Department of Electronic Systems

Highway 4 Sletteløkka - indoor noise reduction potential of a change of pavement.

Author:
Jelena Mihajlovic Rubin

Supervisor:
Guillaume Dutilleux

External supervisor:
Sigmund Olafsen

May 2022

Department of Electronic Systems
Norwegian University of Science and Technology

Problem Description

At Sletteløkka, Oslo, there is experimental evidence that high noise levels originating from Highway 4 exceed the applicable noise limits in dwellings. Considering the topography and the average height of buildings, a noise barrier would bring little noise reduction. The purpose of the project is to evaluate the potential acoustical benefit of a change of pavement. Indoor noise levels for the existing and for potential pavements will be evaluated with noise prediction method defined in octave bands (CNOSSOS-EU). The accuracy of these methods' predictions will be tested by comparison with measurements. Alternative noise abatement techniques will be investigated if the applicable indoor noise limits cannot be met by changing the pavement.

Summary

The thesis aims to investigate the ability of various types of pavements to reduce road traffic noise on the building façade and indoors at Sletteløkka, Oslo. The study involves field measurements and prediction calculations. The calculation has been conducted in CadnaA software in octave bands in the frequency range 63 Hz - 8 kHz, according to a common noise assessment method developed in the European Union (CNOSSOS-EU). Measured global L_{den} is 71,5 dB(A) and $L_{Aeq,24h}$ is 65,6 dB(A), while calculated L_{den} is 70 dB(A) and $L_{Aeq,24h}$ is 66,4 dB(A) outside the façade in Linderudlsetta 9b in the area of interest. On the other hand, measured global L_{den} indoor is 36,5 dB(A), while calculated L_{den} indoor is 35 dB(A). The deviation between the measurement and the model corresponds to CNOSSOS uncertainty of ±2dB(A); thus, the model can predict noise levels as a part of strategic noise planning.

The model yields noise levels outside the façade at Linderudsletta 9b and Sletteløkka 33a. Estimated global L_{den} indoors is 36,5 dB(A) and 26,1 dB(A) respectively. The investigated noise measures at the source are road surface measures (alternative pavements), noise screening, and traffic management measures (reduction in traffic volume and vehicle speed). According to the findings, the latter indicates a significant indoor noise level reduction of 5-6 dB.

Acknowledgments

This master's thesis is the final part of my Master of Science degree in Electronic System Design at the Norwegian University of Science and Technology (NTNU). The project was suggested by Brekke & Strand AS.

Firstly, I would like to thank Brekke & Strand for providing equipment to conduct measurements, software to perform calculations and simulations, and permitting me to work from their office space.

I would like to express my warmest gratitude to my supervisors, Guillaume Dutilleux at NTNU and Sigmund Olafsen at Brekke & Strand, for their guidance and advice during the project.

Special thank goes to my beloved husband, Torbjørn Rubin, and my family for their continuous support. Your love was what sustained me this far.

A big thanks to Øystein Meland (Brekke & Strand), Truls Berge (SINTEF), and Jostein Aksnes (Statens vegvesen) for discussing and helping on the project. Finally, sincere gratitude goes to Dragan Novkovic and Filip Petrovic for being a great inspiration and support before and during my master's studies.

Contents

Chapter 1

Introduction

According to the relevant noise authorities, World Health Organization [4] and European Environment Agency [5], environmental noise is of a great public concern. Long-term exposure to environmental noise is associated with significant negative health consequences [4]. Traffic noise is in particular the biggest environmental noise problem today. It has a negative impact on both wildlife and human health and well-being. In Europe, at least 20% of the population live in the areas where traffic noise levels exceed the norm. Precisely, about 113 million people are affected by long-term day-evening night traffic noise levels of at least 55 dB(A). The prolonged exposure to environmental noise is estimated to cause 12 000 premature deaths, and it is linked to 48 000 heart disease cases in Europe each year. In addition, it is estimated that 22 million people suffer chronic noise annoyance, and 6.5 million people suffer chronic sleep disturbance[5].

1.1 Case background

In this thesis, the sound source of interest is the old national highway, Rv4, Trondheimsveien, in Oslo, Norway. Many homes along Trondheimsveien, on the stretch between Sinsenktysset and Grorud, have been affected by high traffic noise levels originating from Rv4. The area is considered the most noise polluted in Norway over the last 25 years. The subject of this study is the neighborhood Sletteløkka that is located north of Rv4 (Trondheimsveien), between Kolåsbakken and Rødtvet. In Slettelkka, there are approximately 540 apartments, with 100 households facing the Trondheimsveien.

In 1997 for the first time the case was studied by COWI in behalf of the Norwegian Public Roads Administration (Statens vegvesen). The final report concluded that noise pollution had a significant impact on many homes in the area. In later years, the Norwegian Public Roads Administration and Rambøll reopened the case. Noise barriers were purposed as a solution, but the project was stopped before its complete execution. In recent years, the traffic volume on Rv4 has continued to grow in response to increased transportation needs in society, and residents in the area are still exposed to high noise levels.Today, the case appears to be a contentious and political issue. The local community, as well as the local authorities, are involved. However, the problem remains.

Brekke Strand Akustikk AS reassessed the noise situation in spring 2020 according to the current regulatory requirements, see [10] [11]. Several alternative measures have been investigated: reductions of noise along the propagation path by means of noise screens, window replacement, traffic volume and vehicle speed reduction. As it is reported in [19], noise barriers cannot reduce noise on building facades or indoors due to terrain conditions. The fact that noise barriers initially divide small outdoor areas into smaller parts is another disadvantage. The replacement of windows in Linderudsletta 1-23 (various numbers) is estimated at NOK 30 million. With closed windows in rooms facing Trondheimsveien, new windows could provide up to a 5 dB noise reduction indoors. Finally, it was concluded in [19] that a reduction in traffic volume and vehicle speed gives significant noise reduction.

This thesis augments the author's semester project "Highway 4 - an investigation into outdoor sound propagation in a dense residual area." The semester project aimed to collect and analyze new data to assess the noise situation in the area. The experimental study was done by conducting sound measurements, resulting in $L_{Aeq,24h}$ to be 67 dB(a), and L_{den} to be 72,5 dB(A) outside the facade in Linderudsletta 9b. Moreover, the prediction was made in SoundPLAN 8.2, employing the Nordic prediction model-Nord96. Finally, the semester project also concludes that a reduction in traffic volume and speed of vehicles could be a suitable solution to the noise problem at Sletteløkka.

1.2 Earlier work

Source-based noise measures have been found to be among the most effective [5]. Hence the suggestion for this study is to investigate new source-based noise abatement strategies, such as road surface measures. Across the literature, there is evidence that the noise generated by the interaction of the road surface and the tyres is the primary source of the overall road traffic noise [3].

T.Berge, J.Ejsmont, P.Mioduszewski, and B.Świeczko-Żurek investigated current source-based noise abatement strategies and the future possibilities in their study [2]. It was found that a noise reduction of 4–6 dB can be achieved by combining optimized tyres and road surfaces. However, the durability of the low-noise road surfaces was addressed as an obstacle.

SINTEF [1] conducted a long-term study that provides results from SPB and CPX measurements performed on a wide range of traditional Norwegian dense road pavements of stone mastic asphalt (SMA) and dense asphalt concrete (AC), in addition to special test pavements. The main findings show that before being exposed to winter conditions and studded tires, a newly laid dense road pavement can be 4-8 dB(A) quieter than the reference value. The increase in noise levels is expected of approximately 3-4 dB after the first winter season. On the other hand, the porous pavements tested in the project appear to provide an average noise reduction in the range of 5-9 dB(A) compared to the reference level. Porous pavements seem to differ from dense pavements in that the increase in noise levels is more noticeable after the second winter season than after the first.

European Asphalt Pavement Association published a report in 2018 on stone mastic asphalt.

The report argues that SMA has prove to be cost-effective, durable, and low-noise. Besides, it has sustainable and environmental benefits.

These findings raised whether or not changing the road surface in the Sletteløkka case would be an effective solution.

1.3 Objectives

In this master thesis, the impact of various pavements along other source-based noise mitigation measures on indoor noise levels have been investigated. In this regard, there are two aspects of the study. Firstly, *in situ* measurements have been conducted. Secondly, the CNOSSOS-EU prediction method for road traffic noise has been employed to create a noise model in CadnaA software. Both aim to determine $L_{Aeq,24h}$ and L_{den} noise parameters. In that way, it is possible to compare the measurements with the model. By verifying the model's accuracy, we can predict sound levels, investigate different measures and finally give recommendations.

The major tasks of this study include the following:

- Field measurements
- Predicting noise levels
- Investigating the effect of various pavements on indoor noise exposure
- Investigating the effect of other source-based noise abatement strategies on indoor noise exposure.
- Strategic noise mapping
- Providing recommendations

1.4 Report outline

The thesis takes a form of a scientific report, and it is organised into several chapters. Chapter 2 lays the theoretical groundwork for the reader to comprehend the study methodology and subsequent findings. The method is outlined in Chapter3, which includes data collection, simulation in CadnaA, and investigation of various scenarios using the CNOSSOS-EU method for road traffic noise assessment. Chapter 4 reveals the experimental results. The results are further discussed in chapter 5, as well as potential sources of errors and uncertainties. Finally, the conclusions are summarized in chapter 6.

The report presupposes the reader is familiar with fundamental acoustic concepts such as sound pressure, sound pressure level, and sound frequency.

Chapter 2

Theory

This chapter provides the theoretical foundation to understand the methodology used, the results obtained, and the accompanying discussion in this thesis. The basic concepts of outdoor noise propagation phenomena are provided in Section 2.1. Section 2.2. deals with the frequency analyses, while section 2.3 outlines noise requirements and noise metrics for evaluating road traffic noise. A brief description of the generation mechanism of road traffic noise and the basic theory of road surfaces are provided in section 2.4. Finally, an overview of the CNOSSOS-EU model for road traffic noise is provided in section 2.5.

2.1 Outdoor sound propagation

The scope of the thesis is outdoor sound propagation. The central tasks involve outdoor sound measurements, which have implications. The sound at the receiver point will always be attenuated in the outdoor environment due to different factors affecting the propagation. The most significant factors are:

- Geometrical divergence (A_{div})
- Atmospheric attenuation (A_{atm})
- Ground effect (A_{ground})
- Meteorological conditions (humidity, precipitation, wind)
- Temperature gradient - refraction
- Obstacles such as barriers and buildings - diffraction ($A_{boundary}$)
- Reflections

The following subsections encompass outdoor sound propagation topics relevant to this thesis. See [14] for a more detailed overview of outdoor sound propagation.

2.1.1 Geometrical divergence

The sound level decreases as the distance from the sound increases. The effect of distance attenuation differs depending on the geometrical properties of the sound source, whether it is a point or a line. Theoretically, the point source is an omnidirectional type of source whose dimensions are small compared to the distance from a listener. The point source produces a spherical wave that spreads equally in all directions. Consequently, the sound pressure level reduces by 6 dB per doubling distance. The sound level at the receiver due to spherical propagation is calculated according to the following equation:

$$L_p = L_w - 20log(\frac{r}{r_0}) + 11 - DI \tag{2.1}$$

where L_w is the sound power level expressed in dB; *r* is the distance from the source to the receiver, in meters; r_0 is the reference distance, 1m, and *DI* is a directional index that is 0 for omnidirectional source.

The line source is narrow in one dimension and long in the other compared to the distance from a listener. The line source radiates sound cylindrically along the line, decreasing by 3 dB per doubling distance.

2.1.2 Atmospheric attenuation

In a real atmosphere, there will be always losses due to thermal conductivity, viscosity and relaxation phenomena. The air absorption depends on the sound frequency and humidity, affecting distances greater than 100 m. In the thesis, the A_{atm} can be neglected due to short measurement distances (none of the sound propagation paths exceed 30m). The same can be said for the refraction phenomena (wave curvature caused by meteorological conditions).[16]

2.1.3 Ground effect

Ground absorption is a significant phenomenon of outdoor sound propagation because it indicates how much sound energy is absorbed or reflected by means of ground, therefore, how much the sound is attenuated. The ground effect differs among various types of surfaces. The concrete is considered rigid or highly reflective. The grass, on the other hand, is soft or absorptive. None of these extreme conditions can be met in practice because the surface is neither infinitely hard nor infinitely soft. Thus, an accurate estimate of ground effects requires information on the surface's absorptive and reflective properties. [14].

The acoustic absorption properties of the ground are associated with the degree of porosity. The acoustic absorption of ground is usually represented by a dimensionless coefficient G, ranging from 0 to 1, with 0 being highly reflective and 1 highly absorptive. The G values are listed in Table 2.5.a in [8]

The interference that occurs at the boundary when the direct wave coincides with the reflected wave is the main cause of ground effect attenuation [9]. The main feature of the interference is the comb filter. Depending on the phase relationship, the interference is either destructive or constructive. When the direct and reflected waves are out of phase, the negative interference happens, and the signals cancel each other; when the direct and reflected waves are in phase, the positive interference happens, resulting in + 6 dB at the receiver, i.e., microphone point.

2.1.4 Diffraction

Diffraction occurs at the top of obstacle edges. The waves bend outward around the edge, spreading out spherically around the diffraction point. Diffraction can only occur if the object is sufficiently large in comparison to the sound wavelength. Waves with a low frequency and thus A long wavelength diffract more effectively around objects than waves with a high frequency and a short wavelength.

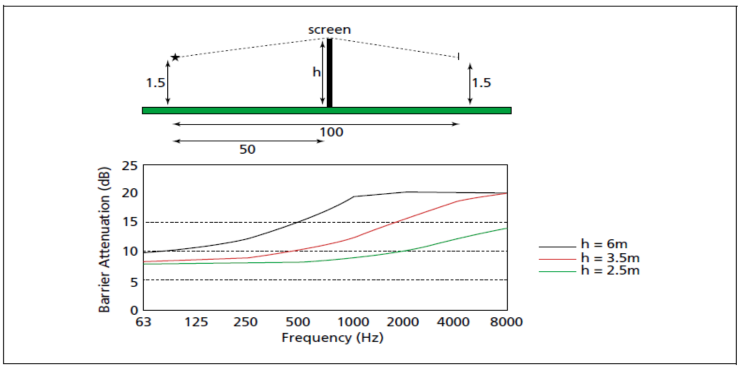

Figure 2.1: *Barrier attenuation for a typical screen is shown in the next diagram as a function of barrier height. A barrier is most effective when placed close to the noise source or receiver. The image is taken from Bruel & Kjær booklet [24]*

2.2 Sound field

Outdoors, sound propagates along different paths through the air in a sound field, characterized by the acoustic properties of the medium.

Free field is a region in space where the sound is not affected by reflections, absorption, refraction, and other phenomena. The free field is characterized by a theoretical point source (see section 2.6. for the point source definition). To satisfy the free field condition, the distance between the microphone and any reflecting surface must be at least twice the distance between the source and the receiver [12].

Near field is a region close to the source where the particle velocity and sound pressure are not in phase. The sound field in this region does not decrease by 6 dB as the distance from the source increases (as it does in the far field).

Diffuse field is a region in space where the sound pressure level is uniform, i.e. the reflected sound dominates, as compared to the region close to a noise source where the direct sound dominates. Measurement yield a noise level equal to the incoming sound level + 3 dB.

Zone with reflections in phase is a region in space where the direct sound coming from the source and the reflection from the surface coincide, forming a comb filter. The size of the zone is frequency-dependent. Measurements yield a noise level equal to the incoming sound level +

6 dB.

2.3 Frequency analyses

The frequency spectrum is a graphical representation of sound pressure level as a function of frequency. It is crucial for understanding the perception of sound because human hearing is frequency-dependent, being the most sensitive between 1-4 kHz. On the other hand, it is less sensitive to low-frequency sound. The human ear has an integrated physiological filter in the inner ear that weights signals differently depending on their frequency. Adequate frequency selection is important in noise analyses because of the diverse nature of the sound; sounds are complex mixtures of pressure variations that vary in phase, frequency, and amplitude. For that reason, noise levels are commonly measured and reported in the octave band or one-third octave band [23]. The octave band is the most basic frequency band, for which the center frequency of each filter band is two times the center frequency of the preceding band. Due to the low frequency resolution, it only gives a rough idea of the frequency spectrum. The most commonly used is the third-octave band, whose width is approximately 22% of the band's center frequency. The third-octave band resembles the auditory system's ability to divide sound into frequency bands, known as critical bandwidth.

2.3.1 Frequency weightings

The A-, C- and Z-weightings were introduced to help to translate the physiological effect of the hearing system into the measurements. A-weighting filter has been considered to corresponds the best to the human perception of sound. However, note that there is a significant attenuation applied by the A-weighting filter for frequencies bellow 500 Hz and above 5 kHz (see Fig. 2.1).

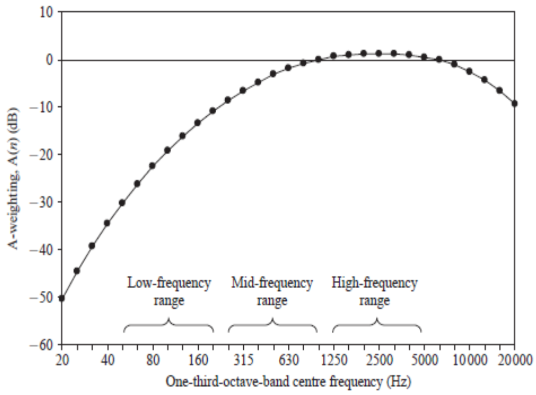

Figure 2.2: A-weighting values over the range of human hearing indicating the low-, mid-, and high-frequency ranges for the building acoustics frequency range. Source: Sound insulation [15]

Using linear weighting may be of greater importance in cases where estimation of indoor traffic noise is a primary task. In such cases, sound transmits through a window or a façade, resulting in low frequencies being transmitted through the building element quite unattenuated. One may use linear weighting because the A-weighting does not correctly account for these low-frequency components. On the other hand, one would use A-weighting when it is crucial to understand which part of the spectrum is the most dominated.[3]

2.4 Noise

Sound can be both desirable and non-desirable. Sound generated by tire/pavement interaction is considered as road traffic noise, and it is non-desirable sound. Road traffic is the most common source of environmental noise in all countries that causes annoyance, health issues and interference. Therefore, traffic noise reduction measures are given top priority.

2.4.1 Noise police

The European Noise Directive (END) is the primary legislative framework in Europe for attaining noise reduction [7]. The directive provides a unified approach across countries to avoiding and preventing environmental noise exposure through strategic noise planning. It is important to highlight that the directive establishes reporting thresholds rather than limit values. On the other hand, countries have independently introduced limit values on a national level by introducing standards and law.

The following are current Norwegian guidelines that have been used:

- Forurensningsforskriften (eng. Norwegian regulations amending regulations on limiting pollution)
- Retningslinje for behandling av støy i arealplanlegging T-1442/2016 (eng. The Norwegian Ministry of Climate and the Environment's Guideline for the treatment of noise in spatial planning T-1442/2016)
- Norwegian Standard NS 8175: 2019 - Sound conditions in buildings specify limit values for sound properties that are considered sufficient to meet the minimum requirement for technical regulations in accordance with the Building Act. There are specific limit values for housing. Requirements are shown in table 2.1.

Table 2.1: *Current Norwegian noise-limitation requirements, both outdoor and indoor.*

Standard	Description	Requirements
Forurensningsforskriften	Outdoor noise level in front of the facade	LAeq24h 42 dB (A)
T 1142-16	Outdoor noise level in front of the facade	Lden 55 dB (A)
NS 8175	Indoor noise level	Lden 30 dB (A)
NS 8175	Indoor noise level in the sleeping areas during the night (23.00- 07.00)	LAF,max 45 dB (A)

2.4.2 Noise indicators

Time-averaged equivalent continuous sound pressure level, $L_{eq,T}$ sums up the total energy over a time period (T), producing a level equivalent to the average sound energy during that time. It is widely used to measure noise that varies with time, and the measurement unit is dB. $L_{eq,T}$ is defined as:

$$L_{eq,T} = 10log_{10}\left[\frac{1}{T}\int_0^T \frac{p(t)^2}{p_0^2}\,dt)\right] \tag{2.2}$$

Where $p_(t)$ is the instantaneous sound pressure at a running time t, and p_0 is a reference sound pressure.
An overall $L_{eq,T}$ can be calculated as follows:

$$L_{eq,T} = 10log_{10}\left[\frac{1}{T}\sum_{i=1}^{N} 10^{0.1\cdot(L_{Aeq,i})}t_i\right] \tag{2.3}$$

Where N denotes the number of L_{eq} events, and t_i is a time period of the *i*th L_{eq}.

These average levels are typically derived from the integration of A-weighted levels. Thus, $L_{A,eq,T}$ is the A-weighted average energy equivalent level over a period T, and it is defined by:

$$L_{A,eq,T} = 10log_{10}\left[\frac{1}{T}\int_0^T \frac{p_A(t)^2}{p_0}\,dt)\right] \tag{2.4}$$

Where $p_A(t)$ is the A-weighted instantaneous sound pressure at a running time t, and p_0 is a reference sound pressure.

To study a global 24-hour long-term noise effect, it is convenient to use a single-number descriptor $L_{A(24h)}$. The A-weighted 24-hour equivalent continuous sound pressure level,$L_{A(24h)}$, describes the average sound pressure level measured over a whole day and it can be calculated by the following equation:

$$L_{A(24h)} = 10log_{10}\left[\frac{1}{24}\sum_{i=1}^{24} 10^{0.1\cdot(L_{Aeq,i})}\right] \tag{2.5}$$

The long-term day-evening-night level, L_{den} is based on $L_{A(eq,T)}$ that is A-weighted average equivalent continuous sound pressure level over all days, evenings and nights per year. It is introduced by EU Directive 2002/49/EC. The unit is (dBA), and the formulation is as follows:

$$L_{den} = 10log\left[\frac{1}{24}(12 \cdot 10^{0,1 \cdot L_{day}} + 4 \cdot 10^{0,1 \cdot (L_{evening}+5dB)} + 8 \cdot 10^{0,1 \cdot (L_{night}+10dB)}\right] \quad (2.6)$$

With a penalty of 5 dB for evening time noise (19.00-23.00) and a penalty of 10 dB(A) for night time noise (23.00-7.00). L_{den} is composed of:

L_{day} - is the A-weighted long-term average sound level as defined in ISO 1996-1: 2016, determined over all the day periods of a year;
$L_{evening}$ - is the A-weighted long-term average sound level as defined in ISO 1996-1: 2016, determined over all the evening periods of a year; and
L_{night} - is the A-weighted long-term average sound level as defined in ISO 1996-1: 2016, determined over all the night periods of a year.

2.5 Road Traffic Noise

The theory presented in the upcoming section is a summary of the material presented in books:
(1) Ulf Sandberg and Jerzy A. Ejsmont, "Tyre/Road Reference Book"
(2) Beckenbauer, Thomas, "Chapter 15: Road Traffic Noise"

Road traffic noise is the primary source of environmental noise pollution among railway traffic and air traffic (Beckenbauer, 2013). Three components directly contribute to the total road traffic noise emission: vehicle, tire, and road. Furthermore, sources of road traffic noise are the powertrain system, exhaust system, tire/road contact, airflow through the vehicle's body, and associated parts. These sound sources interact, resulting in three distinct noises:
• Propulsion (engine) noise is excited by engine and exhaust system.
• Rolling noise is excited by tire/road contact.
• Aerodynamic noise is excited by the incident airflow around the vehicle's body.

2.5.1 Tyre/road noise sources

Tire-road noise generation related phenomena are divided into two main groups: vibration and aerodynamic mechanisms. The former is generated by radial and tangential vibrations of tread elements produced in the interaction between the tire and pavement surface. Vibration mechanisms are associated with low frequency noise emissions, and they influence the tire-road noise below 1 kHz. On the other hand, aerodynamic mechanisms are associated with high-frequency noise emissions. Those mechanisms are related to the compression and expansion of air volumes enclosed between the tire and pavement surface, and they are characterized by frequencies higher than 1000 Hz. Altogether has been found to have a significant impact on overall tire/road noise.

Acoustical and mechanical impedance of a road surface is two other phenomena related to amplification and reduction mechanisms that significantly impact tire/road noise. The mechanical impedance of the tire treads is much lower than the road surface's mechanical impedance, leading to an impedance mismatch at the tire/road interface. For that reason, the road surface is a significant sound radiator.

Other significant phenomena in the sound enhancement mechanism are air and pipe resonance. The former can be explained by analogy the tire/road configuration to the mass-spring system. The air volume of the thread cavity of the tire acts like a spring; the air between the thread and the road interface acts as a mass, thus, resulting in Helmholtz alike resonance. Not only the Helmholtz resonance, but the pipe resonance is present in the tire/road system. Tread patterns of all kinds constitute a theoretical pipe, which resonance frequency depends on the geometrical properties.

2.5.2 Basic theory for road surfaces

The road (pavement) system consists of the base and surface courses (top layer). The base course carries the load. The surface course is subject to wear and weathering and will need to be replaced or maintained. Furthermore, the road surface comprises the following categories of materials: stones, sand, filler, and binder. Stones, also known as chippings, are typically the most dominant component of a road surface. Sand and fillers are usual materials of the base course., while the filler is a material composed of fine particles. Altogether, stones, sand, and filler account for roughly 90-95% of the total weight. The remaining 4-8% is the binder, the most common of which is bitumen ("asphalt") and cement. To sum up, there are two types of commonly used road surfaces (pavements):

• *Concrete surface (base course).* The term concrete refers to a mixture of stones and sand bound together with a binder such as bitumen or cement. According to the structural behavior, concrete surfaces are classified into two types: (1) flexible and (2) rigid. The flexible surfaces use bitumen (asphalt) as a binder, whereas the rigid use cement. The cement concrete pavement has two functions simultaneously: the load-carrying base and the wearing surface. It is durable and low-cost; however, it is noisy. Although bituminous concrete lacks the strength of traditional cement concrete, it remains the most popular material for most paving applications. Bituminous concrete is durable enough to withstand years of road traffic, and it is easy to maintain and repair. It also provides a smoother and quieter ride than cement surfaces, reducing noise pollution near highways and other busy roads.

• *Surface dressings (cheap seals).* The underlying concrete surface (base course) is usually covered with a layer of stones. That presents a single surface dressing; a double surface dressing includes a second layer of binder and stones.

2.5.3 Dense and porous pavements

Proper material proportioning is critical because it determines the type of pavement and its characteristics. That refers to stones and sands of various sizes. The sizes above 2 mm constitute the aggregate and are considered stones or chippings. In contrast, the sizes between 0.063 - 2 mm are considered sand. Extra fine sand with a particle size of less than 0.063 mm is called a filler. Sand and filler together create a mastic. The following is a typical configuration of a dense asphalt concrete (DAC) surface:

Stones, aggregate (2-16 mm) 40-50%, Sand (0.063 – 2 mm) 35-45%,
Filler (<0.063 mm) 5-10%, Binder (bitumen) 4-8%

In DAC, the voids are around 5% by volume. The surface will be porous if approximately 20% of the volume is void content. Such a pavement is called porous asphalt concrete (PAC).
Stone mastic asphalt (SMA) is a type of asphalt concrete popular worldwide for surfacing heavy traffic roads. SMA is a good compromise of dense and porous asphalt concrete. However, aggregates and filler fractions are proportioned in such a way to avoid getting a porous surface. The SMA has several advantages over the standard DAC, including increased strength and reduced wear. Besides, longer service life, relatively thin configuration, and lower noise emission levels impart sustainable environmental benefits.

2.6 Common noise assessment methods for Europe (CNOSSOS-EU)

Commission Directive of the European Union established Common NOise aSSessment methOdS (CNOSSOS-EU) for road, railway, aircraft, and industrial noise on May 19th, 2015, according to Directive 2002/49/EC of the European Parliament. The directive aims to provide action plans based on strategic noise mapping to prevent and reduce the negative effect of environmental noise. In addition, the overall goal for the implementation of CNOSSOS-EU is to provide a standard method for noise assessment across European Union countries. The values of noise indicators $Lden$ and $Lnight$ shall be defined employing the assessment method given in a revision of Annex II of the Directive.

The following subsections describe parts of CNOSSOS - EU model for road traffic noise that are the most relevant for this theses. The model can be divided into two parts: the emission model and the propagation model.

2.6.1 Source modelling

The traffic flow is defined by a theoretical source line. In other words, the road traffic noise source can be interpreted as a sum of all point (noise) sources on the road, i.e., a sum of each vehicle in the traffic flow. In terms of noise emission characteristics, these vehicles are divided into four groups:

Category 1: Light motor vehicles
Category 2: Medium heavy vehicles
Category 3: Heavy vehicles
Category 4: Powered two-wheelers

The calculations shall be performed by firstly defining the number and the average speed for each vehicle category per lane. When modeling a road with multiple lanes, each lane shall be represented by a source line positioned in the center of the lane. In the following text it will be presented how the model in fact works. We will first look at the noise emission of the individual vehicle.

The emission model for each individual vehicle consists of a set of mathematical equations representing the two main noise sources, rolling and propulsion (aerodynamic noise as a part of rolling noise sources). The calculation shall begin with determining the sound power level of one of the sources (rolling or propulsion) as a function of the vehicle speed v_m:

$$L_{W,i,m}(v_m) = A_{i,m} + B_{i,m} f(v_m) \tag{2.7}$$

where $L_{W,i,m}$ is the instantaneous directional sound power and it is expressed in dB (re. 10-12 W/m).
Furthermore, the calculations shall be made by considering each source line as the total sound power of light, medium, and heavy motor vehicles (categories 1, 2, and 3). At this point, the total sound power corresponds to the energetic sum of the rolling and propulsion noise, respectively. For m=1, 2, or 3, the sound power level of the source lines ($L_{W,i,m}$) is defined as:

$$L_{W,i,m}(v_m) = 10 * log_{10}(10^{L_{W,R,i,m}(v_m)/10} + 10^{L_{W,P,i,m}(v_m)/10}) \tag{2.8}$$

where $L_{W,R,i,m}$ is the sound power level for the rolling noise, and $L_{W,P,i,m}$ is the sound power level for the propulsion noise.

Note that for category 4, only propulsion noise counts as the source.

Equation 2.10 is valid in case of the following conditions: a constant vehicle speed, a flat and dry road surface, an air temperature of 20 C, exclusion of studded tires, and a virtual reference road surface consisting of an average of dense asphalt concrete 0/11 and stone mastic asphalt 0/11, between 2 and 7 years old and in a representative maintenance condition.

However, these reference conditions can not always be met in practice due to the following factors affecting road traffic noise emission: presence of studded tyres, air temperature, road gradient, acceleration and deceleration of vehicle and, the type and condition of road surface. For a more comprehensive description, see [8].

2.6.2 Sound propagation model

The CNOSSOS method operates on a geometrical model, considering the ground and obstacles. Sound propagation occurs along the propagation path, d_p that is a mean ground plane between the source and the receiver, z_s and z_r. The equivalent height of the source h_s and receiver h_r is orthogonal to the mean ground plane.

The sound level in favorable (given) and homogeneous conditions, L_f and L_h respectively, is calculated as:

$$L_{f;h} = L_{W,0} - A_{f;h} \tag{2.9}$$

Where $L_{W,0}$ is the sound power of the source, and $A_{f;h}$ represent the total attenuation along the propagation path, and it boils down to the following:

$$A_{f;h} = A_{div} + A_{atm} + A_{boundary} \tag{2.10}$$

Where the terms A_{div}, A_{atm} and $A_{boundary}$ are described in the Section 2.1. Furthermore, $A_{boundary}$ may contain A_{ground} and A_{diff}, where latter is the attenuation due to diffraction.

2.7 Road traffic noise abatement strategies

Source-based noise mitigation measures are most effective measures for reducing the noise pollution[17]. The main source-based noise abatement measures are: legalisation, low-noise pavements, traffic management, low-noise tires, low-noise vehicles, driver behaviour.

Legislation is by far the most effective and cost-effective method of reducing noise at source. These limits are already in place in most countries, either at the national or supranational level. Furthermore, the regulatory approach is not only the most effective in terms of noise reduction, but it is also the most cost-effective way to achieve environmental noise reductions. [17]

As mentioned before, the main sources of road noise are engine (propulsion) noise and rolling noise. However, the rolling noise is currently the most dominant noise component of road traffic noise. The pavements characteristics (surface roughness, porosity and elasticity) are of a great interest in dampening the noise as they define acoustical properties of a road surface. For that reason, a selection of a type of pavement is significant in reducing the road traffic noise.

Traffic management measures play a significant role in reducing noise emission levels, particularly in cities where the composition of traffic is important. In most cities, light vehicles tend to dominate the average continuous sound pressure level, LAeq, and thus Lden and Lnight; heavy vehicles, on the other hand, tend to influence the composition of peak or maximum noise levels (such as Lmax or Lpeak), which are more closely linked to annoyance and sleep disruption [17]. Thus, traffic management measures that reduce the number of heavy vehicles in noise-sensitive residential areas at night (such as night-time restrictions) have the potential to reduce noise occurrences.

Chapter 3

Method

This chapter outlines the methodology employed in this thesis. Section 3.1 describes the procedure of sound measurements. Section 3.2 overviews the noise model development.

3.1 Field measurements

The primary task of this thesis is to assess the degree of noise exposure inside dwellings at Sletteløkka, Oslo. As direct measurements of indoor traffic noise are usually challenging because of the negative impact of the background noise, an indirect method of measuring indoor traffic noise was conducted according to the method that Olafsen employed in his study [21], and it requires:

- Outdoor measurements of road traffic noise levels in 1/3 octave bands

- Measurement of transmission loss through the building element(s) in 1/3 octave bands

All measurements were taken in the third-octave band, in the frequency range of 20 Hz – 20 kHz. However, the analysis is performed in the frequency range from 50 Hz to 5 kHz.

3.1.1 Site description

Figure 3.1 depicts a satellite image of the highway Rv4, Sletteløkka, Oslo. The terrain between the road and the buildings is somewhat elevated regarding the road. Furthermore, it is grass-covered. The buildings are four stores tall.

(a)

(b)

Figure 3.1: (a) A satellite image of the highway Rv4, Sletteløkka, Oslo, (b) The red cross represents a microphone location on the balcony in Linderudsletta 9b, Sletteløkka, Oslo.
Both images are taken from ”Google Earth’

In Linderudsletta 9b, the living room and bedroom are oriented towards the Trondheimsveien, highway Rv4, and are directly exposed to traffic noise. The apartment is fully furnished; thus, the rooms are well damped. The windows are double-glazed, which provides good sound insulation. However, not all windows and balcony doors appeared to be correctly installed. The balcony is approximately of 5 m^2 (see Figure 3.2). The distance between the balcony and the road's center line is 33 meters (see Figure 3.3).

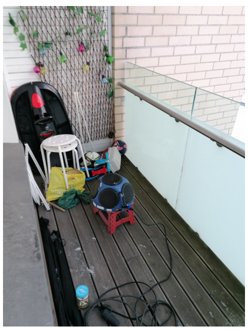

Figure 3.2: *The balcony located in Linderudsletta 9b, Sletteløkka, Oslo.*

3.1.2 Outdoor measurements

The outdoor traffic noise measurements have been carried out on two different occasions: on January 13th-14th, 2021 in Linderudsletta 9b, and on November 16th, 2021, in Linderudsletta 13. Measurements have been taken following the Norwegian standard for measurements of road traffic noise, NS 8174. Figures 3.3 and 3.4 depict outdoor measurement locations.

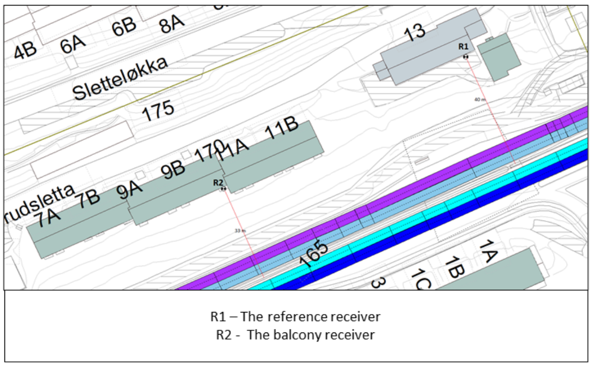

Figure 3.3: *The image is a screenshot from the CadnaA noise model representing outdoor measurement locations. The distance from the source, which is the central line of the highway Rv4, and the receiver R1 is 33 m, whereas it is 40 m from R2.*

The outdoor noise measurements have been performed continuously every hour within the reference time to characterize the noise emission from the traffic within this specific time interval. Because the estimate of $LAeq, 24$ is based on a 24-hour measurement, the reference time is the entire day. Traffic was counted automatically with the traffic counter radar during the both occasion.

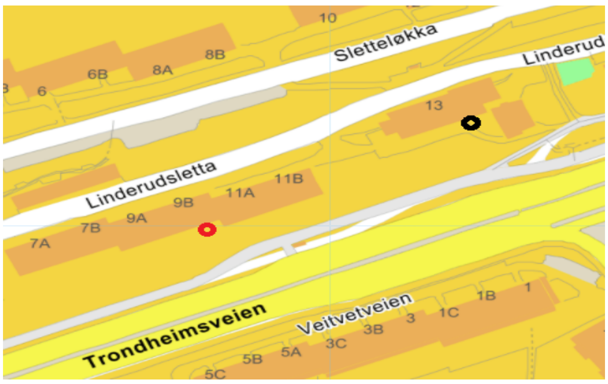

Figure 3.4: *The red circle represents the measurement location in January 2021, while the black circle represents the measurement location in November 2021. The image is a screen shot from "Gule sider"*

Due to the covid-19 pandemic, the traffic volume (AADT) in November 2021 is a better approximation than the traffic volume in January 2021. As a result, the measurement and traffic data captured in November 2021 were used to validate and calibrate the noise model compared to actual measurements. In that regard, the balcony in Lunderudsletta 9b was chosen as the model's emission point because the task is to determine the indoor noise level in that apartment.

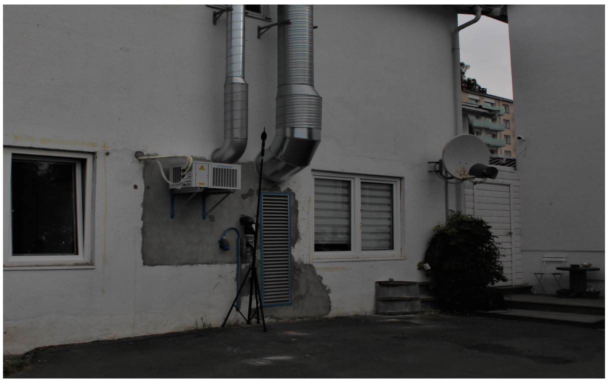

Figure 3.5: *Measurement location on the second occasion as the reference receiver point in the noise model.*

Figure 3.3 represents the measurement location in November 2021. The microphone was mounted on a microphone stand near the ventilation system, i.g., two pipes and a compressor box. The microphone was placed inside the +3 dB reflection zone, 0.25 meters from the facade. The microphone's height is 3 meters.

Meteorological data are taken from **www.yr.no** and are presented in table 3.1.

Table 3.1: *Meteorological conditions on each measurement occasion.*

Measurement description	Date and time	Temperature	Wind	Humidity
Direct outdoor road traffic noise measurement (I)	start: 13/01/2021 at 17.00 end: 14/01/2021 at 13.00	average: -5°	6 m/s	80 %
Direct outdoor road traffic noise measurement (II)	16/11/2021	average: 3°	3 m/s	85 %

3.1.3 Transmission loss measurements

In this thesis, we use the transmission loss measurement data that have been collected during the semester project. Transmission loss measurements including outdoor as well as indoor measurements were conducted according to the Nordtest method [12]. The measurements have been carried out in two locations, on the 1st floor on 13^{th} of January 2021, in Linderudsletta 9b, and on the ground floor on 22^{nd} of February 2021, in Sletteløkka 33a.

The indoor and outdoor levels have been measured sequentially using a condenser microphone, an amplifier, and a loudspeaker. An amplifier with a self-contained white/pink noise generator was used to generate a pink noise signal with an intensity of 110 dB. The signal was sent to the loudspeaker, which generated pink noise in the sending room. The sending room is a selected one indoors, and outdoors it is the balcony. According to the Nordtest method, three loudspeaker positions were decided on-site for indoor measurements, whereas only two loudspeaker positions were available for the measurements on the balcony. Several loudspeaker positions are preferable such that an artificially generated sound field reminds the actual road traffic noise-induced field.

On both occasions, the measuring microphone was swept in front of the façade at 0.25 meters. Although mounting the microphone on the façade for façade measurements is preferable, the studies have shown that using sweeps has no negative impact on the accuracy [20]. In addition, each probe was taken for 30 seconds to ensure an average sound pressure level. Only levels in third-octave bands have been measured. It was not necessary to distinguish between sound transmission through the wall, ventilation openings, and windows due to the nature of the task, nor was it necessary to take reverberation time measurements. In the case of open windows, high noise levels are present.

3.1.4 Post-processing of measurement data

The post-processing of the measurements was done using Microsoft Excel, Matlab, and CadnaA. The measured global A-weighted sound pressure level and 1/3 octave band values were exported to Excel via NorXfer. As only octave band spectrum is needed for comparison with CNOSSOS model, the measured 1/3 octave bands were converted to octave bands by logarithmic summation of the belonging three frequencies. The process was repeated to compute Lden in octave bands. Finally, A-weighted filtering was applied to all octave band values. Matlab was used to plot the data.

3.1.5 Other data acquisition

Traffic and pavement data collection was done during the early stage of the study. For that purpose, traffic data was downloaded and saved locally as excel file from the Norwegian Public Roads Administration (Statens vegvesen) website: **www.vegvesen.no/fag/trafikk/trafikkdata**. The data provides all needed information for in-depth analysis and evaluation of the noise traffic situation, such as date, time, vehicle length, speed, direction and the gap between vehicles, which allows for accurate vehicle classification.

Table 3.2 lists pavement data that the Norwegian Road Administration (Statens vegvesen) provided on a request.

Table 3.2: *Road surface (pavement) data for the current situation at Rv4, Sletteløkka, Oslo. These data are prerequisites for the noise exposure prediction model.*

Number of lane	Type of pavement	Year of instalation	Dimensioning
Lane 1	AC 16 with PMB	2011	110 kg / m2 (44 mm), width 3.9 m
Lane 2	SMA 11 with PMB	2013 or 2014	no data available
Lane 3	SMA 11 with PMB	2016	110 kg / m2 (44 mm), width 4.2 m
Lane 4	SMA 11 with PMB	2021	90 kg / m2, width 4 m

3.2 CNOSSOS(EU) - Noise simulation

The noise level at the receiver and the noise propagation along the transmission path can be both measured and calculated. The calculation is preferable or is the only possible method in the following cases:

• In case of future levels need to be predicted
• In case of alternative development and noise reduction scenarios need to be compared
• In case of noise maps need to be produced
• In case of limited access to the measurement position

Noise calculations (i.g., noise maps) are made using computer programs that have integrated one or several noise prediction models. The type of software and model is usually determined at a national level or by the industry sector. In this thesis, noise calculations have been done according to the CNOSSOS- EU method for road traffic noise, ranging from 63 Hz to 8 kHz in octave bands in CadnaA software.

3.2.1 Source modeling

As discussed in chapter 2, the appropriate development of a noise model requires specific input data. In the case of the road as a noise source, the following is necessary to create a model:
1. Input data on the number of vehicles for each lane.
2. Input data on the vehicle categories for each lane.
3. Input data on the speed of vehicles for each lane and optionally for different vehicle categories.
4. Input data about the road surface for each lane.

Note that the noise model calculation takes into account studded tyres data that is taken from:
https://www.nettavisen.no/nyheter/vinterdekk-oslo-og-akershus-med-rekordlav-piggandel/s/12-95-3423870715

3.2.2 Receiver modeling

CadnaA software simulates the outdoor noise emission impact on the facade of interest and outdoor area. Not only is the source of great importance for the determination of noise levels at the receiver point, but also the receiver.

As mentioned in section 3.1 and shown in figure 3.3, the microphone location in Linderudsletta 13 was chosen for the reference receiver point in the noise model. The balcony in Linderudsletta 9b and the veranda in Sletteløkka 33a, on the other hand, has been used as emission points in the noise prediction calculations. For convenience, we introduce three abbreviations for these three receivers: R1, R2, and R3, respectively. The reference receiver's height is 3.2 meters, while the balcony and veranda receiver's height is 3.3 m away from the ground, above the terrain. All three receivers are set to be 0.25 m away from the facade.

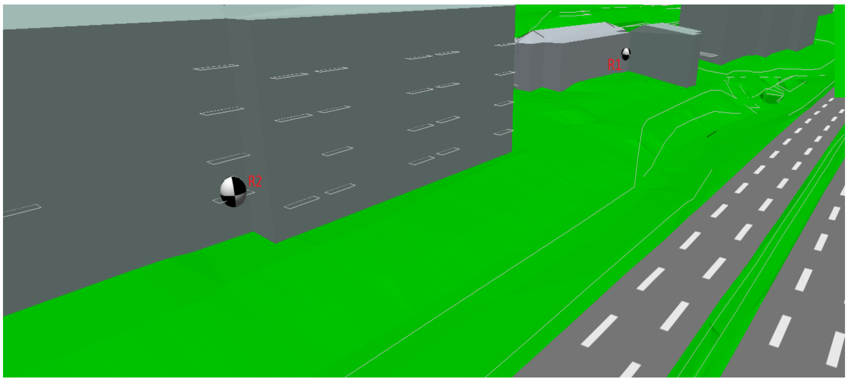

Figure 3.6: *A 3d screen shot from the simulation.*

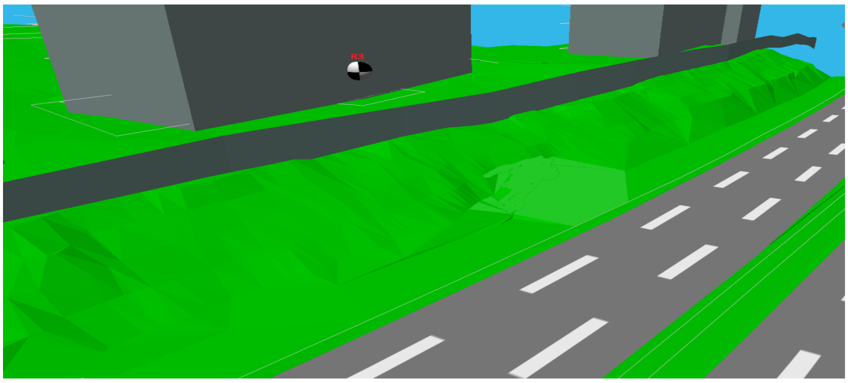

Figure 3.7: *3d screen shot of R3 from the simulation.*

3.2.3 Noise barrier modeling

The effect of noise screening has also been investigated in the modeling. The aim is to compare the effect with the existing barrier at Sletteløkka 33. The prediction is made for an absorbing barrier for two different heights, 4m and 6m, outside the balcony at Linderudsleta 9b.

The modeled barrier is 165 m above sea level. Figure 3.8 represents the area of interest, with the red line representing the barrier. The distance from the barrier to the road center line is 17 m.

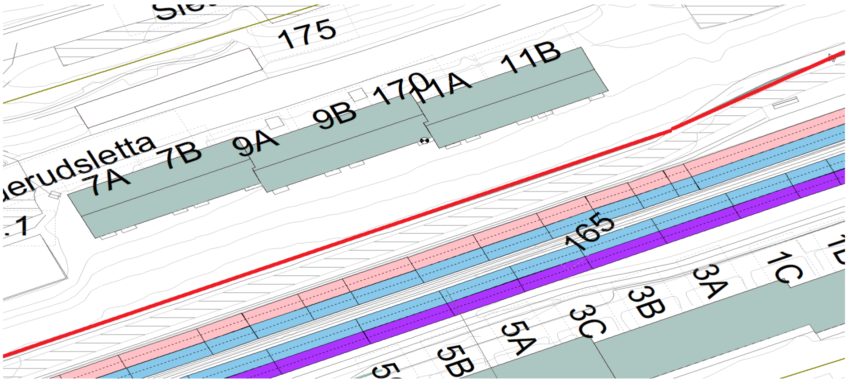

Figure 3.8: *A 2d screen shot from Cadna.*

Figure 3.7 represents a 3d view of the existing noise barrier in front of the receiving point R3. The existing barrier is 3m in height and approximately 22 m away from the road centerline. It is located on top of a hill, 170 m above sea level. However, the road is 165 m at sea level.

3.2.4 Modeling of the propagation path

At a receiver R, there will always be some losses. According to the CNOSSOS-EU, attenuation along each propagation path in the noise model depends on some crucial factors:

1. Distance between the source and receiver
2. Ground factor
3. Diffraction around corners, and on all objects vertically as well as horizontally oriented
4. Reflections

Note that the atmospheric attenuation can be neglected (see subsection 2.1.2 for the clarification). The noise calculation are made in homogeneous conditions since the propagation distances are relatively short. Moreover, the direct path between the source and receiver is considered an approximation of G=1. Reflections are considered of maximum order of 3. Projection of lines sources impacts the calculated partition.

3.3 Comparison between model and measurements

The aim of comparison between the measured and modeled L_{den} octave band spectra is to ensure the accuracy of the model. To make the comparison, we first need to establish a reference model. Finally, we use the reference model to calculate and predict L_{den} noise levels and associated indoor levels at the emission point.

3.3.1 Reference model

The reference model consists of road Rv4 as the source and three receivers, R1, R2, and R3 (see subsection 3.2.2). In the prediction, we have been using R2 and R3 as emission points because we are interested in indoor noise levels in those two apartments. A sketch of the methodological approach opted in this study is presented in figure 3.7.

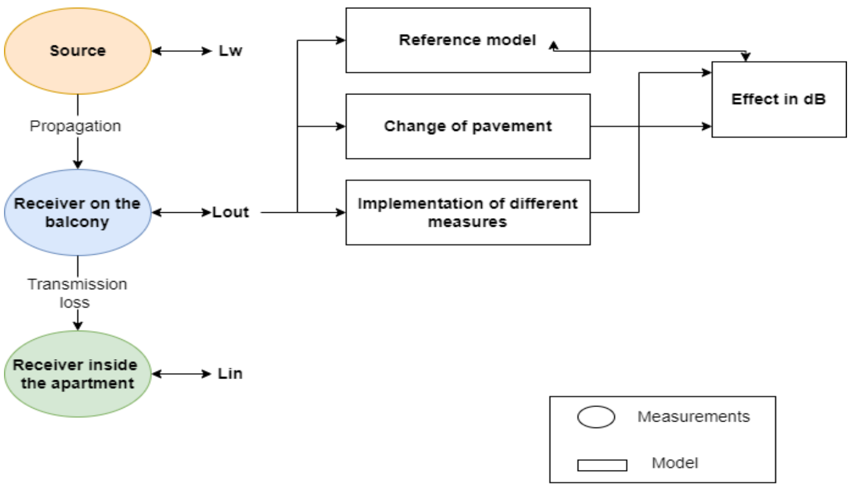

Figure 3.9: *Figure depicts the relationship between the measurements and the model, with ellipsoids representing the measurements and rectangles representing the model.*

Following the establishment of the reference model, two source-based noise measures have been investigated:

1. Change of pavement
2. Traffic management measures

Finally, the effect of these measures has been compared with the reference model by comparing L_{den} octave band spectra.

3.3.2 Selection of road surfaces

In our noise model, the highway Rv4 is the source. The current pavement configuration is required to be determined in order to create a noise model. Table 3.3 is the most accurate representation of the current situation. According to the CNOSSOS-EU, the reference surface is the stone mastic asphalt (SMA_11), i.e., CNS_1. The surfacing in lane 4 dates from May 2021, meaning it has not been exposed to winter conditions by November 2021. Therefore, we set CNS_1 as a road surface for lane 4. Lanes 2&3 are somewhat older. Due to that, we had to test a few pavements to find one approximately 1-2 dB higher than CNS_1. It was found that the German mastic stone, i.e., DEU_SMA8_11, fits this discrepancy in decibels. Lanes 1 equivalent to AC_16 is FIN_01, a combination of SMA and DAC with 16mm aggregate. After establishing the pavement surfacing, alternative road surfaces were tested to examine the pavement change potential concerning noise levels. See table 3.4 for the alternatives.

Table 3.3: *Current road configuration*

	Type of road surface	Equivalent in CadnaA
Lane 1	AC 16	FIN01
Lane 2	SMA 11	DEU/SMA8_11
Lane 3	SMA 11	DEU/SMA8_11
Lane 4	SMA 11	CNS_01

Table 3.4: *Tested alternative road surfaces*

	Type of road surface	Equivalent in CadnaA
Alternative 1	porous	AT_\OPA
Alternative 2	stone mastic CNS_\06	SMA_\NL8_11
Alternative 3	low noisy porous	FRA_\R1P
Alternative 4	low noisy non porous	FRA_\R1N
Alternative 5	asphalt concrete	DEU_\AC11_\30_\60

3.3.3 Implementation of different measures at the source

Aside from the potential for pavement changes and noise screening effect, a reduction in traffic volume and vehicle speed has been investigated. In that regard, three scenarios have been investigated by changing the input parameters at the source in the reference model:

- **Scenario 1.** Reduction in vehicle speed for all vehicle categories from 60 km/h to 50km/h.
- **Scenario 2.** Reduction in traffic volume by 50%
- **Scenario 3.** Combination of both

3.3.4 Estimation of indoor noise level

Noise exposure prediction models yield free field outdoor noise levels, neglecting transmission loss of building elements. Thus, transmission loss measurements have been conducted to determine indoor noise levels. Finally, indoor levels have been calculated by subtracting measured transmission loss values from predicted outdoor levels.

3.4 Equipment

Manufacturer	**Serial number**	**Model**	**Description**
Norsonic	1403721	Nor140	Sound level meter
Norsonic	-	Nor280	Power amplifier Accessories incl. : Main cable, output connector, wireless on/off remote control
Norsonic	-	Nor275	Hemi-dodecahedron loudspeaker
Norsonic	-	Nor1494	Loudspeaker cable
Norsonic	-	Nor1216	Measurement microphone
Norsonic	-	-	Microphone cables
Norsonic	-	Nor1256	Sound Calibrator
Manfrotto	-	-	Microphone stand

Table 3.5: Equipment list

Chapter 4

Results

4.1 Comparison between model and measurements

Figure 4.1 shows a comparison of octave band spectra for the modeled and measured L_{den}. The black curve represents the measured spectra, whereas the red curve represents the modeled spectra. The results indicate that the modeled noise spectra are underestimated compared to the measurements noise spectra, particulary at lower frequencies, at 63 Hz and 125 Hz.

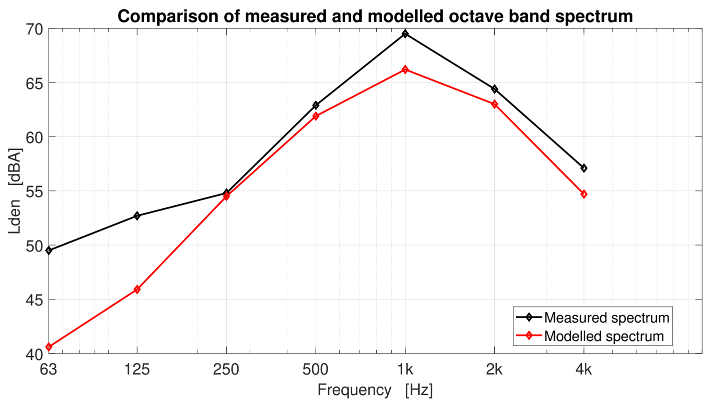

Figure 4.1: *Comparison between modeled and measured A-weighted octave band spectra.*

Figure 4.2 depicts the level difference between the measured and modeled A-weighted octave band spectra. At the lowest considered frequency, at 63 Hz, there is a significant level difference of 9 dB, while at 125 Hz, the difference is approximately 7 dB. The deviation is close to 0 at 250 Hz. Moreover, a slight increase in the levels difference can be observed at 500 Hz, 2 kHz, and at 4 kHz, where the difference varies between 1 - 2.4 dB. At 1 kHz, the deviation is 3.3 dB.

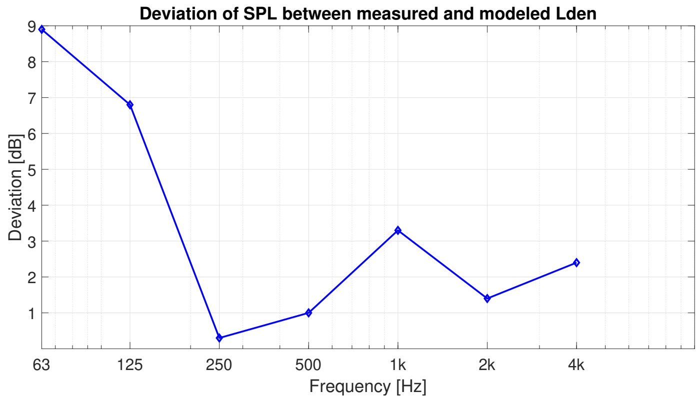

Figure 4.2: *SPL difference between measured and modeled L_{den}.*

4.2 Noise model results

The noise model has been developed to calculate noise levels outside the facade for several scenarios. The aim is to investigate how different measures at the source affect indoor noise levels. In that regard, the following section provides noise model predicted results.

4.2.1 Immission point spectra influenced by different road surfaces

Figure 4.3 shows octave band spectra for several tested pavements at the receiving point R2, the balcony in Linderudsletta 9b. The test pavements are taken from the CNOSSOS-EU library. The red straight line represents the current pavement situation (see table 3.3 for the current road configuration). The interrupted red line represents the effect of porous pavement. The black dotted line represents the spectrum of typical Dutch stone mastic asphalt. Furthermore, the black straight line depicts the spectrum of French low noise nonporous pavement, whereas the black interrupted line depicts the spectrum of French low noise porous pavement.

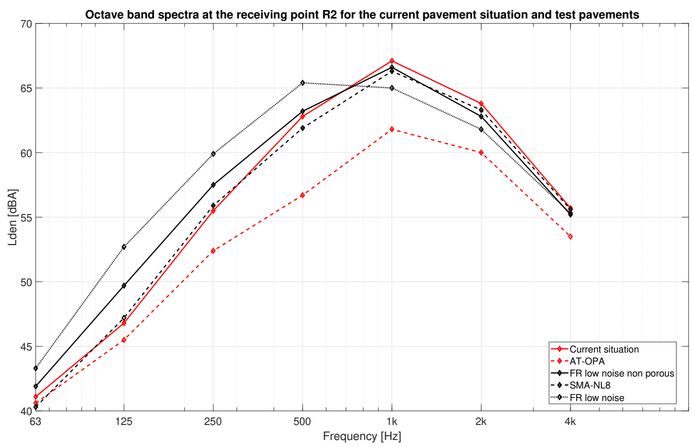

Figure 4.3: *Predicted A-weighted octave band spectra at receiving point R2 influenced by different road surfaces.*

Figure 4.4 represents the effect of pavement change as a level difference between the current road configuration and alternatives.

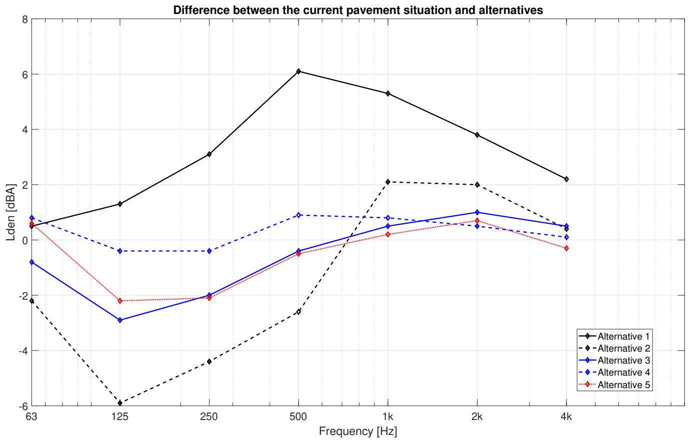

Figure 4.4: *SPL difference between the reference pavement and alternatives. Alternative 1. Compares the reference pavement with AT-OPA; Alternative 2. Compares the reference pavement with FR-R1R; Alternative 3. Compares the reference pavement with FR-R1N; Alternative 4. Compares the reference pavement with SMA-NL8; Alternative 5. Compares the reference pavement with DEU-OPA11;*

Alternative 1 in Figure 4.4 provides a significant noise reduction of 6 dB(A) at 500 Hz and 1 kHz. Alternative 2 has a negative impact on low frequencies, with a 6 dB increase at 125 Hz and a 2 dB decrease at 1 kHz. Alternatives 3 and 5 do not appear to contribute to noise reduction. Alternative 4 exhibits roughly the same effect as the reference pavement.

4.2.2 Implementation of different measures at the source

To compare the current noise situation at two different locations in the area of interest, we have calculated L_{den} in octave bands at the receiving points R2 and R3. The results are depicted in figure 4.7. It can be observed that the existing barrier impacts noise levels at the receiving point, R3 (the red curve).

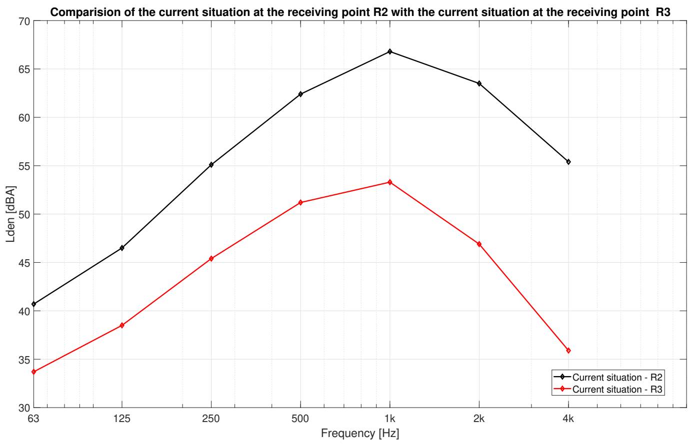

Figure 4.5: *Predicted A-weighted octave band spectra at the receiving points R2 and R3.*

We modeled noise barriers outside of the receiving point R2 to investigate the effect of noise screening at that receiving point, and the results are shown in figure 4.6.

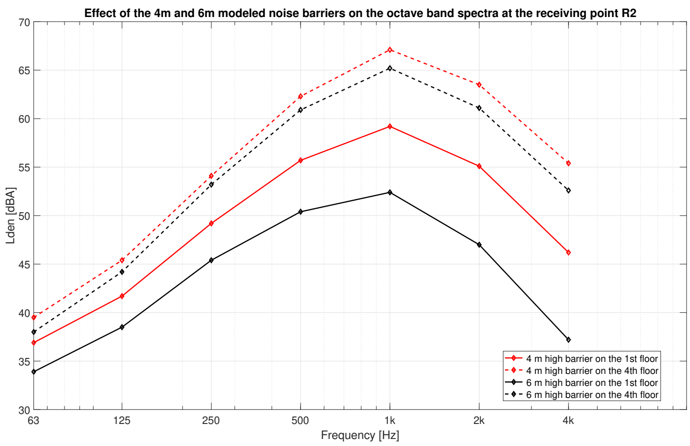

Figure 4.6: *Predicted A-weighted octave band spectra for two different noise barrier heights at the receiving point R2, on the 1st and 4th floor in Linderudsletta 9b.*

Figure 4.7 compares the effect of the existing noise barrier of 3m height at the receiving point

R3 with the effect of the modeled noise barrier of 4m height at the receiving point R2 on the octave band spectra.

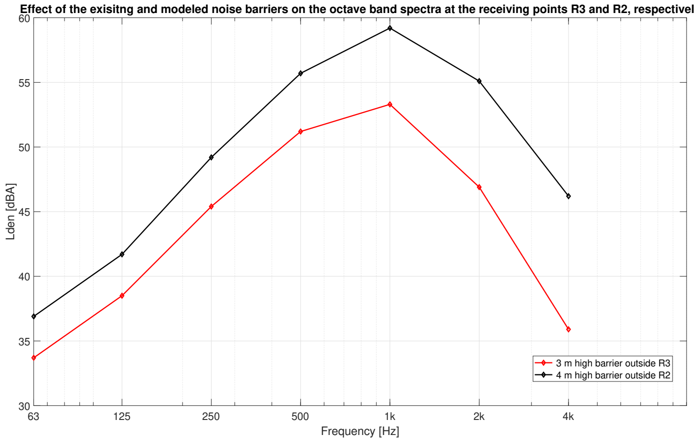

Figure 4.7: *Comparison of different noise barrier heights effect on the receiver spectra relative to the specific topography.*

Figure 4.8 and figure 4.9 depict predicted results regarding the traffic volume and vehicle speed reduction as a possible noise measure at the source. See subsection 3.3.3 for the description of the proposed scenarios.

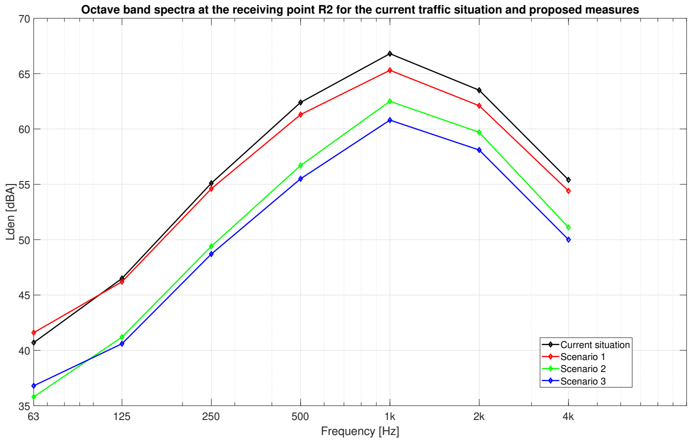

Figure 4.8: *Comparison of A-weighted octave band spectra for the current traffic situation and purposed measures at the receiving point R2.*

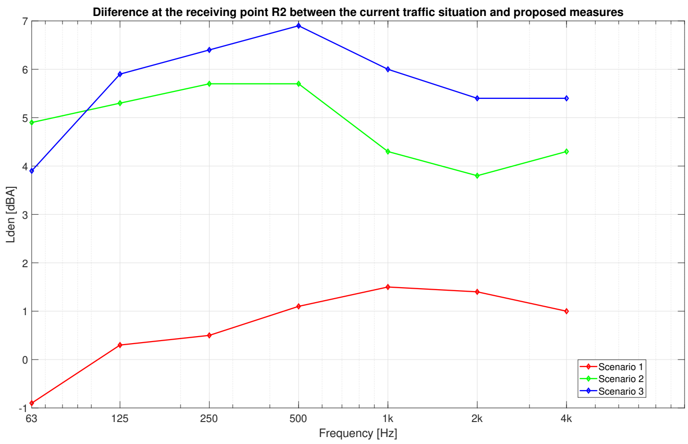

Figure 4.9: *SPL difference between the current traffic situation and purposed measures at the receiving point R2.*

It can be seen on figure 4.9 that the blue curve gives the best result as the difference in noise levels between the current situation and scenario 3 is the largest.

4.2.3 Indoor noise levels

Table 4.1 displays an overview of the estimated global L_{den} and L_{Aeq} at Linderudsletta 9b. The calculations consider the current noise situation as well as the investigated traffic measures, the three scenarios. We do not consider the estimation of indoor levels in the apartment on the ground floor at Sletteløkka 33a. The effect of the existing barrier has been proven to attenuate the emission noise indoors such that noise levels are within the limit.

Table 4.1: Estimation of the global noise indicators L_{den} and L_{Aeq}. See table 2.1 for the noise limits in Norway.

Description of measure	**Current situation**	**Scenario 1**	**Scenario 2**	**Scenario 3**
L_{den} inside the living areas	35	33,5	30,3	28,8
L_{den}$ in front of the façade	70	68,5	65,3	63,8
L_{Aeq} in front of the façade	66,4	65	62,1	60,6

Estimated L_{den} indoor octave band spectra are shown in figure 4.10.

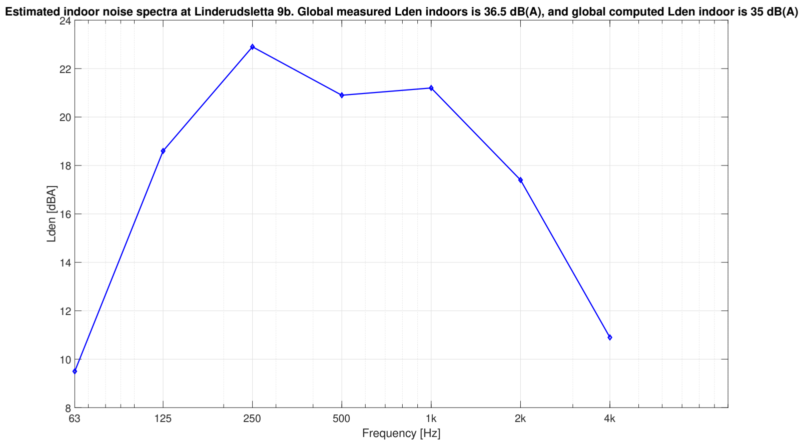

Figure 4.10: *Predicted Lden indoor octave band spectra in Linderudsletta 9b. Estimated global* L_{den} *indoor is 35 dB(A) which is 5 dB above the recommendation [11].*

4.3 Measurement results in 1/3 octave band spectra

Figure 4.11 shows results of measured traffic noise in 1/3 octave band spectra and A-weighted.

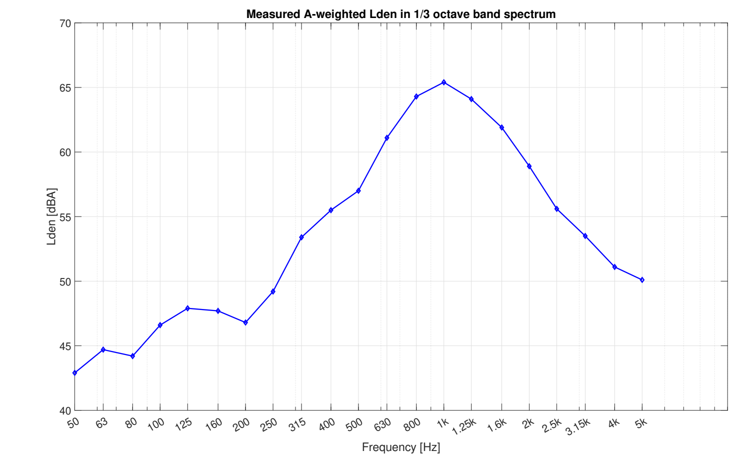

Figure 4.11: A-weighted measured Lden

Chapter 5

Discussion

5.1 Comparison between measurements and model

The model in figure 4.1 is mostly accurate above 200 Hz, but it is underestimated at lower frequencies. The deviation plot (see Figure 4.2) shows a significant difference between the measurements and the model at 63 Hz and 125 Hz. The reason for this might be interpreted in several ways. Firstly, the CNOSSOS-EU does not account for the background noise. Secondly, this difference may be due to a comb filter effect at low frequencies, which results in + 6dB at the microphone location. However, at 63 Hz, the SPL is +9 dB, indicating an increase in intensity by double. This extra energy may originate from the exhaust and ventilation system, see figure 3.5 for the visual description. Moreover, the façade acts as a perfect reflector at 250 Hz. At the receiving point, direct and reflected waves are out of phase, yielding destructive interference where signals cancel each other. As a result, a minimum level difference of 0.3 dB at 250 Hz is found. A deviation of 1-3 dB is observed above 250 Hz, corresponding to a CNOSSOS uncertainty of ±2dB(A).

5.2 Noise model results

Section 4.2 presents the noise model predicted results. The analyses has been done in octave band spectra in the frequency range from 63 Hz to 4kHz, because the estimation of indoor noise spectra uses the transmission loss measurement data (The frequency range of interest in building acoustics is 50 Hz - 5 kHz.). In the model, the receivers are the same distance from the façade as the actual microphone in the field. Thus, the analyses do not take into account the reflections.

5.2.1 Immission point spectra influenced by different road surfaces

First, the impact of pavement changes on noise level spectra at the receiver was investigated, and the results can be seen in section 4.1.2., in figures 4.3 and 4.4. The Austrian porous pavement type gives an initial noise reduction of approximately 6 dB(A). According to the Sintef long-term study [1], a decreased noise reduction is expected after the first winter due to Norwegian weather. Because porous pavement has larger voids (up to 20%), the effect of clogging and a higher degree of pavement wear are present. As a result, the use of porous pavement on Norwegian roads is inefficient in terms of both cost and maintenance. However, not all low-noise pavements seem to provide a significant noise reduction. It has been found that the French low-noise porous type of pavement is not effective as the Austrian; at 500 Hz, a difference between these two types is approximately 8 dB in favor of the Austrian porous pavement (see figure 4.4). Finally, the results from section 4.2.1 indicate that the effect on noise generation of the reference pavement configuration is similar to the Dutch stone mastic asphalt.

5.2.2 Implementation of different measures at the source

Section 4.2.2. provides the results of the noise screening effect and the reduction in traffic volume and vehicle speed. The plot in figure 4.5 shows that noise levels are lower at receiver R3 than at receiver R2. The increased attenuation is likely due to the existing noise barrier outside R3. Furthermore, the barrier is located on a hill, acting as a porous natural barrier (see figure 3.7 for a visual description). The hill is approximately 5 m high, resulting in a total obstacle height of 8 m.

Further, the noise screening effect on the 1st and top, 4th floor in Linderudlsletta 9b has been tested. The prediction results are presented in figures 4.6 and 4.7. The modeled barrier of both heights attenuates traffic noise only on the first floor; however, attenuation does not appear on the top floor. Figure 4.7 shows that a 4m high barrier does not attenuate enough at 1 kHz, where the predicted result exceeds the norm (see table 2.1 for the limitations). On the other hand, a 6 m high barrier is merely experimentation. It is often not realistic for reasons such as high cost and view-blocking. The area between the building and the road is relatively narrow; therefore, installing such a high vertical obstacle is not an option.

Finally, the reduction in traffic volume and vehicle speed has been studied. The results show that scenario 3 is the best solution among the three scenarios in terms of the impact of emission noise on the receiver R2 (see figures 4.8 and 4.9). At 1kHz, the difference in noise level between the current situation and scenario 3 is significant 6 dB. Besides, table 4.1 shows the global estimated L_{den} and L_{Aeq}. It is found that the reduction in all vehicle categories by 50% in combination with the suggested speed limit of 50 km/h attenuates the traffic noise inside the apartment in Linderudsletta 9b for 5-6 dB.

5.3 Measured A-weighted L_{den} in 1/3 octave band spectra

The curve on the plot in figure 4.11 is a typical road traffic noise spectra. Due to the A-filtering, the low frequencies are significantly attenuated, resulting in low values in the range from 50 Hz to 250 Hz, as shown in figure 4.11. Further, a prominent peak at 1 kHz can be observed. According to the literature, the propulsion noise is associated with higher values at low frequencies, with a maximum of 50 – 100 Hz. On the other hand, rolling noise is associated with peaks around 1 kHz.

According to Beckenbauer [18], the noise produced by motorized vehicles depends on driving speed, and it differs for propulsion and rolling noise. As a rule of thumb, the noise generated by the interaction between the tires and the road (the rolling type of noise) becomes more significant as the speed increases. The rolling noise of light vehicles dominates the propulsion noise for speeds above 50 km/h, while for speeds under 50 km/h, the propulsion noise is dominated. In the case of heavy-duty vehicles, the propulsion noise dominates the rolling noise for speeds less than 75 km/h and even more so for speeds less than 50 km/h. Overall, we can conclude that the propulsion and rolling noise contribute to the total sound power levels.

5.4 Recommendations

A significant percentage of heavy-duty vehicles is present on the highway Rv4, resulting in higher global $Lden$ due to the penalty during the night hours (see Appendix for the traffic data). By limiting heavy traffic, the noise situation may improve. Besides, the reduction in the number of light vehicles is equally significant. To address challenges in approaching the act of traffic management, we propose the following:

- To divert the heavy traffic from Rv4 to another road.
- To increase the travel cost on sections of the highway Rv4 where noise is the issue.
- To ameliorate legalization in terms of the speed limit and low-noise tires.

5.5 Future work

As discussed earlier, the main sources of road noise are engine (propulsion) noise and rolling noise. However, the rolling noise is currently the most dominant noise component of road traffic noise. The pavements characteristics (surface roughness, porosity and elasticity) are of a great interest in dampening the rolling noise as they define acoustical properties of a road surface. Therefore, a further research shall focus on investigating another surface treatments and their acoustical benefits.

Another subject of interest would be to investigate different constructs and shapes of noise barriers, including partial and complete covering.

Chapter 6

Conclusion

Measurements and prediction calculations using CNOSSOS-EU have been performed to assess the degree of road traffic noise in Sletteløkka, Oslo. The calculations were done in CadnaA software in octave bands in the frequency range from 63 Hz to 4kHz. After comparing the measurement spectrum with the modeled spectrum, a deviation of ±2dB(A) was found for frequencies above 200 Hz, indicating high accuracy of the model. The model was further used to predict noise levels on the balcony in front of the facade and indoors in Linderudsletta 9b. Simulations were generated to illustrate the current noise situation and the best calculated measure. Outdoors, estimated global L_{den} was found to be 35 dB(A), and measured global L_{den} was found to be 71,5 dB(A), which is approximately 15 dB above the recommendations. Indoors, estimated global L_{den} was found to be 35 dB(A), and measured global L_{den} was found to be 36,5 dB(A), being approximately 5 dB above the national limit. Therefore, this study aimed to investigate standard source-based noise measures to reduce these high noise levels, such as a potential for pavement change, a noise screening effect, and traffic management measures. It was found that the reduction in traffic volume by 50% and the speed limit of 50 km/h gives a significant indoor noise level reduction of approximately 6 dB.

Five test road surfaces were selected from the CNOSSOS library to investigate the possibility of reducing noise levels indoors by changing the pavement. It was found that stone mastic asphalt is the most suitable for Norwegian conditions with heavily loaded traffic. Conducting more acoustical measurements would benefit the project.

Bibliography

[1] T.Berge, F. Haukland, A. Ustad "Environmentally friendly pavements:Results from noise-measurements 2005-2008", Sintef ICT Acoustics, February 2009

[2] T.Berge, P.Mioduszewski, J.Ejsmont, B.Świeczko-Żurek, "Reductionof road traffic noise by source measure - present and future strategies", Institute of Noise Control Engineering, 2017

[3] U. Sandberg, J.A. Ejsmont, "Tyre/Road Noise Reference Book", Informex, SE-59040 Kisa, Sweden, 2002

[4] World Health Organization and Regionalbüro für Europa, "Environmental noise guidelines for the European Region", 2018, Available at: http://www.euro.who.int/en/publications/abstracts/environmental-noise-guidelines-for-the-european-region-2018

[5] European Environment Agency, "Environmental noise in Europe", 2020, Available at: https://www.eea.europa.eu/publications/environmental-noise-in-europe

[6] European Environment Agency, "TEC 110 2010 Good practice guide on noise exposure and potential health effects", Available at: https://www.eea.europa.eu/publications/good-practice-guide-on-noise

[7] 'Environmental Noise Directive 2002/49 EC.' Available at: https://ec.europa.eu/environment/noise/directive_en.htm

[8] CNOSSOS-EU "Common Noise Assessment methods for road, railway, aircraft, and industrial noise", Official Journal of The European Union, 2015

[9] SETRA "French road noise prediction - Noise propagation computation method including meteorological effects (NMPB 2008)", june 2009

[10] Retningslinje for behandling av støy i arealplanlegging (T-1442/2021)

[11] Norwegian Standard NS 8175, "Lydforhold i bygninger - Lydklasser for ulike bygningstyper", (Acoustic conditions in buildings — Sound classification of various types of buildings)

[12] Nordtest Method for Road Traffic: Measurement of Noise Emission - Survey Method, NT ACOU 056

[13] Norwegian Standard NS ISO 1996-2:2017, “Acoustics - Description, measurements and assessment of environmental noise. Part 2”

[14] T. F. W. Embleton, ‘Tutorial on sound propagation outdoors,’ The Journal of the Acoustical Society of America, vol. 100, no. 1, 1996. Available: https://doi.org/10.1121/1.415879.

[15] C. Hopkins, “Sound insulation”, Elsevier Ltd., First edition 2007, Oxford, UK

[16] Gerhard Muller and Michael Moser. Handbook of Engineering Acoustics. Springer, 2013.

[17] Murphy Enda, King Eion “Environmental Noise Pollution: Noise Mapping, Public Health, and Policy” ISBN: 978-0-12-411614-6

[18] Beckenbauer, Thomas, “Chapter 15: Road Traffic Noise”, 2013

[19] Brekke & Strand AkustikK AS, report AKU - 01

[20] S. Olafsen, D. Bard, M. K. Strand, and T. F. Espejo, “Methods of field measurements of facade sound insulation”, Noise Control Engineering Journal, Sep. 2015, doi: 10.3397/1/376342.

[21] S. Olafsen,“ Sound insulation against traffic noise in wooden houses ”, Baltic-Nordic Acoustical Meeting, 2002

[22] W. Kropp and J. Bérillon, ‘A theoretical model to investigate the acoustic performance of building facades in the low and middle frequency range’, Acta Acustica united with Acustica, vol. 84, no. 4, pp. 681–688, 1998.

[23] Bernhard R., Wayson R., “ An Introduction to Tire/Pavement Noise of Asphalt Pavement ”, Available at: https://www.vaasphalt.org/wp-content/uploads/2012/07/anintroductiontotire-pavementnoiseofasphaltpavement.pdf

[24] Bruel & Kjær, “Environemntal Noise”

Chapter 7

Appendix

7.1 Traffic data

Table 7.1: Hourly traffic input data used in the thesis

Lane	Day	Evening	Night
1	266	142	23
2	290	220	56
3	832	605	123
4	1445	504	259

Table 7.2: Percentage of vehicles from category 2+3 on left. Percentage of vehicles from category 3 in 2+3 on right

Lane	Day	Evening	Night
1	13,7	10,1	14,5
2	11,6	3,2	7,7
3	38,6	25,0	48,4
4	18,7	21,8	30,4

Lane	Day	Evening	Night
1	19,3	15,6	21,1
2	18,0	8,0	33,3
3	35,7	55,3	57,8
4	37,7	50,7	53,0

7.2 Noise simulation results - noise maps

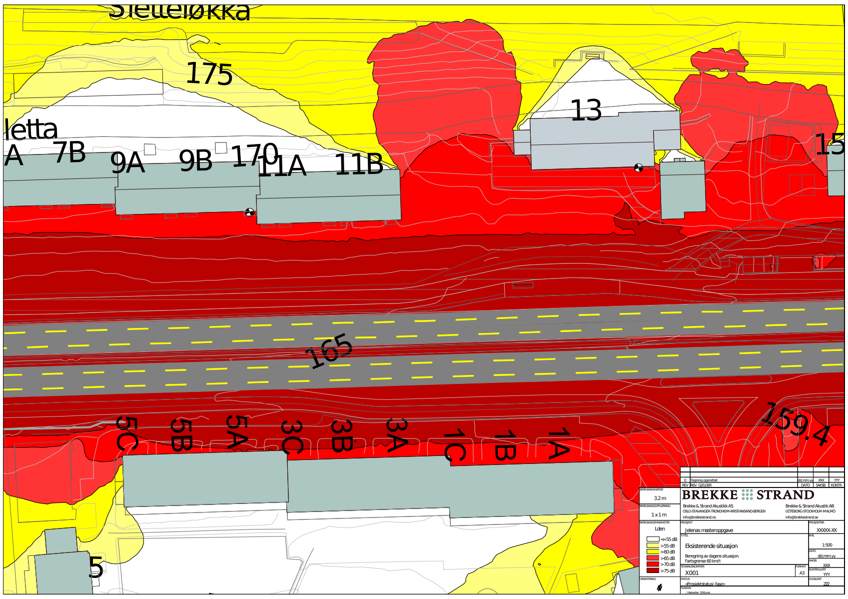

Figure 7.1: Noise map presents a current noise situation in front of the facade at Linderudlsetta 9b, Oslo

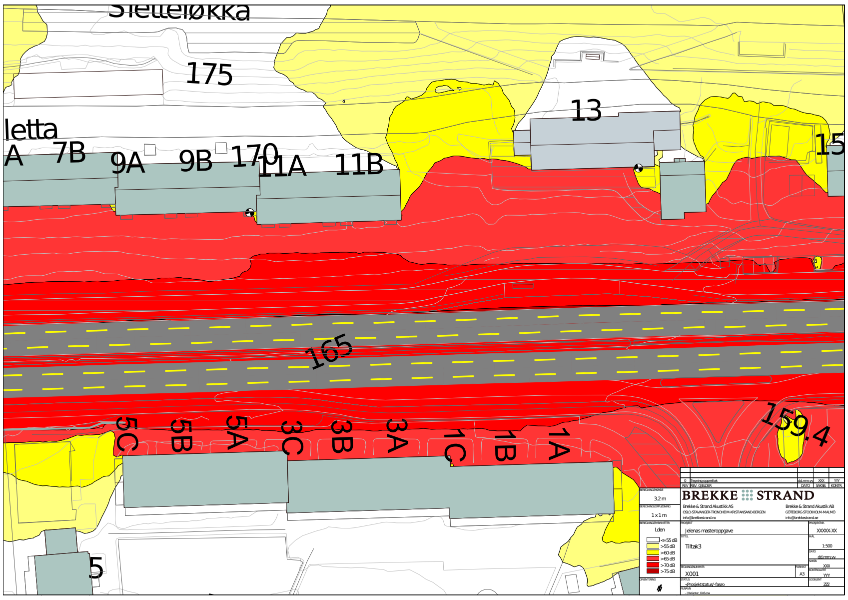

Figure 7.2: Noise map presents the best calculated measure in front of the façade at Linderudlsetta 9b, Oslo

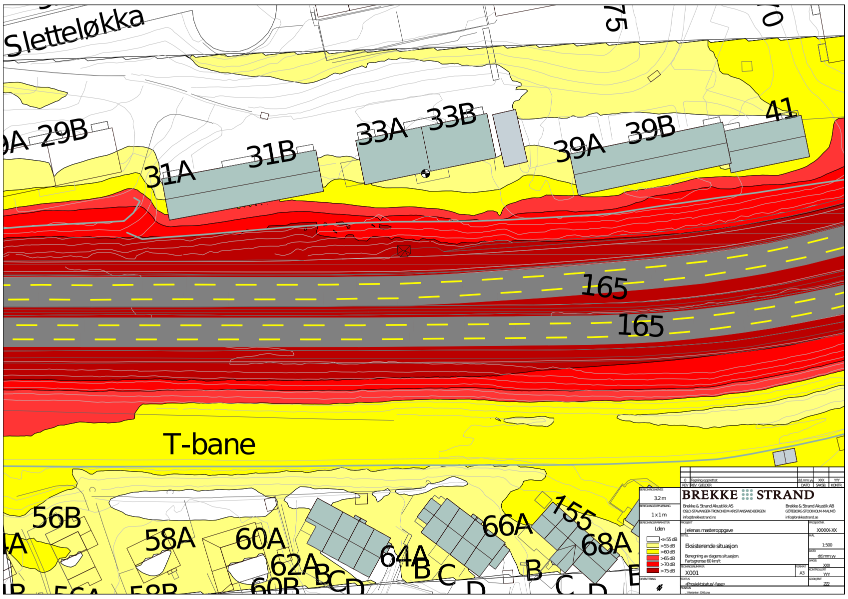

Figure 7.3: Noise map presents a current noise situation in front of the façade at Sletteløkka 33a, Oslo

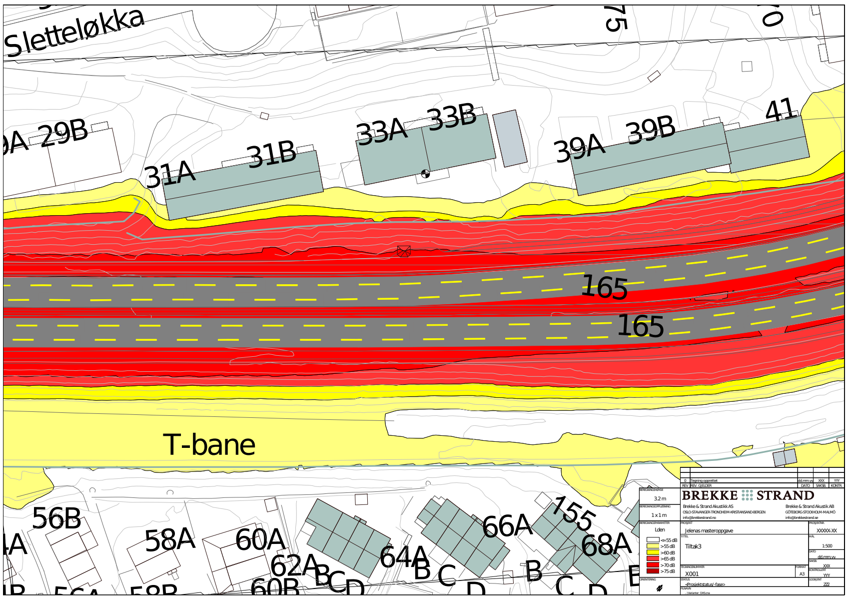

Figure 7.4: Noise map presents the best calculated measure in front of the facade at Sletteløkka 33a, Sletteløkka, Oslo