drive a Norsonic 250 semi-dodecahedron loudspeaker. The sound level was measured using a Norsonic 118 parallell analyzer equipped with statistical analysis in 1/3-octave bands. The measurements with fixed microphone positions have been analyzed based on the equivalent level. The measurements with microphone sweeps have been analyzed using the equivalent level as well as the L_5 and L_{95} in 1/3-octave bands.

4. MEASUREMENT RESULTS - AVERAGES

In figure 5 the results of the measurements are given. The microphone positions directly on the window have a nominal +6 dB façade reflection, the microphone positions in front of the façade and the sweeps have a nominal +3 dB façade reflection. The equivalent level is the absolute value of the energy average for each type of measurement. The values from the fixed positions and the sweeps have been corrected with +3 dB in order to be comparable with the measurements on the windows.

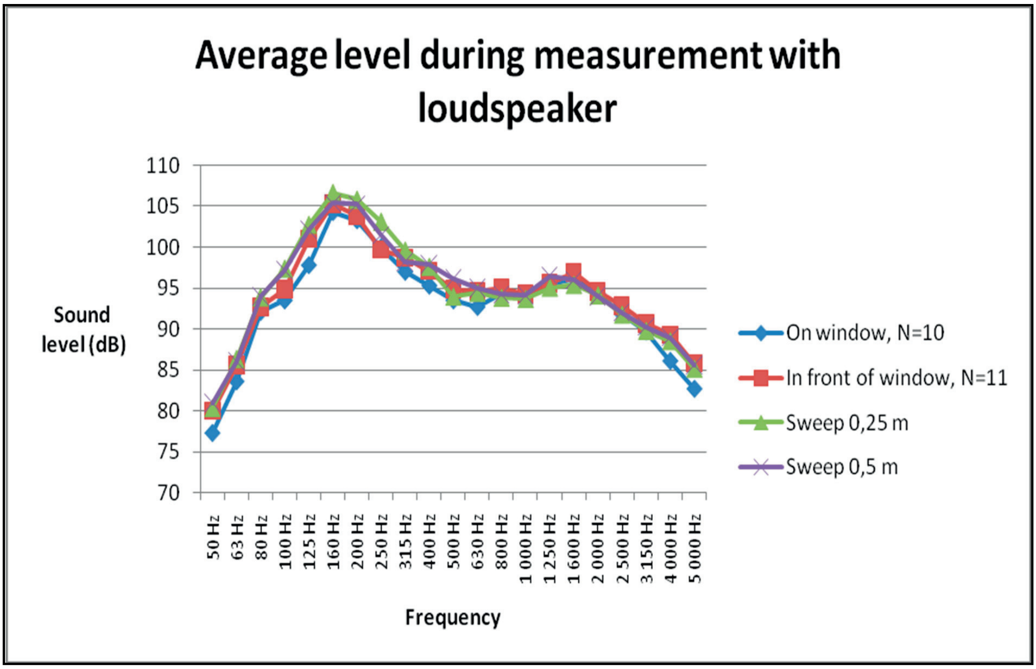


Figure 5 Measured level on and in front of window

In order to clarify differences between the methods of measurement, the level differences are shown in figure 6. The energy average of the measurements with the microphone on the window are set to 0 dB, the results for the other measurements are shown relative to the energy average of the measurements of sound level on the window.

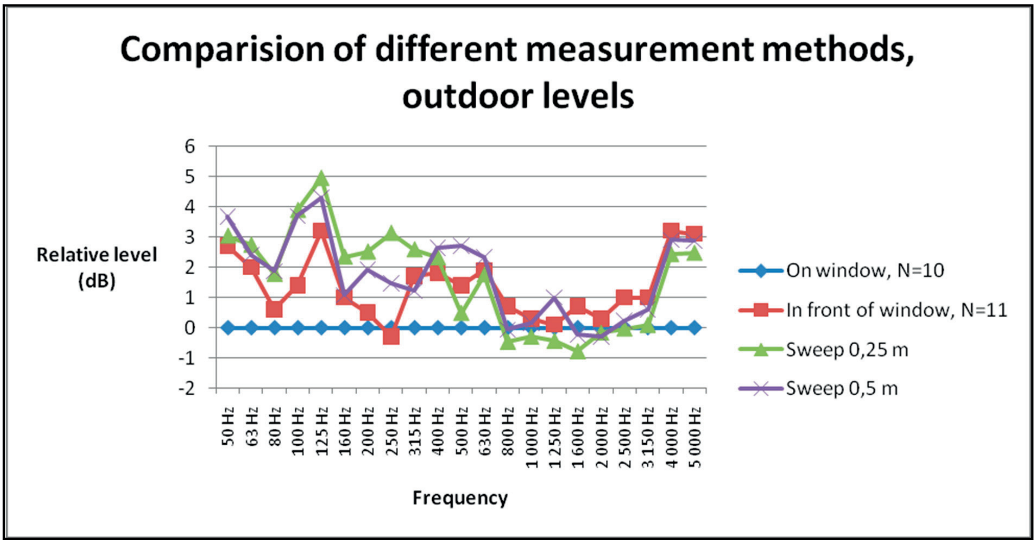


Figure 6 Relative averaged sound level of different types of microphone positions

5. MEASUREMENT RESULTS – UNCERTAINTY

For the measurements with fixed microphone positions the discussion of the uncertainty is based on the standard deviation between these positions. For the sweeps the duration of the measurement is sufficient to allow for the use of the statistical properties of the measurement itself. Figure 7 below shows the calculated standard deviation in the measurement series on the façade and the series using fixed microphone positions in front of the façade.

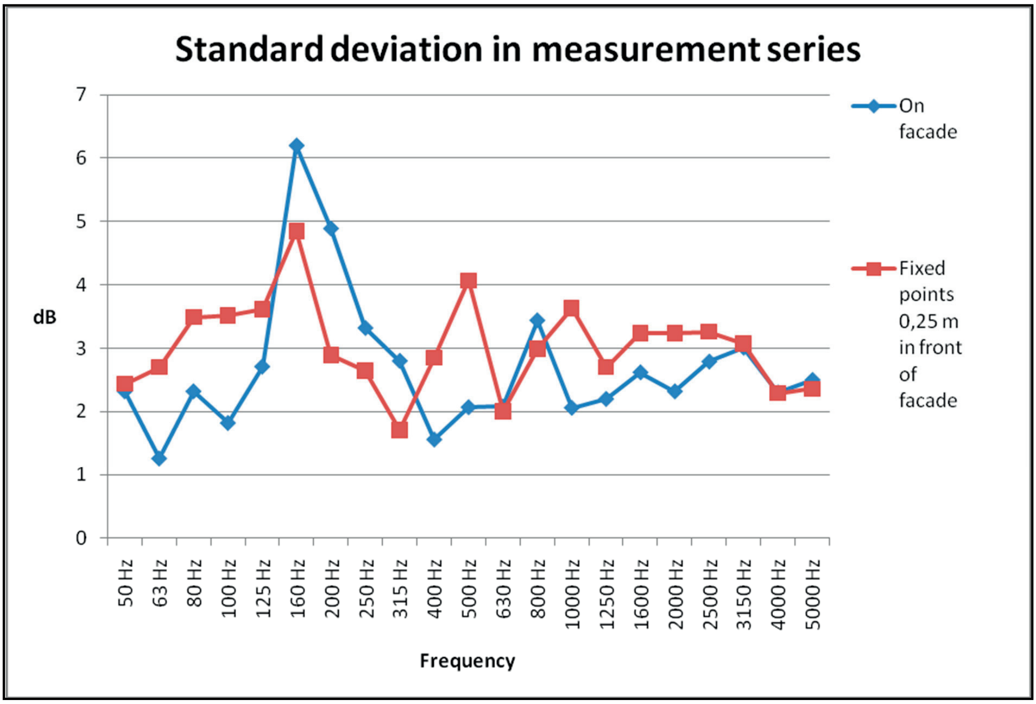


Figure 7 Standard deviation of measurement series with microphone in different fixed positions

The 160 Hz band is clearly most critical for both methods. In this case the uncertainty seems higher for the microphone positions on the façade than for the microphone positions in front of the façade.

For measurements using microphone sweeps the statistical properties of each measurement are given directly from the instrument. The Norsonic 118 equipped with the statistics option [7] (Option 4: Statistical calculation of LN values) automatically measures the statistical level distribution in 1/3-octave bands in parallel during the measurement. For these sweeps the difference between the L_5 (the sound level exceeded during 5% of the measurement time) and the L_{95} (the sound level exceeded during 95% of the measurement time) is assumed to be a good approximation of the width of the 90% confidence interval.

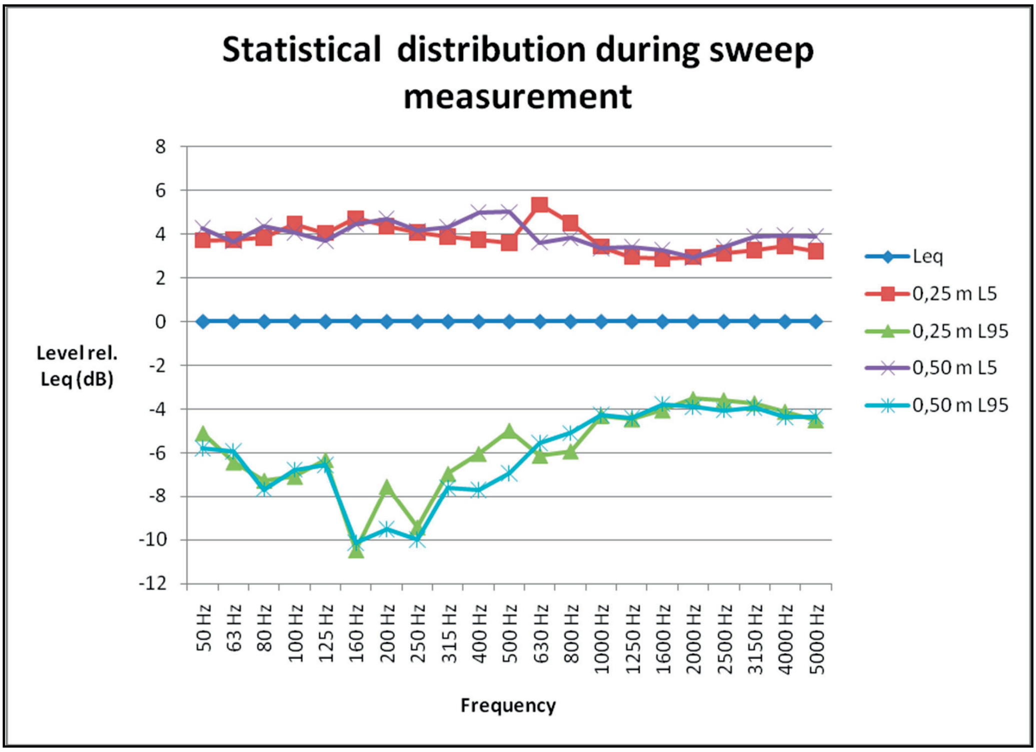


Figure 8 Statistical properties of sound level during microphone sweeps at 0,25 m and 0,50 m

The L_5 (the level which is exceeded during 5% of the measurement) shows an even curve, but the L_{95} (the level which is exceeded during 95% of the measurement) shows clear dips at 160 – 250 Hz. Clearly this frequency range is critical. In some points there must a clear destructive interference at these frequencies.

6. DISCUSSIONS AND FURTHER RESEARCH

The shown example from a field study indicates that measurements can be made with the microphone in front of a façade equally well as on the façade. It would seem that there is no gain in accuracy using microphone positions on the façade compared to microphone positions in front of the façade. This paper only shows results from one measurement, however other, still unpublished, measurements give similar indications. There are several avenues of research that will be investigated further:

- A number of tests during field façade sound insulation measurements should be made. During each of these tests microphone positions on the façade, fixed positions in front of the façade and microphone sweeps in front of the façade should be used.
- It should be controlled whether the taping of a microphone onto a window influences the mechanical properties of the window so much that it changes the result of the sound insulation measurement to a significant extent.
- Analysis by theoretical calculations and/or measurements to determine the actual reflection properties of typical façade materials should be made.
- Investigations into the consequences of measurements using a source position quite close to the façade to be measured should be made. In cases like balconies or external corridors this is the only available solution.

It should also be noted that for the global methods in ISO 140/5 [1] using a microphone position 2 meters in front of the façade, it is stated that “The precision is not known”.

7. CONCLUSIONS

The presented field measurement indicates that the interference between direct and reflected sound can be averaged out either by sweeping the microphone in front of the façade or by measuring using a sufficient number of fixed combinations of loudspeaker and microphone positions. It would seem that the façade does not quite act as a mirror reflector of sound.

In the field it is not always possible to mount a microphone directly onto the façade for measurements of sound insulation. In these cases it is fully acceptable to use either:

- microphone sweeps at 0,25 m or 0,5 m in front of the façade or
- a sufficient number of fixed microphone positions in front of the façade

in order to determine the outdoor level for use in a façade sound insulation measurement.

ACKNOWLEDGEMENTS

My sincere thanks go to all my colleagues at Brekke & Strand akustikk for daily inspiration.

REFERENCES

[1] ISO 140/5. Acoustics - Measurement of sound insulation in buildings and of building elements - Field measurement of airborne sound insulation of façade element and facades, 1998.

[2]Umberto Berardi, Ettore Cirillo, Francesco Martellotta
"Interference effects in field measurements of airborne sound insulation of building facades", proceedings Internoise 2010, Lisboa

[3]Sigmund Olafsen, "Sound insulation against traffic noise in wooden houses", proceedings BNAM 2002, Lyngby

[4]Sigmund Olafsen, Per Kåre Limmesand, "Control of sound insulation in glass facades at Oslo's Opera House", proceedings ICA, Sydney, 2010

[5]Sigmund Olafsen, "Prediction and measurement of indoor noise from road traffic", lecture at Tsinghua University Building Acoustics Forum, Beijing, 2011

[6]Sigmund Olafsen, Lars B. Hov, "Room acoustics considerations for indoor noise from road traffic", proceedings BNAM 2004, Mariehamn

[7]Norsonic product description, http://www.norsonic.com/index.php?sideID=1492

Article IV

Methods of field measurements of facade sound insulation

Sigmund Olafsen[a], Delphine Bard[b], Maria Kristin Strand[c] and Teresa Fernández Espejo[c]

(Received: 3 July 2015; Revised: 14 October 2015; Accepted: 14 October 2015)

The purpose of this article is to describe generally usable methods to measure the sound insulation of a facade in cases where a setup according to standards such as ISO 140/5 or ISO 16283/3 cannot be achieved. The methods discussed use a loudspeaker as the source of a test signal since background noise on the interior receiving side in many cases prevents the use of traffic as a noise source. The measurements presented in this article have been made using two loudspeaker positions at different angles. Three different ways of placing the microphone are considered. The microphone can be placed in fixed points directly on the facade, in fixed points at the same distance in front of the facade, or swept in front of the facade. The data presented are all taken from actual field measurements. The results are shown as a comparison between the levels acquired and the uncertainty associated with the different methods.

Primary subject classification: 51.3; Secondary subject classification: 72.5

1 INTRODUCTION

This article deals with methods to measure facade sound insulation where the available space is insufficient to allow measurements according to current international standards. This may be because there is no practical way to place the loudspeaker 5 or 7 m away from the facade, or it may be because there is no access to the facade in order to mount the microphone directly onto the facade.

The introduction has been divided into three parts. Section 1.1 deals with reasons to measure facade sound insulation. Section 1.2 describes briefly the history of methods for measurement of facade sound insulation. Section 1.3 introduces what have been considered the main challenges when the microphone is placed at a short distance in front of the facade.

This article will deal with the outdoor sound field only. Furthermore, the description will be limited to results from actual field measurements. In most of these cases the measurements are not completely according to standards such as ISO 140-5[1] or its successor ISO 16283-3[2] as this has not been possible. The indoor sound field in the frequency range of interest can normally be measured to a sufficient accuracy using fixed microphone positions or sweeps[3]. In Sec. 2 the outdoor microphone positions used are described. Section 3 gives a discussion of the level differences between different microphone positions. Section 4 deals with the internal validity within each type of microphone position.

1.1 Reasons to Measure Facade Sound Insulation

There are two important uses of measurement of facade sound insulation:

1. Indirect measurement of indoor noise level by means of measuring outdoor noise level and facade sound insulation
2. To check compliance of a component or of the whole facade with given regulations or design specifications

The first of these main reasons comes into its own when indoor background noise level is too high to allow direct measurement of indoor noise levels[4] from outdoor sources like road or rail traffic. In these cases the indoor noise spectrum is measured indirectly as:

$$L_{i(f)} = L_{o(f)} - D_{(f)}, \quad (1)$$

where

- $L_{i(f)}$ is the indoor noise spectrum, level as a function of frequency, usually in 1/3-octave bands;

---

[a] Brekke & Strand akustikk as, P.O. Box 1024 Hoff, NO-0218 Oslo, NORWAY and Lunds Tekniska Högskola, Box 118, 22100 Lund, SWEDEN; email: Sigmund.olafsen@brekkestrand.no.

[b] Lunds Tekniska Högskola, Box 118, 22100 Lund, SWEDEN.

[c] Brekke & Strand akustikk as, P.O. Box 1024 Hoff, NO-0218 Oslo, NORWAY and Lunds Tekniska Högskola, Box 118, 22100 Lund, SWEDEN.

- $L_{o(f)}$ is the outdoor noise spectrum measured outside the facade;
- $D_{(f)}$ is the level difference between outdoor and indoor noise measured with an artificial noise source, usually a loudspeaker.

It is essential that these measurements are made with a suitable spectral resolution. In the case of road or rail traffic noise 1/3-octave bands are usually a quite suitable bandwidth.

The second main reason for measurements of facade sound insulation is to control whether a building component or a facade as a whole complies with design requirements. This may be used to check a whole facade like a wall at an airport or a component like a window in a concrete wall in a residential building.

1.2 A Brief History of Methods of Facade Sound Insulation Measurements

The first systematic compilation of possible alternative solutions for the practical execution of measurement of level difference or sound insulation in building facades dates back to the early 1970s[5]. Investigations of the relative merits of varying microphone positions also have a long history[6]. There have also been made investigations into how to place a loudspeaker. These investigations include how far away from the facade the loudspeaker should be placed, at what angle it should be placed and which requirements should be set to the directivity of the loudspeaker[3,7,8]. The relevant international standards describe where to place a loudspeaker[1,2]. It is sometimes difficult to adhere completely to the current international standard for field measurements of sound insulation measurements of whole facades or facade elements. These standards prescribe measurements with the microphone directly on the facade for building components or 2 m in front of the building for whole facades. These positions are most likely given in order to avoid problems with interference between the direct sound and reflections from the facade. Theoretical calculations indicate that such interference could be a severe problem[9–12] due to a "comb filter" effect. This comb filter effect is caused by the sound wave reflected from the wall being out of phase with the direct sound wave from the sound source. The problem would be expected to be most severe at the frequency where the difference in pathway between direct and reflected sound is equal to half the wavelength. The lowest frequency with destructive interference at the outdoor microphone position could potentially coincide with the double wall resonance of a window[13], giving rise to an uncertain estimate of indoor noise levels. There are also national standards, e.g. in Norway, that require outdoor noise to be measured either with the microphone on the facade or in a free field without interference from buildings[14]. However, in many cases the field measurements of sound insulation must be made with the microphone in front of the facade[15,16]. This may be the case in narrow city streets or other situations where the facade is not accessible. It may also be the case in situations where the only possible solutions to be able to measure sound insulation are to raise the microphone from the ground with a telescopic rod or to hang the microphone cable from the roof.

1.3 The Challenges of Mounting the Microphone in Front of the Facade

This article will discuss the relative accuracy of measuring with the microphone on the facade compared to measurements with the microphone in front of the facade. The frequency range under consideration is the 1/3-octave bands from 50 to 5000 Hz, which is considered the building acoustics frequency range[11]. Measurement of sound insulation at frequencies below 50 Hz is not an easy task in the field and requires a large sound source. At frequencies above 5000 Hz there is rarely a problem, as these frequencies are attenuated in most constructions, even with poor craftsmanship.

There are, however, theoretical difficulties when using microphone positions on the facade as well as for fixed microphone positions or sweeps in front of the facade. One problem is that measurements with microphones positioned on the facade are not directly comparable to laboratory sound insulation measurements for building components. These laboratory measurements are performed between two reverberant rooms. Another problem is that, strictly speaking, the given method in standards[1,2] for building components is only valid when the component to be tested in the field has a much lower sound insulation value than the rest of the facade. This last condition is typically met for a window with low sound insulation values mounted in a brick or concrete wall. For a window with high sound insulation values mounted in a lightweight wooden wall the window could sometimes even have a better sound insulation than the wall. To many readers this case may seem rare, but it is quite often met in practice in Norway, where there are many houses with wooden or other lightweight facade walls and windows with high quality double glazing. Thus the requirements for a field test of a building component according to ISO 140/5, appendix B, could be violated in many cases.

2 METHOD

The loudspeaker method of ISO 140/5 and ISO 16283/3 requires a distance of at least 7 m from the loudspeaker to the facade to be measured. In the great majority of the cases, this distance is simply not available. The assignments have been to measure the sound insulation of a facade and/or to determine an indoor sound level from outdoor sources. Some possible reasons that the desired geometric configurations are not available may be:

- The facade to be tested is in a narrow street where the loudspeaker has to be placed on the pavement and the microphone must be swept outside the facade to be evaluated, or the facade is inaccessible for other reasons.
- The task is to verify the sound insulation of the facade between an external corridor and a bedroom, where only the width of the external outdoor corridor is available.
- The task is to determine the indoor noise level in a house by the roadside at a distance of 3 or 4 m from the highway, again a loudspeaker at a distance of 7 m is impossible.
- The measurement must be made from a lift which allows for neither a sufficient distance from the facade nor access to direct mounting of the microphone on the facade.
- The facade in question is behind a balcony which is open to the side, but has another balcony hanging over and/or standing beside it, thus introducing reflections from the sides.

Theoretical calculations indicate that a comb filter effect is to be expected with a microphone as close to the facade as 0.25 m[9,10]. ISO 140/5[1] stated in a note about a global loudspeaker method: "Because of uncontrolled interference effects, systematic errors will occur, particularly at low frequencies," and this statement applies at a distance of 2 m in front of the facade. The purpose of the present investigation is to quantify these systematic errors and investigate the consequences of measuring at a short distance in front of the facade. Previous calculations[10] indicate that with a perfectly reflecting facade, no other reflecting surfaces and a perfect point source in a single position generating the noise, the comb filter would show up at the high end of the building acoustics frequency range, around 5000 Hz, with a microphone at a distance of 0.03 m in front of the facade. This type of calculation indicates that the lowest frequency where comb filter effects should be expected will go down as the distance from the facade is increased. Even at 2 m distance in front of the facade these calculations show a pattern of interference effects in 1/3-octave bands, to some extent influencing the whole building acoustics frequency range from 50 to 5000 Hz.

The calculations mentioned above are based on assumptions of a perfectly reflecting facade, no other reflecting surfaces and a point source generating the noise. These assumptions are clearly not fulfilled in real measurements. The facade will always have some absorption and some diffraction, often there are other reflecting surfaces, and the loudspeaker has finite dimensions. This article describes a way of handling the problems by analysis of the results of several field measurements where at least two, normally three different types of microphone position as well as at least two loudspeaker positions have been used. Measurement results from 59 facades are included in this article. Only 13 of the cases studied had reflections from only the facade under study. The remaining 46 also had other reflections from other structures in the vicinity.

2.1 Overview of Main Types of Measurements

There are three different types of positions of microphones that have been investigated.

- Microphone placed directly on the window, at least 5, normally 10 different positions of the microphone for each given loudspeaker position have been used.
- Microphone in front of the facade, at fixed positions at a distance of 0.25 m.
- Sweep in front of the facade, at a distance of 0.25 m.

The primary focus of the article is to show the observed difference between these different types of microphone positions. Sometimes a sweep in front of the facade is the only viable way of measuring the outdoor sound level during a measurement. This generates a need for knowledge about how this type of measurement relates to measurements with the microphone directly on the facade.

It could be useful to mention three types of idealized sound fields before going more into detail about the individual types of measurement. The first type of sound field is the free field, where there are no reflections at all. This case does not occur when measurement of facade sound insulation is performed. Another type of sound field is a diffuse field, where reflections are equally likely to occur in any direction. This case would correspond to a 3 dB increase in sound level compared to free field conditions. The third and final type of idealized sound field is the case with all reflections being in phase with direct sound, thus giving rise to a 6 dB increase in sound level compared to the free field.

Measurements with microphones mounted directly onto a facade would be expected to have the reflections in phase with the direct sound and give a result 6 dB higher than measurements in a free field. Measurements in front of a facade will neither be in a diffuse field nor have all reflections in phase, and so this type of measurements has been considered to give rise to a high and unpredictable degree of uncertainty.

For all measurements included in this article at least 2 loudspeaker positions have been used and averaged into the results. Normally one loudspeaker position has been at an angle of 45°, and one loudspeaker position normal to the facade to be tested. This is different from relevant international standards[1,2] which require a spatial angle of 45°. For measurements in fixed positions on or in front of the facade at least 10, normally 20 combinations of loudspeaker and microphone position have been used. For measurement with sweeps at least one sweep for each loudspeaker position has been used. During measurements Norsonic power amplifiers 260 or 280 and Norsonic hemi-dodecahedron loudspeakers 250 or 275 have been used. These comply with requirements of relevant standards. The test signal was pink noise from the signal generator which is built into the analyzer or in the amplifier.

Many of the sites have other reflections than the reflections from the facade itself. Table 1 shows the configurations used. In some cases, there are reflections from a side wall. In other cases, the facade is on an external corridor or gallery, leaving only a short distance between possible positions of a loudspeaker and the facade to be measured. There are also cases with external corridors or balconies where the loudspeaker has to be placed on top of a 90 cm high barrier or rail. Finally there are cases where the facade is inside a balcony or terrace with both a floor and a ceiling. It is often necessary to control the sound insulation of the whole facade or of its components in such cases. The cases with other reflections than the one from the facade under test have been analyzed separately. It is essential to include these cases in the considerations as they occur much more frequently than the cases with only reflections from the facade to be measured.

The uncertainty of the methods utilizing fixed microphone positions is described using the standard deviations in each of the 1/3-octave bands in the frequency range in each set of measurements. For the microphone sweeps, the results are presented as the statistical distribution of each measurement given as the $(L_5 - L_{eq})$ and as $(L_{95} - L_{eq})$, both in 1/3-octave bands. The L_5 is defined as the level exceeded 5% of the integration time. L_{95} is defined as the level exceeded 95% of the integration time. In addition, the statistical distribution between individual measurements in fixed points has been compared with the statistical analysis of the sweep for one of the sites where measurements have been performed.

2.2 Measurements with the Microphone on the Facade

This type of measurement is meant to be used for control of compliance with design data for building components that have a substantially lower sound insulation than the rest of the facade[1]. It is important that the microphone is held on to or otherwise fastened directly to the facade. The ISO standard requires a maximum distance of 15 mm from the surface of the facade to the center of the microphone. In practice this is the equivalent of mounting the microphone directly on a window with adhesive tape. For these measurements a minimum of two loudspeaker positions and five microphone positions for each loudspeaker position have been used. These measurements would be expected to show a sound level 6 dB higher than in a free field.

2.3 Measurements with the Microphone in Fixed Positions in Front of the Facade

This type of measurement has been used extensively as a basis for calculation of indoor noise levels[4,13,15–17].

Table 1—Configurations of loudspeaker positions, number of microphones and other information.

	Microphone on facade	Microphone in front of facade	Sweep
Loudspeaker positions	~normal to facade + ~45° horizontal angle, 10 microphone positions for each	~normal to facade + ~45° horizontal angle, 10 microphone positions for each	~normal to facade + ~45° horizontal angle, 1 minute sweep for each
Test signal	Pink noise	Pink noise	Pink noise
Horizontal distance, loudspeaker to facade	Minimum 1.5 m	Minimum 1.5 m	Minimum 1.5 m
Sound power level of noise generator, amplifier and loudspeaker	120 dB	120 dB	120 dB

For this article, only measurements at controlled distances in front of the facades are included in the analysis. These measurements have been performed during the years 2010–2015. A standard distance of 0.25 m has been used. For these measurements a minimum of two loudspeaker positions and five microphone positions for each loudspeaker position have been used. In most cases 10 microphone positions have been used for each of the loudspeaker positions. These measurements have the disadvantage of the potential comb filter effect. On the other hand there is the advantage that these measurements would be expected to show levels similar to a diffuse field at high frequencies, i.e. 3 dB higher than a free field measurement. At high frequencies these measurements can be compared directly to laboratory measurements between two rooms with diffuse fields.

2.4 Measurements with Swept Microphone

Measurements using a swept microphone have been presented earlier for individual cases[10]. These measurements are made at a distance of 0.25 m. The statistical properties of the sound level during the sweep are of interest, not just the equivalent level. In order to enable comparison between measurements using a swept microphone with measurements with fixed microphones, statistical analysis of the sound level during the sweep was performed. The results from the sweeps are given as the differences between L_5, L_{eq} and L_{95} in 1/3-octave bands. The point of this type of measurement is to show the variation in levels as the microphone moves past the facade. The sweeps can be made either horizontally or vertically, as long as the whole surface is reasonably well covered. Figure 1 shows a picture of sweeping the microphone, a typical situation where it would be very difficult to perform the control measurements in any other way. Only one loudspeaker position is shown on the photos. The measurements with swept microphone would be expected to show properties similar to measurements with microphones in front of the facade.

3 RESULTS — MEAN VALUES FOR EACH MEASUREMENT METHODS

The three types of microphone positions give slightly different levels. Two comparisons have been performed. The first one is between microphone on the facade vs. microphone in front of the facade. The second one is between the values obtained by using sweeps vs. fixed microphone positions in front of the facade.

3.1 Microphone on the Facade vs. Microphone in Front of the Facade

The measured difference between microphone on and 0.25 m in front of the facade is shown in Fig. 2. A difference of 0 dB between on and 0.25 m in front of the facade is equivalent to the facade being a perfect reflector and direct and reflected wave being in phase at 0.25 m from the facade. If the difference between measurements on the facade and 0.25 m in front of the facade is 3 dB, it is equivalent to a diffuse field where constructive and destructive interferences cancel each other. When the difference between microphone on

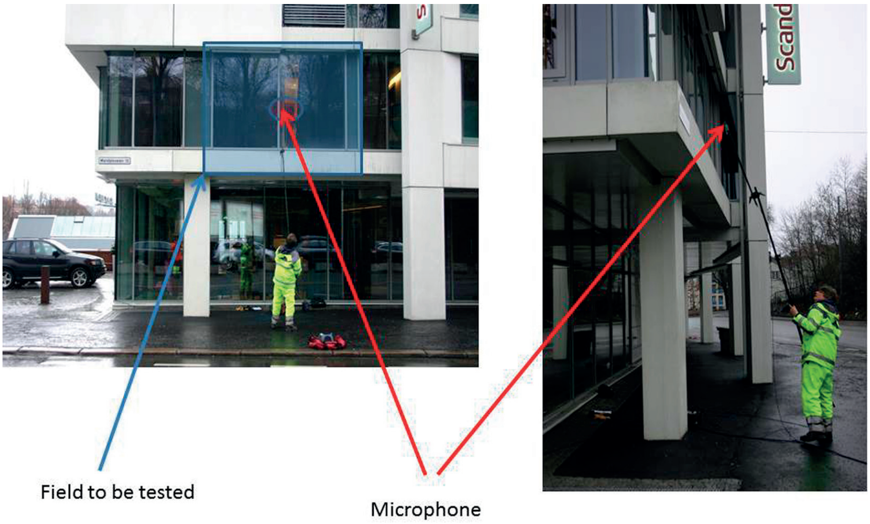


Fig. 1—Example of using sweep from the ground.

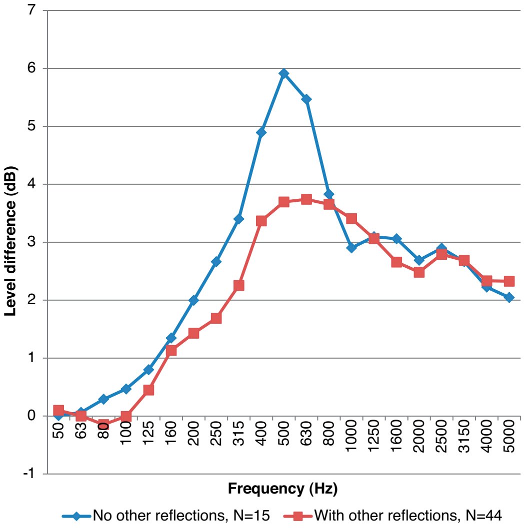


Fig. 2—Difference in level between microphone on and in front.

the facade and 0.25 m in front of the facade exceeds 3 dB, there is a comb filter effect. The difference between a microphone in the facade and a microphone 0.25 m in front of the facade is small at low frequencies increasing to a peak at 500 Hz. The peak is much clearer when there are no other reflections present than the one from the facade itself. There are 15 cases without other reflections, 44 cases with other reflections. There is no single measurement causing the peak at 500 Hz, the general shape of all differences look similar to the average shape. When other reflections are present, the peak almost disappears.

There is very little difference, on average less than 1 dB, between the microphone on the facade and in front of the facade at frequencies below 125 Hz. This could be explained by the reflection being well in phase with the direct sound. In the range from 160 to 500 Hz the difference increases up to 6 dB at 500 Hz for the case with no other reflections. This shows some destructive interference between direct sound and reflected sound, but it does not amount to a cancellation. A level 6 dB lower than measured on the facade is equivalent to a free field level, and this difference is much smaller than expected from simple calculations[10]. However, the difference between using a microphone on the facade and in front of the facade is smaller when there are other reflections present, and it does not exceed 4 dB in any 1/3-octave band in this case. The difference between microphone on the facade and 0.25 m in front of the facade is very similar to what would be expected in a diffuse field in the case with other reflections present.

Care should be taken in the use of results from measurements made with the microphone mounted 0.25 m in front of the facade under test. It should be noted that quoted laboratory test results are normally based on measurements between two rooms with diffuse sound fields. A field measurement using a microphone mounted in front of the facade will give a higher outdoor level than a diffuse field, thus overestimating the actual sound level onto the facade and underestimating the sound insulation of the facade in the frequency range up to at least 160 Hz. In the frequency range between 315 and 630 Hz the measurements with the microphone in front of the facade will underestimate the actual sound level incident onto the facade even when using the average of two loudspeaker positions in cases where there are no other reflections present. However, when there are other reflections present, the level goes less than 1 dB under that expected from a diffuse field at all frequencies. So with other reflections present, less than 1 dB overestimation of the sound insulation in the facade should be expected.

3.2 Microphone Sweeps vs. Fixed Microphone Positions in Front of the Facade

The difference between measurements with sweeps and with fixed positions is shown in Fig. 3. These differences are taken as the average of 15 cases without other reflections, 41 cases with other reflections. These differences may be due to the measurement procedure itself. When sweeping a facade at ground level, the

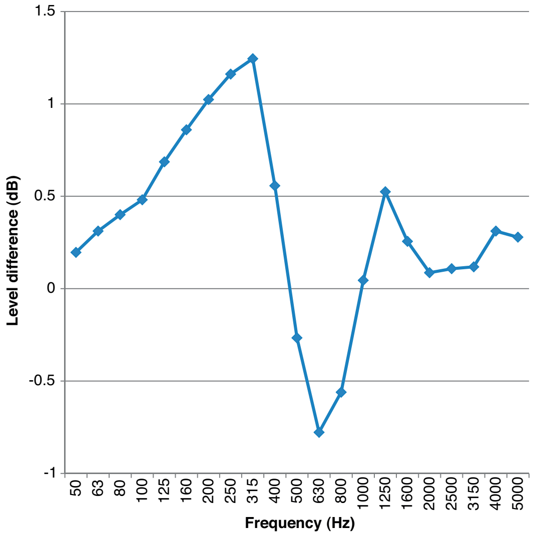


Fig. 3—Difference in level between sweep and fixed points in front.

operator shields the microphone from the loudspeaker at some times during the measurement. The differences are smaller than other uncertainties.

4 RESULTS — STATISTICAL PROPERTIES FOR EACH TYPE OF MEASUREMENT

The results in this section are given as the most important statistical properties of each type of measurement. The standard deviation in a series of measurements is taken as a measure of the uncertainty of the measurements that have been made using fixed microphone positions. The accuracy of the measurements with a swept microphone has been investigated by comparing the statistical distributions of the levels in fixed points with levels during the sweep. For these measurements there is a difference between cases with extra reflections and cases where the only reflection is from the facade to be investigated. The noted standard deviations could be used in planning of measurements of sound insulation in facades by using a number of microphone positions suitable for the required accuracy of the determination of indoor noise level. The background noise level has been at least 10 dB below the test signal in all bands at all locations included in the data presented. In order to reduce problems arising from any given loudspeaker position, at least two loudspeaker positions have been used for every measurement, one normal to the facade to be tested and one approximately 45° to the side.

4.1 Results with the Microphone on the Facade

The data are given as the sample standard deviation among at least 10 microphone positions from each measurement. Figure 4 shows the average of the standard deviation from these cases. In cases where there are other reflections present the uncertainty at low frequencies is rather high, with a standard deviation of around 3 dB. For the cases where there are no other reflections, the uncertainty is much lower. It seems the standard deviation at frequencies below 400 Hz is lower without other reflections than when other reflections are present. This could be due to the resulting sound pressure at the microphone consists of just direct sound and a reflection in phase at low frequencies. The uncertainty in the determination of the outdoor level may be critical for the correct determination of the indoor level[3]. The resulting uncertainty must be considered when deciding on the number of microphone positions to be used. It should also be noted that the presence of other reflections will influence the available accuracy of the result at low frequencies.

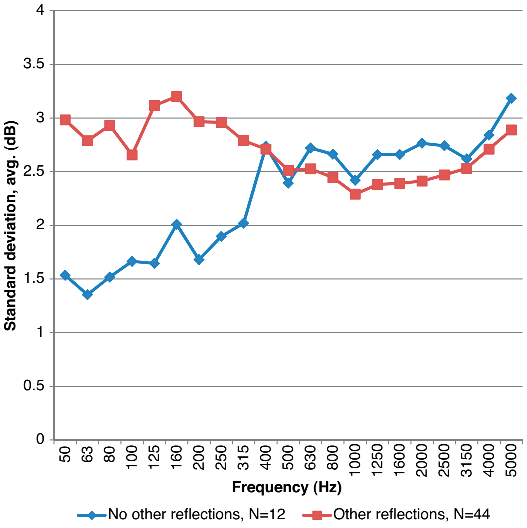


Fig. 4—Standard deviation as a function of frequency, microphone directly on the facade.

4.2 Results with the Microphone in Front of the Facade — Fixed Positions

The data are given as the standard deviation among at least 10 microphone positions from each measurement. Figure 5 shows the average of the standard deviations from the individual sites. The patterns are very similar to those with the microphone on the facade. However the standard deviation is higher than for the measurements with the microphones on the facades. This is especially true for the case without other reflections. Just like for microphone positions directly on the facade, the uncertainty of the measurement may influence the determination of indoor levels.

4.3 Results with the Microphone Swept in Front of the Facade

The results from measurements with a microphone swept in front of the facade are given in Fig. 6 for the sweeps performed at 0.25 m in front of the facade. In the cases of sweeps only one or two measurements have been performed, so instead of standard deviation between measurements, the statistical distribution within each measurement has been presented. In cases where more than one sweep has been performed, the energy average of the L_N parameters has been chosen for analysis. The statistical analysis has been made with the time constant FAST. In Fig. 6 the difference between L_5, L_{eq} and L_{95} has been shown for the individual measurements. The L_{eq} for each measurement is defined as

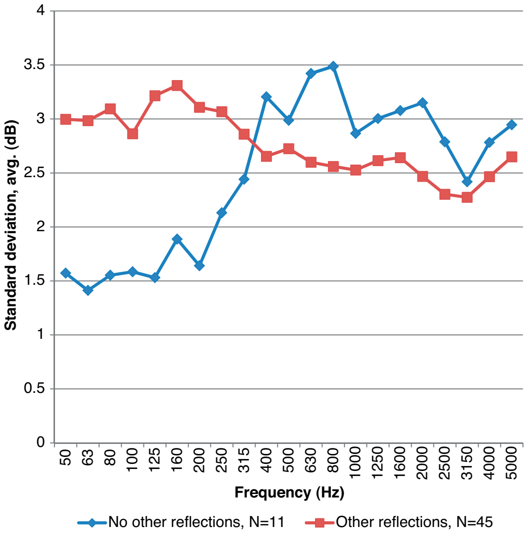


Fig. 5—Standard deviation as a function of frequency, microphone in front of the facade.

0 dB. The asymmetric results in dB is as should be expected[9,10]. This is because the destructive interference causing the dips in L_{95} has a much greater influence on the dB level than the constructive interference causing the L_5 to stay above L_{eq}. Typically the difference between L_5 and L_{95} is around 10 dB at low frequencies decreasing somewhat at higher frequencies.

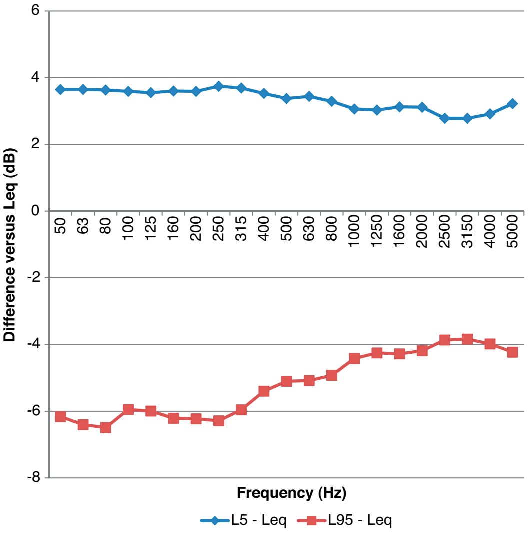


Fig. 6—Statistical properties of sweeps 0.25 m in front of the facade.

4.4 Comparing Measurements with Fixed Microphone Positions

It has been customary to recommend that sound insulation measurements be performed with the microphone on the facade or in a free field[1,2,14]. The reason for this is probably that theoretical calculations indicate that there will be a significant problem with destructive interference if the microphone is placed in front of the facade[9,10]. In Fig. 7 is shown the average of the standard deviation from microphone positions on the facade as compared to microphone positions in front of the facade. This figure shows a small, but clear difference in favor of positioning the microphone on the facade for frequencies up to 2000 Hz.

A majority of the measurements have been made on sites where the sound field is disturbed by multiple reflections. An analysis has been made for cases without disturbing multiple reflections. Figure 8 shows the results from the measurements without other reflections. In this case the apparent accuracy of the measurement is much better, both with the microphone on the facade and with the microphone in front of the facade. In this case the measurements with the microphone on the facade are clearly better than those with the microphone in front of the facade over most of the frequency range in question. In both cases there is a much higher standard deviation at frequencies above 315 Hz. This could tentatively be explained by destructive interference between direct and reflected sound for the

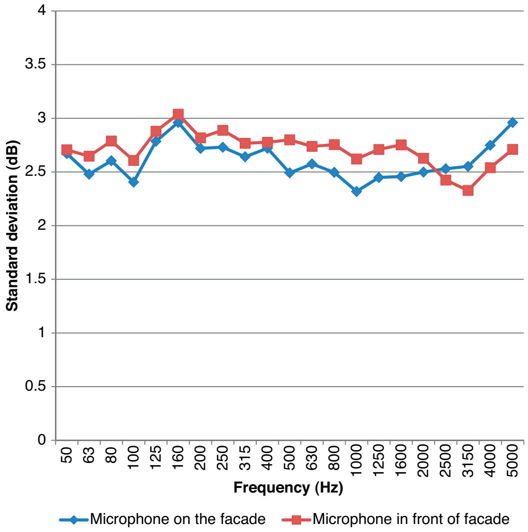


Fig. 7—Standard deviation with microphone on the facade and in front of the facade, grand average.

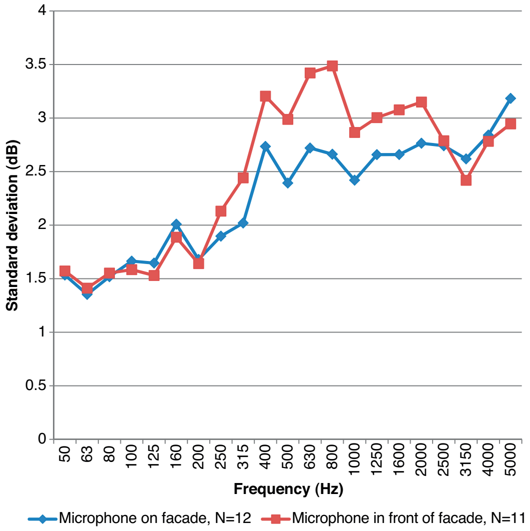


Fig. 8—Standard deviation in situations without other disturbing reflections.

case with the microphone in front of the facade. Simple calculations assuming a totally reflecting facade have shown that interference effects should be expected in this frequency range[10].

Figure 9 shows the corresponding results from the measurements where other reflections are present. In these cases the measurements with the microphone in front of the facade are almost as good as the measurements with the microphone directly on the facade. With other reflections present, the standard deviation increases at lower frequencies, but not at higher frequencies.

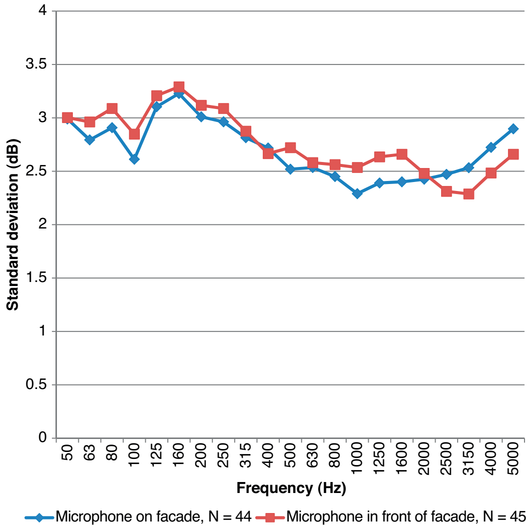


Fig. 9—Standard deviation in situations with other disturbing reflections.

4.5 Comparing the Statistical Distribution of Microphone in Front of the Facade, Fixed Microphone vs. Sweep

The statistical distribution of measured L_{eq} levels from individual measurements with fixed microphone positions has been compared with the statistical distribution with the time constant FAST. The Norsonic 118 and the 140 that have been used for these measurements perform a statistical analysis measuring the level exceeded during 0.1%, 1%, 5%, 10%, 50%, 90%, 95% and 99% of the elapsed time. Only the L_5 and L_{95} have been presented as these percentiles can be conveniently compared to the statistical properties of measurements with 20 fixed points. Figures 10 and 11 show the difference between the L_5 and L_{95} for one of the measurement points. The tendency in other bands is the same as in these bands; the statistical distribution in the sweep is very similar to the statistical distribution between fixed point measurements. The sweep smooths out the spectrum slightly more than individual points.

5 CHOICE OF MEASUREMENT METHOD

The most important motivation behind choice of solution for facade sound insulation is to achieve a sufficient accuracy at a reasonable cost. It should be borne in mind that measurements with microphone positions

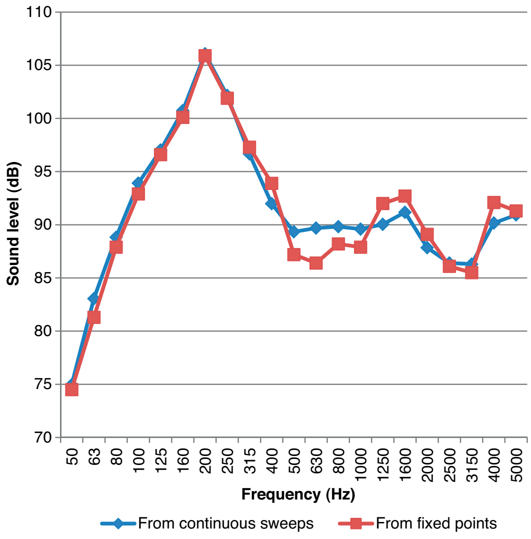


Fig. 10—Comparison of statistical distribution with fixed points and with sweep; L_5.

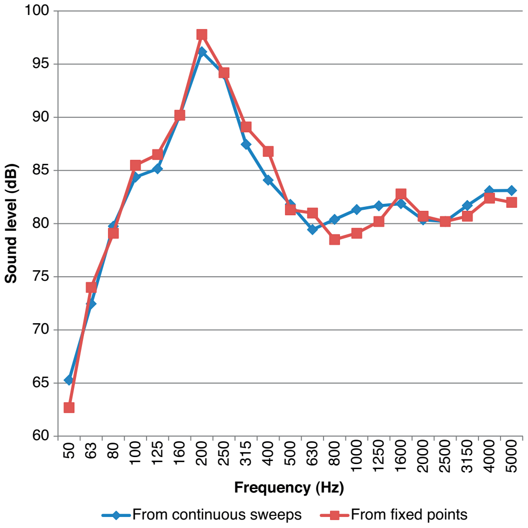


Fig. 11—Comparison of statistical distribution with fixed points and with sweep; L_{95}.

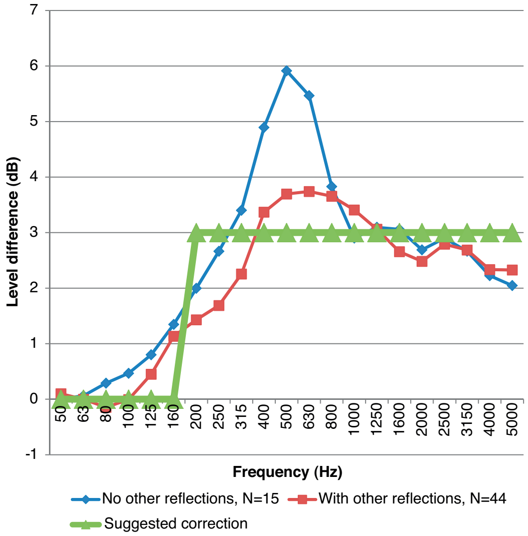


Fig. 12—Suggested correction between microphone on and in front.

on the facade are always preferable. Measurements with the microphone placed 0.25 m in front of the facade are far better than should be expected from simple calculations. Care should be taken in cases where frequencies in the range 315 – 630 Hz are critical and the only reflecting surface is the facade itself. There is a clear indication in Figs. 7, 8 and 9 that the accuracy of the measurement is slightly better if the microphone is placed on the facade than with the microphone in front of the facade. However, the difference in accuracy is quite small. A bit more surprising is the fact that these measurements indicate quite a large uncertainty in measurements with the microphone on the facade as well. This uncertainty may be critical for the correct determination of indoor noise level[3,13]. In actual field work it is not always possible to mount the microphone on the facade[16]. The investigations indicate that the sound insulation in the facade can be measured using microphone positions in front of the facade provided a sufficient number of microphone positions are used. In other cases it may be possible to use sweeps, e.g. the walls and windows shown in Fig. 1. This facade is not easily accessible in any other way, as the site cannot easily be reached with a lift. In these cases the sweep is the only available solution. It will almost always be possible to perform a sweep either by using a microphone hung from the roof or placed on a lightweight rod handled from the ground.

In cases where other reflections (in addition to the one from the facade itself) also give interference, the uncertainty of the measurement increases. In these cases the difference between microphone positions on the facade and in front of the facade is reduced. It is still better to use microphone positions on the facade, however.

The accuracy of any measurement can always be improved using a larger number of combinations of loudspeaker and microphone positions. In the cases presented, the problem of destructive interference can be observed, but only as an uncertainty in the measurements. It seems that the expected comb filter effect when using microphone positions in front of the facade is much less severe than expected from calculations[9,10].

The measurement positions cannot be directly compared. Until further knowledge is collected, it is suggested that the two positions on or in front are considered to give the same result at frequencies up to and including 160 Hz, and that the position on the facade is considered to give 3 dB higher level than in front from 200 Hz upwards. The suggested simplified correction is shown in Fig. 12.

6 CONCLUSIONS

When possible, microphone positions on the facade should be preferred. If positions on the facade are not available, acceptable results can be achieved using microphone positions in front of the facade, either with a fixed microphone or with sweeps. In cases with other reflections present than directly from the facade, acceptable results are achievable also with a microphone mounted in front of the facade. This is due to the other reflections creating a sound field that is quite close to a diffuse field. The only case which still presents difficulties is when the surface of the facade is not available for mounting a microphone and there are no other reflections than the direct one from the facade. Still in this case measurements can be made provided care is taken in the interpretation in the frequency range from 315 to 630 Hz.

7 REFERENCES

1. "Acoustics – Measurement of sound insulation in buildings and of building elements – Part 5: Field measurements of airborne sound insulation of façade element and facades", ISO 140/5, (1998).
2. "Acoustics – Field measurement of sound insulation in buildings and of building elements – Part 3: Façade sound insulation", ISO/TC 43/SC2, ISO/DIS 16283-3, (2014).
3. U. Berardi, "The position of the instruments for the sound insulation measurement of building facades: From ISO 140-5 to ISO 16283-3", *Noise Control Engr. J.*, **61**(1), 70–80, (2013).
4. S. Olafsen, "Sound insulation against traffic noise in wooden houses", *Baltic-Nordic Acoustical Meeting*, (2002).
5. K.A. Mullholland, "Method for measuring the sound insulation of facades: Factors to be considered", *International Building Council for Research, Studies and Documentation, Acoustics Commission Meeting*, (1970), Reprinted in Applied Acoustics, **4**, 279–286, (1971).
6. F.L. Hall, M.J. Papakyriakou and J.D. Quirt, "Comparison of outdoor microphone locations for measuring sound insulation of building facades", *J. Sound Vibr.*, **92**(4), 559–567, (1984).
7. J.L. Sánchez Bote, A. Perero González and J. José Gómez Alfageme, "Influence of loudspeaker directivity and measurement geometry on direct acoustic levels over facades for acoustic insulation tests with the International Standard ISO 140-5", *Applied Acoustics* **73**(4), 440–453, (2012).
8. J.L. Sánchez Bote, A Perero González and J. José Gómez Alfageme, "Procedure for verification of sound source coverage over façades according to the International Standard ISO 140-5", *Applied Acoustics*, **73**(9), 977–985, (2012).
9. U. Berardi, E. Cirillo and F. Martellotta, "Interference effects in field measurements of airborne sound insulation of building facades", *Noise Control Eng. J.*, **59**(2), 165–176, (2011).
10. S. Olafsen, "Sound insulation measurements of facades with variable microphone positions", *InterNoise11*, (2011).
11. C. Hopkins, *Sound Insulation*, Butterworth-Heinemann, ISBN 978-0-7506-6526-1, Chapter 5.1.3, "Façade sound insulation", (2007).
12. C. Hopkins and Y. Lam, "Sound fields near building facades — Comparison of finite and semi-infinite reflectors on a rigid ground plane", *Applied Acoustics*, **70**(2), 300–308, (2009).
13. K. Haugen and S. Olafsen, "Analysis of low-frequency resonances in façade sound insulation spectra", *InterNoise08*, (2008).
14. *Måling av lydnivå fra veitrafikk*, NS 8174 (the Norwegian standard for measurements of road traffic noise, in Norwegian).
15. S. Olafsen and M.K. Strand, "Field versus laboratory sound insulation of windows", *InterNoise09*, (2009).
16. S. Olafsen and P.K. Limmesand, "Control of sound insulation in glass facades at Oslo's Opera House", *ICA 2010*, (2010).
17. S. Olafsen, "An empirical way to calculate indoor noise from road traffic noise", *EuroNoise03*, (2003).

Article V

BNAM2012
Joint Baltic-Nordic Acoustics Meeting
June 18th - 20th 2012 Odense, Denmark

Measurements of facade sound insulation using a loudspeaker or railbound vehicles as sources

Sigmund Olafsen
Brekke & Strand akustikk, P.O. Box 1024, NO-0218 Oslo, Norway, sigmund.olafsen@brekkestrand.no

Lunds Tekniska Högskola, Box 118, SE 22100 Lund, Sweden

The paper will describe the advantages and disadvantages of using a loudspeaker versus using railbound vehicles as signal sources for measurements of the sound insulation of a façade. It's based on measurements from five sites, one ordinary railway site, one site with the tram as source, and 3 sites with Oslo's metro as source. At mid-frequencies, typically 200 to 1000 Hz, the resulting sound insulation from measurements with loudspeaker or train is almost identical. At frequencies below 200 Hz, the loudspeaker appears to indicate a higher sound insulation than the railbound vehicles. This is also the case at frequencies above 1000 Hz. At low frequencies, the discrepancy could be due to a groundborne component from the railbound vehicle, resulting in a lower apparent sound insulation. At both high and low frequencies, the discrepancy could be due to an insufficient signal to noise ratio when the railbound vehicle is used as source. The paper will give recommendations for which cases should be measured using loudspeaker, railbound vehicles or both as a signal source for façade sound insulation measurements in houses close to railways or railbound urban transport lines like trams and metros.

1 Introduction

Indoor noise in residences from railbound vehicles will generally consist of two components. The first component is the airborne noise (L_{ia}), the second component is the groundborne noise (L_{ig}). It is important to determine as accurately as possible the relative influence of the two components. In existing houses it is often most practical to measure the sound insulation using both a loudspeaker and railbound vehicles as sound sources. For the presented measurements, the microphones have been in the same positions for both types of measurement. The loudspeaker has been placed in different positions in such a way as to simulate as well as possible the average direction of the path of the passing train.

The aim of this investigation has been to determine the difference between apparent sound insulation using the railbound vehicle and the loudspeaker as signal sources. Details about the microphone position are not critical for this difference.

2 Measurement method

2.1 Instrumentation

The measurements presented in this paper have been performed using a Norsonic 121 two-channel analyzer. The aritificial sound source used in the measurements have been made with a Norsonic 280 noise generator and power amplifier and a Norsonic 250 hemi-dodecahedron loudspeaker. The loudspeaker generates a sufficiently strong measurement signal in the frequency range 50 Hz to 5000 Hz to give a proper indoor level. Measurements have been made with a time resolution of 1 second and a frequency resolution of 1/3-octave bands.

2.2 Analysis of measurements

The analysis has been made on a basis of the overall Leq values for each of the measurements. The start and stop of each individual measurement has been made manually in all cases.

Analysis of the time profile shows that the indoor level in some 1/3-octave bands does not vary during the measurement when using the railbound vehicles as sound sources. This is probably due to background noise being higher than the signal. This phenomenon leads to an underestimation of the sound insulation of the façade at high frequencies. In the 5 presented cases, the frequency band where this effect becomes significant varies from 500 Hz to 2 kHz.

2.3 Sites

The measurement sites are all situated close to the tracks. A short description of the sites, details of the measurement methods and the results is given below. The microphone positions were always in front of the façade to be measured. There is no clear standard for measurements with the microphone placed in front of the façade [1,2]. However, there exists research into the merits of such measurements [3,4,5,6,7]. The ISO standard [2] is under revision. Some of the material presented in this paper may be used in that revision. The presented level differences are energy average attenuations for each site. A total of 5 sites are included in this study, called train 1, tram 1, metro 1, metro 2 and metro 3.

3 Details and results for each site

The sound insulation values measured using the railbound traffic as source are not correct for high frequencies. At these frequencies, the indoor level is due to background noise, and so the presented value is an underestimation. The values are shown in order to demonstrate how large the underestimation could be.

3.1 Site Train 1

The house in question is situated 30 meters from a railway line with 2 tracks. The measurements included in this presentation were made with 4 outdoor and indoor microphone positions. For each combination of outdoor and indoor microphone position, 1 measurement was made using train passages and one measurement with white noise from a loudspeaker. The loudspeaker was placed on top of the fence on a balcony approximately 2 meters in front of the façade.

In this site, there is little discrepancy between the apparent sound insulation at frequencies above 50 Hz, while the apparent discrepancy at high frequencies start at 500 Hz. This seems reasonable, as the sound levels from the railway are not particularly high at this site.

There is little influence of groundborne noise at this site.

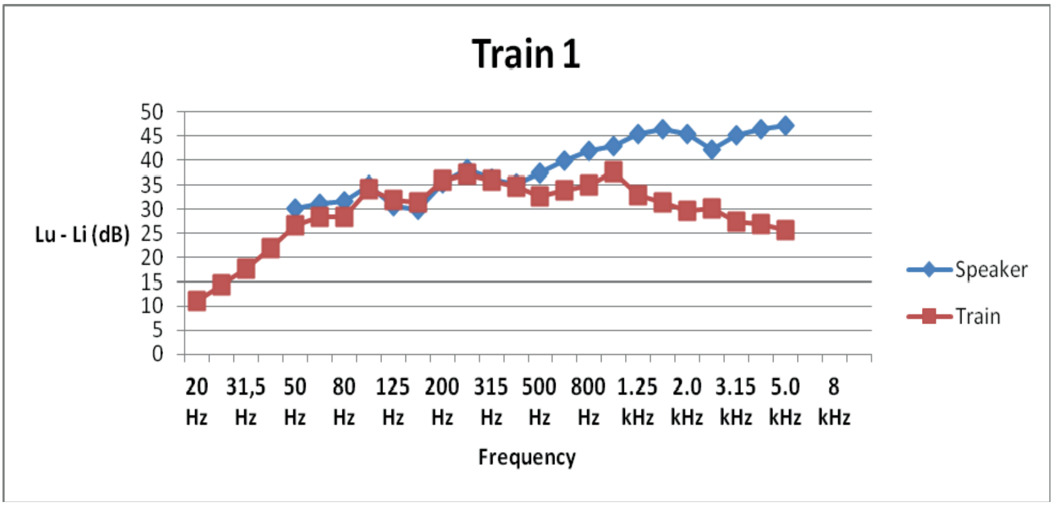


Figure 1: Level difference at site train 1

3.2 Site Tram 1

Site tram 1 is a house close to very close to a turning circle for the tram. The speeds are very low. The tram line is so close to the house that the inbound and outbound trams give different results, The level differences are based on microphone sweeps during loudspeaker test signals and tram passages. The distance to the outbound tram line from the façade is 13 m, to the inbound tram line 8 m. The presented values are averages of 4 measurements.

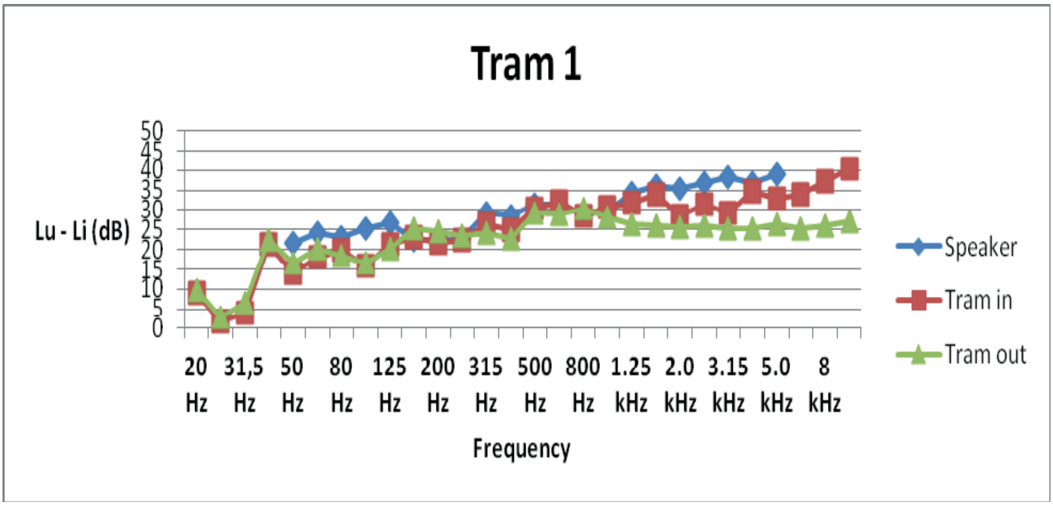


Figure 2: Level difference at site tram 1

At this site, there is a discrepancy between the sound insulation values at freqeuncies below 125 Hz. This is an indication that there might be a groundborne component in the indoor noise. At frequenices above 1000 Hz, there is a discrepancy between the sound insulaiton measured with the loudspeaker as source and the measured values with the tram as source.

3.3 Site metro 1

Site metro 1 is approximately 25 meters away from a new metro line. The measurements were made on a balcony faicng the metro line. Loudspeaker measurements were made with the source on top of the balcony fence approxiamately 3 meters away from the façade. 10 passing metro trains were used in the analysis. 2 loudspeaker positions with 6 microphone positions for each were used for the measurements with loudspeaker. Figure 3 shows the results from this site.

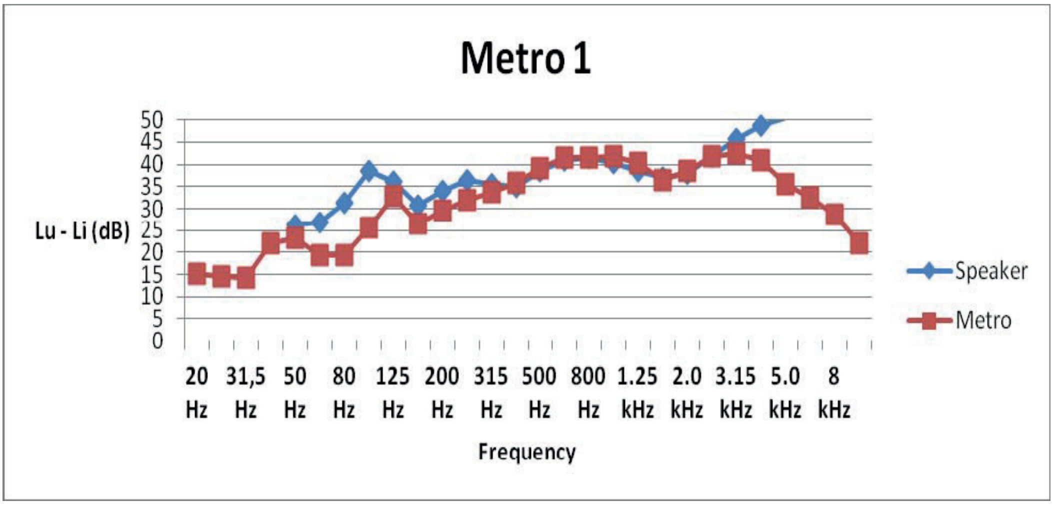


Figure 3: Level difference at site metro 1

At this site there's a discrepancy between loudspeaker and vehicle measurement up to 315 Hz, a higher frequency than in other cases. The discrepancy appears again at 3,15 kHz and upwards. There were no feelable vibrations nor audible structureborne sound in this case. In this case no vibration measurements were made, but it seems reasonable to assume that there is a contribution from groundborne noise anyway.

3.4 Site metro 2

The house where the measurements were made is 30 meters from the metro line. The presented levels are based on 10 metro train passages and 2 loudspeaker positions with each 5 microphone positions. The results are shown in figure 4.

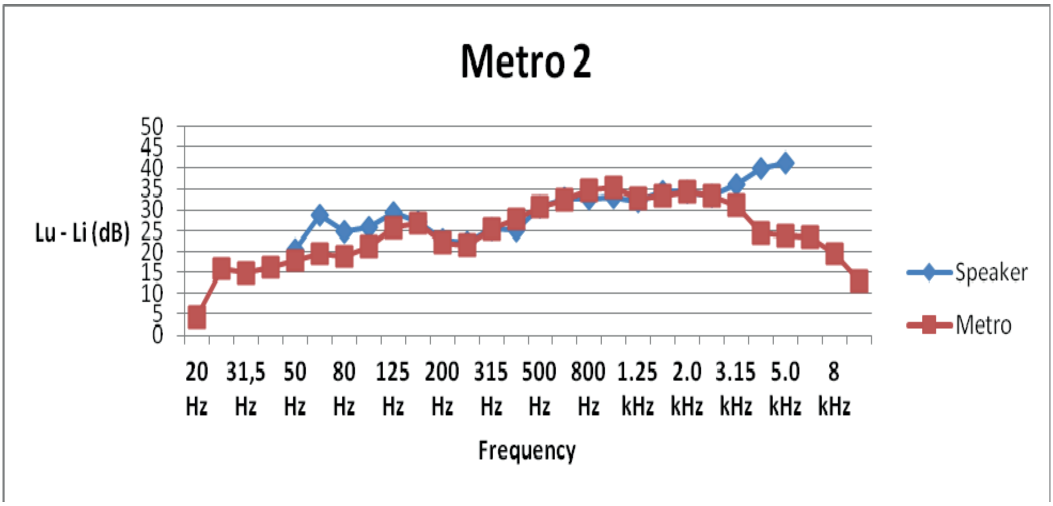


Figure 4: Level difference at site metro 2

In this case the discrepancy at low frequencies goes up to 125 Hz, and it starts again at 3,15 kHz.

3.5 Site metro 3

This site is at 17 meters from the metro tracks. The measurements were made with 10 passages of metro trains. Loudspeaker measurements were made using 2 microphone sweeps. The results are shown in figure 5.

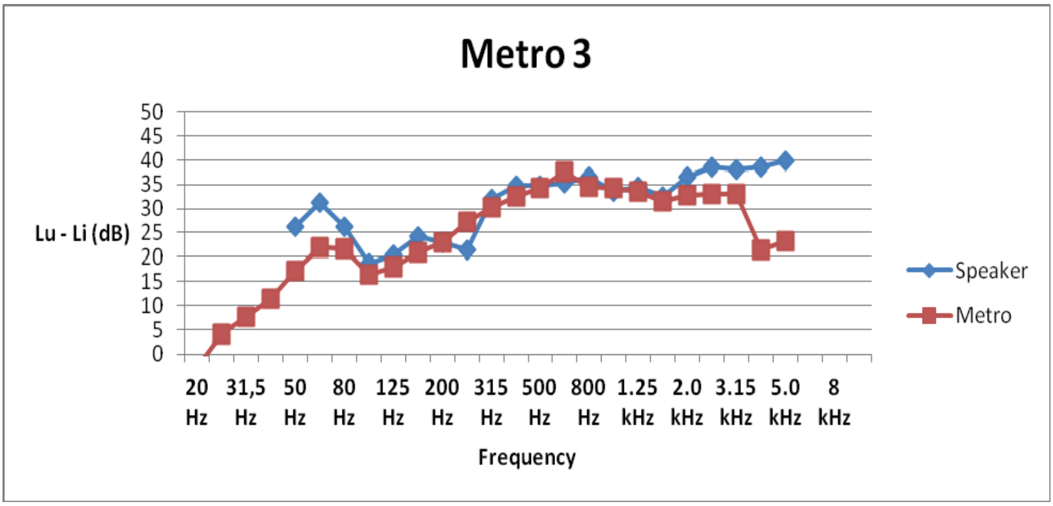


Figure 5: Level difference at site metro 3

There is a discrepancy at frequencies from 80 Hz downwards, and from 2,5 kHz upwards.

4 Further research

This paper is part of a project to acquire a better understanding of indoor noise from railbound vehicles. One question that comes naturally to mind, is whether the difference in measured insulation spectrum between the loudspeaker and the railbound vehicles has any practical significance. That is, will sounds at frequencies below 200 Hz or above 1000 Hz contribute to the total noise exposure? At low frequencies, groundborne noise is certainly a problem that cannot be solved using sound insulation measurements with a loudspeaker as source. The groundborne noise from railbound sources in residences is a particularly annoying type of noise. So in some cases there may be little difference in terms of overall weighted sound insulation index, but still the groundborne contribution is very important for the perceived noise situation.

More research into the sound field in front of the facade is required. In many practical cases it might be necessary to make the measurements using microphone positions in front of the facade. It would seem that the interference effects predicted by theory is not so critical in real field measurements.

Measurements of groundborne noise transmission is also required. The transmission of vibrations from the ground into buildings is not completely understood.

5 Acknowledgements

Thanks to Kollektivtransportproduksjon and Jernbaneverket. Kollektivtransportproduksjon AS runs Oslo’s metros and trams. Jernbaneverket is responsible for tracks and infrastructure of Norway’s railways. I would also like to extend my sincere thanks to my Ph. D. Mentor Delphine Bard at LTH as well as my colleagues at Brekke & Strand akustikk, in particular Arild Brekke, Atle Stensland and Tore F. Killengreen.

6 Conclusions

There’s definitely a difference between the measured level difference using the railbound traffic or a loudspeaker as noise sources. In the frequency range 200 Hz – 1000 Hz the two sources give similar results, and both are acceptable. At lower frequencies than 200 Hz, the railbound vehicles will give an apparently lower sound insulation (and higher indoor level). It seems reasonable to assume that this is due to a groundborne contribution to the indoor noise level. At frequencies above 1000 Hz, there is insufficient noise energy in the railbound vehicle to give a good measurement of indoor noise level. The measured indoor values form railbound vehicles above 1000 Hz do not go above the background noise level, thus the sound reduction in the facade may be much better than indicated. It seems necessary to use both a loudspeaker and a railbound vehicle as noise sources in order to achieve a complete picture of the sound insulation.

References

[1] NS 8177 Acoustics - Measurement of sound pressure level from rail traffic, july 2010.

[2] ISO 140/5 Acoustics - Measurement of sound insulation in buildings and of building elements - Field measurement of airborne sound insulation of façade element and facades, 1998.

[3] Umberto Berardi, Ettore Cirillo, Francesco Martellotta “Interference effects in field measurements of airborne sound insulation of building facades”, Noise Control Engineering Journal, pp. 165-176, 2011

[4] Sigmund Olafsen, “Sound insulation against traffic noise in wooden houses”, proceedings BNAM 2002, Lyngby

[5] Sigmund Olafsen, Per Kåre Limmesand, ”Control of sound insulation in glass facades at Oslo’s Opera House”, proceedings ICA, Sydney, 2010

[6] Sigmund Olafsen, “Prediction and measurement of indoor noise from road traffic”, lecture at Tsinghua University Building Acoustics Forum, Beijing, 2011

[7] Sigmund Olafsen, “Sound insulation measurements of facades with variable microphone positions”, proceedings Internoise 2011, Osaka

Article VI

BNAM 2014
Baltic-Nordic Acoustics Meeting
June 2 - 4 2014 Tallinn, Estonia

Transfer functions of vibrations from metro trains to houses

Sigmund Olafsen
Brekke & Strand akustikk as, P.O. Box 1024 Hoff, NO-0218 OSLO, Norway
Lunds Tekniska Högskola, Lund, Sweden, so@brekkestrand.no

This paper will present some of the results from measurements of vibrations from metro trains in Oslo. The results presented here are limited to the transfer functions between the ground outside the house and the floors inside the house. Measurements from 18 houses are included in this analysis.
For all the houses considered vibrations have been measured with triaxial transducers. At least 10 events with passing trains have been measured for each house. The transfer functions of vibrations have been calculated for three orthogonal directions:

X	horizontal normal to the track
Y	horizontal parallel with the track
Z	vertical

The measurements were made in 1/3-octave bands in the frequency range 1 – 80 Hz. Transfer functions have only been calculated for the frequency bands where both outdoor and indoor vibration level was well above the sensitivity of the measurement chain. Presented transfer functions are shown from outdoor to basement, outdoor to ground floor and outdoor to first floor.

1 Introduction

The purpose of the investigations is to find a practical way to describe the relation between outdoor vibrations and indoor vibrations from urban local railbound traffic like metro trains or trams. This paper deals with the magnitude of vibrations in three orthogonal directions. Only the maximal vibration levels with time weighting SLOW have been measured for each passage of the metro trains. The measurements have been commissioned by Sporveien Oslo, the publicly owned company that runs the metro trains and trams in Oslo. Some measurements have been performed to check the predictions made for the project Kolsåsbanen, where an old tram line has been replaced by a modern metro. Other measurements have been made in places where residents have complained about vibrations and/or groundborne noise.

2 Method

The description of the method is divided into four parts:

- A description of the measurements
- Analysis of the results as averaged spectra from a series of passages in one point
- Analysis of the variation between train passages in one of the measurement points
- Analysis of the ratio between horizontal vibrations and vertical vibrations

Many of the presented measurements have been made during controls along the new Kolsås line, which used to be a tram line, but which is in the process of being upgraded to a metro line. Extensive vibration abatement measures have been included in the construction of the line, including testing of propagation of vibration before traffic was introduced on the new rails [1]. Some measurements included in this paper were also made on other metro lines in Oslo.

The average speed of the individual train passage has been retained for later analysis. The ground conditions and the construction of the house are reasonably well known in most cases, as is the rail corrugation.

2.1 Measurements

In each house included in the analysis, the indoor vibration level has been compared to the outdoor vibration level at the same distance as the wall of the house. The frequency range used in the analysis is the 1/3-octave bands from 1 Hz to 80 Hz. Single number ratings have been calculated according to NS 8176 [2]. Earlier Japanese investigations have shown very regular transfer functions for vibrations independent of source [3].

In many cases the vibration level in some frequency bands to be measured is below the reliable range of the sensors. Measurements have been made using geophones or accelerometers, some triaxial and some vertical. When the registered value in a frequency band is less than 6 dB above the noise floor of the instrumentation chain, the measured values have been discarded from further analysis. The response of the geophones fall off below 5 Hz. This reduced sensitivity of the geophones at the lowest frequencies has been corrected in the analysis. The measurements have been made simultaneously with up to 3 triaxial sensors and 3 single-axis sensors using a 12-channel analyzer. As parts of the spectrum have been discarded, not all response functions show the complete frequency range from 1 Hz to 80 Hz. This type of transfer functions are acquired from the average values from a measurement in a point.

2.2 Analysis of spectra from a series of train passages

In all the presented cases the analysis has been based on the average of 10 to 30 train passages. In the paper only transfer functions in the z direction have been presented for this type of measurement. A position just outside the house in the same distance from the tracks as the walls facing the track has been used as reference for the transfer functions. The ratios have been calculated for each direction separately. The floor levels have been defined relative to the ground on the side of the house facing the tracks. Norwegian houses are often placed in sloping terrain. This means that the definition of the floor is not always obvious. The terms used are as follows:

- Ground floor means a floor on the same level as the ground facing the tracks
- Basement means a floor one level below the ground facing the tracks
- First floor means a floor one level above the ground facing the tracks

2.3 Transfer function spectra for individual trains in a point

Transfer function spectra for each train passage have been analyzed in one direction in one point. These transfer functions vary between the individual train events. It has been recommended to calculate transfer function spectra from each individual event before averaging instead of using the ratio between averaged spectra [4].

2.4 Relation between horizontal and vertical vibrations

The weighted velocities have been compared between different directions. Currently only the ratio between averages from each measurement session has been shown.

3 Results

The results are shown as transfer function spectra for the three specified types of floor levels in the vertical direction. In addition the vibrations in the horizontal versus vertical directions have been show as weighted velocities.

3.1 Transfer functions in the vertical direction – averaged series of train passages

Logarithmic scales have been used in order to be able to show these transfer function spectra in the same diagram. Figure 1 shows the transfer function spectra for indoor vertical vibrations on the same floor level as the ground facing the tracks.

The most striking property of the graph is the wide variation of the results. In most cases the indoor vibrations have a lower intensity than the outdoor vibrations. There is no consistent pattern to be discerned in the spectrum shapes however. The span is greatest for the measurements of transfer functions between ground level and outdoor, from less than 0,01 to 55. Most of the spectra have transfer function values in the range from 0,2 to 2.

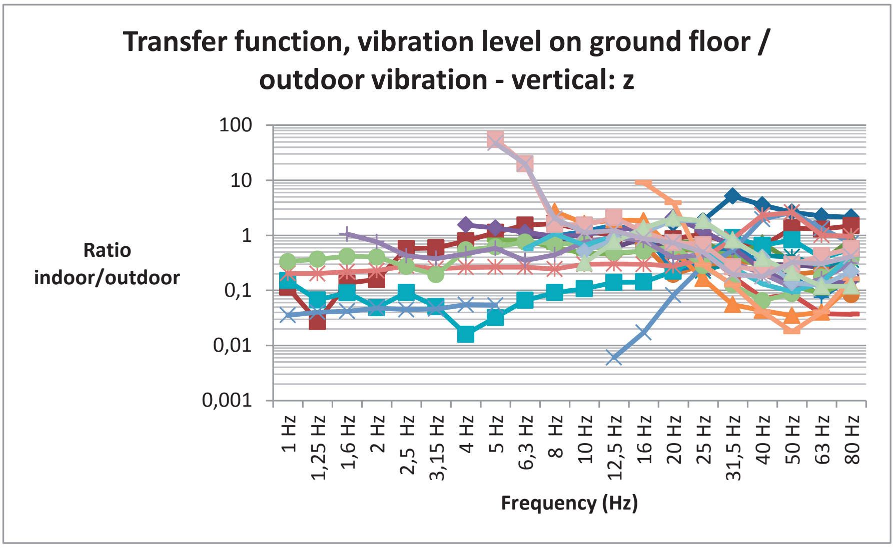


Figure 1 Transfer function between ground floor vibrations and outdoor vibrations

The highest values, where the indoor levels are more than 50 times higher than the outdoor levels in the 5 Hz 1/3-octave band, have been carefully checked. No error has been found in the measurements. So far it seems that there are occasional cases of very high or very low transfer functions at certain frequencies.

The transfer function spectra for first floor/outdoors and basement/outdoors are shown in figures 2 and 3. There is no clear and obvious pattern in these spectra either.

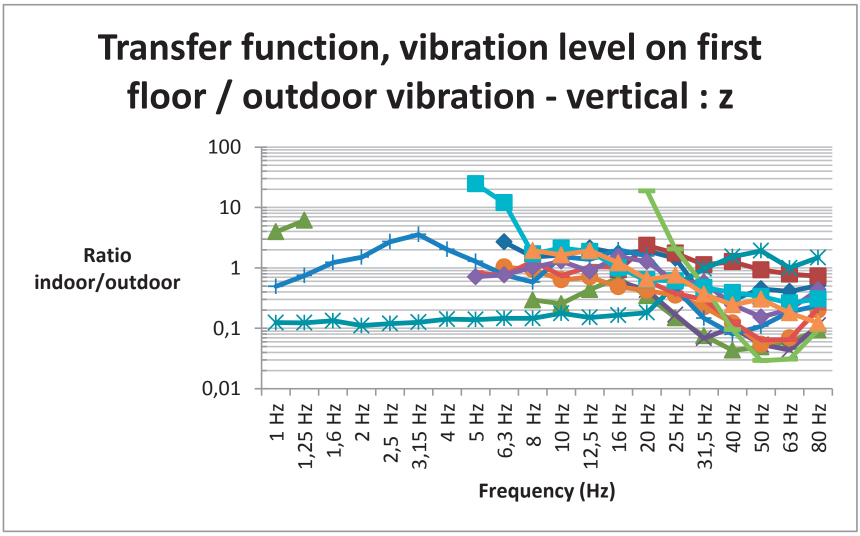


Figure 2 Transfer functions between first floor vibrations and outdoor vibrations

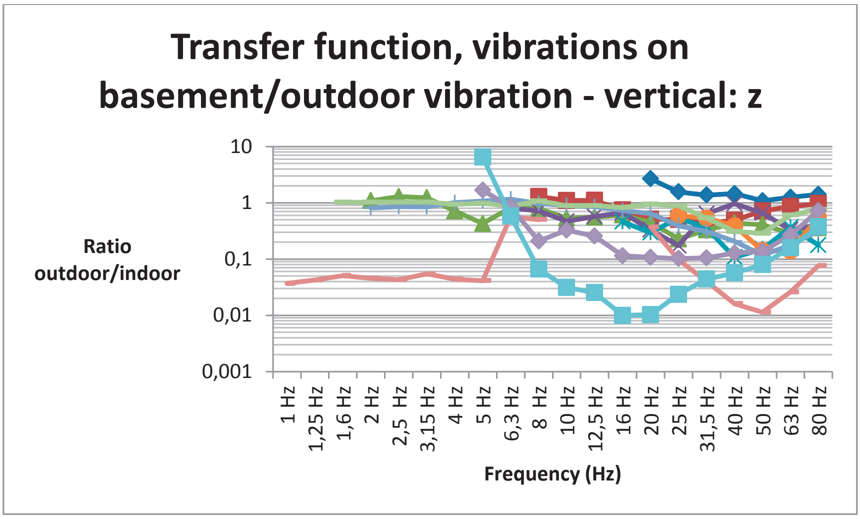


Figure 3 Transfer function between basement vibrations and outdoor vibrations

3.2 Transfer functions for individual train passages

The transfer functions between individual train passages for a given immission point are shown in figure 4. These presented values are for vertical vibrations.

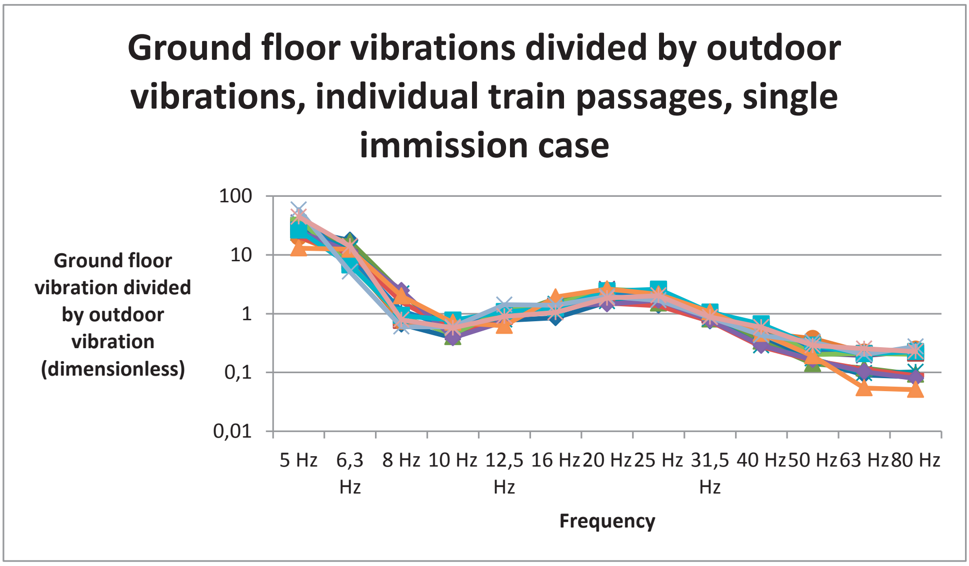


Figure 4 Ground floor vibrations divided by outdoor vibrations, vertical (z), different trains, same immission point

Frequencies below 5 Hz had to be taken out of the analysis as the measured level was not sufficiently above the sensitivity of the instrument chain. The logarithmic scale has been used to enable a presentation in a single graph. The scale camouflages the variability. The figure shows some characteristics which seem to show up in most cases, though. All the spectra have the same general shape.

3.3 Horizontal versus vertical vibration levels

Figure 5 shows a comparison between outdoor horizontal and vertical vibration levels.

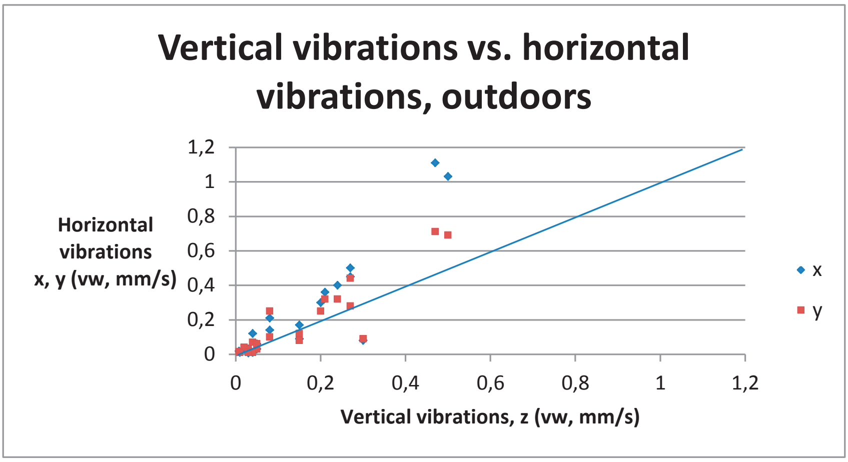


Figure 5 Vertical vs. horizontal vibrations outdoors

The dots above the blue line show horizontal vibration levels higher than vertical vibration levels. It would seem fair to say that horizontal and vertical vibration levels are of the same order of magnitude.

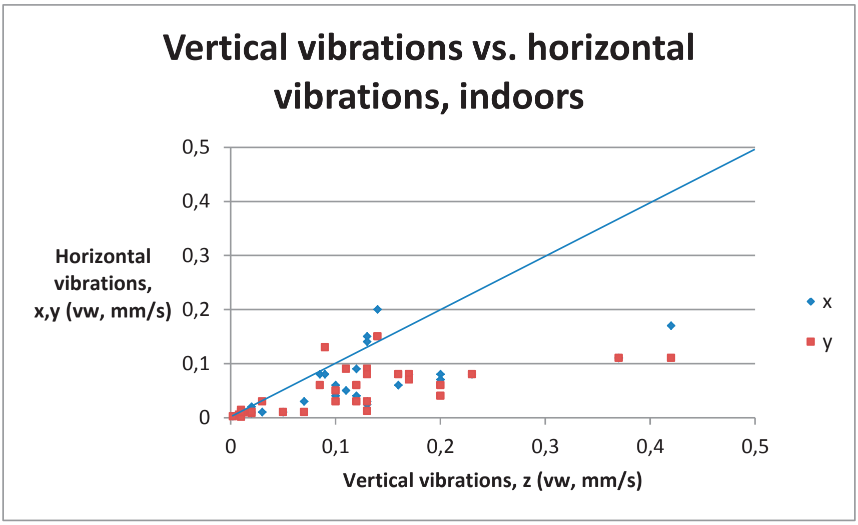


Figure 6 Vertical vs. horizontal vibrations indoors

Figure 6 shows the weighted vibration levels indoors, again vertical vibrations vs. horizontal vibrations. The indoor vibration levels show a somewhat different pattern from the outdoor vibrations. The indoor horizontal vibration levels are often lower than vertical vibration levels.

4 Further research

It would be too simple to assume that there is a fixed relation between vibrations in different directions. It is also too simple to assume that there is a fixed relation between outdoor and indoor vibrations or between floor levels in the same house. There are many other parameters that should be taken into account:

- Quality of the rail
- Construction of the track
- Speed of the passing train
- Ground conditions between the track and the house
- Vibration abatement measures
- Foundation of the house
- Construction of the house

It might also be that vibration varies over time, possibly with the seasons. Fortunately most of the parameters quoted above have been noted during our measurements. We have also already made similar measurements in other houses. Planned research activities include:

- A regression analysis of weighted vibration velocity on all available and relevant factors to see whether the overall vibration level can be predicted on an empirical basis with sufficient accuracy to be useful
- Analysis of more cases of calculating transfer functions for individual train passages instead of only for the averages
- An investigation of whether dominant frequencies in indoor vibration levels are due to how the house is constructed

5 Conclusions

Ratios of vibration levels between outdoor and indoor, between individual passages and between orthogonal directions have been presented. So far no consistent pattern has emerged. Some directions for further analysis have been suggested.

References

[1] Teresa Fernandez Espejo, Sigmund Olafsen, Arild Brekke, "Measurement procedures for vibration propagation from railway tracks", *Proceedings Internoise 2013, Innsbruck*

[2] NS 8176 "Vibrasjoner og støt – Måling i bygninger av vibrasjoner fra landbasert samferdsel og bedømmelse av vibrasjonspåvirkning på mennesker". The Norwegian standard for vibration measurements.

[3] Yoshihiro Hirao, Sunao Kunimatsu, Takuji Hamamoto, "Development of wireless measurement system for ground-borne vibration in buildings and measurements for vibration amplifications of detached houses", *Proceedings Internoise 2011, Osaka*

[4] Personal communication from C. Madshus at NGI, Oslo, Norway

Article VII

Measurements of vibrations and noise from metro trains

Sigmund Olafsen[a,b]; Arild Brekke[a]; Atle Stensland[a]; Tore Fodnes Killengreen[a]; Delphine Bard[b]
[a] Brekke & Strand akustikk as, P.O.Box 1024 Hoff, NO-0218 OSLO, NORWAY
[b] Lunds Tekniska Högskola, LUND, SWEDEN
Corresponding author: sigmund.olafsen@brekkestrand.no

PACS: 43.50.Lj; 43.40.-r

ABSTRACT

Measurements of vibrations and groundborne noise from Oslo's metro trains are presented together with measurements of rail corrugation. The measurements have been performed in 12 residences. In all cases measurements of triaxial vibrations on a living room floor have been made. In some cases groundborne noise or rail surface corrugation has also been measured. Measurements have been made on a multichannel analyzer to allow simultaneous acquisition of data for all transducers. Data from at least 10 events have been collected for each house.

1. INTRODUCTION

Oslo Region Transport Engineering Section, the public company that runs Oslo's metro and tram networks, started to replace the 40 year old metro trains in 2006. The transition to the new Siemens MX-3000 trains was completed by 2010. Within a short time, increased complaints due to groundborne noise and vibrations from the metro trains were heard from the residents living close to the tracks. On this basis, a series of measurements was started in February 2011. The primary purpose of the measurements was to establish the actual situation and compare it with existing Norwegian guidelines and regulations. Measurements showing that the new MX-3000 trains did indeed give rise to a different spectrum of noise and vibrations have already been published.[1]

The performed measurements presented in this paper may, together with other investigations, become a part of the groundwork for a better understanding of the transmission of vibrations from metro trains into building foundations and living rooms in residences. Measurements of vibrations from railbound sources have a long tradition[2] as have investigations into the transfer from the ground into buildings[3,4,5]. There exists a Norwegian empirical method for calculating vibrations from railbound vehicles[6,7], and recent Japanese research[8] into vibration transmission in lightweight houses. Methods also exist for measuring vibration transmission in the ground[9], but this method is possibly a bit too comprehensive for surveys of existing situations. Vibrations may vary considerably from site to site, even at small distances.[10]

This paper deals with measured values for vibrations, groundborne noise and rail corrugation. The term groundborne noise is used for noise that has propagated as vibrations through soil or rock between the track and the house. A good general reference for groundborne noise from railbound vehicles is given by Chris Jones.[11]

2. REQUIREMENTS FOR NOISE AND VIBRATIONS

Oslo Region Transport Engineering Section tries to maintain good relations with its neighbors, and tries to control and reduce noise and vibration complaints as much as reasonably possible. As a response to the increased complaints after the introduction of the MX trains, several noise and vibration abatement measures have been put into use. It has been desirable to reduce the noise and vibrations to a lower level than required by law or regulations. The applicable regulations for existing situations and new lines are described below. These regulations apply to Norwegian conditions; other types of criteria have been suggested in other countries[12].

Norwegian regulations, for situations where both the house and the metro line have existed from before 1979, are given separately for noise and vibrations[13]. It is the objective responsibility of the owner of the noise source to comply with this set of regulations. For noise, the requirement is given as a 24-hour equivalent level. This requirement is given as an indoor level with windows and ventilation devices closed. The noise limit is $L_{Aeq24h} \leq 42$ dB. This noise limit is hardly exceeded at all along Oslo's metro lines. For vibration the requirement is given as $v_{w95} \leq 0{,}6$ mm/s in the vibration direction with the highest vibration level.

For planning of new lines, the requirements are stricter than for existing situations. The recommended values for groundborne noise for the recently reopened line Kolsåsbanen[14], has been L_{Amax}, FAST ≤ 37 dB. For airborne noise, the ordinary Norwegian regulations for indoor noise from outdoor sources[15], $L_{Aeq'24h} \leq 30$ dB and L_{5AF},night ≤ 45 dB. For vibrations the limit has been set by general Norwegian guidelines[14] to $v_{w95} \leq 0{,}3$ mm/s.

3. METHOD

It was decided to use simultaneous measurements of several parameters for each passage of a train set. The MX-3000 runs in fixed sets of 3 or 6 cars. In all cases at least 10 passages were measured. For most of the passages the average speed during the passage was measured with a stop watch.

Both vibrations and noise were measured in 1/3-octave bands in the quoted frequency ranges. For each parameter the single number value, L_{Amax},FAST for noise and v_w, SLOW for vibrations, was calculated for each passing train.

For each of the houses triaxial vibrations were measured on a living room floor. Other measurements were also performed, but this article will describe only the triaxial vibration in one point. Vibrations were measured as acceleration in dB relative to 10^{-6} m/s^2 and converted to vibration velocities. Vibration axes were defined as follows: x is the horizontal direction normal to the metro track, y is the horizontal direction parallel to the metro track, z is the vertical direction. Vibrations are presented in the frequency range 10 Hz to 1000 Hz, the maximal value with the time constant SLOW. Analysis of vibrations was performed according to NS 8176[16]. The measurements were performed using a small triaxial accelerometer. This small accelerometer has insufficient sensitivity to assure a satisfactory signal/noise ratio at frequencies below 10 Hz in some cases. However, experience has shown that there is a limited level of vibrations below 10 Hz from the metro trains to be investigated.

For each measured passage the measured maximal vibration velocity in each 1/3-octave band was multiplied by a filter factor. The square root of the sum of the squares of the weighted velocities in each frequency band is the weighted vibration velocity (v_w) for that passage. The quoted result for a point is a statistical value, $v_{w,95,}$ based on a lognormal distribution.

$$v_{w,95} = \overline{v_{w,\max}} + 1{,}8 * \sigma$$

where $v_{w,max}$ is the weighted velocity according to NS 8176[16]. A lognormal distribution of the measured data is assumed according to this standard, and σ is the standard deviation of the measured velocities. It is expected that 95% of the passing trains will give rise to a lower vibration value than the quoted $v_{w,95}$.

Groundborne noise was measured in at least one room at each location. Noise measurements were made in the frequency range 20 Hz to 20000 Hz, with the time constant FAST. The summary in table 1 give the A-weighted value as the $L_{A,max95}$ with a statistical analysis similar to that made for vibrations, but based on a normal distribution.

$$L_{A,\max 95} = \overline{L_{A,\max}} + 1{,}65 * \sigma$$

where $L_{A,max}$ is the maximal A-weighted sound level in each case, σ is the standard deviation of the measured sound pressure levels. The given value is the linear average of the dB values plus 1,8 times the standard deviation.

Rail surface corrugation was also measured on a sufficiently long stretch past each house in order to give a good measure of the rail quality on the part of the track that gave a significant contribution to groundborne noise and vibration for the house investigated. The corrugation was measured on both rails in both directions with ATP RSA. The data were recorded with a Squadriga from Head Acoustics and analyzed with their software.

4. MEASUREMENTS

The performed measurements are shown in Table 1. Measurements in February and March 2011 were made in 7 points along Oslo's metro line 1 (Frognerseterlinjen), 1 point along line 3 (Østensjøbanen), 3 points along

Table 1. *Performed measurements*

Site	Triaxial vibrations – position	Groundborne noise – position	Ground and foundation conditions	Rail surface corrugation
1-1	Underground bathroom	Underground bedroom	Concrete structure at least 6 m below ground	Yes
1-2	Ground floor living room	Underground living room	Firm clay	Yes
1-3	Bedroom 1st floor	Underground living room	Firm clay	Yes
1-4	Kitchen ground floor	Bedroom underground	Firm clay	Yes
1-5	Kitchen ground floor	Bedroom underground	Firm clay	Yes
1-6	Living room ground floor	Bedroom underground	Firm clay	Yes
1-7	Living room ground floor	Living room underground	Probably clay	No
3-1	Living room ground floor	Bathroom underground	At least 40 meters of clay	No
4-1	Living room ground floor	Underground living room	Probably clay	No
4-2	Living room ground floor	Undergroud living room Underground bedroom	Probably clay	No
4-3	Living room ground floor	Underground living room	Probably clay	No
6-1	Living room ground floor	Underground cellar room	Probably clay	No

line 4 (Lambertseterbanen), and 1 point where several lines run on the same tracks.

4.1. Houses where vibrations and groundborne noise was measured

The houses where measurements were made are detached or vertically divided. All of these houses had a wooden or other lightweight vertical structure above ground. In two of the houses, the floor where vibrations were measured was a concrete structure cast in situ. The structure below ground is concrete or stone. Most of the houses are on sloping ground, making the definition of the floors somewhat difficult. The levels have been defined based on the side of the house facing towards the metro line. The term underground is used for rooms with the floor below ground level on the side facing the metro line. The term ground floor is used for rooms with the floor roughly on the same level as the terrain on the side facing the metro. The term 1st floor is used for rooms with the floor roughly one story above ground level on the side facing the metro. The distance is defined as the distance from the house wall closest to the track to the centerline of the metro midway between the tracks.

For the six houses where detailed results are presented, the ground conditions have been controlled against the report from tests performed during the design stage of the latest improvements to the line[17]. This is described together with the results of measurements for each of these houses.

4.2. Vibration and groundborne noise measurements

The presented series of measurements were made in February and March 2011. The measurement setup in each case was decided on the spot after asking the house owners where the noise and vibration problem was perceived as most severe. Strictly speaking this is not quite in accordance with the standard[16], which requires that vibrations be measured where the level is highest. This is usually at a midpoint of the longest span of the structure. In most cases the triaxial vibrations were measured in a room above ground, the groundborne noise was measured in a room underground. Figure 1 shows a typical example of the mounting of the triaxial accelerometer.

Figure 1. *Rig and the triaxial accelerometer*

4.3. Rail corrugation measurements

Along the line with the most complaints, line 1 Frognerseterlinjen, it was also decided to measure the rail corrugation according to ISO3095-2005[18]. The condition of the rail has been known to be a factor determining the indoor noise and vibrations in nearby dwellings[19, 20, 21]. Accordingly practical tools to measure rail corrugation have been developed[22]. Figure 2 shows the measurements of the rail corrugation. For the other houses, it was not considered necessary to measure the rail corrugation, because the track was in such a poor condition that it was replaced anyway.

Figure 2. *Preparing to measure rail corrugation.*

5. MEASURED RESULTS

5.1. Overview

An overview of the measured results is given in Table 2. The table gives the weighted overall results. A more detailed description of the results from the houses where the rail corrugation was measured follows below together with a more detailed description of the ground conditions.

5.2. Spectra of noise, vibrations and rail corrugation

For six of the houses it's possible to show the spectra of all three parameters together. As the houses are different, a short verbal description of each house is also given. The distance to the metro is given from the house wall to the centerline between the tracks.

5.2.1. House 1-1

This is a modern house where the foundations go down at least 6 meters below ground. It's a semi-detached house. Above ground it's connected with one other house; below ground this chain of two houses is connected with a similar chain of two houses through an underground parking garage. The structural material is concrete below ground, where all the measurements presented have been made. The ground conditions under the track is bedrock just a couple of meters below ground, thus the house it probably built on bedrock.

The measurements of triaxial vibrations were made at a level one floor lower than the metro line. The average measured vibration spectrum is shown in figure 3. The measured level of groundborne noise is shown in figure 4. The results of the rail surface analysis are shown in figure 5.

Table 2. *Overall results.*

House	Distance (m)	V_{w95} x (mm/s)	V_{w95} y (mm/s)	V_{w95} z (mm/s)	L_{AFmax} groundborne (dB)	Rail corrugation
1-1	16	0,07	0,06	0,08	42	Worn rails, broadband corrugation
1-2	16	0,02	0,02	0,12	36	Worn rails, corrugation peak at 12,5 cm
1-3	15	0,03	0,03	0,05	37	Worn rails, corrugation peak at 12,5 cm
1-4	13	0,40	0,29	0,34	37	Worn rails, broadband corrugation
1-5	11	0,05	0,06	0,12	34	Worn rails, corrugation peak at 4 cm
1-6	27	0,02	0,03	0,06	41	Worn rails, broadband corrugation
1-7	10	0,27	0,20	0,40	50	Track replaced - not measured
3-1	70	0,07	0,06	0,08	31	Not measured
4-1	26	0,16	0,13	0,12	30	Track replaced - not measured
4-2	19	0,20	0,08	0,14	42	Track replaced - not measured
4-3	9	0,03	0,03	0,08	38	Track replaced - not measured
6-1	16	0,05	0,06	0,16	39	Not measured

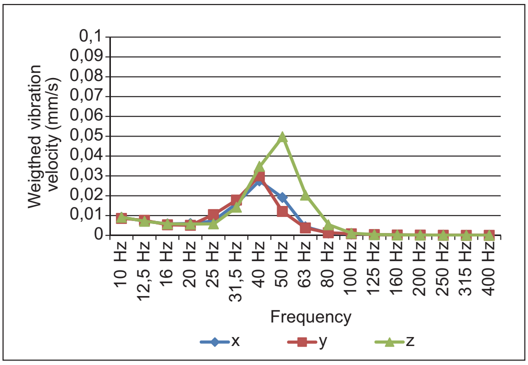


Figure 3. *House 1-1, measured vibrations.*

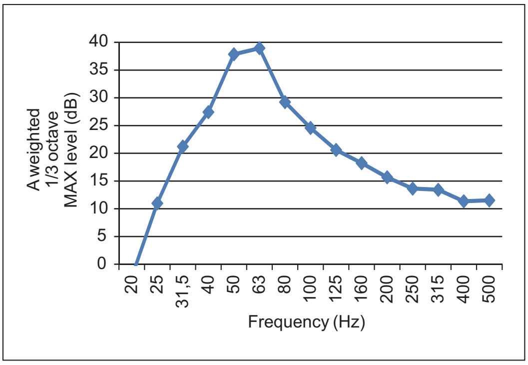


Figure 4. *House 1-1, measured groundborne noise.*

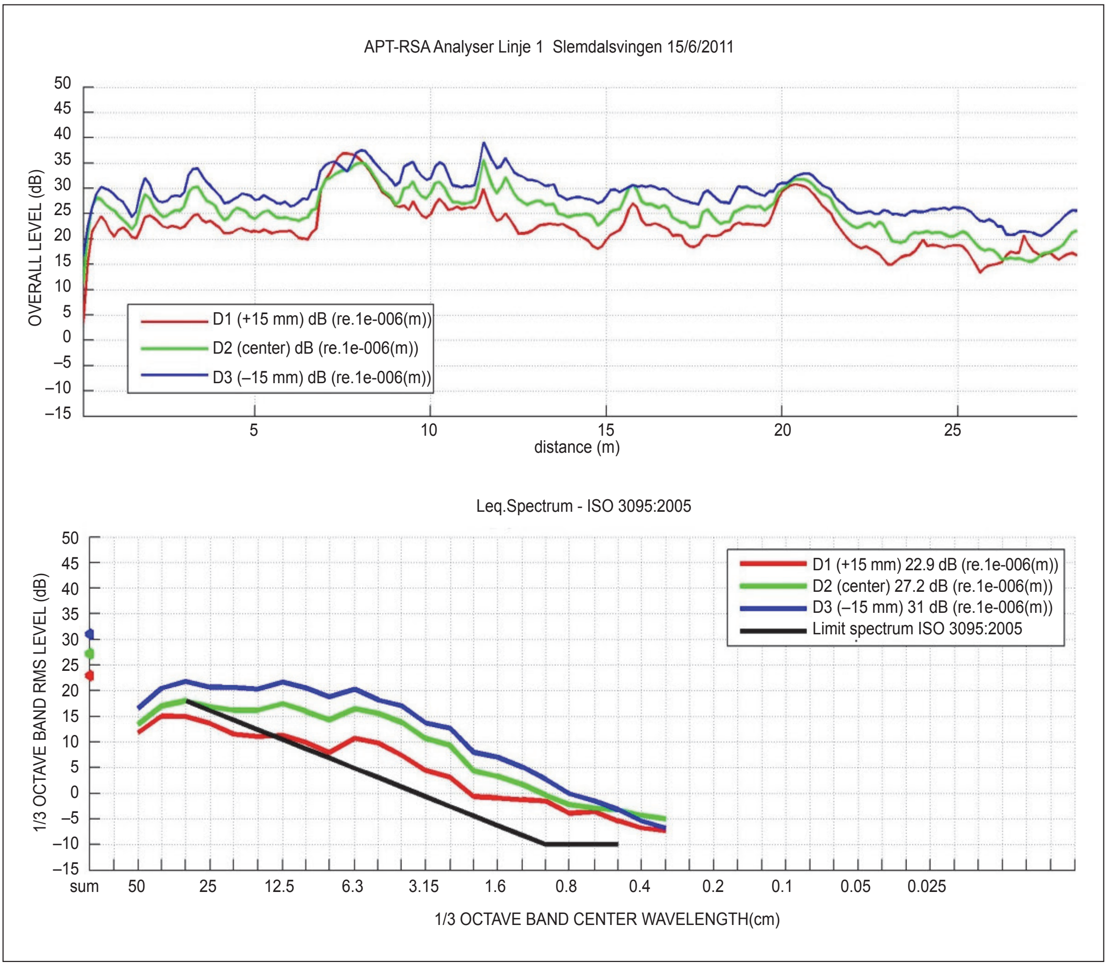


Figure 5. *House 1-1 – rail corrugation.*

The vibrations in the X and Y directions peak at 40 Hz, the vibrations in the Z direction peak at 50 Hz, and the frequency with the highest contribution to the A-weighted level of groundborne noise is 63 Hz. The rail surface analysis gives no indication of a clear pattern of wear on the rails. The trains have different speeds on the different tracks here. For this house, there is not sufficient justification to claim any correlation between rail wear and indoor noise and vibrations.

5.2.2. Houses 1-2 and 1-3

These two houses are neighbors, and the houses are built in the same project. For both houses the structure below ground is concrete, from the ground floor up it's a wooden structure. For both houses the measurements of groundborne noise were made in an underground room with very little airborne contribution to the measured noise. The vibration measurements in house 1-2 were made on the living room floor, which is roughly on the same level as the metro line. The vibration measurements in house 1-3 were made on a bedroom floor roughly 3 meters higher than the metro line. The houses are so close to each other that the rail surface was measured in one go for both houses.

The vibration spectra show different patterns for these two houses. Figure 6 shows the measured vibrations in house 1-2, while figure 7 shows the measured vibration levels in house 1-3. It is reasonable to assume that the different shape of the vibration spectra is due to the different response of the house on the ground floor (house 1-2) and on the first floor (house 1-3).

The groundborne noise spectrum of house 1-2 is shown in figure 8, while the noise spectrum of house 1-3 is shown in figure 9. The shape of the groundborne noise spectra is very similar for these two houses, with a clear peak at 50 Hz.

The rail surface analysis shows a clear pattern of a repetitive wear on the rails. The speed of all the trains

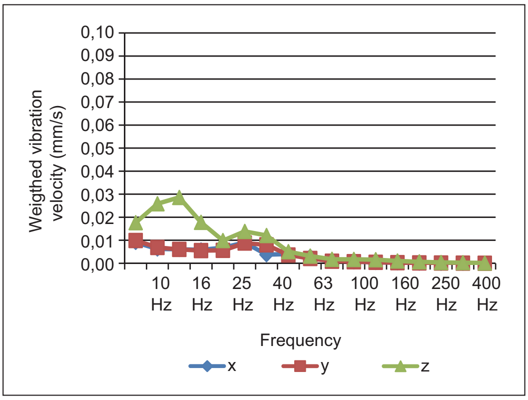


Figure 6. *Vibrations in house 1-2.*

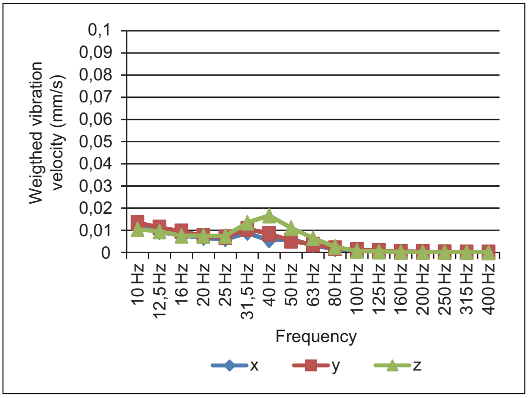


Figure 7. *Vibrations in house 1-3.*

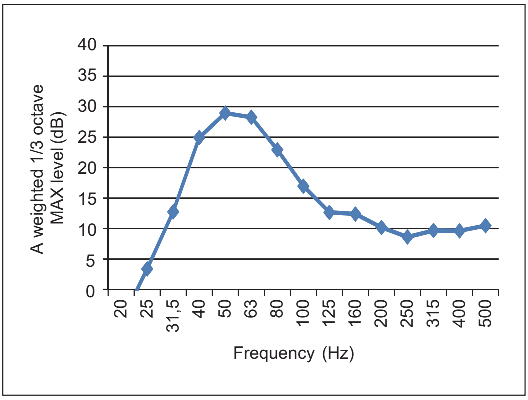


Figure 8. *Groundborne noise in house 1-2.*

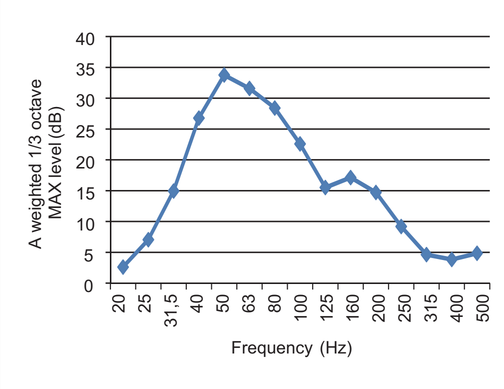


Figure 9. *Groundborne noise in house 1-3.*

passing by was in the range 6-7 m/s. The rail surface analysis shows a peak at 12,5 cm wavelength. This could correspond to a frequency in the range of 50 Hz. The results of this measurement are shown in figure 10.

The match between the critical frequencies of groundborne noise is good, the 50 Hz peak is still there when A-weighted. For the vibrations it is more difficult to find any connection.

The ground conditions under the track close to these houses seem to be thick layers of firm clay.

5.2.3. House 1-4

This house is close to the metro line. It has a concrete substructure, and the floor of the 1st floor is a concrete slab. The walls above ground are wooden structures. The vibration levels are measured on the kitchen floor. This floor is roughly on the same level as the metro line. The groundborne noise is measured on a bedroom at a level about 3 meters lower than the metro line. For this house, there is a pronounced difference in vibrations depending on the direction of the trains. The inbound trains towards the city centre are closest to the house, and they give rise to substantially higher vibration levels. The measured vibration levels for this house are the highest measured in this report. The vibration was clearly feelable during the passage of the metro trains, and the groundborne noise was definitely uncomfortable during the passages. The measured vibration levels on the kitchen floor are shown in figure 11, while the measured groundborne noise is shown in figure 12.

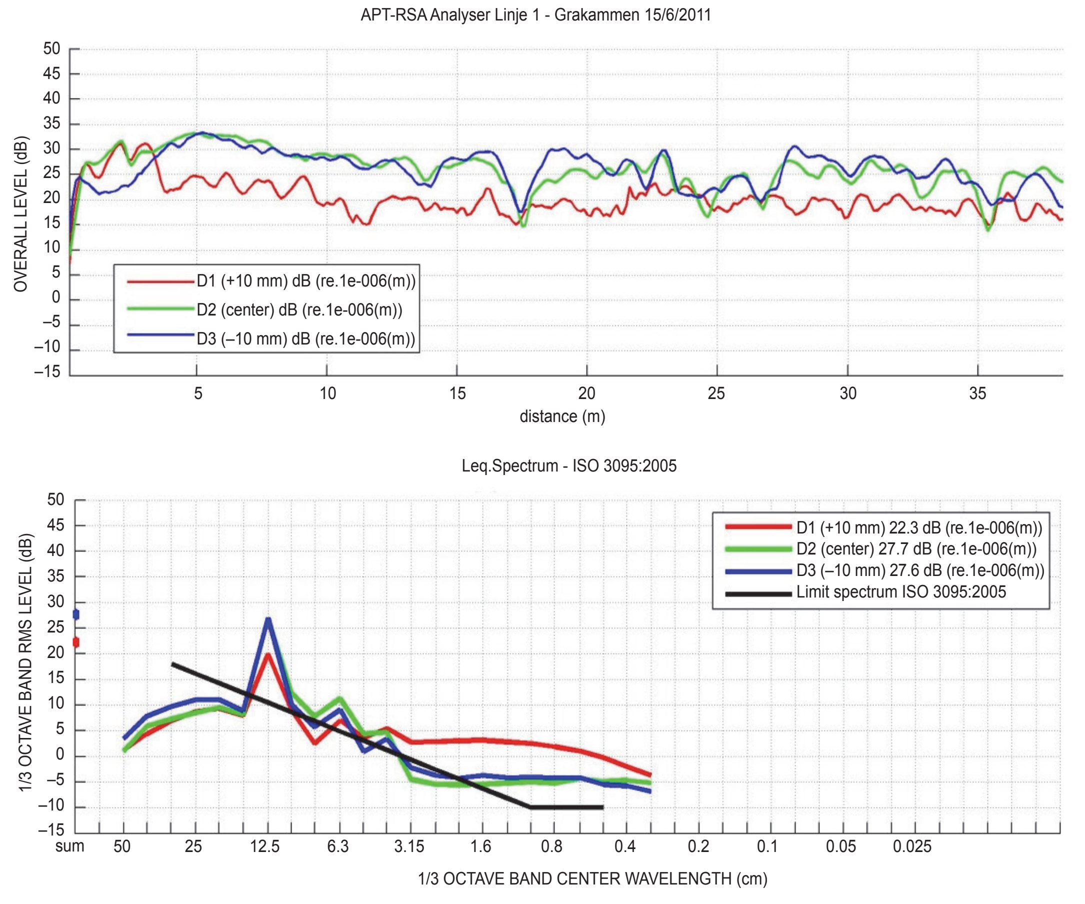


Figure 10. Rail surface analysis for house 1-2 and 1-3.

The rail surface analysis shows the rails are clearly worn, well above the limit spectrum given in ISO 3095:2005. But there are no clear peaks in the rail surface analysis. The results of the measurement are shown in figure 13. For this house the trains in both directions were running at speeds of 25 – 30 km/h, which might correspond to frequencies in the range 17 Hz to 33 Hz when the train runs on a rail with

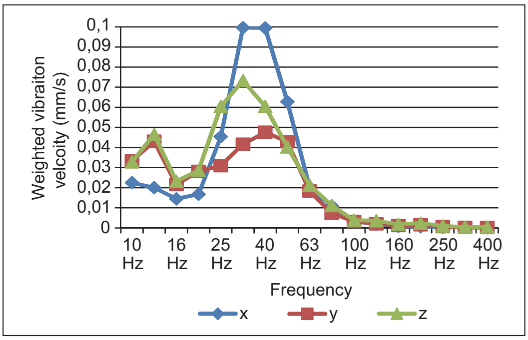


Figure 11. *Vibrations in house 1-4.*

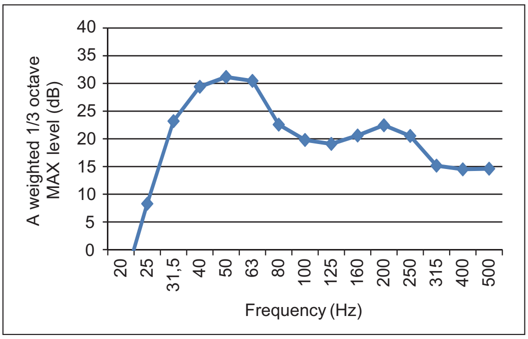


Figure 12. *Groundborne noise in house 1-4.*

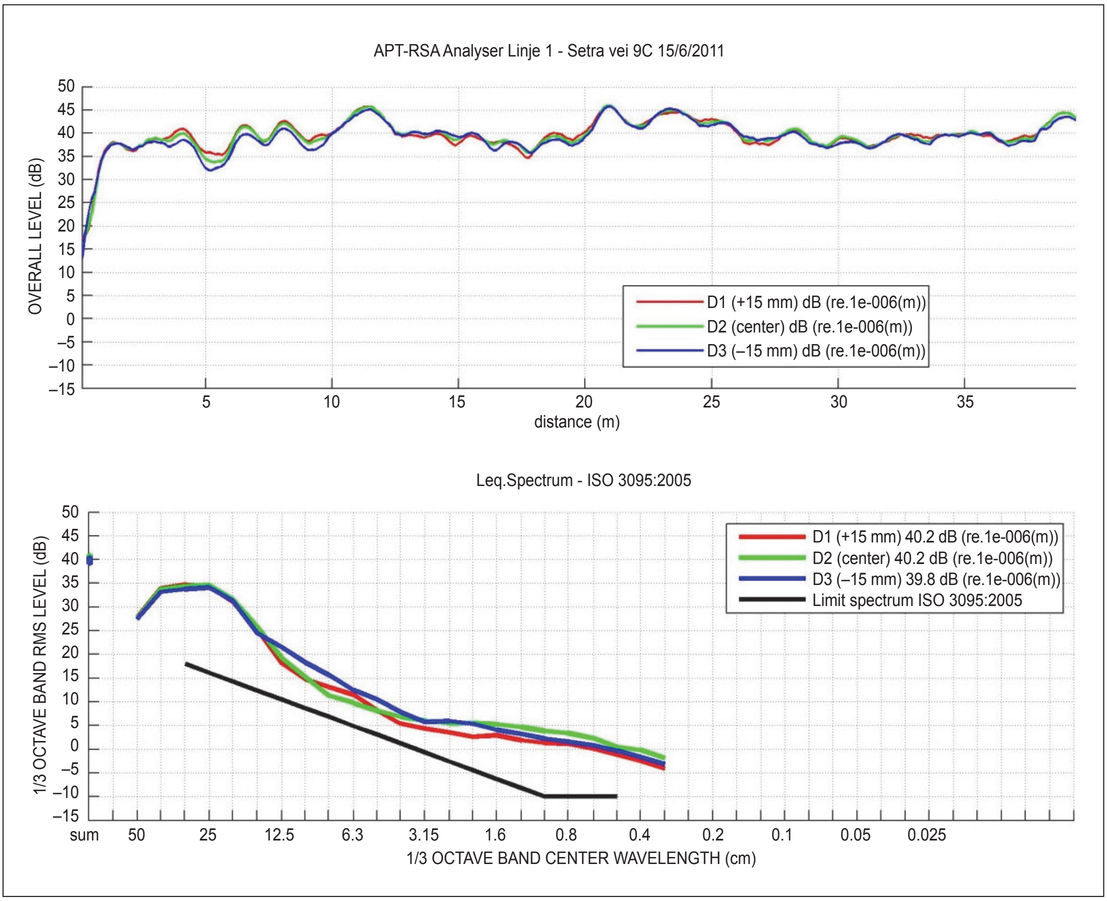


Figure 13. *Rail surface analysis for house 1-4.*

corrugation wavelengths of 25 to 40 cm. This is a reasonable but not perfect match between the peak frequencies for rail corrugation, vibrations and groundborne noise.

The ground conditions under the track for this house seem to be firm clay down to bedrock 5-10 meters below the track.

5.2.4. Houses 1-5

The house is close to the metro line. The structure below ground is concrete, above ground it's a wooden structure. The vibration levels are measured on a kitchen on the ground floor. This floor is on roughly the same level as the metro line. The measurements of groundborne noise were made in a bedroom on the same level without windows facing the metro line. Interestingly the vibrations show peaks at different frequencies in different directions. The measured vibration levels are shown in figure 14, while the measured groundborne noise levels are shown in figure 15.

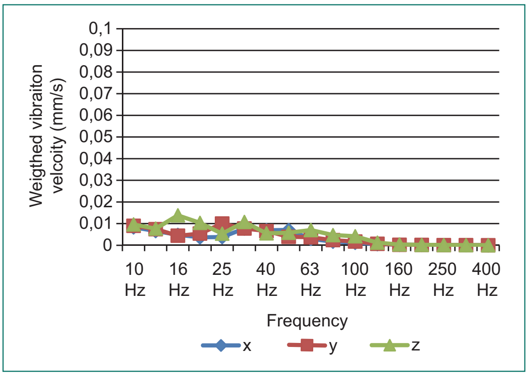


Figure 14. *Vibrations in house 1-5.*

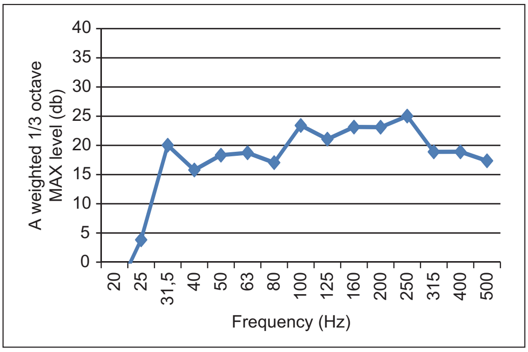


Figure 15. *Groundborne noise in house 1-5.*

A detail picture of the rail past these houses is shown in figure 16, while figure 17 shows another view of the rail. The rail surface analysis shows a clear peak at 4 cm wavelength. In addition the rails are generally worn. The results of the measurement are shown in figure 18. There is no clear peak in the spectra of the groundborne noise and vibrations. There is however a small top in the noise of groundborne noise at 250 Hz, which could fit in with the rail corrugation measurements.

Figure 16. *Detail of rail*

Figure 17. *Averview of rail*

The ground conditions under the track for this house seem to be firm clay down to bedrock 5-10 meters below the track.

5.2.5. Houses 1-6

This house lies higher than the metro line. The vibration measurements are made on the ground floor in a living room. The vibration levels are distributed over a wider frequency range than for most of the houses. The vibration levels are shown in figure 19, while the groundborne noise levels are shown in figure 20. The rail surface analysis, figure 21, shows that the rails are generally worn past this house without any clear peak.

The ground conditions on the track itself are as follows: Firm clay down to about 5 meters below the track, where bedrock was found. It is quite likely that the house rests on firm clay and/or bedrock.

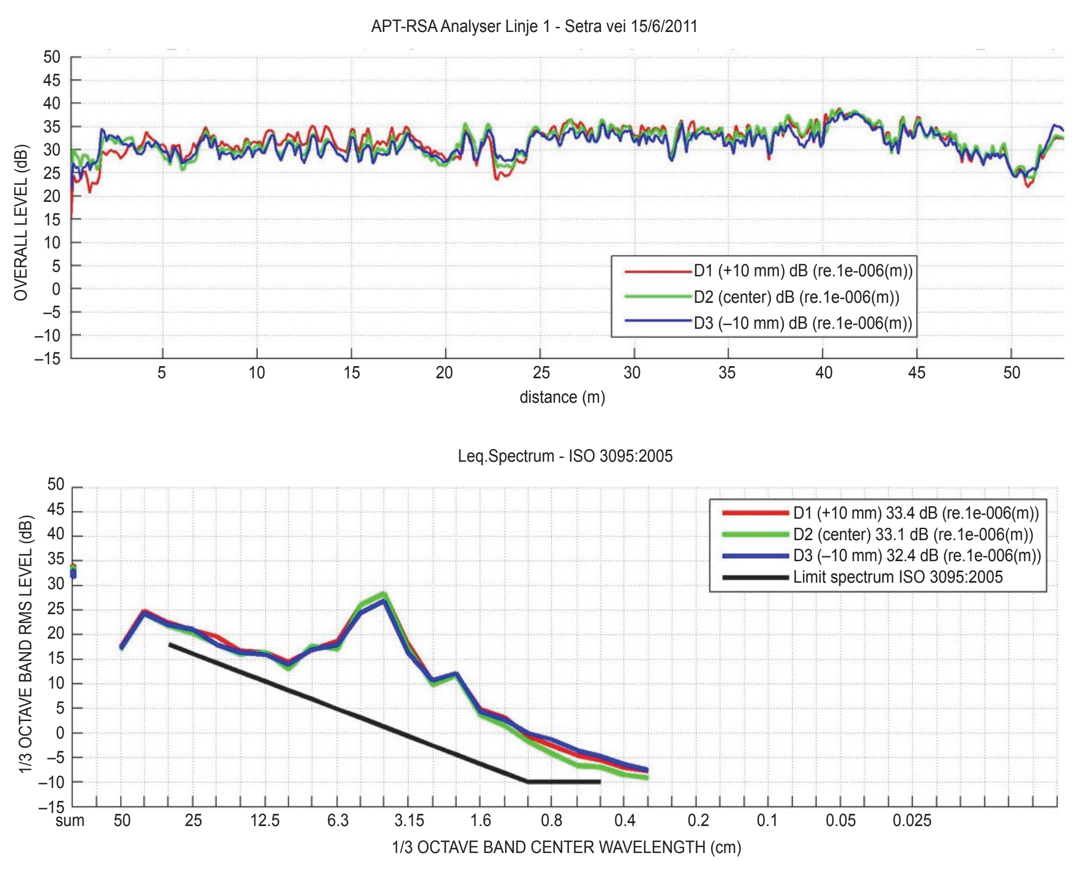


Figure 18. *Rail surface analysis for house 1-5.*

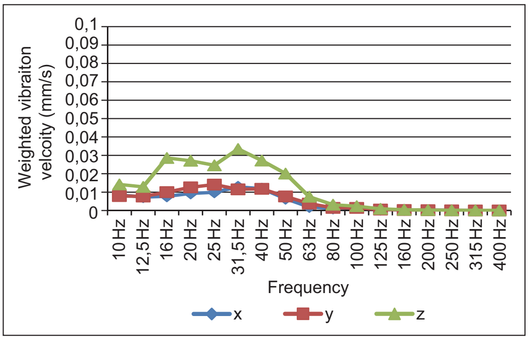


Figure 19. *House 1-6, vibrations.*

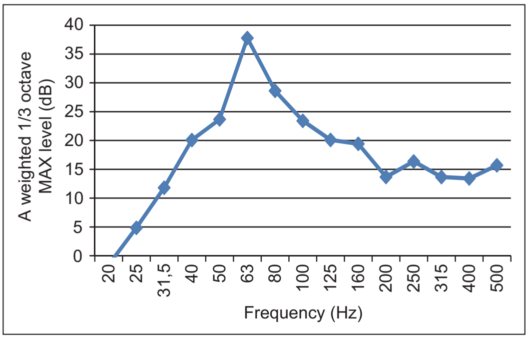


Figure 20. *House 1-6, groundborne noise.*

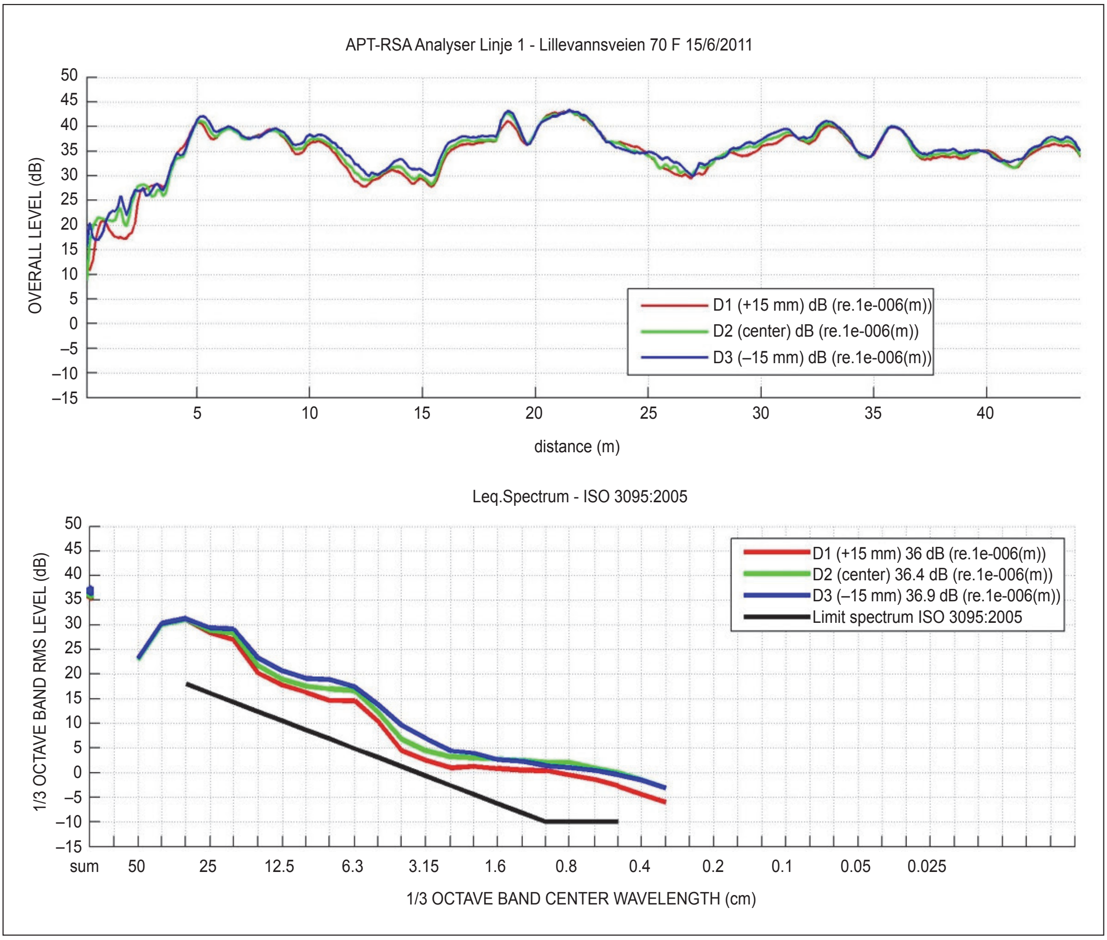


Figure 21. *House 1-6, rail surface analysis.*

6. COMMENTS

Measurements of vibrations and groundborne noise from Oslo's metro have been presented. This article should be viewed as a pilot report from an ongoing project to learn about the sources and transmission paths of vibrations into houses. The measurements of rail surface corrugation show that the rails are worn, in some cases in a repetitive pattern. For the houses 1-2 and 1-3 there is a reasonable match between the spectra of the rail corrugation and the groundborne noise, but not for vibrations. In house 1-4 there is a reasonable match between the peak frequencies of rail corrugation, groundborne noise and floor vibrations. For house 1-5 there is some indication of a higher noise contribution at a frequency compatible with the rail corrugation measurements.

7. CONCLUSIONS

The A-weighted spectra of groundborne noise are similar in shape for all the houses. The vibration spectra do not show a consistent pattern. More data are needed, particularly regarding transfer functions between the ground, the building foundation and the floors in the rooms. It is likely that worn rails cause increased noise and vibrations in houses along the metro lines. In four of the houses where measurements have been made, the connection is indicated by the measurement results.

8. FURTHER RESEARCH

The presented measurements of vibrations, noise and rail surface do not point out a clear correlation. There is a need for a larger series of measurements in other houses.

8.1. *Transfer functions from ground to house*

Japanese research has shown well behaved transfer functions between vibrations in the ground[8], vibrations on the building foundations and vibrations on the floors of residences. This even applied to houses exposed to vibrations from different types of sources of vibration. It would be very interesting to measure such transfer functions on Norwegian houses. Initial measurements indicate that the transfer functions may be less predictable than in Japanese houses[23]. This may be due to Japanese houses being earthquake resistant and more uniformly built than Norwegian houses. Future measurements will include transfer functions.

8.2. *Transfer of vibrations from trains to the ground*

The transfer of vibrations from the metro train via the track into the surrounding ground is not well known. It is very likely that the construction of the boggies, the wheels and the track may all be critical. Another factor to be considered is that the metro trains are usually only a source of vibration at short distances. The whole area between the track and the house may actually be within the near field. This requires further research.

8.3. *Seasonal variations*

All the residence owners that have been visited during these measurements have claimed that the vibration levels vary significantly between winter and summer. In particular many of the house owners claim increased vibration levels during especially cold periods. It is quite possible that this is correct, as it is quite conceivable that the mechanical properties of the soil change with the seasons. It could be investigated using long-term measurements of vibrations in one point.

ACKNOWLEDGEMENTS

Our sincere thanks go to Oslo region transport engineering section (Kollektivtransportproduksjon, the publicly owned company that runs Oslo's metros and trams). This company has commissioned the measurements and allowed the publication of the results. In addition we would like to thank Lars Fredrik Nordin of Brekke & Strand akustikk for proofreading the manuscript and several suggestions for improvement to the text.

REFERENCES

[1] Sigmund Olafsen, "Difference in levels of groundborne noise and vibrations between the T-1300 and MX-3000 metro trains in Oslo", *BNAM 2012, Odense.*

[2] Jørgen Jacobsen, "Measurement of vibration in buildings, proposal for a Nordtest method", *BNAM 1988, Tampere, pp. 231-234.*

[3] Jørgen Jacobsen, "Propagation of ground-borne vibrations from railways", *BNAM 1988 Tampere, Tampere, pp. 235-238.*

[4] S. Ljunggren, "Noise from underground railways – a state of the art review", *Internoise 1996 Liverpool, pp. 409-414*

[5] R J Greer, K.M.Collins, "Groundborne noise and vibrations: the pitfalls", *Internoise 1996 Liverpool, pp. 415-420*

[6] Madshus,C, Bessason, B, Hårvik, L, "Prediction model for low frequency vibrations from high speed railways on soft ground." *International workshop on Railway and Tracked Transit System Noise, 5. (5. IWRN). Voss, Norway, June 1995. Proceedings pp. 3.3.1 – 3.3.10.* Also published in Journal of Sound and Vibration.

[7] Arild Brekke, "Vibration and structure borne noise from railways", *BNAM 1994 Aarhus, pp. 363-368.*

[8] Yoshihiro Hirao, Sunao Kunimatsu, Takuji Hamamoto, "Development of wireless measurement system for ground-borne vibration in buildings and measurements for vibration amplifications of detached houses", *Internoise 2011, Osaka*

[9] *ISO 14837 – Part 3: Measurement "Ground-borne noise and vibration arising from rail systems", 2012,* Christian Madshus,

[10] Chris Jones, "Low frequency rail vibration", chapter 12 in "*Railway noise and vibration. Mechanisms, modeling and means of control*", edited by David Thompson, Elsevier, 2009

[11] Chris Jones, "Ground-borne noise", chapter 13 in "*Railway noise and vibration. Mechanisms, modeling and means of control*", edited by David Thompson, Elsevier, 2009

[12] Jorge Patricio, Fernando Schiappa de Azevedo, "Emission of noise at home by vibrating slabs and walls, a new criterion to evaluate ambient vibration", *Acta Acustica* **92,** *pp. 654-660.*

[13] Forskrift om begrensning av forurensning (forurensningsforskriften), Kapittel 5. Støy - kartlegging, handlingsplaner og tiltaksgrenser for eksisterende virksomhet. This regulation (in Norwegian) gives the requirements for indoor noise levels for existing houses exposed to noise from existing sources.

[14] Design criteria for Kolsåsbanen

[15] *Acoustic conditions in buildings. Sound classification of various types of buildings.* NS 8175:2012, (In Norwegian).

[16] *Vibrasjoner og støt – Måling I bygninger av vibrasjoner fra landbasert samferdsel og bedømmelse av vibrasjonspå-virkning på mennesker (In Norwegian)* NS 8176.

[17] Kollektivtransportproduksjon AS. ”*Oppgradering strømforsyning og vedlikehold Holmenkollbanen. Grunnundersøkelser. Datarapport.*” March 30th, 2009, from Monica Bakkan of Multiconsult (in Norwegian, about the ground conditions along the metro line 1 - Holmenkollbanen).

[18] *Railway applications -- Acoustics -- Measurement of noise emitted by railbound vehicles* ISO 3095 – 2005,

[19] Henrik Möller & Mats Backholm, “Noise comparison of Helsinki street car rail structures”, *BNAM 1988 Tampere, pp. 247-250.*

[20] Siegfried Riemens, “Noise control of tramcar noise by grinding the rails*”, Internoise 1993 Leuven, pp. 1451-1454.*

[21] P. C. Dings, “Rail corrugation: Consequences for railway noise”, *Internoise 1996, Liverpool, pp. 215-218*

[22] Geert Desanghere, Tom Vanhonacker, “Development and validation of a rail surface analyser for accurate quantification and evaluation of rail corrugation and track work acceptance after acoustic grinding”, *Internoise 2007 Istanbul.*

[23] Sigmund Olafsen, “Transfer functions of vibrations from metro trains to houses “, *BNAM 2014 Tallinn.*