Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Information Technology and Electrical Engineering
Department of Electronic Systems

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An investigation into the psychoacoustic characteristics of train noise in Oslo, and their effect on annoyance

Master's thesis in Electronics Systems Design and Innovation
Supervisor: Guillaume Dutilleux and Sigmund Olafsen
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Summary

As the population grows in our major cities, so does our need for public transport. It is important to evaluate the noise impact from public transport, as it can cause feelings of annoyance or stress, and lead to adverse effects on people's life quality and/or work environment. To do this, data about noise emission from existing railways needs to be collected and evaluated. Presently, most data collected is of the A-weighted sound pressure level, but this is not believed to give the full picture, as socio-acoustic surveys give different annoyance ratings than what the A-weighted sound pressure level values indicate. It is hypothesised in this study that there exists psychoacoustic parameters which can help uncover possible reasons for this discrepancy between the measured noise level from trains and the perceived annoyance.

The following thesis attempts to investigate what psychoacoustic characteristics affect short-term annoyance caused by train pass-bys, and how. This was done by collecting recordings of 53 pass-bys of trains running on Oslo's metro lines, and calculating their A-weighted sound pressure level as well as the psychoacoustic parameters loudness, sharpness, roughness, fluctuation strength, impulsiveness and tonality using computer software. These parameters were compared to the signals' annoyance ratings, found from listening tests performed on 25 participants, to investigate the correlation.

It was found that the sound energy content, represented by the sound pressure level and loudness of the signals, and high-frequency content, represented by sharpness and tonality, had the largest effects on annoyance. This is consistent with previous studies of railway noise. It is suggested that psychoacoustic parameters should be used in a greater capactiy in future assessment of environmental noise. Brekke & Strand have now decided to start including psychoacoustic parameters in their noise evaluations of Oslo's railways. This will hopefully lead to better insight into annoyance-related factors of train noise, and possible solutions to reduce noise pollution from trains.

Sammendrag

Etter hvert som befolkningen vokser i våre største byer, vokser også vårt behov for offentlig transport. Det er viktig å vurdere støynivået fra offentlig transport, da det kan ha uønskede effekter på folks livskvalitet og/eller arbeidsmiljø, og føre til stress og irritasjon. For å gjøre dette må data om støyemisjon fra eksisterende jernbaner samles inn og evalueres. For tiden er det A-vektet lydtrykksnivå som brukes mest i målinger av togstøy, men dette antas å ikke gi hele bildet, da sosio-akustiske undersøkelser viser en annen grad av irritasjon enn det man skulle kunne anta basert på det A-vektede lydtrykknivået. Denne studien antar at det finnes psykoakustiske parametere som kan bidra til å avdekke mulige årsaker til dette avviket mellom det målte støynivået fra tog og den opplevde irritasjonen.

Denne masteroppgaven forsøker å undersøke hvilke psykoakustiske parametre som påvirker den kortvarige irritasjonen forårsaket av støy fra togpasseringer, og hvordan. Dette var gjort å finne det A-vektede lydnivået, samt de psykoakustiske parameterne lydstyrke, skarphet, grovhet, svingningsstyrke, impulsivitet og tonalitet for 53 togpasseringer. Disse resultatene var såsammenlignet med signalenes irritasjonsverdier, funnet fra lyttetester utført på 25 deltakere, for å undersøke eventuelle korrelasjoner.

Det ble funnet at lydenergiinnholdet, representert ved lydtrykksnivået og lydstyrken, og høyfrekvent innhold, representert ved skarphet og tonalitet, hadde de største effektene på irritasjon. Dette stemmer overens med tidligere studier av jernbanestøy. Det er foreslått at psykoakustiske parametere skal brukes i større grad i fremtidig vurdering av miljøstøy. Brekke & Strand har nå bestemt seg for å inkludere psykoakustiske parametere i deres fremtidige støyevalueringer av Oslos jernbaner. Dette vil forhåpentlig føre til bedre innblikk i irritasjonsrelaterte faktorer av togstøy, og kanskje gi nye løsninger for å redusere støy fra tog.

Preface

This is a master thesis submitted to the Norwegian University of Science and Technology (NTNU), Department of Electronic Systems. The thesis is part of a larger project called Metronova, which is an investigation on peoples experience of noise from the metro lines in Oslo, put forth by the consulting firm Brekke & Strand Akustikk AS. My focus has been on psychoacoustic components to train noise, and their effect on peoples annoyance.

I would like to thank my supervisor at Brekke & Strand, senior advisor Sigmund Olafsen, for his help and optimism during this project, as well as for his enthusiam for railway noise. I would also like to thank my supervisor at NTNU, Guillaume Dutilleux, for all his helpful input and comments throughout the process.

Additionally, I wish to thank Tim Cato Netland, lab engineer at NTNU, for his help in providing equipment for the listening test. I would like to thank Alice Hoffman, the other supervisor in the Metronova project, for providing the basis for the listening test code in Matlab and for being helpful in introducing the psychoacoustic concepts. I am also grateful to Andris Broks, another student involved in the Metronova project and with whom I did all the outdoor noise measurements, for all his help and collaboration.

Finally, I wish to express my gratitude to my family, for all their help and encouragement throughout my life, but especially these last five years. I am also very appreciative for Trondheim and the great friends I have made here, both at NTNU and at Studentersamfundet i Trondhjem, without whom I would certaintly not have made it through.

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Abbreviations

SPL = Sound pressure level
L = Loudness
S = Sharpness
R = Roughness
FS = Fluctuation strength
I = Impulsiveness
T = Tonality
A = Annoyance
GUI = Guided user interface

Chapter 1

Introduction

1.1 Background

As urban populations grow, and the global push for low-emission solutions in all areas of life is increasing, there is a great demand for cities to expand and improve their public transport sector. One of the main considerations in doing so, is noise pollution, which can cause stress and annoyance for the surrounding residents, and in severe cases lead to health issues. To reduce the impact of train noise on populations, it is important to quantify what it is, and how it occurs. To do this, one can argue that it is not enough to know the sound pressure level output from these trains. Understanding the sound quality metrics of the train noise may give a better indication of its annoyance levels, and therefore its impact on the environment. In understanding the specific characteristics of the noise that causes annoyance, more efficient solutions to the problem may be found.

This master thesis is written in collaboration with Brekke & Strand, and is a part of their Metronova project. One of Brekke & Strand's major clients is Sporveien T-banen AS, the state owned railway company that runs the train and tram lines in Oslo and Akershus. The noise and vibration monitoring program for the metro lines started in 2016, and was modeled using the experiences made from a similar monitoring of the tram lines, that has been going on since 2007 [1]. Several hundred noise measurements have been made, at 11 different points along the metro line track. The Metronova project currently consists of four parts, the first of which concerns socio-acoustic surveys of vibrations from Oslo's train lines. From Brekke & Strand's experience with measurements and socio-acoustic surveys of noise, it seems that people are more annoyed at the noise emitted by trains than what is expected given the sound pressure levels measured.

The other parts of the Metronova project are split into three master theses, all completed during the spring of 2019. One pertains to interviews of people living next to the metro lines about noise and vibrations, performed by Therese Öquist, a student of Public health science at NMBU. Another consists mainly of listening tests performed by

Andris Broks, another student of Acoustics at NTNU, where train signals are evaluated by the participants on their psychoacoustic characteristics. The final part of the project is this thesis, which measures trains signals' psychoacoustic parameters using computer software, and compares these values, as well as the A-weighted sound pressure level, to annoyance ratings found using listening tests. This way, one hopes to find an explanation for the discrepancy between annoyance ratings and noise levels. The overall goal of the Metronova project is to increase information on noise emissions from Oslo's metro lines, and the project is expected to continue beyond this thesis.

1.2 Oslo's Metro Lines

As stated in the previous section, the five metro lines in Oslo and Akershus are run by Sporveien T-banen AS. The newest line, Lørenbanen, opened in 2016. There are 115 MX 3000-trains by Siemens running on the tracks. The train models are from 2006 to 2011, all similar in design. Each train consists of three cars, and the trains usually run as two trains linked together [1], giving them a total length of up to 110 meters (corresponding to 6 cars) and a capacity of up to 800 passengers. In 2017, the metro lines carried 118 million passengers [2]. There is only one type of track, and this is a ballast type. There is existing information on rail corrugation, and track decay has also recently been measured at one of the sites used in this study.

The trains usually operate at speeds between $20 - 50$ km/h, due to the curvature of the track and short distances between stops. The highest speeds are up to 70 km/h, at a few sites. The main noise components are motor noise at lower speeds, and rolling noise, which is caused by surface irregularities in the wheel and rail contact area [3]. There may also be some screening effects, caused by nearby barriers which affect the propagation of sound.

1.3 Aim

This study intends to investigate the possible causes of the discrepancy between the measured noise levels along the metro line and the amount of annoyance the noise creates. The hypothesis is that there are characteristics of the noise which can not be measured by sound pressure levels alone, but which may be measured by psychoacoustic parameters. It is postulated that noise made for example when the track is curved, sloped, and/or wet, is more annoying than when it is straight, flat, and/or dry.

The aim of this study is to gain a greater understanding of the characteristics of the noise from a passing train, in different locations and under different conditions. This is done by comparing the sound pressure level of these pass-bys, as well as their psychoacoustic parameters such as loudness, sharpness and tonality, with their annoyance as perceived by listeners.

1.4 Placement in research

The A-weighted sound pressure level measures is an objective measurement of sound pressure level that weights its frequency components to account for the way human hearing works. It is the unit of measurement most commonly used in evaluating environmental noise. However, there has long been questions as to if it is accurate enough [4]; if the sound levels alone contain enough information to calculate measures of human response to noise [5]. The main reason for why it is still widely used instead of other parameters such as loudness, is because it is used in a wide body of regulations and standards, and these regulations can be hard to change and slow to adapt to new solutions. Another reason is that loudness requires a lot more computational power and it has consequently not been an accessible option which can be measured in a handheld meter, for example. However, as technology advances this has become possible, and it is therefore useful to investigate various psychoacoustic parameters as potential alternatives to the A-weighted sound pressure level.

Psychoacoustics is a growing field of science. As of now, it is mainly used in ensuring the sound quality of products, such as refrigerators or cars, but its usefulness in other areas of acoustics is becoming more and more apparent. As it is largely based on more subjective measurements, it is a harder field to standardize, which leads to greater variations and uncertainties in the different methods of measurement. In recent years, a few loudness standards have been established, such as DIN 45631/A1 [6] and ISO 532 [7], as well as the DIN 45692 standard for sharpness [6]. Further standardization is needed to increase the availability of pscyhoacousatic parameters in noise measurements, which has great potential, especially in classifying environmental noise. In order to develop valid calculation models to be standardized, however, more research is needed on the different psychoacoustic phenomena [8].

Attempts have been made at finding alternative measures of environmental noise, as in the 2008 article ”Evaluating roadside noise barriers using an annoyance-reduction criterion”[9], where it was found that the A-weighted SPL may not be a valid indicator of the effects of a roadside noise barrier on annoyance. The article suggest using the loudness level or correcting the A-weighted SPL for low-frequency noise as an improved method of evaluating annoyance-reduction in noise barriers. An investigation of the influence of sound energy, spectral content and the regularity of fluctuations on annoyance was presented at the 2018 Eurnoise conference[10]. In the same study, it was found that existing indices, such as the TETC (Total Energy of Tonal Components), created by Trollé *et. al.*[11], could be relevant for accounting for some aspects such as high frequency content, but more research was needed to find and test models of annoyance. A statistical parameter called ”traffic noise annoyance on roads and rails” was suggested by Michael Cik *et. al.*[12]. This index takes into account low-frequency fluctuation strength, and the psychoacoustic parameters of loudness and sharpness, to evaluate the subjective annoyance.

1.5 Outline

First, the theory behind the measurements will be explained in chapter 2, including literature study, acoustical terms and definitions, and theory about sound propagation outdoors and the noise sources present in railway traffic. The psychoacoustic parameters used will also be introduced and explained. The test procedure and the equipment used for measuring train pass-bys is explained in chapter 3, as well as information about the measurement location and tram type. This section also describes the listening test set-up and procedure, as well as the post-processing of the results. The measurement results are presented in chapter 4, along with the results from the listening test. The eight different parameters are compared, and these results, as well as some regression analyses, are also presented in this chapter. The results are further discussed in chapter 5, as well as problems during the measurements and possible sources of errors or uncertainties. Finally, conclusions are made in chapter 6.

Chapter 2

Overview of the involved fields

Theory of outdoor sound propagation and sources of train noise are explained in this chapter. The functions of the ear, as well as some mechanisms of human hearing are also described. Then, other acoustic terms used are given, before finally, the psychoacoustic parameters sharpness, roughness, fluctuation strength, impulsiveness, tonality and annoyance are defined. Some background knowledge is required, but this chapter aims to give the reader a greater understanding of the existing theory that lies behind this study.

2.1 Outdoor propagation of train noise and its sources

Sound is defined as the ”movement of particles in an elastic medium about an equilibrium position”, where audible sound is sound ”of such character as to be capable of exciting a sensation of hearing” [13]. Noise is audible sound which causes disturbance, impairment or health damage, where health is defined as a state of complete physical, mental and social well-being [14]. Noise pollution increases with population density, and it is an environmental issue with harmful health effects [5].

When measuring the sound pressure level of noise from train pass-bys, there are several factors to take into account. The measurements will be performed outdoors, at short distances from the source to the receiver. The terrain type and contour will affect the ground absorption of sound, as well as the types of reflections. Solid obstacles blocking the sound propagation path from the source to the receiver may cause screening effects (p. 25, [15]). Nearby reflecting surfaces such as building facades will also contribute to the attenuation and scattering of the sound (p. 25 [16]). Conditions such as heavy wind and rain will increase background levels, from the rustling of leaves to the sound of rain hitting pavement. Rain may also increase noise levels due to the tracks and wheels becoming wet (p. 28, [15]).

2.1.1 Noise sources in railway traffic

When measuring the noise emitted by railway traffic, one should also consider its sources. Noise from railway traffic depend on three different factors - engine noise, rolling noise, and aerodynamic noise. The prevalence of each factor is largely dependent on the speeds of the vehicles. Trams operate at such low speeds that aerodynamic noise will not be dominant and can be disregarded. The most important factors that decide the amount and type of vibrations are the type of trains, the number of trains passing by, the quality of the wheels and rails, as well as the speeds of the trains [3].

The noise from engines is determined by the main engine, whose components, and therefore noise output, vary greatly depending on the type of train. The sound power output from the engine also depends on the speed of the train, as well as the number of traction units (motors). The rotational speed of the traction unit, and its load and acceleration matters; as does the type and number of cooling air fans and their rotational speed, and the performance of the exhaust silencer (in the case of an internal combustion engine) [3].

The sound pressure level increases with the speed, as well as the length and weight of the trains. The number of trains passing by, as well as the regularity of these, will affect the amount of noise pollution created in the area, and also how much the surrounding population is affected. Noise from trains passing by in the evening and night are more likely to be considered annoying [15].

Rolling noise is caused by surface irregularities, or roughness, in the wheel and rail contact area. The quality and maintenance of the wheels and rail tracks will affect the amount of rolling noise. Regularly performing grinding of the track helps prevent roughness [3].

2.2 Mechanisms of human hearing

The train noise measurements and recordings will be examined with regards to their effect on humans. Therefore, it is necessary to have an understanding of how the human ear perceives sound. The human ear receives sound pressure from its surroundings, and converts it to nerve impulses which are sent to the brain. The ear consists of three main parts: the outer, middle and inner ear (see figure 2.1). The outer ear consists of the pinna, concha and the ear canal, and its main function is to focus the sound signal on the eardrum (also known as the tympanic membrane) and into the ear canal leading to the middle ear [17]. The pinna and concha also filter sound frequencies to help with sound localization [5].

The most important function of the middle ear is impedance matching: increasing the pressure of the signal so the low impedance airborne sounds can travel through the high impedance liquid-filled inner ear without reflecting all the acoustical energy. This is done by focusing the sound from the ear drum onto the oval window, which has a much smaller diameter than the ear drum. The ossicles bones connect the ear drum to the oval window and act as a lever. The decrease in area between the ear drum to the oval windom, com-

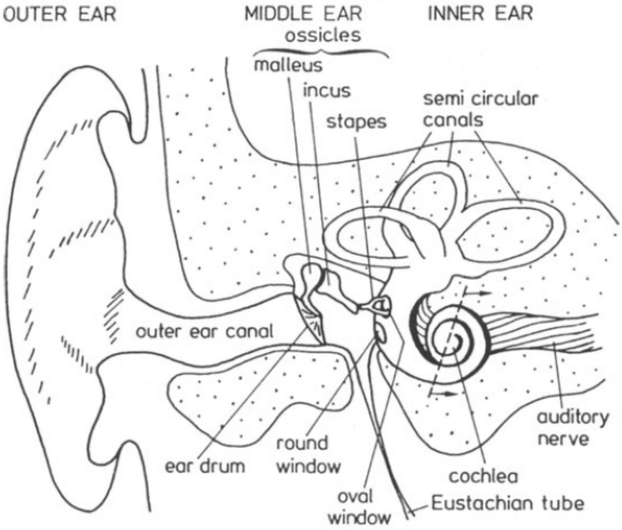


Figure 2.1: The human ear and its parts[17]

bined with the motion of the ossicles bones, increase the pressure of the signal so that an almost perfect match between the impedances of the middle and inner ear is reached, and the sound can travel to the inner ear without significant losses in energy [17].

The inner ear's main function is converting the received mechanical signal into electrical impulses to send to the brain. This is done by breaking up the signal into simpler components. The basilar membrane is frequency selective, meaning different places along the membrane and therefore different inner hair cells are sensitive to certain frequencies, much like a frequency analyzer that consists of overlapping band-pass filters. The outer hair cells receive signals from the brain to amplify weak sounds [5].

2.2.1 Critical bands

The human audible hearing range is between 20 Hz and 20 kHz. In human hearing, sounds which are close in frequency are combined into particular frequency bands, called "critical bands" [6]: the widest bands within which individuals cannot differentiate between narrower bands within the same critical band [7]. The bandwidth increases with the center frequency [18]. The audible frequency range is divided into 24 critical bands, measured in the unit Barks [17], which is the critical band rate [6].

2.2.2 Auditory filters

Auditory filters determine the frequency selectivity of the cochlea, and are associated with points along the basilar membrane [19]. The cochlea can be described as acting like a mechanaical spectrum analyzer, being made out of overlapping filters whose bandwidth equal the critical bandwidth.

2.2.3 Masking

Masking can be both the process and the amount by which ”the threshold of audibility for one sound is raised by the presence of another (masking) sound” [13]. The difference in this threshold is measured in decibel. Masking can occur both spectrally, as in one frequency masking another frequency close in number, or temporally, where one sound which is louder in sound level can mask another sound that occurs either up to 50 ms before it (backward masking) or 200 ms after it (forward masking) [5]. These maskings occur due to the auditory filters in the ear, as well as due to processes in the brain which cause delays or prioritations of different sounds.

2.3 A-weighted equivalent continuous sound pressure level

To attempt to compensate for the differences in how a sound level meter receives a signal compared to how the human ear works, different frequency weighting curves exist, where the most commonly used is the A-weighting [20]. The A-weighting curve is a standardised bandpass filter which reflects the frequency response of the ear. This filter is found from the equal loudness contour at 40 phon (see figure 2.2 in section 2.4.1), which is the curve that describes at which sound pressure level pure tones of different frequencies sound equally as loud as a 1 kHz tone which is played at 20 dB.

The equivalent continuous sound pressure level $L_{eq,T}$ is the logarithmic definition of sound level given by the time-averaged sound pressure signal recorded by a sound level meter. The A-weighted equivalent continuous sound pressure level $L_{Aeq,T}$ is measured in decibels (dB). It is a logarithmic scale that measures the ratio between the squared sound pressure p_A^2 of the signal and a squared reference pressure p_0^2, during a stated time interval of duration T:

$$L_{Aeq,T} = 10 \log_{10} \frac{\frac{1}{T}\int_{t_1}^{t_2} p_A^2(t)\mathrm{d}t}{p_0^2} \tag{2.1}$$

where $p_A(t)$ is the A-weighted instantaneous sound pressure at time t, and $p_0 = 20$ μPa is the reference pressure in air [21]. In this study, $L_{Aeq,T}$ is found using the software ArtemiS SUITE Pro 9.2 (shorthand Artemis), by HEAD Acoustics (see section 3.2.1).

2.4 Psychoacoustic parameters

Psychoacoustics is the scientific study of how sound is perceived. Psychoacoustic parameters describe specific characteristics of a sound heard by a listener [19]. Examples include the sharpness of a sound, its pitch, or even other descriptors such as ”dieselness” [19]. These are properties of an acoustical signal that can be rated and recognized in a consistent way by listeners [19]. Psychoacoustic parameters can be helpful in determining the amount of nuisance in a sound environment, and in creating a fuller picture than what is possible with strictly objective measurements. As when calculating $L_{Aeq,T}$, Artemis is used to calculate all psychoacoustic parameters used in this study (apart from annoyance, which is found from listening tests). The six psychoacoustic parameters sharpness, roughness, fluctuation strength, impulsiveness, tonality were chosen from the ones available from Artemis' psychoacoustic modules ([22; 23]) to cast a wide net of train noise characteristics that could have a possible impact on a listeners' annoyance. These parameters, as well as annoyance, are explained in detail in the following sections.

2.4.1 Loudness and loudness level

Loudness describes how loud a sound is perceived to be, where the sounds are ordered on a scale from soft to loud. Subjective loudness can be compared to the objective parameter of sound level, and is the most common psychoacoustic parameter used in noise evaluation. It is defined as the subjectively perceived strength of a sound compared to a reference pure tone at 1 kHz having a level of 40 dB presented binaurally from the front in free field. Loudness is measured in *sone*.

The loudness *level* is a related, but slightly different parameter, measured in *phon*. In this definition, the loudness level of any sound is the sound pressure level of the 1 kHz to which it sounds equal in loudness (so a sound which appears to be as loud as the reference tone at 40 dB would have a loudness level equal to 40 phon). By having listeners compare a large number of tones to pure tones of 1 kHz at different levels, contours of equal loudness have been determined, as illustrated in figure 2.2 [5].

One method of calculating loudness is the DIN 45631/A1 method (2010), a standardized procedure of finding the total loudness level and loudness in free field [6]. The subjective loudness of a complex sound is found by calculating the specific loudness from the total intensity within each critical band, and then summing these up with some weighting function for the bands [19].

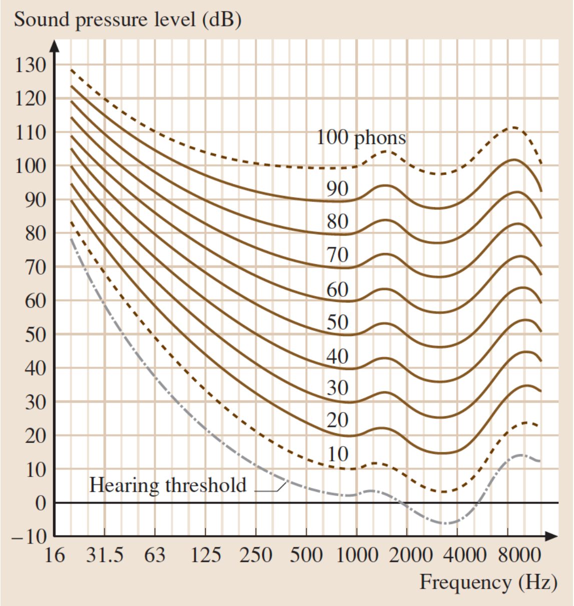


Figure 2.2: Equal-loudness contours for pure tones in a free sound field, expressed in loudness level [5].

2.4.2 Sharpness

The psychoacoustic parameter sharpness is closely connected to the spectral content of the sound, as well as the centre-frequency of narrow-band sounds. Sharpness is measured in *acum*, and the reference sound producing 1 acum is defined as a narrow-band noise one critical-band wide at a centre frequency of 1 kHz having a level of 60 dB [17]. A signal which is high in sharpness will have strong high frequency components.

The standardized method used to calculate sharpness in this study is the DIN 45692 [6]. This is a calculation method based on research by Widmann [24], which in turn is a continuation of a calculation method suggested by von Bismarck in his 1974 paper ”Sharpness as an attribute of the timbre of steady state sounds” [25]. This method does not take into account the influence of absolute loudness on sharpness perception. It is based on the specific loudness distribution of the sound, with an emphasis on the loudness of high frequency components.

2.4.3 Roughness

The roughness of a sound is, like sharpness, related to spectral content, and is measured in *asper*. Roughness is perceived for sounds with modulation frequencies between 15 and 300 [19]. The reference roughness 1 asper is a 60 dB, 1 kHz tone that is 100% modulated in amplitude at a modulation frequency of 70 Hz [17]. Figure 2.3 shows how the roughness of 100% modulated tones at different centre frequencies follow modulations frequencies. The maximum roughness is perceived for sounds with a 1 kHz centre frequency. The impression of roughness strongly decreases for very low or high modulation frequencies, meaning roughness' dependency on the modulation frequency can be seen as having a band-pass characteristic [26].

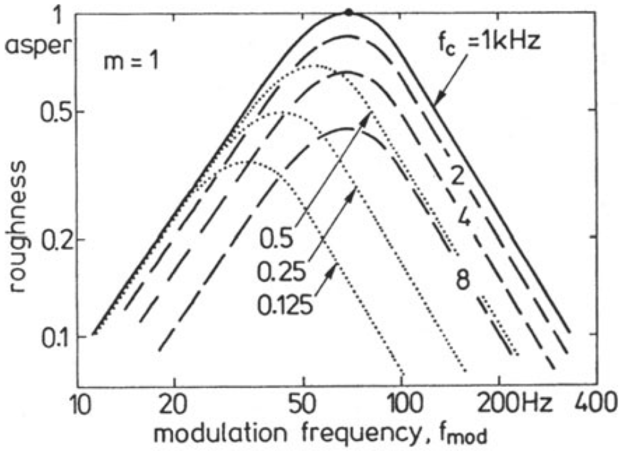


Figure 2.3: Roughness of 100% modulated tones at centre frequencies between 125 Hz and 8 kHz [17]

In Artemis, the roughness is calculated by simulating the process of human hearing, using a hearing model as according to Sottek [26; 27]. Similarily to the method of calculating loudness, the audio signal is first filtered to account for the effects of it passing through the outer and middle ear, and then into overlapping filters whose bandwidth equal the critical bandwidth, to simulate the auditory filters in the basilar membrane (see section 2.2.2). The partial roughness is found by first determining envelopes of the partial band signals, and lowering exitation levels to account for the threshold of hearing. A third order low-pass filter is used to remove the variations in envelope that are above a critical rate such that they are not noticable to the human ear [26]. Envelope variations are distorted in a non-linear way, and the autocorrelation function is calculated. A high-pass filter is applied, and with combined the third order low-pass filter, this models the typical band-pass characteristic as described previously. To account for masking effects, strong partial roughnesses are weighted more strongly. Total roughness is calculated by integrating the partial roughnesses.

2.4.4 Fluctuation strength

The fluctuation strength describes the perception of slow modulations in the range from one to 20 Hz. The fluctuation strength is given in *vacil*, where 1 vacil describes a 60 dB, 1 kHz tone with 100% amplitude modulation at 4 Hz [19]. Calculating fluctuation strength in Artemis is similar to the way roughness is calculated, but with an adaptation in the algorithm so that the maximum fluctuation strength is obtained at 4 Hz instead of 70 Hz [22].

2.4.5 Impulsiveness

The impulsiveness of sound refers to the amount of impulsive content perceived in the sound [28], both in number and in magnitude. There are several different methods to quantify impulsiveness, but the one used in this study comes from the Artemis suite Advanced Psychoacoustics Module [22], which is based on a hearing model and measured in *iu* (impulsiveness unit).

2.4.6 Tonality

Tonality describes the perceived tonal character of a signal, and measures the proportion between tonal components and noise components in the spectrum of a signal. This allows a distinction between tones and noise. A sound is perceived as tonal if they contain distinct tones or narrow-band noise [26], and this is visible as pronounced peaks in the frequency spectrum of a sound. The tonality is measured in a so-called tonality unit tu, where a value of 1 tu results from a sinusoidal at 1 kHz and 60 dB [19].

The method for calculating tonality in Artemis is based on the loudness as well as the Sottek hearing model [27], where the loudness of tonal and non-tonal components are separated using an autocorrelation function [22]. The loudness of the tonal components are used as the basis for calculating the total tonality. The model also takes the human hearing threshold, as well as both spectral and temporal masking, into consideration. This method of calculating tonality is measured in *tuHMS* (tonality unit according to the Hearing Model of Sottek).

2.4.7 Annoyance

Annoyance is subjective, and can be described as a feeling of disturbance, disstatisfaction, displeasure, irritation or nuisance. In psychoacoustics, annoyance can be described as the degree of such feelings that a sound creates in a listener. The ISO 15666 standard, regarding the ”Assessment of noise annoyance by means of social and socio-acoustic surveys”[29], defines noise-induced annoyance as ”one persons’ individual adverse reaction to noise”. In this study, annoyance does not have a unit but is measured on a scale from zero to ten.

Chapter 3

Methodology

Recordings of train pass-bys were made using a dummy head with a microphone on left and right side of the ”head”, at four outdoor locations along the railway lines. A total of 53 pass-bys were recorded. These recordings were used to calculate both the sound pressure level and a series of psychoacoustic parameters. The calculations were performed using computer software Artemis. A listening test was performed on 25 participants, who were asked to rank the annoyance of all 53 recordings. The location, as well as the acoustical environment, meteorological conditions, and the background sound pressure level was registered. Other post-processing of the results was done using spreadsheet software and Matlab, as well as the statistical computing software R.

3.1 Measurements of noise from train pass-bys

The objective of the noise measurements was to record signals similar to those heard by persons close to the track, and use these for psychoacoustic analyses. The measurement procedure was guided by the ISO3095 standard for measurements of noise emitted by rail-bound vehicles [30], as well as theory on outdoor noise propagation (see section 2.1). The equipment used for the measurement and its set-up, as well as the measurement locations and positions are given in the following sections. Some key factors that were considered in the measurements of noise from train pass-bys, such as the acoustical and meteorological conditions are also presented.

3.1.1 Acoustical environment

For optimal outdoor recordings, the acoustical environment should be such that unhindered sound propagation exists. This is achieved by ensuring the ground surface at the receiver is 0 to -2m relative to the top of the rail, and that the area is free of sound absorbing matter (ex. snow, tall vegetation) and reflective covering (ex. water). The area should be free of people, and the observer shall be in a position which does not significantly affect the measured sound levels [30]. The area should also be sufficiently far from any buildings, at least 20 m (p. 25, [16]).

The background sound pressure level should not be loud enough to significantly influence the measurements. The maximum value of the background noise level $L_{Aeq,T}, T =$ 20 s (see equation 2.1) at all measurement positions should be at least 10 dB below the final result obtained when the sound source is present.

3.1.2 Meteorological conditions

Meteorological conditions should be recorded, including the temperature, humidity, and wind speed and direction. When performing sound level measurements outdoors, the preferred weather conditions are on a dry and clear day or night, with either no wind or a light wind (around 2 m/s) blowing in a direction from the source towards the measurement location (page 10, [31]). Heavy winds and/or precipitation should be avoided, as this will increase background noise levels, and may also be damaging to equipment. Electronic equipment may be adversely affected as temperatures get close to $0°$C, and so a temperate environment (around $20°$C) is preferred.

3.1.3 Equipment and set-up

Outdoor measurements were made using an artificial head with two microphones. This is a typical set-up for subjective evaluation of noise as the distance between the microphones gives information about the time delay of the signals, and using a dummy accounts for the filter effect of the human head and torso [32]. The microphones were connected using a SQuadriga II recording system, where the microphones on the left and right side of the artificial head were connected via a Norsonic power supply.

The microphones were calibrated both before and after the measurements, to ensure accurate values. The calibration is done using a Norsonic type 1251 calibrator, giving out a 1 kHz pure tone at 114 dB. The speed of each train pass-by was recorded manually using a stopwatch. The approximate temperature and wind speed was found using an online weather service. A background recording was also made at each location.

The type and number of equipment used for the measurements, as well as their manufacturer, model and serial number are given in table 3.1. The list contains only the most essential items, and equipment such as cables, microphone stands, and measuring tape are not included. In the original measurements, it was intended to use two additional microphones. As these measurements were ultimately not used, their specifics have been omitted from the equipment list.

Table 3.1: Equipment list, outdoor measurements

Type	Manufacturer	Model	Serial/License No.
Mobile recording system	HEAD Acoustics	SQuadriga II	33201914
Artificial head	Brüel & Kjær	1899850	33221268
Microphone	Norsonic	1225	106902
Microphone	Norsonic	1225	106903
Pre-amplifier	Norsonic	Type 1202	30318
Pre-amplifier	Norsonic	Type 1202	30512
Power supply	Norsonic	Type 336	20578
Stopwatch	Asaklitt	WT035	20180570743
Software	HEAD Acoustics	ArtemiS SUITE Pro 9.2	-
Laptop	MacBook Pro	A1708	FVFXLC55HV22

3.1.4 Measurement locations and positions

The measurements were performed for trains going in both directions, at four locations along the track in Oslo: Borgen, Dalbakkveien, Voksenlia and Tjensrud, see figure 3.1. The locations were chosen due to their varying topological and track conditions which will give a variety of resulting noise. The location sites and the positioning of the dummy head in regards to the tracks are given in more detail below.

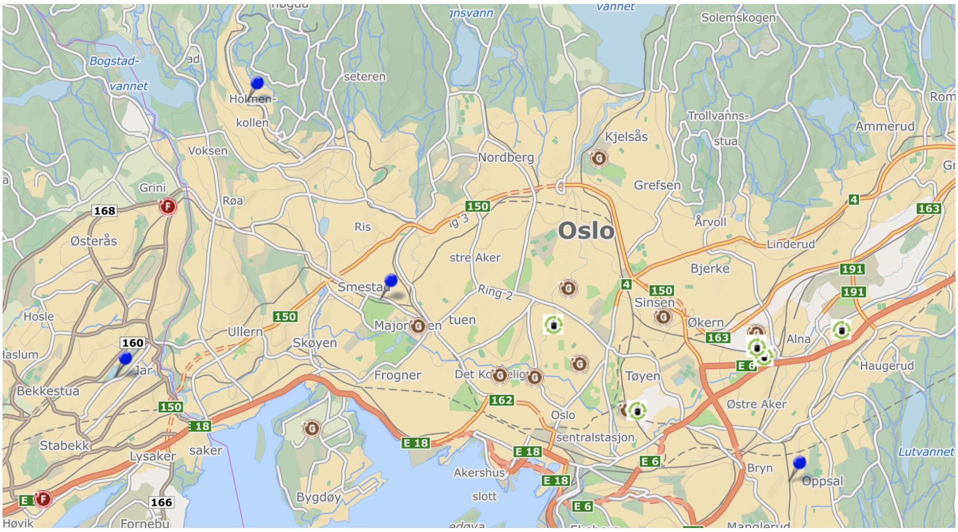


Figure 3.1: Map of Oslo, with blue pins illustrating the measurement locations

Measurements at Dalbakkveien, 12.02.19

The measurement position by Dalbakkveien is shown as the blue pin in the bottom right corner of figure 3.1. A picture taken at the site near Dalbakkveien is given in figure 3.2, and shows the artificial head placed on a snowbank, approximately 7.5 m from the centre of the tracks going out of the city and 11.3 m from the centre tracks going in to the city. Also visible in the picture, is a microphone that was not used in this study, which should be disregarded. The ground surface was approximately flat from the tracks to the test site area, but, as visible in the picture, the area was covered in snow. The nearest major obstacle wrt. sound propagation was an apartment building approximately 18 m behind the equipment.

Figure 3.2: The placement of the artificial head near Dalbakkveien

Measurements at Voksenlia, 25.02.19

Voksenlia station is located in Holmenkollen (see the blue pin in the top left corner of figure 3.1), at 330.5 m above sea level [33]. The equipment was set up around 300 m from the station, where the tracks are both slightly sloped and slightly curved, as shown in figure 3.3. The dummy head was placed 5.5 m from the centre of the tracks going out of the city, and 10.2 from the centre of the tracks going in to the city. As near Dalbakkveien, the test site area was covered in snow, and the nearest building was approximately 18 m away.

Figure 3.3: A train passing by the measurement location near Voksenlia

Measurements at Borgen, 25.02.19

The third measurement location was chosen approximately 300 m from Borgen train station, shown as the blue pin near Smestad on the map (figure 3.1). The test site area was near a cemetary, and behind the tracks was a heavily trafficked road, which meant that there was more background noise than at the other locations. The nearest building was around 50 m from the site. The artificial head was placed 5.7 m from the centre of the tracks going in to the city, and about 10.4 m from the centre of the tracks going out. The trains passed every four to ten minutes during the time of the measurement. As visible in figure 3.4, which shows the placement of the dummy in regards to the fence, there was snow on the ground at the time of the measurements.

Figure 3.4: The artificial head placed near Borgen

Measurements at Tjensrud, 28.02.19

The final measurements were taken in a residential area between the train stations Jar and Ringstabekk, and its location is shown as the blue pin furthest to the left in figure 3.1. As visible in figure 3.5, there was a lot of snow in the area, including a not insignificant snow bank by the artificial head. Like in the other figures, other microphones not used in this study should be disregarded. The head was placed 9.4 m from the centre of the tracks going to Ringstabekk (in the direction away from the city), and 13.6 m from the centre of the tracks going to Jar (in the direction to the city). The nearest buildings were over 30 m away from the test site area.

Figure 3.5: The equipment set up at Tjensrud

3.2 Psychoacoustic methodology

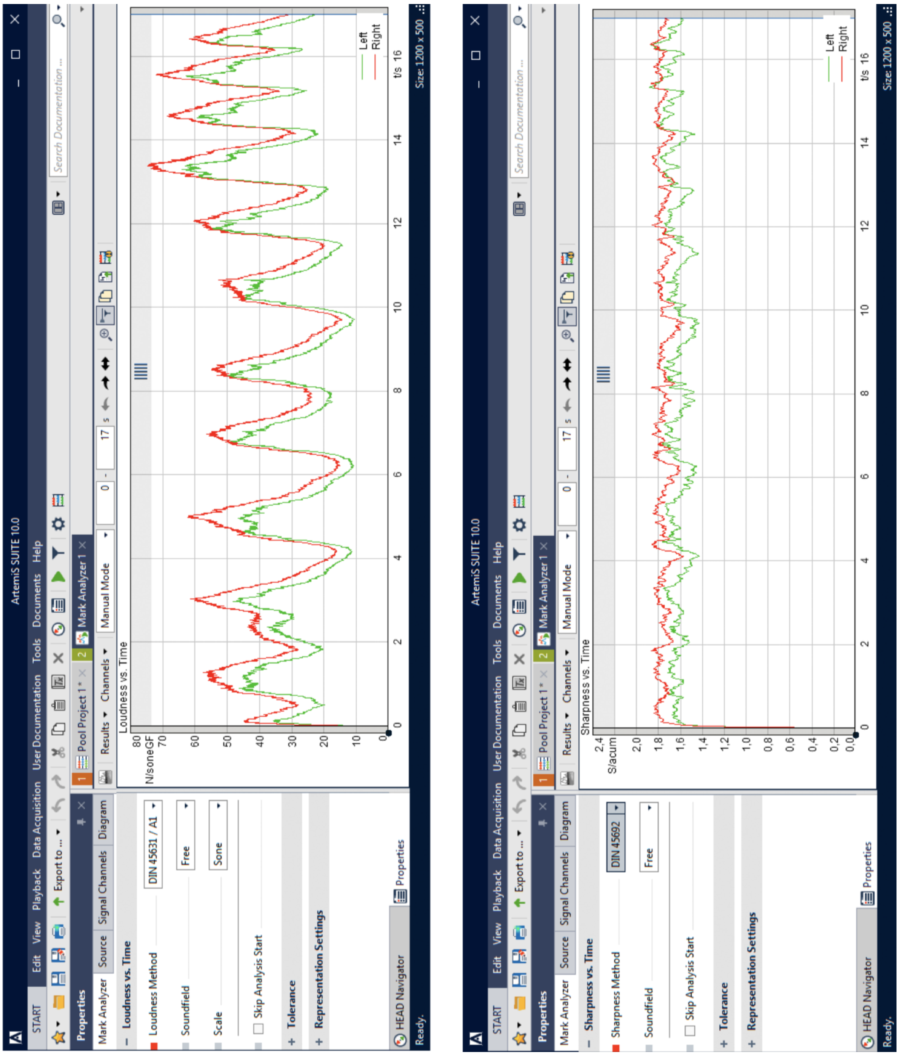
The method of analysing pscychoacoustic parameters using the recorded pass-bys is described below. The six psychoacoustic parameters, as well as the A-weighted sound level, were found using Artemis. The recorded signals were then the subject of a listening test, where listeners were asked to rank the annoyance of the signals. The details of this test are also given in the sections below. This test was performed using a Guided User Interface (GUI) in Matlab.

3.2.1 Analysing psychoacoustic parameters in Artemis

Artemis is a software used for recording, analysis and playback, and was developed specifically for the field of acoustics and vibration. The psychoacoustic parameters (loudness, sharpness, roughness, fluctuation strength, impulsiveness, tonality, as described in detail in section 2.4) were determined from the sound level recordings. The specific models used in this study are as follows:

1. Loudness vs. Time [6]
2. Sharpness vs. Time [6]
3. Roughness (Hearing Model) vs. Time [26]
4. Fluctuation Strength vs. Time [22]
5. Impulsiveness (Hearing Model) vs. Time [22]
6. Tonality (Hearing Model) vs. Time [22]

A screenshot of the program is given in figure 3.6, and shows an example of both loudness and sharpness calculations. For more information on how the parameters were calculated, see section 2.4.



Loudness vs. Time
Loudness Method: DIN 45631 / A1
Soundfield: Free
Scale: Sone
☐ Skip Analysis Start

Sharpness vs. Time
Sharpness Method: DIN 45692
Soundfield: Free
☐ Skip Analysis Start

Figure 3.6: A screenshot of two calculations in Artemis, from the psychoacoustic module application note [23].

3.2.2 Listening tests

Listening tests were performed (in Norwegian) on 25 participants, eight female and 17 male (mean age = 24; standard deviation = 3.5). The test was performed in a quiet room on the NTNU campus in Trondheim, Norway, during April 2019. No compensation was given for participating in the test. The test was mainly adapted from a pre-existing test made in Matlab by Alice Hoffman for her doctoral thesis on traffic noise [34].

The participants were asked to imagine that they were walking or standing close to a train track, and rate the annoyance of the recorded pass-bys on an 11-point-scale from zero to ten, where zero would be described as not annoying at all, whereas ten would mean the sound was extremely annoying. The equipment list is given in table 3.2. A screenshot from the test display is given in figure 3.7. The participants were able to listen to the same sound several times if needed, but the entire signal had to be played through at least once in order to be able to proceed to the next. In addition to rating the annoyance on a scale, it was possible to give additional comments on each sound. Prior to the test, a questionnaire was filled out to give information on gender and age, and other factors such as hearing ability. The duration of the experiment varied, but generally lasted around 15 minutes.

Table 3.2: Equipment list, listening test

Type	Manufacturer	Model	Serial/License No.
Headphones	Beyerdynamic	DT 770 Pro	-
Headphone amplifier	Symetrix	SX204	801204AAC727
Software	Matlab	R2018b	833468
Laptop	MacBook Pro	A1708	FVFXLC55HV22

Lytt til lyden og avgjør hvordan det passer inn med erklæringen nedenfor

Lyden er "irriterende"

Vennligst skriv kommentarer her!

Figure 3.7: Screenshot from the listening test

3.3 Post-processing and representation of results

In addition to being the basis of the listening test, Matlab was also used in general file management and in presenting results. The raw data six psychoacoustic parameters as well as the sound level, all found using Artemis (see section 3.2.1 for more details), and the average annoyance found from the listening tests, were collected into one spreadsheet using Matlab. This spreadsheet was used for multivariant data analyses using the software R with an NMBU plugin [35].

Chapter 4

Results

First, the A-weighted sound level, as well as the six psychoacoustic parameters, all found using Artemis, are presented for each location. Then, the results from the listening test, were participants rated each pass-by's annoyance, are given. Then, all eight parameters are compared, and general trends shown. Finally, regression analyses are made to further investigate the dependence of each parameter on annoyance.

4.1 Measurements and results from Artemis

The recordings were made between 11.02.2019 and 28.02.2019, with temperatures ranging from zero to five degrees, and wind speeds from zero to two meters per second. The weather ranged from sunny to overcast, and there was snow on the ground. At Voksenlia, the trains were runnning on an old tram track, and so average speeds were low. At Borgen and Dalbakkveien, the track was almost flat and straight, allowing for higher speeds of up to 70 km/h. A total of 53 pass-bys were recorded. The trains where all of the same type, the MX 3000-train by Siemens. At Dalbakkveien, both three-car trains and six-car trains (where two three-car trains were linked together) passed by, whereas at Voksenlia there were only three-car trains running. At Borgen, the trains passing by where mostly six-car trains, apart from two pass-bys which were of three-car trains. At Tjensrud, only six-car trains pass-bys were recorded. The speeds of the pass-bys recorded ranged between 27 to 78 km/h.

The values for the sound pressure level (SPL), as well as the psychoacoustic parameters loudness (L), sharpness (S), roughness (R), fluctuation strength (FS), impulsiveness (I) and tonality (T) were found using the Artemis software. The results are presented as the averages of all pass-bys, for each direction and both channels. Results from one background noise recording (with recording time $T > 20$ sec) at each location and on each channel are also given.

4.1.1 Results from Dalbakkveien

There were 16 pass-bys measured in total at Dalbakkveien, with a wide range of speeds from 38 to 78 km/h. The pass-bys are of both three-car and six-car trains. The average results from seven pass-bys going into town, and nine pass-bys going out of town, as well as from a background noise recording from the right and left channels are given in table 4.1. The area was relatively quiet, as it was in a residential area in the daytime, however some disruptions occured, such as airplane noise and a hammer banging in the distance. During the time the measurements were performed, trains passed every six to ten minutes in each direction. The tables shows trains going out of the city measuring consistently higher values for all parameters than those going into the city.

Table 4.1: Results from right and left channels, Dalbakkveien, where Bg is the background noise measurement.

	SPL [dBA]	L [soneGF]	S [acum]	R [asper]	FS [vacil]	I [iu]	T [tuHMS]
In (R)	63.7	25.1	1.42	0.0318	0.0248	0.248	0.239
(L)	64.1	26.0	1.47	0.0325	0.0237	0.245	0.248
Out (R)	72.8	39.9	1.63	0.0439	0.0481	0.333	0.255
(L)	75.5	45.9	1.72	0.0463	0.0890	0.416	0.255
Bg (R)	45.3	8.85	0.704	0.0222	0.0138	0.200	0.339
(L)	42.9	8.30	0.667	0.0228	0.0101	0.218	0.239

4.1.2 Results from Voksenlia

All pass-bys at Voksenlia were of three-car trains, with speeds ranging between 27 and 30 km/h. The averaged results from the ten pass-by measurements taken at Voksenlia and processed in Artemis are given in table 4.2. This location was also in a quiet residential area, but with a lot of bird chatter present. During the time of the measurements, trains passed every 15 minutes in each direction. The averages are based on five pass-bys going into the city, and five going out of the city. This was the location that measured the highest levels of sharpness, with average values between 2.86 and 3.32 acum. The background noise was also found to have higher levels of sharpness than anywhere else. The sound levels were on the lower end, compared to the other sites, but the loudness levels for trains going out of the city are comparable to those at Dalbakkveien, which had significantly higher sound levels. The roughness was found to be around 0.3 asper in both directions, and the fluctuation strength 0.3 vacil. The background recording gave higher values for impulsiveness than the ones found from the pass-bys. Trains going out of the city were found to have the highest tonalities measured.

Table 4.2: Results from right and left channels, Voksenlia, where Bg is the background noise measurement.

	SPL [dBA]	L [soneGF]	S [acum]	R [asper]	FS [vacil]	I [iu]	T [tuHMS]
In (R)	59.1	28.9	2.92	0.0291	0.0336	0.297	0.465
(L)	62.2	35.2	3.26	0.0310	0.0322	0.291	0.446
Out (R)	61.3	38.2	2.86	0.0301	0.0299	0.241	1.746
(L)	64.5	46.9	3.32	0.0332	0.0312	0.269	1.712
Bg (R)	34.5	7.78	2.17	0.0175	0.0542	0.485	0.578
(L)	34.8	8.77	2.40	0.0173	0.0564	0.557	0.687

4.1.3 Results from Borgen

At Borgen, both three-car and six-car trains' pass-bys were recorded, and their speeds ranged from 46 to 59 km/h. The results from the 16 measurements taken at Borgen and processed in Artemis are given in table 4.3. The results are found from the averaged values of nine pass-bys going into the city, and seven going out of the city. The highest sound levels were recorded here, as was the highest values of loudness. This location also had the highest background levels, due to the road behind the tracks. This location also measured the strongest fluctuation.

Table 4.3: Results from right and left channels, Borgen, where Bg is the background noise measurement.

	SPL [dBA]	L [soneGF]	S [acum]	R [asper]	FS [vacil]	I [iu]	T [tuHMS]
In (R)	77.9	66.6	1.97	0.0502	0.0642	0.397	0.234
(L)	74.6	55.7	1.75	0.0457	0.0567	0.381	0.237
Out (R)	63.0	25.4	1.35	0.0301	0.0392	0.312	0.234
(L)	61.6	24.4	1.32	0.0293	0.0292	0.285	0.216
Bg (R)	52.7	11.5	1.08	0.0214	0.00383	0.202	0.377
(L)	51.5	11.10	1.08	0.0214	0.00380	0.200	0.388

4.1.4 Results from Tjensrud

At Tjensrud, a total of 11 pass-bys were recorded, all from six-car trains. The speeds measured ranged from 40 to 49 km/h. This location was also in a residential area, and there was not a lot of background noise, apart from bird chatter. During the time of the measurements, trains passed every 15 minutes in each direction. Results from five pass-bys going into town (to Jar), and from six going out of town (to Ringstabekk) were averaged on each channel. The results processed in Artemis are given in table 4.4. The highest values of tonality where found here, going into the city.

Table 4.4: Results from right and left channels, Tjensrud, where Bg is the background noise measurement.

	SPL [dBA]	L [soneGF]	S [acum]	R [asper]	FS [vacil]	I [iu]	T [tuHMS]
In (R)	66.3	30.9	1.60	0.0354	0.0269	0.245	0.533
(L)	68.4	32.7	1.65	0.0378	0.0272	0.263	0.496
Out (R)	63.1	24.4	1.41	0.0293	0.0211	0.220	0.373
(L)	64.6	26.0	1.45	0.0305	0.0215	0.221	0.370
Bg (R)	37.0	3.92	0.958	0.0146	0.00379	0.221	0.334
(L)	38.0	4.46	0.975	0.0152	0.00338	0.225	0.329

4.1.5 Comparing the measurement results

The highest sound pressure levels recorded, as well as the highest loudness, were found at Borgen, for trains going into the city. The lowest average SPL was found at Voksenlia, however this was also the location of the highest values of sharpness. The pass-bys from trains going into the city by Dalbakkveien, as well as the trains going out of the city by Borgen and Tjensrud, show similar values of average loudness, between 24.4 and 26.0 sone.

4.2 Results from the listening tests

The 53 stereo signals were listened to using headphones, and rated on their annoyance from zero to ten by 25 participants. The full ratings, averaged for each signal, can be found in appendix A. Table 4.5 gives the values further averaged to represent the pass-bys going in each direction, at all locations. The highest averaged annoyance ratings were found at Voksenlia, where the noise was described as very sharp by one listener. Two commented that the screeching noise heard in signals from Voksenlia was annoying, and one compared the noise to a circular saw (and said this was not a favorable comparison). Another comment about a signal from Voksenlia said the perceived electrical noises felt unsafe, leading to discomfort for the listener. The lowest annoyance ratings were found by Dalbakkveien, going in the direction into the city.

Table 4.5: The average annoyance at each location, found from the listening tests, where Bg is the background noise measurement.

	Average annoyance
Dalbakkveien (In)	4.42
(Out)	6.73
Voksenlia (In)	7.94
(Out)	8.53
Borgen (In)	7.47
(Out)	4.77
Tjensrud (In)	6.09
(Out)	4.97

4.3 Comparing parameters

The full multivariate analysis comparing the seven psychoacouastic parameters (annoyance, loudness, roughness, sharpness, fluctuation strength, tonality and impulsiveness), as well as the SPL, is given in figure 4.1. The results were plotted using R Commander and the NMBU plugin, and SPL is denoted here as ”levelA”. From comparing all the other parameters with the annoyance, it is possible to see three general groups of patterns. The fluctuation and the impulsiveness follow the same trend, and do not seem have a correlation with annoyance.

The SPL and loudness, as well as roughness, also seem to follow the same pattern. Comparing them with annoyance, it is clear that they have some correlation with annoyance, where their increase corresponds with an increase in annoyance. However, there is one group of results which is not especially high in neither SPL, loudness, nor roughness, but has high ratings of annoyance. It seems that for these measurements, sharpness and tonality are more strongly correlated with annoyance, and these two parameters also seem to follow a similar pattern. For sharpness and tonality, only those which are high in value seem to relate to the annoyance rating.

Examining these patterns in figure 4.1, it seems that to find a good predictor of annoyance, it is necessary to take either the sound pressure level or the loudness, where the values seem to have a relatively linear relationship with annoyance, apart from one set of values. To account for the annoyance of this set of values, the predictor should be made in combination with sharpness, as high values of sharpness seem to yield high values of annoyance. These four parameters are given in figure 4.2, plotted using R Commander and the NMBU plugin. In this figure, each parameter is plotted against the three other parameters, to see how they are correlated with each other. The graphs are displayed on a grid, and the units are given at the sides. As annoyance is rated on a metric scale from zero to ten, there is no unit displayed for it.

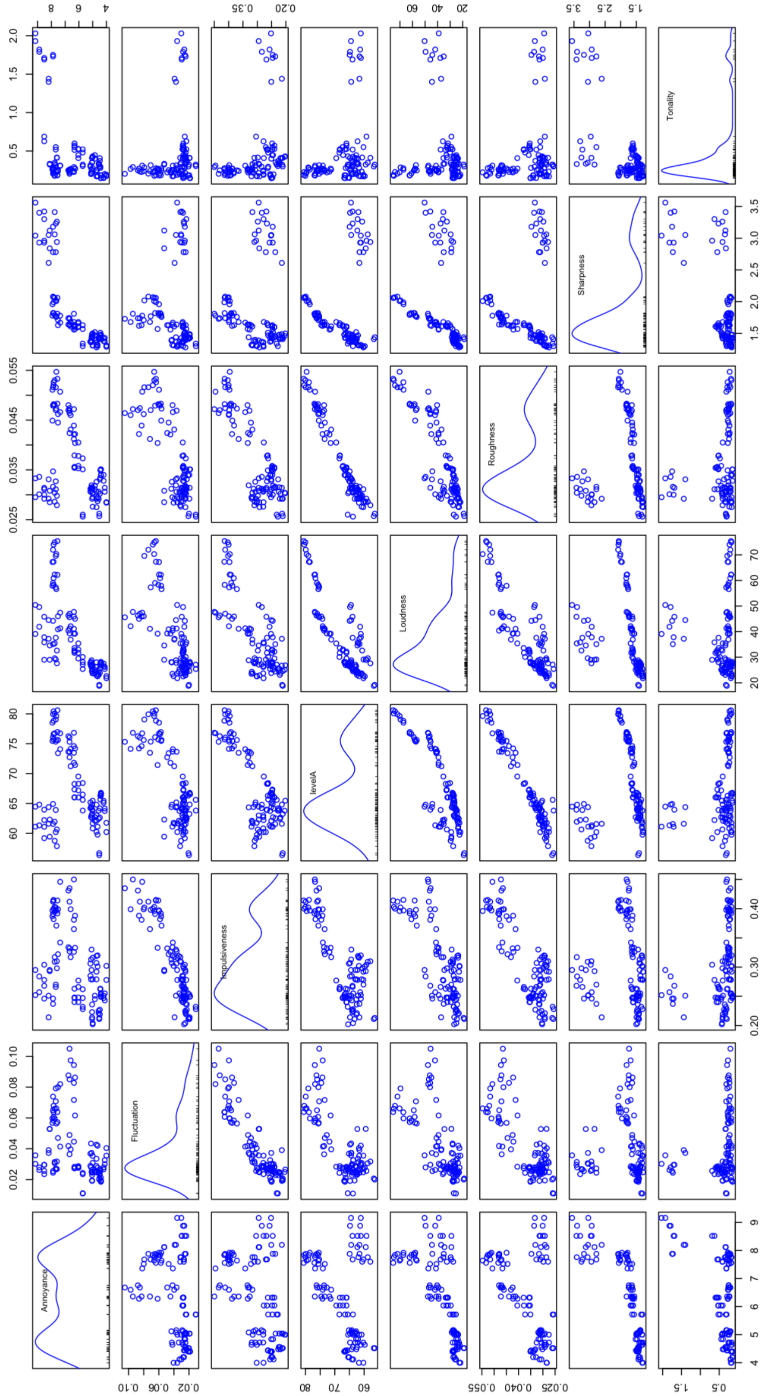


Figure 4.1: Comparing the seven psychoacoustic parameters as well as the sound level

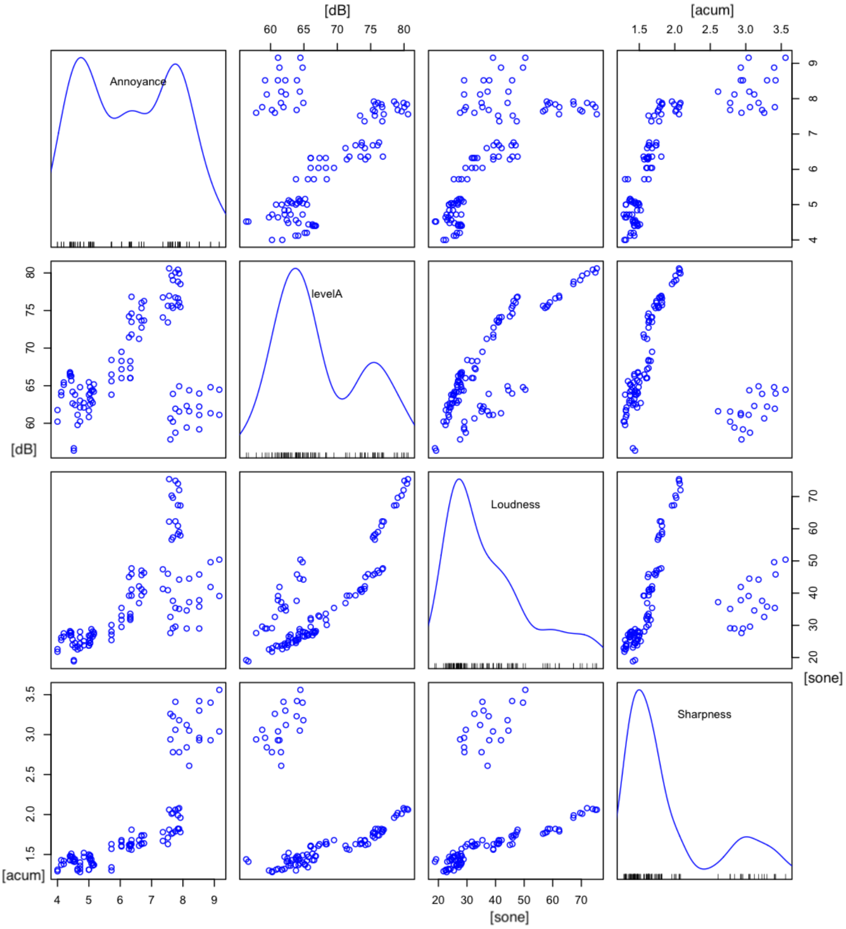
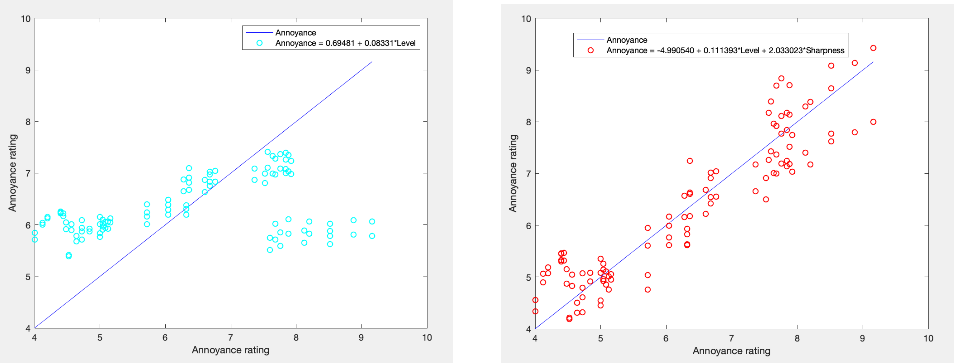


Figure 4.2: Comparing the sound level, sharpness and annoyance

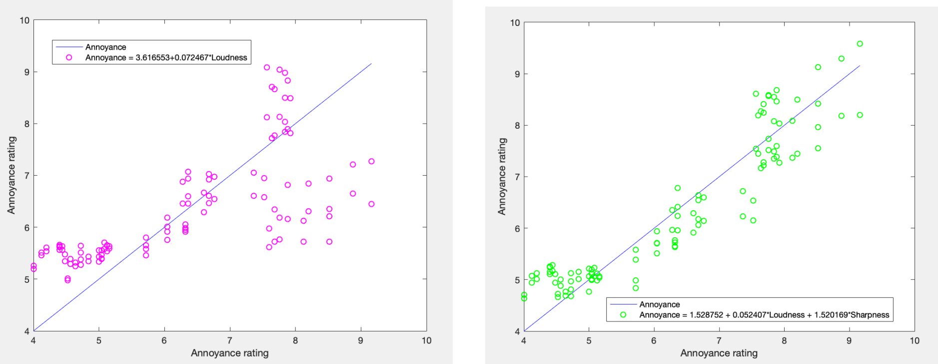
4.4 Regression analyses

Linear regression analyses were made using a linear model from the NMBU plugin in R Commander. Five models were made; one using only the level and one using only loudness; as well as one using level and sharpness and one using loudness and sharpness, and finally one using only sharpness. The models are found in appendix B, and figures of each equation plotted against the actual annoyance are found in figure 4.3. From the figures, it is clear that combining sharpness with either SPL or loudness yields the results closest to those of the actual annoyance.



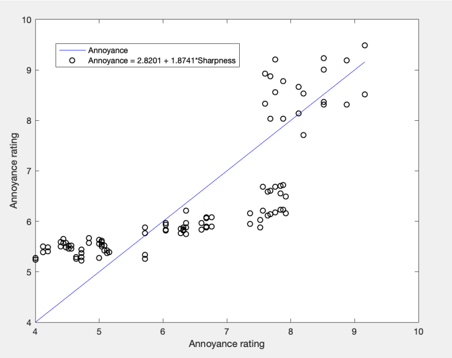
(a) Annoyance ∼ SPL

(b) Annoyance ∼ SPL + Sharpness



(c) Annoyance ∼ Loudness

(d) Annoyance ∼ Loudness + Sharpness



(e) Annoyance ∼ Sharpness

Figure 4.3: Linear regression analyses

Chapter 5

Discussion

In this chapter, the results will be discussed in further detail, as will possible sources of error and limitations in the study. Suggestions as to work that could be done to further this study are also made. The results show that sharpness is needed in combination with either loudness or SPL in order to fully understand the human responses to noise from trains running along Oslo's metro line. In the future, sharpness should be included when assessing train noise.

5.1 Interpreting the results

When trains emit non-sharp noises, the loudness or A-weighted sound pressure level can be a good indicator of its annoyance as perceived by a listener. Such is the case for approximately 80% of the signals recorded in this study.The A-weighted sound pressure level is the parameter that is most familiar and used in the field today, as well as both in standards of measurements and government directives. However, from the results it is apparent that, at least for the trains running on the tracks in Oslo, the A-weighted sound level alone is not sufficient to accurately predict the annoyance of train noise, as was hypothesised in the introduction. If a noise is very sharp, this is a sound quality whose great annoyance is not observable in these parameters alone. This may be a major cause of the discrepency between the previous sound pressure levels measurements and findings in socio-acoustic surveys done by Brekke & Strand.

From figure 4.3, plotting the different linear regressions models, it is clear that the best estimators for annoyance are found when combining sharpness with either SPL or loudness. The lowest standard errors are found in the model which combines loudness and sharpness (see appendix B). For non-sharp signals, SPL and loudness are still the parameters which most accurately predict annoyance, but in order to fully estimate human responses to train noise in Oslo, sharpness values may need to be included in the assessment. This is consistent with previously discussed findings, which have found sharpness and high-frequency content to be relevant factors in assessing noise from railways [12; 10].

5.2 Limitations

The following sections discuss potential limitations or flaws in the equipment used in the experiment, in the train measurements and listening test, as well as other potential problems worth mentioning. There seems to be a lot of variation in the types of noise signals emitted by the trains running in Oslo at different locations. As the trains were of the same kind for all measurements, the differences are most likely caused by the conditions of the tracks and the surrounding environment, as well as the speed of the train. The results are also likely affected by the distances from the source to the receiver, which varied from 5.5 m for trains going out of the city at Voksenlia, to 13.6 m for trains going into the city at Tjensrud.

5.2.1 Equipment

The microphones were calibrated before and after the measurements, and are assumed to be accurate. The measurements were made in temperatures between 0 and 5 degrees, which are not optimal for equipment. However, there are no indications that this has affected the results, as the equipment did not fail under the duration of the measurements.

5.2.2 Measurements

These measurements were not made under optimal conditions, as there was snow on the ground at all locations, and some vegetations such as trees and bushes. However, the locations chosen were assumed to be far enough away from buildings as to not cause screening effects, and the ground surface over the test site area was less than 2m relative to the top of the rail.

The signals recorded were all made at different distances between the noise and receiver, and this will have had an effect on the results. They were also made under different acoustical environments, and from train sources at different speeds running on inconsistent railway tracks. However, as the signals were subjectively assessed for their annoyance, this is not believed to be a problem. Any effects, such as a decrease/increase in the sound pressure level, will have a corresponding effect in the annoyance felt by the listeners.

5.2.3 Calculating parameters in Artemis

As there are several different ways of calculating psychoacoustic parameter, different methods may have yielded different results. When calculating the values for each signal, cut-offs were made to ensure that only the pass-by was used in the evaluation. However, the cut-off was done in a slightly inconsistant manner, which may lead to some uncertainties in the results.

5.2.4 Possible problems with the listening test

The listening test could have been improved by using a slider between 0 and 10 instead of a scale, as this would give more room for variations in the assessments. The participants cannot be said to be an accurate representation of the population, as they were all students in their 20's, and 68% male. Three of the participants were also studying Acoustics and familiar with environmental noise concepts, such as railway noise and noise-induced annoyance.

Although listeners were asked to imagine themselves walking or standing near the tracks, they were in fact in a quiet room and listening on headphones. This difference in environment means that there are some uncertainties in how the results correspond to the human response of the same noise sources in the actual environment they were recorded in. It also means that the results do not represent the residential noise impact for those who live along the track. However, it is plausible that the causes of residential annoyance are related to those of a perceived annoyance in a listening situation.

Whereas one listener said they got used to the noises after a while, and therefore became less annoyed, another said they only got more annoyed as the experiment went on, and so it is uncertain if the amount of signals or the length of the experiment had an effect on perceived annoyance one way or the other. However, as the signals were given in different, random sequences for each experiment, this may have dampened any potential effects.

5.2.5 Post-processing in Matlab and R

If there are any errors in the post-processing done in MATLAB, this will also affect the accuracy of the results, however there are no indications that this is the case. The linear regression models were made using R Commander and the NMBU plugin, and it is assumed that these are accurate.

Chapter 6

Conclusion

This research project aimed to investigate which sound qualities of train noise contribute to annoyance. This was done by evaluating the sound pressure levels, as well as the psychoacoustic parameters of loudness, sharpness, roughness, fluctuation strength, impulsivity and tonality using measurements of train pass-bys and analysing these in Artemis. The perceived annoyance was found using a listening test. The most important discovery of this study is the high effect in annoyance that highly sharp noises seem to have. This is an effect which is not detected by traditional measurements of the A-weighted sound pressure level, or even the psychoacoustic parameter of loudness. As sharp noises are a common part of train noise, sharpness values should be considered when evaluating the total environmental impact of train noise. It is possible that there are instances not covered by this study where other parameters may also contribute to annoyance, for example under different weather and/or rail conditions. As Brekke & Strand have decided to include psychoacoustic parameters in their future evaluations of train noise, a fuller picture of Oslo's train noise emissions can soon be a reality.

6.1 Future work

Brekke & Strand have now planned to include psychoacoustic parameters in their yearly reports on the noise from trams and trains running in Oslo. This will lead to a more expansive data knowledge of the environmental noise, which can be used to further investigate possible indicators of annoyance from train noise, and can hopefully also be applied to other trains in other locations in Norway and around the world. In future evaluations of train noise, it could be useful to consider sharpness values. More research on human responses to noise, as well as efforts to standardize methods of measuring psychoacoustic parameters are needed to increase psychoacoustics' applicability in environmental noise evaluation. As there have been several previous attempts to create annoyance indices which take into account psychoacoustic parameters, such as the "traffic annoyance on roads and rails"[12], it could be useful to see if any of these can be applied to more accurately evaluate the noise impact from the Oslo metro lines.

Bibliography

[1] S. Olafsen and A. Stensland, “Environmental noise and vibration monitoring of oslo’s metro lines,” in *BNAM*, (Reykjavik), 2018.

[2] Sporveien, “Om sporveien t-banen.” `https://www.sporveien.com/inter/omktp/artikkel?p_document_id=2416976`. Accessed on 2019-02-18.

[3] International Workshop on Railway Noise, *Noise and Vibration Mitigation for Rail Transportation Systems : Proceedings of the 9th International Workshop on Railway Noise, Munich, Germany, 4 - 8 September 2007.* International Workshop on Railway Noise, 2008.

[4] J. Parmanen, “A-weighted sound pressure level as a loudness/annoyance indicator for environmental sounds - Could it be improved?,” *Applied Acoustics*, vol. 68, 2007.

[5] T. D. Rossing, *Handbook of Acoustics*. Springer, 2007.

[6] HEAD Acoustics, “Application note: Psychoacoustic analyses 1: Loudness and sharpness calculation,” 2018.

[7] Technical Committee ISO/TC 43, Acoustics, “ISO standard 532-1: Acoustics - Methods for calculating loudness - Part 1: Zwicker method,” *International Organization for Standardization*, 2017.

[8] K. Genuit, “Need for standardization of psychoacoustics,” *The Journal of the Acoustical Society of America*, 2010.

[9] M. E. Nilsson, M. Andhn, and P. Lsna, “Evaluating roadside noise barriers using an annoyance-reduction criterion,” *Acoustical Society of America*, 2008.

[10] M.-F. Catherine, V. Pierre-Augustin, and B. Jules, “Short-term annoyance due to railway noise in urban areas: indices accounting for different annoying acoustical features,” in *Euronoise*, 2018.

[11] A. Trollé, "Acoustical indicator of noise annoyance due to tramway in in-curve operating configurations," *Acoustical Society of America*, 2013.

[12] M. Cik, K. Fallast, and M. Fellendorf, "Annoyance of traffic noise on roads and rail," *Journal of the Transportation Research Board*, pp. 16–22, 2012.

[13] International Electrotechnical Commission, "Acoustics and electroacoustics." `http://www.electropedia.org/iev/iev.nsf/index?openform&part=801`. Accessed on 2019-06-06.

[14] W. H. Organization, "Constitution of the world health organization." `https://www.who.int/about/who-we-are/constitution`. Accessed on 2019-06-06.

[15] A. Garcia, *Environmental Urban Noise*. WIT Press, 2001.

[16] H. L. Nielsen, *Railway Traffic Noise - Nordic Prediction Model*. The Nordic Council of Ministers, 1996.

[17] E. Zwicker and H. Fastl, *Psychoacoustics. Facts and models*. Springer, 3rd ed., 1999.

[18] S. A. Gelfand, *Hearing: An Introduction to Psychological and Physiological Acoustics*. Informa UK, 5th ed., 2010.

[19] A. Hoffman, "Lectures on psychoacoustics," (Oslo, Norway), 2019.

[20] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics*. John Wiley & Sons, 4th ed., 1999.

[21] Technical Committee ISO/TC 43, Acoustics, Subcommittee SC 1, Noise, "ISO standard 1996-1:2016: Acoustics - Description, measurement and assessment of environmental noise - Part 1: Basic quantities and assessment procedures," *International Organization for Standardization*, 2016.

[22] HEAD Acoustics, "Artemis suite advanced psychoacoustics module (code 5016)," 2018.

[23] HEAD Acoustics, "Artemis suite psychoacoustics module (code 5012)," 2018.

[24] U. Widmann, "Untersuchungen zur schrfe und zur lstigkeit von rauschen unterschiedlicher spektralverteilung," *DAGA '93, Bad Honnef*, pp. 644–647, 1993.

[25] G. von Bismark, "Sharpness as an attribute of the timbre of steady state sounds," *Acta Acustica united with Acustica*, vol. 30, pp. 159–172, 1974.

[26] HEAD Acoustics, "Application note: Psychoacoustic analyses 2: Calculating psychoacoustic parameters in artemis suite," 2018.

[27] R. Sottek and K. Genuit, "Models of signal processing in human hearing," *International Journal of Electronics and Communications*, pp. 157–165, 2005.

[28] A. M. Willemsen and M. D. Rao, “Characterization of sound quality of impulsive sounds using loudness based metric,” 2010.

[29] Technical Committee ISO/TC 43,Acoustics, Subcommittee SC 1, Noise, *ISO/TS 15666: Acoustics - Assessment of noise annoyance by means of social and socio-acoustic surveys*. 1st ed., 2003.

[30] Technical Committee ISO/TC 43, Acoustics, Subcommittee SC 1, Noise, *ISO 3095: Acoustics - Railway applications - Measurement of noise emitted by railbound vehicles*. 3rd ed., 2013.

[31] D. Templeton, *Acoustics in the Built Environment*. Butterworth-Heinemann, 1993.

[32] E. L. Iglesias, D. G. Figueroa, and R. S. M. Castillo, “Comparison between subjective evaluation and psychoacoustic parameters for car steering wheel rattle noise assessment,” *European Acoustics Association*, 2016.

[33] Wikipedia, “Voksenlia stasjon.” `https://no.wikipedia.org/wiki/Voksenlia_stasjon`. Accessed on 2019-05-30.

[34] A. Hoffman, *Auralization, perception and detection of tyre-road noise*. Goteborg, Sweden: Chalmers University of Technology, 2016.

[35] K. H. Liland, “R Commander and the NMBU plugin.” `https://repository.nmbu.no/R/`. Accessed on 2019-04-28.

Appendix A

Average annoyance of the 53 signals

Table A.1: The average annoyance at Dalbakkveien, found from the listening tests.

Dalbakkveien	Average annoyance
In	4.5200
	4.4000
	4.1200
	4.4000
	4.8400
	4.2000
	4.4400
Out	6.7600
	6.3600
	6.6800
	6.6800
	6.2800
	6.6000
	7.5200
	6.3600
	7.3600

Table A.2: The average annoyance at Voksenlia, found from the listening tests.

Voksenlia	Average annoyance
In	7.6000
	8.5200
	8.1200
	7.7600
	7.6800
Out	7.8800
	9.1600
	8.5200
	8.8800
	8.2000

Table A.3: The average annoyance at Borgen, found from the listening tests.

Borgen	Average annoyance
In	7.6400
	7.7600
	7.5600
	7.8400
	5.0800
	7.9200
	7.8400
	7.6800
	7.8800
Out	5.1200
	4.7200
	4.7200
	4.0000
	5.1600
	5.0000
	4.6400

Table A.4: The average annoyance at Tjensrud, found from the listening tests.

Tjensrud	Average annoyance
In	6.3200
	6.3200
	6.0400
	6.0400
	5.7200
Out	4.4800
	5.0400
	5.7200
	5.0000
	5.0400
	4.5600

Appendix B

Linear regression models

Table B.1: Annoyance $\sim$ SPL

	Estimate	Standard error
Intercept	0.69481	1.43621
SPL	0.08331	0.02120

Table B.2: Annoyance $\sim$ SPL + Sharpness

	Estimate	Standard error
Intercept	-4.990540	0.627927
SPL	0.111393	0.008618
Sharpness	2.033023	0.087592

Table B.3: Annoyance $\sim$ Loudness

	Estimate	Standard error
Intercept	3.616553	0.291999
Loudness	0.072467	0.007325

Table B.4: Annoyance $\sim$ Loudness + Sharpness

	Estimate	Standard error
Intercept	1.528752	0.194245
Loudness	0.052407	0.003955
Sharpness	1.520169	0.089460

Table B.5: Annoyance $\sim$ Sharpness

	Estimate	Standard error
Intercept	2.8201	0.2750
Sharpness	1.8741	0.1398

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