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IN APPLIED ACOUSTICS

The effect of sound absorbing surfaces for acoustic planning of road infrastructure

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Abstract

Traffic noise has a negative impact on concentration and learning, causes annoyance, sleep disturbance, impedes recuperation and relaxation and increases the risk of cardio-vascular disease, mental illness and premature deaths. Traffic noise is a particular urban problem; more than 20 % of the population in the EU are exposed to traffic noise levels which are harmful to health, with road traffic being the dominating source.

This thesis is focused on road traffic noise from large-scale infrastructure situated in urban areas. These environments, with multi-lane roads, bridges, ramps, supporting walls and noise barriers as well as adjacent building façades, form complex landscapes of thousands of square meters of sound reflecting surfaces.

In this PhD project it has been investigated whether it is necessary to adjust or complement the Nord2000 road noise prediction method to assess the noise levels in urban areas more accurately. Suggestions have been made for improving noise calculations and predictions of the noise-reducing effect of changes in the absorption indices of surfaces in infrastructure.

Absorption data to use in the calculations were obtained with the SOPRA method for measuring the sound reflection index of road noise barriers in-situ, i.e., in direct sound field. The data were subsequently used in the Nord2000 model to calculate the effect of applying absorbers on existing noise barriers in real sites. Both the placement and the type of absorber were investigated. The studies showed that: (1) Absorbers reduce the traffic noise levels. (2) The effect of absorbers is strongly site dependent. (3) Different types of absorbers result in different noise level reductions.

Furthermore, an evaluation of the Nord2000 results using the Boundary Element Method, BEM, indicates that Nord2000 may underestimate the effect of absorbers on noise barriers, especially for situations involving multiple reflections between the noise barrier and other vertical surfaces.

With the results of this project, the intention is to continue the work towards a methodology for acoustic planning of road infrastructure.

Keywords: Road traffic noise, urban infrastructure, Nord2000, noise barriers, sound absorption, sound reflection index, RI_Q , SOPRA measurement method, direct sound field, Direct Field Absorption model.

List of Publications

[**Paper A**] Monica Waaranperä, “Why noise control must be considered in the context of sustainable development”. *Proceedings Inter-Noise 2022*, Glasgow, U.K (2022).

[**Paper B**] Monica Waaranperä, Jens Forssén, Wolfgang Kropp, “Measurement of sound reflection using the SOPRA method”. *Proceedings Forum Acusticum 2023*, Turin, Italy (pages 4239-4246), DOI: 10.61782/fa.2023.0855 (2023).

[**Paper C**] Monica Waaranperä, Jens Forssén, “Time-domain model of spherical wave reflection in a flat surface with absorber character – application to the SOPRA measurement method”. *Applied Acoustics 2024*. DOI: 10.1016/j.apacoust.2024.110251 (2024).

[**Paper D**] Jens Forssén, Monica Waaranperä, “Modelling of spherical wave reflection in an absorbing flat surface considering its finite size - application to traffic noise barriers”. *Applied Acoustics 2025*. DOI: 10.1016/j.apacoust.2025.111115 (2025)

[**Paper E**] Monica Waaranperä, “Application of absorption data from SOPRA sound reflection index measurements in Nord2000 road noise calculations – results from a case study”. *Proceedings BNAM 2026, Gothenburg, Sweden* (2026).

Author contributions. The author contributed as author or co-author to Paper B, Paper C and Paper D, which were developed in close collaboration with Jens Forssén and Wolfgang Kropp. The author’s contribution to the papers was approximately 80%, 60% and 40%, respectively.

Publication not included in this thesis due to an overlap in content:

Monica Waaranperä, “Acoustic effect of sound absorbing materials and surfaces in road infrastructure”, *Licentiate thesis*, Chalmers University of Technology, Gothenburg, Sweden (2024).

Preface

This doctoral thesis is the result of research conducted the Division of Applied Acoustics, Department of Architecture and Civil Engineering at Chalmers University of Technology. The work was carried out as an Industrial PhD project financed by Trafikverket, the Swedish Transport Administration, (Project No 2020/26456).

First, I would like to thank the Swedish Transport Administration, for giving me the opportunity to conduct this research in a field that I have been professionally engaged for more than 30 years, transportation noise and traffic noise abatement. In this regard, I would especially like to thank my project supervisor Karin Blidberg (National traffic noise coordinator), the project managers of the Bygga research portfolio: Ylva Millde, Pia Nilsson and Kajsa Ström, and my boss Ingmarie Ahlberg at the Investment department.

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Till mina kära - Dan, Sakarias, Mira, Eikka och Victor - för att ni finns!

Göteborg, September 2026
Monica Waaranperä

Acronyms

AADT:	Annual average daily traffic
ABS 16:	Swedish name for DAC 16 (maximum stone size 16 mm)
BEM:	Boundary Element Method
DAC 16:	Dense Asphalt Concrete (maximum stone size 16 mm)
DL_{Aeq} :	Difference between A-weighted equivalent noise levels (dB)
EEA:	European Environment Agency
END:	The European Noise Directive (2002/49/EC)
EU:	European Union
L_{Aeq} :	A-weighted equivalent continuous noise levels (dB)
$L_{Aeq,24h}$:	24 hours A-weighted equivalent continuous noise levels (dB)
L_{DEN} :	Day-Evening-Night A-weighted equivalent continuous noise level with 5 dBA penalty for evening-time noise and 10 dBA penalty for night-time noise (dB)
RI :	Sound reflection index (dB)
RI_Q :	Quick sound reflection index (dB)
SMA 11:	Stone Mastic Asphalt (maximum stone size 11 mm)
TRV:	Trafikverket (the Swedish transport administration)
WHO:	The World Health Organization

Contents

List of Publications	iv
Preface	vi
Acronyms	viii
I Overview	1
1 Introduction	3
1.1 Traffic noise impact	3
1.2 Problem definition	4
1.3 Objectives and aim	6
1.4 Thesis outline	7
1.5 Limitations	8
2 The acoustic effect of surfaces in road infrastructure	9
2.1 Method	9
2.2 Inventory of road infrastructure materials	10
Surface materials	10
Noise barriers	11

2.3	Determination of sound reflective properties	12
	Sound reflection measurements of noise barriers and walls . . .	13
2.4	The Direct Field Absorption (DFA) model	18
3	Test cases	21
3.1	Method	22
3.2	Studied sites	22
	Sites 1 and 2	23
3.3	Measurements	25
	Measurement conditions and traffic volume	25
	Measurement results, Site 1	30
	Measurement results, Site 2	32
	Measurements, observations	33
3.4	Calculated sound levels	35
	Input data	36
	Calculation settings	40
	Calculation results, Site 1	41
	Calculation results, Site 2	42
3.5	Comparison between calculated and measured sound levels . .	44
	Comparison Site 1	44
	Comparison Site 2	48
	Standard weather conditions	53
	Observations, Sites 1 and 2	54
3.6	Site 3	56
	General description	56
	Measurements and calculations	58
3.7	Conclusions from the case studies	64
	Calculations vs. measurements	64
	Effect of wind and other weather conditions	65
3.8	Suggestions for noise calculations	66
3.9	Uncertainty	67
4	Acoustic effect of absorbers	69
4.1	Effect of absorber location	70
	Situations and receiver positions	70
	Input data and calculation settings	70
	Absorber application	71

Result, Site 1	72
Result, Site 2	73
Conclusion about absorber location	77
4.2 Effect of absorber type	78
Results	80
Conclusion about absorber type	83
4.3 Validation using the Boundary Element Method	84
Introduction	84
The Nord2000 road noise prediction method	84
The 2.5D BEM	85
Test situations	86
Frequency range	91
Results	92
Discussion about BEM for Nord2000 evaluation	97
5 Discussion	105
6 Summary of appended papers	109
7 Conclusion and Future Work	113
7.1 Conclusion	113
7.2 Future work	115
References	117
II Papers	121

Part I

Overview

CHAPTER 1

Introduction

1.1 Traffic noise impact

Transport noise pollution is one of the most widespread environmental health risks in Europe. The European Environment Agency, EEA, reported in 2025 [1] that more than 20% of the population within the EU countries, over 110 million people, are exposed to traffic noise levels which are harmful to health ($L_{DEN} > 55$ dB), for which road traffic is the primary cause (92 million people). It is a particular urban problem which is growing with the increasing urbanisation. In Sweden, more than two million people are exposed to traffic noise levels above the Swedish guidelines ($L_{Aeq,24h} > 55$ dB) outside of their dwellings [2]. The majority of them live in urban areas which are affected by noise from road traffic.

Traffic noise causes annoyance, sleep disturbance, increases the risk of mental illness, cardiovascular disease (hypertension, stroke, heart attacks) and diabetes. For Europe, it is estimated that chronic exposure to noise from transport contributes to more than 70 000 premature deaths every year [1], [3]. Moreover, the environmental noise affects concentration and learning negatively and children are especially vulnerable. Noise exposure is also a

matter of inequality. Socio-economically weaker groups in society are both more exposed and more vulnerable to environmental noise, with less influence, resources or means to change their situation [1], [4].

According to the EEA, transport noise pollution should be considered in economic terms, as it causes a large burden of disease. In the EU, the cost of disturbance, disease and impaired cognitive development in children were in 2025 estimated to more than 110 billion Euro every year [1]. Except for the burden on health care and social systems, noise exposure also leads to a loss of productivity of workers and cause a substantial depreciation of real-estate value [5]. Furthermore, traffic noise disturbs nature and wildlife, resulting in emigration, increased mortality, lower reproduction and reduced populations of species.

Thus, environmental noise has very well-established links to adverse economic, ecological and social impacts and noise mitigation is relevant to several of the United Nations 17 Sustainable Development Goals (SDGs) of the Agenda 2030 [6]. For traffic noise, the SDG No.3 - Good Health and Well-being, and No.11 - Sustainable Cities and Communities, are often considered the most relevant. However, as expressed in Paper A, taking noise control action could also be motivated by the 10th SDG - Reduced Inequality.

The Swedish Transport Administration, Trafikverket, has adopted the Agenda 2030 in the strategy for the national transport system, "Accessibility in a sustainable society - Target 2030" [7]. Trafikverket states that the transport system can contribute to 12 of the sustainable development goals of Agenda 2030. One of the goals for the long-term objectives and strategy of the Trafikverket Target 2030 is expressed as "No one is killed or seriously harmed in the transport system, neither in accidents nor by air pollution or noise".

1.2 Problem definition

This project is focused on large-scale road infrastructure and its significance for the traffic noise levels in urban surroundings. Such infrastructure may comprise multi-lane roads, bridges, ramps, supporting walls, noise barriers etc., forming complex landscapes of thousands of square meters of hard surfaces, see Figure 1.1. The noise that is emitted by traffic in these locations is reflected on all surfaces, increasing the total noise levels in the neighbouring

areas where hundreds of thousands of people live and work [2]. Typically for these areas, the noise is present day and night, all year round, affecting the lives indoors and outdoors. In Sweden, there are older neighbourhoods where the roads have grown into multi-lane motorways, as in Figure 1.2, and there are recent developments close to the largest traffic infrastructures, which have increased the number of inhabitants with high traffic noise levels outside of their apartments.

Correspondingly, the largest and most expensive infrastructure projects are often situated in urban areas. New constructions can change the acoustic conditions, but the noise calculation models, the input data and the evaluation methods may not be sufficient to accurately predict the changes in noise levels or the characteristics of the noise in the surroundings. This has led to complaints about noise disturbance and costly extra noise reducing measures after the projects formally have been closed. And when noise mitigation measures are planned, there is a risk that the optimal solutions are missed or not assessed correctly, which also can affect the socio-economic cost-benefits analyses of the measures.



Figure 1.1: Large-scale infrastructure cutting through a small-scale urban area.



Figure 1.2: Multi-lane road in older neighbourhood.

As a further matter, the connection between the equivalent noise levels (L_{DEN} and $L_{Aeq,24h}$) used in impact assessments of traffic noise and the level of annoyance can be questioned. A Danish study from 2016 [8], based on a questionnaire with approximately 7 000 respondents, showed that the proportion of residents reported being highly annoyed (HA) by traffic noise was **2–3** times higher in areas along motorways than in areas along urban streets, at the same L_{DEN} level. Apparently, there are more factors contributing to the traffic noise disturbance than can be described by the A-weighted equivalent sound levels.

1.3 Objectives and aim

Described above are the reasons for the PhD project, in which it is studied whether it would be effective to alter the hard surfaces in road infrastructure to reduce the sound reflections and thus decrease the noise levels from the traffic. This especially concerns locations where multiple sound reflections could be expected, which may not be sufficiently considered with the ordinary noise prediction method and standard calculation settings. In this work, it

is investigated whether it is necessary to adjust or complement the Nord2000 road noise prediction method [9], [10], to assess the noise situation more accurately (Chapter 3), and to be able to prove the effect of installing absorbers or changing the materials or surfaces in the constructions of the infrastructure (Chapter 4). A prerequisite for the latter is available absorption data to use in the calculations (Chapter 2).

This is an industrial PhD project, and the ambition is to use the results in the development of a methodology for acoustic planning of complex urban road infrastructure. The methodology is primarily intended for the Swedish Transport Administration (Trafikverket), e.g., for implementation into the noise abatement plans and road design instructions, but possibly also for other road authorities.

1.4 Thesis outline

This thesis is structured as follows:

- Chapter 1 introduces the motivation (also expressed in Paper A), problem definition, research objectives and aim.
- Chapter 2 comprises an inventory of surfaces in road infrastructure and in-situ sound reflection index RI_Q measurements of noise barriers and walls with the SOPRA method (described in Paper B). This includes development of a model for assessing the results of the measurements, the Direct Field Absorption (DFA) model, presented in Paper C. The DFA model can also be used to estimate the RI_Q below the low-frequency limit of a measured absorber surface, which was confirmed by comparison with calculations using the Boundary Element Method, BEM (in Paper D).
- Chapter 3 contains comparisons between calculated and measured sound levels in three test cases, with concluding suggestions for improving noise calculations and evaluations.
- Chapter 4 concerns acoustic effects of absorbers. It is examined if different absorber applications and absorption coefficients on noise barriers affect the calculated noise levels in urban settings (partly presented in

Paper E). Including validation of calculated results from Nord2000 with BEM.

- Discussion is presented in Chapter 5.
- Chapter 6 presents a summary of appended Papers A-E.
- Chapter 7 ends the thesis with conclusions, future work and suggestions for research topics.

Parts of Chapter 2 and Chapter 3 are based on material previously presented in the author's licentiate thesis [11], revised and expanded for the present dissertation.

1.5 Limitations

- Road surface treatments are not included in this study. It is already a major research field and considered out of scope of the current work.
- Railway noise and specific railway constructions are not considered, even though railway tracks and traffic may be present in urban infrastructure landscapes.
- The intrinsic sound insulation of installed noise barriers is not examined or measured.

CHAPTER 2

The acoustic effect of surfaces in road infrastructure

This chapter includes an inventory of materials and surfaces in road infrastructure, in-situ sound reflection measurements of noise barriers and walls, and development of a model for assessing the results of the reflection measurements.

2.1 Method

The planned approach for this study was to first map the common construction materials that form the surfaces of road infrastructure. Second was a search for existing data of the acoustic properties of those materials, i.e., their sound reflective or absorptive properties, information which was found to be generally lacking for construction materials and also for on-site constructed noise barriers, Section 2.2. Consequently, in-situ sound reflection measurements were necessary and thus performed to obtain absorption indices, Section 2.3 (subsequently applied in the calculations of the effect of absorbers in Chapter 4). To enable evaluation of the results from the sound reflection measurements in direct sound field, the Direct Field Absorption, DFA, model was developed and the possible usage of the DFA model for estimating the

reflection indices below the low frequency limits of the measurements was confirmed by Boundary Element Method (BEM) calculations, Section 2.4.

2.2 Inventory of road infrastructure materials

The inventory of road infrastructure materials is based on own experience as well as interviews with road planners and designers, bridge construction specialists and architects at the Swedish Transport Administration.

The mapping included common materials that are found in the infrastructure itself: bridges, pillars/columns, supporting walls, tunnel mouths, road restraint systems and noise barriers, see Figure 2.1, as well as adjacent areas like berms, slopes, embankments, rock cuts, etc. In addition, questions were asked about alternative or new materials or designs that could be possible to use instead in or on certain construction parts, especially with acoustic considerations. As previously mentioned, road surface was excluded from the inventory.



Figure 2.1: (a) Concrete and steel motorway bridges over a local street, (b) urban road canyon (motorway ramp, bus stop and bike lane), with supporting walls and noise barriers.

Surface materials

The inventory confirmed that concrete is the most common construction material in traffic environments in Sweden. In general, concrete is acoustically hard

and sound reflecting, even though there are concrete products with porous layers which can be sound absorbing.

Other surfaces comprise soil or vegetation on slopes and embankments, and rock cuttings, see Figure 2.2a. In noise calculation models, bare rock is considered acoustically fully reflecting, while surfaces with vegetation can be considered partly sound absorbing, depending on the assumed impedance class of the vegetation or ground [9]. In urban areas other materials can occur, mostly as claddings on concrete constructions or rock. Stone gabions (see Figure 2.2b), perforated brick and ceramic tiles are examples of materials that are used as claddings, assumed to be sound absorptive, or at least less sound reflective than, for instance, solid concrete. In any case, the resulting sound absorptive effect is rarely controlled after the construction and absorption data for this kind of infrastructure surfaces in direct sound field were thus not found in the inventory.



Figure 2.2: (a) Concrete and polycarbonate noise barriers on top of rock cutting, (b) claddings of stone gabions on rock cuttings and supporting walls.

Noise barriers

The dominating material in noise barriers in Sweden is wood or timber. Other common types of noise barriers are made of concrete, perforated metal sheet cassettes, steel mesh elements and transparent plastic or glass sheets (Figure 2.3).

Road traffic noise barriers fall under the GPR, the European General safety Product Regulation, meaning that any road noise barrier product sold within



Figure 2.3: (a) Concrete and metal sheet noise barrier, (b) transparent noise barrier.

the EU market must be assessed and CE-marked according to the Product standard EN 14388 [12]. For this purpose, there are standards to test both acoustic and non-acoustic characteristics. Acoustically, most noise barriers are tested according to the EN 1793 parts 1 [13] and 2 [14], concerning sound absorption and sound insulation in diffuse sound field, i.e., in laboratory. But lately, more manufacturers test their products in accordance with the standards EN 1793, parts 5 [15] and 6 [16], for sound reflection and sound insulation under direct sound field conditions, similar to the real situations along the roads, i.e., in-situ.

Many of the installed noise barriers are not manufactured industrially but so called “built on-site”. Those are seldom tested according to the acoustic test standards, nor are their intrinsic performances (sound absorption and insulation) verified after installation. Consequently, there is no acoustic information about them.

2.3 Determination of sound reflective properties

During the inventory of road infrastructure materials, it was found that if any acoustic data for construction materials existed, they had been acquired in laboratories under diffuse sound field conditions in accordance with building acoustics standards [17], and measurements of road noise barriers have shown that absorbers function differently in-situ, i.e. in direct sound field [18]. Thus,

it was necessary to perform in-situ measurements to obtain reflection data for direct sound field application. The European standard method to measure road noise barriers, the EN 1793-5[15], was under consideration when another option was presented, the SOPRA method [19], [20], [21], [22], a quicker and partly simplified version of the EN 1793-5, developed to allow faster in-situ measurements of sound reflection in road noise barriers (but not for product qualification).

However, the SOPRA method was not yet established and first it had to be studied, the equipment gathered and the signal processing prepared in accordance with the prescribed method that referred to EN 1793-5. Then, after test measurements indoors and outdoors, it was decided to use the SOPRA method for reflection measurements of both noise barriers and other infrastructure surfaces. The method, the preparatory work and set-up are described in Paper B. The subsequent measurements and results are summarised in the following chapter.

Sound reflection measurements of noise barriers and walls

The sound reflecting properties of five noise barriers, all but one installed along roads or railroads, and three types of walls on train platforms have been measured with the SOPRA method, see Figures 2.4 and 2.5. All objects were supposed to be sound absorbing, but their effects had not been confirmed after installation or construction. None of the noise barriers had been tested with the standard methods to measure the sound reflection under direct sound field conditions, the EN 1793-5 (for road noise barriers) or EN 16272-5 (for rail noise barriers) [23], but one of them had been measured in laboratory with the diffuse field method EN 1793-2. There is no standardised method to measure sound reflection in other kinds of infrastructure surfaces in direct sound field.

Three of the noise barriers were measured on the backside (with the same absorber surface as on the roadside) since the roadsides were not accessible due to heavy traffic and narrow road shoulders. However, the risk of transmitted traffic noise from the roadside must be considered when measuring on the backside. In one of the backside measurements the traffic could be heard through the noise barrier, probably due to poor sealing between the acoustic panels of the barrier (this was also evident in the rather inconsistent results of the measurements of different barrier sections). Though, when the mea-

surements are performed as intended, i.e., on the roadside, this should not be a problem as long as there are no other noise sources on the backside of the barrier.

The result of the SOPRA measurements is a calculated function of frequency in one-third octave bands called the quick sound reflection index, RI_Q , to distinguish it from RI , which is the reflection index obtained by performing the standard test method according to EN 1793-5. (Note that the quick method cannot be used for assessing or declaring the acoustic performance of a noise barrier product.) To achieve a valid measurement for the full frequency range of the method, i.e., 200–5 000 Hz, the absorbing noise barrier section has to be at least 5 m tall, according to [19]. In case of smaller dimensions (height or width), the low frequency limit f_{min} for the valid part of the measurement increases. The calculated RI_Q is based on the lowest reliable one-third octave band and the reduced frequency range must be specifically noted as $RI_{Q,(f_{min}-5000Hz)}$.

Overviews of the measured noise barriers and walls are presented in Figures 2.4 and 2.5 with the calculated single number ratings, DL_{RIQ} , which are summarising their performance when applied to a normalised road traffic spectrum [24]. The SOPRA measurement method and the definitions of the indicators RI_Q and DL_{RIQ} are described in Paper B.

2.3 Determination of sound reflective properties

	Object (Measurement date)	Type	Height (m)	Micro- phones	DL_{RIQ} (dB)	Comments
	Timber, wood wool panels. Non-roadside (2023-04-12 and 2023-08-16)	Timber with absorbing wood wool panels (mineral wool filling)	3.9	4 mics, m_2-m_5	DL_{RIQ} , 250- 5000 Hz 1.7 - 3.3	
	Steel mesh, large panels Non-roadside (2023-08-16)	Steel mesh with absorber	4.0	4 mics, m_2-m_5	DL_{RIQ} , 250- 5000 Hz 5.0	Mic 3 sound refl from border of acoustic panels?
	Steel mesh, small panels Non-roadside (2023-08-15 and 2023-10-16)	Steel mesh cassettes, with absorber	4.9	4 mics, m_2-m_5	DL_{RIQ} , 250- 5000 Hz 1.9 – 3.7	Transmitted noise from road traffic, due to bad sealing between the cassettes?
	Metal cassettes Between railroad road. Measured on roadside (2023-08-15)	Metal cassettes with absorber	3.5	4 mics, m_2-m_5	DL_{RIQ} , 250- 5000 Hz 6.0	Type measured in laboratory with the diffuse field method EN 1793-1, $DL_{\alpha} = 12$ dB

Figure 2.4: Overview of measured noise barriers. DL_{RIQ} = Single number rating of the Quick sound Reflection Index, for 200–5 000 Hz if barrier height > 5 m, for 250–5 000 Hz if barrier height is 3–5 m.

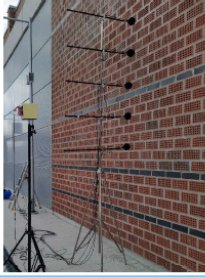
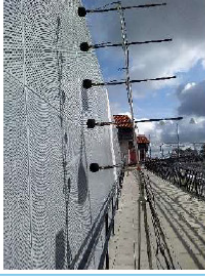
	Object (Measurement date)	Type	Height (m)	Micro- phones	DL_{RIQ} (dB)	Comments
	Porous concrete elements, steel posts Prototypes measured in factory yard (2025-08-20)	70 mm porous concrete with 30 mm solid concrete backing	4.14 over concrete slab	5 mics, m_2-m_8	DL_{RIQ} , 200-5000 Hz 5.6 DL_{RIQ} , 315-5000 Hz 5.9	NOTE: used only 4 mics, m_2-m_5 , in the calculation of RI_Q
	Perforated brick. Train station (2023-08-23)	Perforated brick wall with absorber	> 5.5	5 mics, m_2-m_8	DL_{RIQ} , 200-5000 Hz 1.3	Same absorber behind the surface as the perforated steel plate on same platform, with DL_{RIQ} , 200-5000 Hz 5.0 dB.
	Perforated steel, mineral wool. Train station (2023-08-23)	Perforated steel plate wall with absorber. Hole size 10 mm.	> 5.5	5 mics, m_2-m_8	DL_{RIQ} , 200-5000 Hz 5.0	Same absorber behind the surface as the perforated brick wall on same platform with DL_{RIQ} , 200-5000 Hz 1.3 dB
	Perforated steel with various hole sizes, LDPE absorber. Train station (2023-08-24)	Perforated steel plate with absorber. Hole sizes 5, 10 and 15 mm	3.5 +	5 mics, m_2-m_8	DL_{RIQ} , 250-5000 Hz 5.0	NOTE: used only 4 mics, m_2-m_5 , in the calculation of RI_Q

Figure 2.5: Overview of measured walls. DL_{RIQ} = Single number rating of the Quick sound Reflection Index, for 200–5 000 Hz if barrier height > 5 m, for 250–5 000 Hz if barrier height is 3–5 m.

An example of a resulting RI_Q spectrum of a frequently used type of noise barrier, comprised of cassettes of perforated metal sheets filled with an absorber, is presented in Figure 2.6 a in one-third octave band values. The calculated $DL_{RI_Q,(250-5000Hz)}$ is 6.0 dB, which is one of the best results of the measured noise barriers, but the single-number value is still half of the corresponding absorption value measured in laboratories, $DL\alpha$, for this type of noise barrier.

The in-situ measurements can also reveal weaknesses of an installed noise barrier, either due to the installation or the design. In the example in Figure 2.6 b, the RI_Q of one of the microphones was largely deviating from the others in frequencies above 800 Hz for all the measured sections of the noise barrier. Since the microphone functioned normally in the free-field measurements at the same site, the RI_Q of the microphone could have been affected by sound reflections from the relatively thick metal borders of the acoustic panels right in front of the microphone position or by poor sealing between the acoustic panels (i.e., the measurements were performed on the backside of the noise barrier).

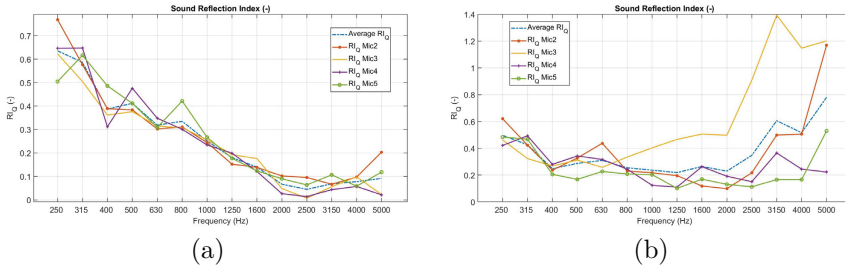


Figure 2.6: Examples of RI_Q spectra of (a) metal cassette noise barrier, $DL_{RI_Q,(250-5000Hz)}=6.0$ dB, (b) metal mesh noise barrier, $DL_{RI_Q,(250-5000Hz)}=5.0$ dB. In (b), note the anomaly of Mic3 (yellow line), which could be an effect of reflections or poor sealing between the acoustic panels.

For using the measured results of reflection measurements in calculations with the Nord2000 model, the RI_Q indices are converted into sound absorption coefficients, α , and inserted in the noise barrier library of the SoundPLAN calculation software [25].

2.4 The Direct Field Absorption (DFA) model

During the in-situ sound reflection measurements, questions arose concerning evaluation of the results, especially for on-site constructed noise barriers or other walls where benchmarks did not exist. To enable assessment, the Direct Field Absorption (DFA) model was developed and applied to the SOPRA measurement method (described in Paper C).

A SOPRA reflection measurement of an absorber results in impulse responses (IR:s), which are the bases for calculating the RI_Q of the absorber using the SOPRA formula (explained in Paper B). The DFA model also delivers impulse responses, though based theoretically on the derived impedance of the absorber. The DFA-IR:s can be entered to the SOPRA formula to calculate the DFA- RI_Q , which then is compared to RI_Q based on IR:s of SOPRA measurements of a wall fitted with the absorber in question, see Figure 2.7. If the results are comparable, one could assume that the SOPRA measurements were adequate. But if there are any significant differences between the DFA and the SOPRA sound reflection indices, the reasons for them, e.g., due to equipment, geometrical uncertainties or background noise, should be investigated.

Except for detecting SOPRA measurement anomalies, the DFA model may be useful for estimating the RI_Q below the low-frequency limit of the in-situ measurements, which depends on the size of the measured absorber surface. The DFA model calculates the reflection in an infinite area, implying that the comparison with the SOPRA- RI_Q only can be considered valid for the same frequency range as the measured absorber area. Thus, its applicability for calculating the reflection indices at low frequencies for finite sized surfaces, larger than the measured area, was tested by using BEM (see Paper D). The RI_Q s for a measured absorber surface and an enlarged absorber were calculated with a 3-D BEM model and compared with the DFA estimation below the low-frequency limit of the measurement. The BEM- RI_Q for the enlarged surface showed a good agreement with the DFA- RI_Q , illustrated in Figure 2.7, where the results for two absorber thicknesses are presented. This confirms the validity of using the DFA modelling at lower frequencies to predict the performance of larger surfaces than measured, at a substantially lower computational cost than using BEM.

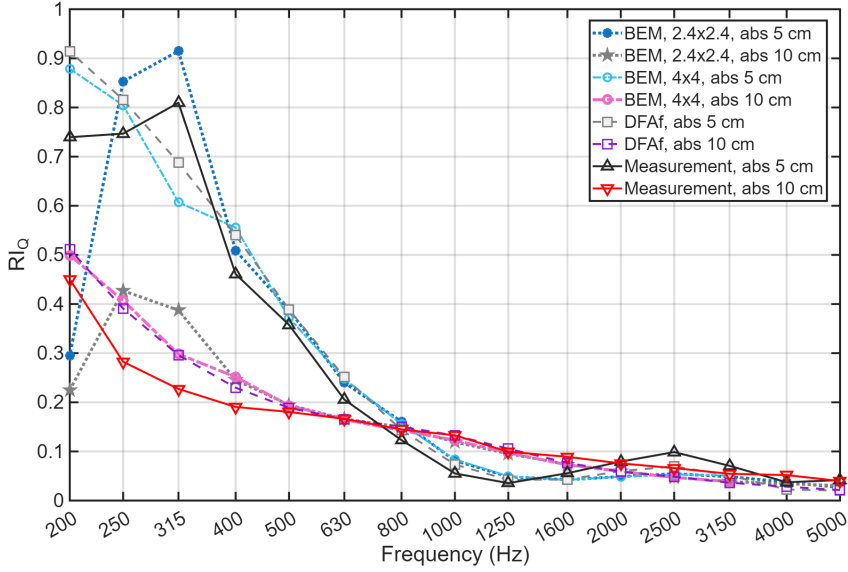


Figure 2.7: Reflection index for absorber thicknesses of 5 cm and 10 cm, from BEM, DFA model and SOPRA measurements (plotted for frequency range 200–5 000 Hz).

Note that the applicability of the DFA-model currently is limited to fibrous porous materials like mineral wool. Further modelling will be required to expand its usage for other types of absorbers, like low-density plastic foam or porous concrete.

CHAPTER 3

Test cases

In 2023, [11], two case studies were performed based on real sites, where the sound levels were measured and compared with calculations in order to examine if it was possible to reproduce the measured sound levels with calculations and which parameters or corrections that were necessary for aligning the calculated results to the measured ones. This led to both anticipated and unexpected results. At the first site, a narrow canyon-like yard between a noise barrier and a long building façade, differences were expected due to its geometry which was beneficial for the occurrence of multiple sound reflections. However, for most receiver positions it was possible to adjust the settings and data for the calculations to align the results with the measured values. But at the second site, with a simple geometry of an open and plain grass surface behind a noise barrier, the comparison between calculated and measured sound levels resulted in quite large differences and the corrections of the data and calculation settings did not improve this.

Now, the measurements and subsequent calculations have been repeated for both sites, mainly to investigate if the previous results and interpretations are robust or not. The underlying question is whether the road noise prediction model Nord2000 is calculating the sometimes not too complex situations

accurately, or if other methods should be recommended to evaluate and complement the calculations. In addition, a separate study of a third site has been conducted by a consultant company in a similar way as the first two, i.e., comparing the results of measurements and calculations.

The purpose of this study is to lower the risk of underestimation of the noise exposure in urban areas that are close to large and busy roads. All studied sites are behind existing noise barriers, but still with high noise levels. These sites are examples of places where people are exposed to quite overwhelming traffic noise levels, e.g. courtyards, local streets, bicycle and pedestrian lanes, parks and playgrounds.

3.1 Method

Sound level measurements are performed for three sites located near a motorway in urban or suburban areas close to major cities in Sweden, followed by traffic noise calculations for the same sites, with standard parameters and settings (Sites 1 and 2) and with parameters adjusted to the present situations during the measurements (all sites). The measured and the calculated noise levels are compared, for the first two sites also with previous measurements and calculations from 2023. Site 3 was only studied in 2025.

The studies focus on areas close to roads in order to avoid influence from other noise sources. Also, this is where the existing noise barriers have the largest sound reducing effect (i.e., the largest insertion loss, IL). Note that the purpose is to compare the results from calculations and measurements from very specific and brief periods of time, not to assess the yearly average traffic noise situation in these locations according to the standard noise mapping methods [10], [26].

The selection of sites for the case studies has been based on certain criteria such as stationary situation, e.g., not under construction, possibility to enter the site safely for the field studies and measurements, available geographical data, and recent traffic data.

3.2 Studied sites

The first two sites have been studied twice, in 2023 and in 2025. The calculations and analyses were performed by the author and the sound level mea-

surements by a consultant company. The same company has also conducted the separate study of the third site in 2025, including both calculations and sound level measurements. The information and results of Site 3 is based on their data and report, which is summarised in Chapter 3.6.

Sites 1 and 2

Sites 1 and 2 are located along the same six-lane motorway through a Swedish municipality. Site 1 is on the north side of the motorway, Site 2 on the south side, about 1 km from Site 1.

The first site is in a 12–15 m narrow yard between residential buildings and a 3.7 m tall noise barrier of concrete and transparent polycarbonate elements, see Figures 3.1 and 3.2. The second site is in a strip of vegetation between a local street and a 3.0–3.6 m tall noise barrier constructed of concrete and metal sheet panels, see Figure 3.3. The nearest buildings are located in a residential area with two-storey houses, 50 m from the noise barrier. At the opposite side of the motorway is a 5.4 m tall noise barrier of concrete and polycarbonate elements, installed between the motorway and an area of larger commercial and residential buildings. Sketches of Sites 1 and 2 are presented in Figure 3.4.



Figure 3.1: Site 1 seen from the opposite side of the six-lane motorway.

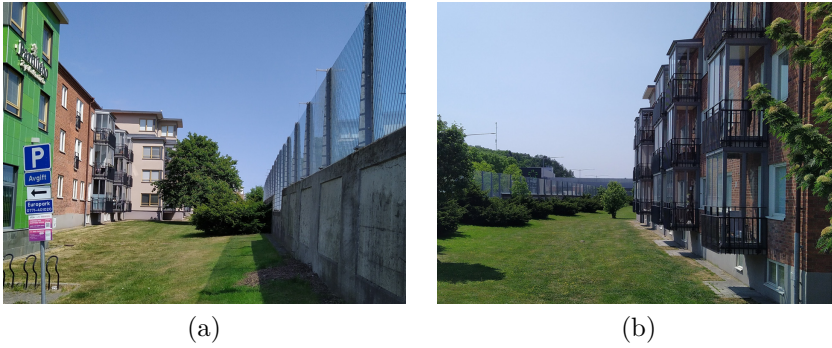


Figure 3.2: Site 1, the yard behind the 3.7 m tall noise barrier seen from: (a) the west, and (b) the east. The distance from the barrier to the nearest façade is 12 m.



Figure 3.3: The strip of vegetation at Site 2 behind a 3.0–3.6 m tall noise barrier south of the motorway. Above the barrier, buildings and the transparent top of the 5.4 m tall noise barrier north of the motorway can be seen.

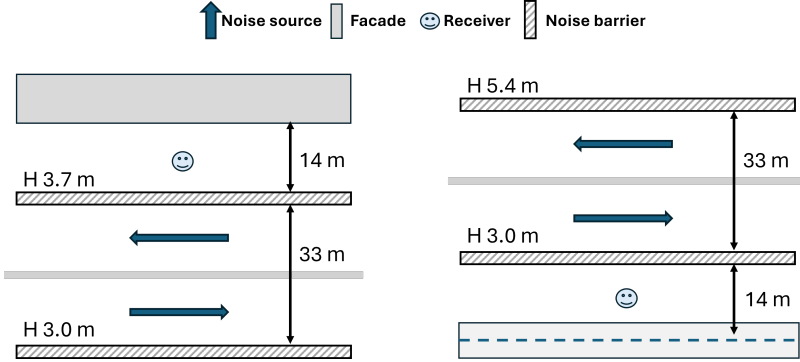


Figure 3.4: Sketch of Site 1 with receiver position between noise barrier and building façade (left), and of Site 2 (right) with receiver position between noise barrier and local street (right). (Figures not to scale.)

3.3 Measurements

Measurement conditions and traffic volume

The sound level measurements were performed at Sites 1 and 2 in November 2023 and October 2025, in accordance with the Swedish standard method [27]. On both occasions, the receiver positions were 2, 4 and 8 m behind the noise barrier and the measurements were carried out with three microphones simultaneously at 1, 2 and 4 m height for each distance, see Figures 3.5a and 3.6. Additional receivers were placed at Site 1 in the backyard behind the houses, 50 m from the noise barrier, see Figure 3.5b. The receiver positions in the texts, tables and graphs are normally denoted with $mp_{1,2}$ (measurement position), d_{xm} (distance) and h_{xm} (height), mp or mp_1 for Site 1 and mp_2 for Site 2. Example: $mp_1d_2h_1$ is Site 1 at the distance 2 m from noise barrier and 1 m above the ground, and $mp_2d_8h_4$ means Site 2 at the distance 8 m from noise barrier and 4 m above the ground.

Traffic data

The measurements were carried out during weekdays and the measurement time periods dT were 10–20 minutes. At Site 1, the 2023 measurements took place between 14.50 and 16.05 in the afternoon and the 2025 measurements



Figure 3.5: Measurement positions at Site 1 north of the motorway: (a) 4 m behind the noise barrier, (b) in the backyard 50 m from the noise barrier (photo: Akustikkonsulten).

at 09.50-11.20 in the morning, i.e., the first set in the beginning of rush-hour and the second just after rush-hour time. At Site 2, the 2023 measurements took place between 09.10 and 10.10 in the morning, at the end of rush-hour, and the 2025 measurements around noon (11.55-13.05). The traffic volume and distribution (vehicle categories) on the motorway were noted during the measurements and are summarised for each measurement time period and the corresponding 24-hour traffic in Tables 3.1 and 3.2, together with the official AADT, the Annual Average Daily Traffic data from 2022 [23]. The differences between the “24-hour” and AADT traffic are also noted in the tables. Table 3.2 also includes traffic in the local street, counted during the sound level measurements in 2025, but not in 2023. The obtained sound level data were delivered as equivalent levels for the measurement time $L_{Aeq,dT}$ as well as normalised to $L_{Aeq,24h}$ with regard to the AADT, 2022 see Tables 3.3 to 3.6. During the measurement periods dT at Site 1 in 2023 the “24-hour” traffic volume was 95-161% larger than AADT 2022, but the vehicle category distribution was similar to the 2022 data. In 2025, the “24-hour” traffic was 24-96% larger than AADT 2022, but the heavy truck category was twice as large.



Figure 3.6: The measurement position 4 m behind the noise barrier at Site 2, south of the motorway (photo: Akustikkonsulten).

Table 3.1: Traffic volume and vehicle category distribution on the motorway for Site 1: the official AADT, the number of passing vehicles during sound level measurement periods dT in 2023 and 2025, respectively, with corresponding 24h-traffic and the difference between 24h-traffic and AADT. NOTE: excluding traffic on entrance/exit lanes.

Position Dist. from nb (m)	AADT 2022 Cat 1/2/3 (%)	Meas.2023 dT : cat 1/2/3 Tot. 24h (Diff AADT) Cat 1/2/3 (%)	Meas.2025 dT : cat 1/2/3 Tot. 24h (Diff AADT) Cat 1/2/3 (%)
D2	38392 94.5/0.9/4.6	10 min: 494/4/21 74736 (+95%) 95.2/0.8/4.0	15 min: 480/6/51 51552 (+34%) 89.4/1.1/9.5
D4	38392 94.5/0.9/4.6	10 min: 556/8/34 86 112 (+124%) 93.0/1.3/5.7	10 min: 468/9/46 75312 (+96%) 89.5/1.7/8.8
D8	38392 94.5/0.9/4.6	10 min: 622/3/25 93600 (+143%) 95.7/0.5/3.8	16 min: 480/7/61 49320 (+28%) 87.6/1.3/11.1
D50	38392 94.5/0.9/4.6	10 min: 664/5/26 100080 (+161%) 95.5/0.7/3.7	18 min: 522/7/68 47712 (+24%) 87.4/1.2/11.4

The AADT at Site 2 is almost the same as at Site 1 (38 000 and 38 392 vehicles, respectively), but the percentage of medium and heavy vehicle is nearly twice as large at Site 2, see Table 3.2. However, in the given traffic data there was only one combined vehicle class for the heavy traffic, i.e., 9.6% including both medium-heavy and heavy vehicles, i.e., Categories 2 and 3. If assuming the same proportion between Category 2 and Category 3 vehicles as for Site 1 (e.g., Category 2 = 0.9/5.5 of 9.6%), Category 2 vehicles would be 1.6% and Category 3 vehicles 8% of AADT, thus, light vehicles, Category 1 = 90.4% of the total traffic volume. This distribution is more similar to the one during the measurement periods at Site 2 in 2025, see last column in Table 3.2.

Table 3.2: Traffic volume and vehicle category distribution on the motorway for Site 2: the official AADT, the number of passing vehicles during sound level measurement periods dT in 2023 and 2025, respectively, with corresponding 24h-traffic and the difference between 24h-traffic and AADT. Note: excluding traffic on entrance/exit lanes. Includes traffic in local street, counted in 2025 (but not in 2023). *Same relative heavy vehicle distribution as Site 1.

Position Dist. from nb (m)	AADT 2022 Cat 1/2/3*	Meas.2023 dT : cat 1/2/3 Tot. 24h (Diff AADT) Cat 1/2/3 (%)	Meas.2025 dT : cat 1/2/3 Tot. 24h (Diff AADT) Cat 1/2/3 (%)
D2	38000 90.4/1.6/8.0	10 min: 334/18/32 55 296 (+45%) 87.0/ 4.7/ 8.3	20 min: 658/9/65 52 704 (+39%) 90.0/1.2/8.9
D2 Local	-	-	20 min: 104/2/3 7848 95.4/1.8/2.8
D4	38000 90.4/1.6/8.0	15 min: 423/18/49 47 040 (+24%) 86.3/3.7/10.0	20 min: 725/11/61 57 384 (+51%) 91.0/1.4/7.6
D4 Local	-	-	20 min: 116/2/2 8640 98.6/1.7/1.7
D8	38000 90.4/1.6/8.0	17 min: 465/17/55 45 108 (+19%) 86.6/3.2/10.2	20 min: 678/7/71 54 432 (+43%) 90.0/0.9/9.4
D8 Local	-	-	20 min: 105/1/2 7776 97.2/0.9/1.8

Weather conditions

At the first measurement occasions, in November 2023, the weather in both sites was overcast with a temperature of -6°C . The 2 m/s wind was coming from north/northeast, i.e., in the direction from receiver to source at Site 1. The headwind condition was noted as a possible source of error for the measurements, especially in the backyard, but was considered as acceptable for the receiver positions close to the noise source, i.e., at 2–8 m from the noise barrier. The ground was slightly covered by fresh snow but not frozen. For the calculations of the November 2023 situation, it was assumed that the road surface was slightly wet and that 10% of the Category 1 vehicles had studded winter tyres.

The weather conditions during the second measurement campaign in October 2025 were for Site 1 overcast, the temperature $+11^{\circ}\text{C}$ and a 4 m/s wind from south-west. For Site 2 it was also overcast, the temperature $+12^{\circ}\text{C}$ with a weak 2 m/s wind from south, i.e., in the direction from receiver to source (i.e., a headwind situation).

For both the 2023 and 2025 measurements, the weather information was obtained from weather services, confirmed on site. According to the measurement standard, measurement of wind speed and wind direction on-site is not required for distances shorter than 30 m from the road [27].

Measurement results, Site 1

The measurement results of Site 1 from 2023 and 2025 are summarised in Table 3.3 as equivalent A-weighted sound levels over measurement period dT , $L_{Aeq,dT}$ and in Table 3.4 as normalised $L_{Aeq,24h}$ -values, based on the AADT 2022 traffic. The $L_{Aeq,24h}$ values from 2025 were higher than the ones from 2023. In the front yard between the noise barrier and house façade, the levels were 0.2–1.4 dBA higher and in the backyard they were 1.8–2.3 dB higher, see Figure 3.7. The large difference in the backyard might be due to the headwind conditions in 2023, which could have directed the traffic noise away from the microphones.

Table 3.3: Site 1, the equivalent A-weighted sound levels over measurement period dT , $L_{Aeq,dT}$ from November 2023 (headwind 2 m/s) and October 2025 (tailwind 4 m/s), and the difference between the measured levels.

Receiver	Meas. 2023 $L_{Aeq,dT}$ (dB)	Meas. 2025 $L_{Aeq,dT}$ (dB)	Diff. Meas 2025-2023 (dB)
$Mp_1 2m@1m$	65,1	65,7	0,6
$Mp_1 2m@2m$	66,1	66,3	0,2
$Mp_1 2m@4m$	68,2	68,8	0,6
$Mp_1 4m@1m$	65,5	65,4	-0,1
$Mp_1 4m@2m$	66,5	66,1	-0,4
$Mp_1 4m@4m$	67,7	67,8	0,1
$Mp_1 8m@1m$	65,3	65,1	-0,2
$Mp_1 8m@2m$	66,7	66,1	-0,6
$Mp_1 8m@4m$	67,6	67,4	-0,2
$Mp_1 50m@1m$	50,8	51,8	1
$Mp_1 50m@2m$	51,7	52,3	0,6
$Mp_1 50m@4m$	52,3	53,4	1,1

Table 3.4: Site 1, the equivalent A-weighted sound levels $L_{Aeq,24h}$ from November 2023 (headwind 2 m/s) and October 2025 (tailwind 4 m/s), and the difference between the measured levels.

Receiver	Meas. 2023 $L_{Aeq,24h}$ (dB)	Meas. 2025 $L_{Aeq,24h}$ (dB)	Diff. Meas 2025-2023 (dB)
$Mp_1 2m@1m$	62,7	63,6	0,9
$Mp_1 2m@2m$	63,7	64,2	0,5
$Mp_1 2m@4m$	65,8	66,7	0,9
$Mp_1 4m@1m$	62,6	63,8	1,2
$Mp_1 4m@2m$	63,6	64,5	0,9
$Mp_1 4m@4m$	64,8	66,2	1,4
$Mp_1 8m@1m$	62,4	63	0,6
$Mp_1 8m@2m$	63,8	64	0,2
$Mp_1 8m@4m$	64,7	65,3	0,6
$Mp_1 50m@1m$	47,6	49,8	2,2
$Mp_1 50m@2m$	48,5	50,3	1,8
$Mp_1 50m@4m$	49,1	51,4	2,3

Measurement results, Site 2

The measurement results of Site 2 from 2023 and 2025 are summarised in Table 3.5 for $L_{Aeq,dT}$ and in Table 3.6 for $L_{Aeq,24h}$. Here, all measured levels from 2025 are considerably higher than the ones from 2023 (see Figure 3.7). One reason could be the traffic in the local street, which in 2025 may have contributed more to the total sound levels in the receiver positions due to the wind direction during the measurements. In addition, the measurement results from 2023 could have been affected by some equipment or post-processing flaw, resulting in underestimation of the actual sound levels.

In both the previous and the new measured sound levels at Site 2, the levels increase with the height above ground and decrease with the distance to the noise source at 1 and 4 m height. The levels at $h=2$ m are quite even at all distances from the noise barrier.

Table 3.5: Site 2, the equivalent A-weighted sound levels over measurement period dT , $L_{Aeq,dT}$ from November 2023 (tailwind 2 m/s) and October 2025 (headwind 2 m/s), and the difference between the measured levels.

Receiver	Meas. 2023 $L_{Aeq,dT}$ (dB)	Meas. 2025 $L_{Aeq,dT}$ (dB)	Diff. Meas 2025-2023 (dB)
$Mp_22m@1m$	58,7	65,5	6,8
$Mp_22m@2m$	60,3	66,4	6,1
$Mp_22m@4m$	69	72,5	3,5
$Mp_24m@1m$	58,7	65	6,3
$Mp_24m@2m$	60,5	67	6,5
$Mp_24m@4m$	65	69,9	4,9
$Mp_28m@1m$	58,9	64,3	5,4
$Mp_28m@2m$	60,9	66,5	5,6
$Mp_28m@4m$	64	68,9	4,9

Table 3.6: Site 2, the equivalent A-weighted sound levels $L_{Aeq,24h}$ from November 2023 (tailwind 2 m/s) and October 2025 (headwind 2 m/s), and the difference between the measured levels.

Receiver	Meas. 2023 $L_{Aeq,24h}$ (dB)	Meas. 2025 $L_{Aeq,24h}$ (dB)	Diff. Meas 2025-2023 (dB)
$Mp_22m@1m$	57,3	63,4	6,1
$Mp_22m@2m$	58,9	64,3	5,4
$Mp_22m@4m$	67,6	70,4	2,8
$Mp_24m@1m$	57,1	62,7	5,6
$Mp_24m@2m$	58,9	64,7	5,8
$Mp_24m@4m$	63,4	67,6	4,2
$Mp_28m@1m$	57,4	62	4,6
$Mp_28m@2m$	59,4	64,2	4,8
$Mp_28m@4m$	62,5	66,6	4,1

Measurements, observations

For both Site 1 and Site 2, the measured $L_{Aeq,24h}$ traffic noise levels (i.e., normalised to AADT) were higher in 2025 than in 2023, see Figure 3.7. At Site 1 this could be expected since there was a weak headwind (in the direction from receiver to motorway) during the 2023 measurements and a stronger tailwind (from motorway to receiver) in 2025. For Site 2, the 2025 measurements during a headwind from south still resulted in higher noise levels than the 2023 measurement with a tailwind from north. The wind direction in 2025 could have increased the contribution of the noise from traffic on a local street behind the microphone positions, i.e., the southern wind steered the noise from the local street towards the microphones in 2025, and vice versa in 2023. (This is confirmed by studies of source contribution in the calculations, see Chapter 3.5.)

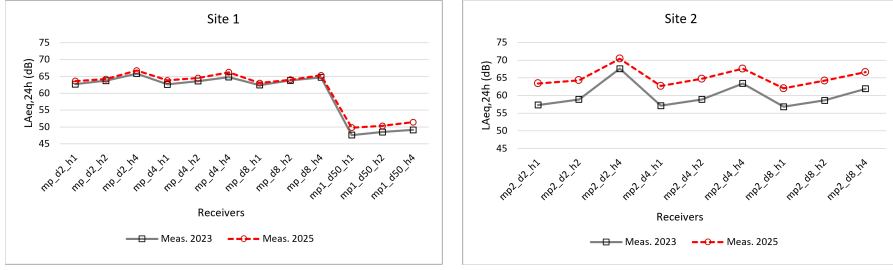


Figure 3.7: Measured $LA_{eq,24h}$ 2023 and 2025 at Site 1 (left) and Site 2 (right).

The AADT equivalent corrections of measured sound levels $LA_{eq,dT}$, were quite different for the two sites, illustrated in Figure 3.8. During the measurement periods dT at Site 1 in 2023 the “24-hour” traffic volume was 95–161% larger than AADT 2022, see Table(3.1), thus the AADT equivalent corrections of the measured levels were between -2.5 and -3.6 dB, i.e., the equivalent noise levels during the measurement periods were up to 3.6 dB higher than the $LA_{eq,24h}$. In Site 1 2025 and in both years at Site 2 the corrections were -1.5 to -2.6 dB.

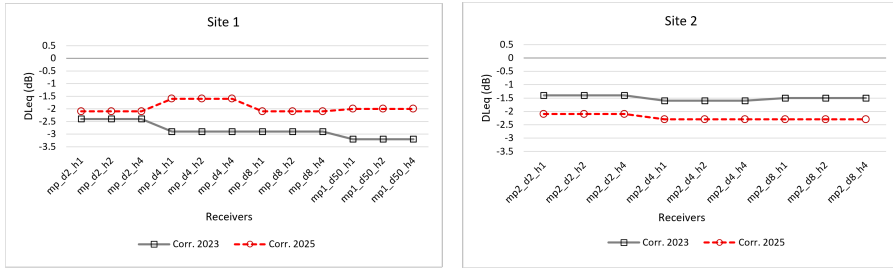


Figure 3.8: AADT correction of measured $LA_{eq,dT}$ 2023 and 2025 at Site 1 (left) and Site 2 (right).

Even though a variation in the traffic flow during day and night is normal for a suburban motorway, especially for the Category 1 vehicles (passenger cars), the large difference between the “24-hour traffic” and AADT 2022 at Site 1 is quite remarkable.

3.4 Calculated sound levels

The following description of the modelling and sound level calculations concerns only Sites 1 and 2. For Site 3, which was studied by a consultant company, there is a separate report summarised in Section 3.6. The sound level calculations were performed with the prediction model Nord2000 Road rev.2006 [9] and the Road traffic source model rev.2015 [28]. The studied sites were modelled in the software SoundPLAN 9.1 [25]. The weather and road surface corrections for the calculations were set to simulate the current conditions during the sound level measurement occasions and thus not according to the standard for calculating L_{DEN} or $L_{Aeq,24h}$ [10]. The AADT (Annual Averaged Daily Traffic) data from 2022, was used for both the 2023 and 2025 calculations. The geometry and other parameters were the same during both measurements in 2023 and 2025. Single-point calculations were carried out at the measured receiver positions. Views from the SoundPLAN models of Sites 1 and 2 are presented in Figures 3.9 and 3.10.

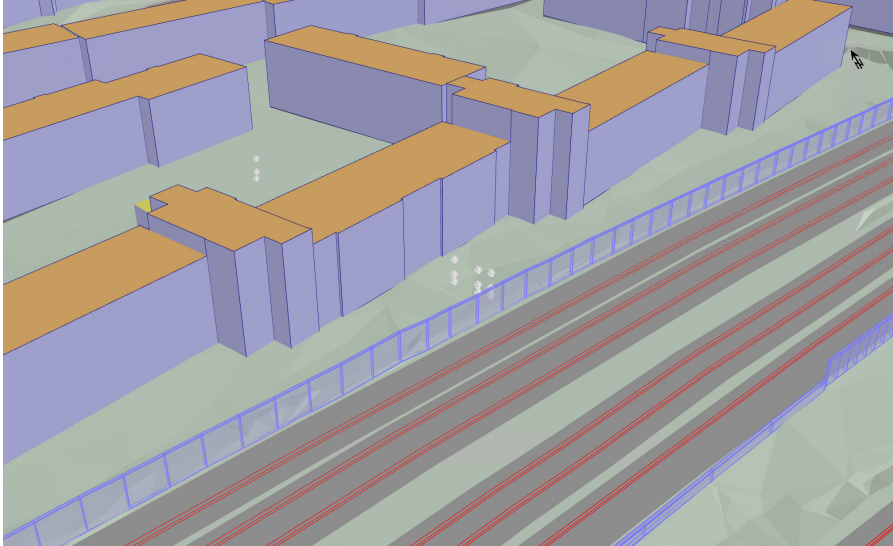


Figure 3.9: The SoundPLAN model at Site 1, the white dots mark the receiver positions for the sound level calculations.

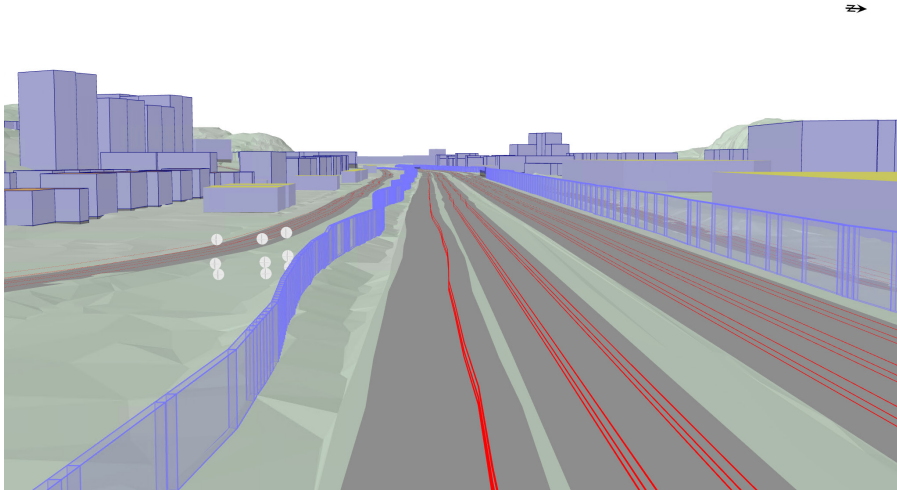


Figure 3.10: The SoundPLAN model at Site 2, the white dots mark the receiver positions for the sound level calculations.

Calculations have also been done with the standard weather settings according to the handbook for Swedish Nord2000 calculations [10], to examine the difference between the results based on the standard weather and the results based on the weather conditions during the sound level measurements, see Chapter 3.5.

Input data

Terrain, road model, buildings and noise barriers

The geometric data, terrain and road models, buildings and noise barriers etc, originated from the END noise mapping 2019 provided by the Swedish Transport Administration. The model was manually complemented (digitised), e.g., with bridges and with buildings that had been constructed after 2019.

Ground impedance

The ground impedance classes were selected after visual inspections on-site, see Table 3.7. The ground was partly covered by a thin layer of fresh snow

Table 3.7: Applied impedance classes, from the Nord2000 model [6] [9]. The higher the flow resistivity, the more sound reflecting surface.

Surface	Impedance class	Flow resistivity, kPa s/m^2
Motorway, dense concrete	H	200 000
Roads, parking lots etc	G	20 000
Compacted dense gravel, porous asphalt	F	2000
Compacted green areas, lawns, parks	E	500
Forrest floors, meadows, ballasted rail beds	D	200

during the measurements in 2023, but since the ground was not frozen it was not considered to affect the ground impedance.

Road characteristics

The characteristics of the motorway and connecting lanes included in the calculations are:

- Motorway with 2 continuous lanes plus 1 entrance/exit lane in eastbound direction, hard shoulder, total width approximately 15 m.
- Motorway with 2 continuous lanes plus 1 entrance/exit lane in westbound direction, hard shoulder, total width approximately 15 m.
- Middle section between eastbound and westbound lanes, approximately 2.75–3.0 m wide.
- Road surface type ABS 16 according to information from the Swedish Transport Administration, 2 years old at the time of the sound level measurements in 2023.
- Probability for wet surface condition, 25% in 2023 and 0% in 2025.
- The parameters concerning the air temperature and status of the road surface were chosen after the current conditions during the measurements in November 2023 and October 2025, see Table 3.8.

Weather conditions

For the comparison of calculated noise levels with measured noise levels, the actual weather conditions during each measurement occasion in Table 3.8 were inserted into the Nord2000 calculation model [9].

Table 3.8: Weather conditions during sound level measurements at Site 1 (S1) and Site 2 (S2) in November 2023 and October 2025, respectively.

Parameter	S1 Nov.23	S1 Oct.25	S2 Nov.23	S2 Oct.25
General Temperature	overcast −6°C	overcast +11°C	overcast −5°C	overcast +12°C
Rel.humidity	N/A	98%	N/A	91%
Air pressure	N/A	1021 hPa	N/A	1020 hPa
Wind	2 m/s	4 m/s	2 m/s	2 m/s
Wind direction	N (head-wind)	SW	NW	S (head-wind)

In Chapter 3.5, the results of calculations with the actual weather situations are compared with results based on “standardised weather”, i.e., a reference weather originating from the Nordic road traffic noise prediction method, RTN 1996 [29]. The standard weather is normally used for traffic noise calculations in accordance with the Swedish guidelines for road and rail traffic noise [30] and for planning noise mitigation measures [10]. Neither the RTN 96 weather nor the very short-term measurement weathers are to be applied for calculation of yearly average noise levels, e.g., L_{DEN} or L_{Night} , where long-term weather statistics for the region or country should be used [31], [32].

Traffic volume and distribution over vehicle categories

The AADT (Annual Averaged Daily Traffic) data from 2022, obtained from the Swedish Transport Administration [33], was used for both the 2023 and 2025 calculations, see Table 3.9. At Site 1, the traffic data for the motorway sections was sorted into three vehicle categories: 1 – cars, 2 – heavy vehicles with 2–4 axles, 3 – heavy vehicles with 4 axles or more, while for Site 2, the measured data was only presented in two categories where the second category represented all heavier vehicles. Therefore, the Site 1 *distribution* of category

2 and 3 vehicles was assumed for all motorway sections at both sites, as well as for the entrance and exit lanes.

Table 3.9: Traffic volume as AADT (Annual Averaged Daily Traffic) 2022 for each vehicle category according to [23]. The heavy vehicle percentage of the total traffic volume in parentheses, MW= motorway. * Only one category for both Cat. 2 and Cat. 3 vehicles, ** Cat.2 and Cat.3 distribution equivalent to Site 1 distribution.

Site	Road section	Cat.1	Cat.2	Cat.3	Cat. 2+3*	Year
1	MW eastbound	18180	159 (0,8%)	904 (4,7%)		2022
1	MW westbound	18089	194 (1.0%)	866 (4,5%)		2022
1	<i>MW, tot. categories</i>	36292 (94,5%)	353 (0,9%)	1770 (4,6%)	2123 (5,5%)	
1	Entr/exit lane	1470 (94,%)			80 (5,2%)	2022
1	<i>Entr/exit, total</i>	1550				
2	MW eastbound	17130			1870 (9.8%)	2022
2	MW westbound	17230			1770 (9.3%)	2022
2	<i>MW tot. categories</i>	34360 (90,4%)	608 (1,6%)**	3040 (8,0%)**	3640 (9,6%)	
2	Exit lane	2150 (86%)			350 (14%)	2022
2	<i>Exit lane, total</i>	2500				

Driving speed

The speed limit on the motorway for all vehicle categories is 80 km/h. However, the traffic measurements on the motorway sections in 2022 indicate that the real average speed is higher, i.e., for Category 1: 88-90 km/h and Category 2 and Category 3: 82 km/h. Sound level calculations were performed with 80 km/h (all vehicles) and with the average driving speeds for the vehicle categories. For the entrance and exit lanes, parallel to the motorway, the driving speed limits 60 and 80 km/h were used.

Noise barriers

Noise barriers are installed on both sides of the motorway, along the entire length between the two study sites. They are constructed in sound reflecting materials like concrete, transparent glass or plastic and metal sheets, i.e., without absorbers. Their heights vary from 3.7 to 5.4 m on the north side, and from 3.0 to 3.6 m on the south side, except at the west end of the south side, which only has a road restraining concrete element of 1.2 m height, and at the eastern end, where the south barrier is gradually lowered from 3.6 to 2.4 m above ground.

Receiver positions

The receivers were positioned at the same locations as the sound level measurements, i.e., at 1, 2 and 4 m height at three distances, 2, 4 and 8 m behind the noise barriers and also, at 50 m distance for Site 1.

Calculation settings

For both the 2023 and 2025 situations, the calculations were performed with the following settings:

- Reflection order: 4 (Site 1) and 3 (Site 2).
- Reflections in façades included. Changed façade absorption from default value of 1.0 dB to 0.2 dB on buildings behind the receiver positions at study Site 1.
- Maximum search radius (distance from source to receiver): 1000 m.
- Maximum reflection distance, receiver: 200 m.
- Maximum reflection distance, source: 50 m.
- Allowed tolerance for each source contribution: 0.1 dB.
- Single point calculations, propagation: Calculate reflection of assigned façade and ignore standard dependent correction.

Changed parameters between the Nov. 2023 and Oct. 2025 calculations:

- For Nov. 2023: 10% studded tyres vehicle category 1, 25% probability for wet road surface, -5°C road surface temperature.
- For Oct. 2025: 0% studded tyres, dry road surface, $+12^{\circ}\text{C}$ road surface temperature.

The weather parameters, e.g., wind speed and direction, were set after the conditions during each measurement (see Table 3.8). The other parameters remained unchanged, e.g., geometry and noise barrier characteristics. Also, for the $L_{Aeq,24h}$ level comparisons (see Chapter 3.5), the traffic amount and distribution were the same, i.e., based on AADT 2022.

Calculation results, Site 1

At Site 1, the calculated 24-hour equivalent sound levels ($L_{Aeq,24h}$) from November 2023, based on the speed limit 80 km/h, are 59–70 dB at the receiver positions in the front yard between the noise barrier and the building façade, see Table 3.10 and Figure 3.11. The calculated levels from October 2025, also based on 80 km/h speed, are 63–73 dB at the receiver positions in the front yard. For both years, the highest levels are just above the noise barrier top ($mp_1d_2h_4$), decreasing with the distance from the barrier. The lowest levels are found near the ground, but while the low levels decrease with the distance from the noise barrier in 2023, they increase with the distance in 2025.

In the backyard behind the house, 50 meters from the noise barrier, the calculated $L_{Aeq,24h}$ is 46–47 dB in 2023 and 51–52 dB in 2025, with the highest levels at 4 m height.

To summarise, ***the calculated noise levels for 2025 are between 3.2 and 7.4 dB higher than for 2023*** (with $v=80$ km/h). The main difference between the 2023 and 2025 calculations is the weather, i.e., the wind speed and direction. The stronger tailwind from source to receiver in 2025 seems to cause up to 7.4 dB higher noise levels than the weak headwind in 2023. The effect of wind direction is further commented in Chapter 3.5.

If the measured average speed is applied instead of the speed limit, the calculated $L_{Aeq,24h}$ levels increase with 0.8–1.0 dB in all receiver positions, see Table 3.10.

Table 3.10: The calculated $L_{Aeq,24h}$ at Site 1 based on speed $v=80$ km/h and average speed $av.v = 89/82/82$ km/h, for the years 2023 and 2025 and the difference between them (note the wind speeds and directions of Nov. 2023 and Oct. 2025).

Receiver	2023 v80, N 2m/s (dB)	2023 av.v, N 2m/s (dB)	2025 v80, SW 4m/s (dB)	2025 av.v, SW 4m/s (dB)	Diff v80 2025- 2023 (dB)	Diff av.v 2025- 2023 (dB)
$mp_1d_2h_1$	60,0	60,8	63,2	64,1	3,2	3,3
$mp_1d_2h_2$	61,3	62,1	65,0	65,9	3,7	3,8
$mp_1d_2h_4$	69,9	70,9	73,1	74,1	3,2	3,2
$mp_1d_4h_1$	59,0	59,9	63,8	64,7	4,8	4,8
$mp_1d_4h_2$	59,9	60,8	65,4	66,3	5,5	5,5
$mp_1d_4h_4$	64,0	64,9	71,0	72,0	7,0	7,1
$mp_1d_8h_1$	58,6	59,5	64,0	65,0	5,4	5,5
$mp_1d_8h_2$	59,8	60,7	65,6	66,6	5,8	5,9
$mp_1d_8h_4$	63,3	64,2	70,7	71,8	7,4	7,6
$mp_1d_{50}h_1$	45,9	46,8	50,8	51,8	4,9	5,0
$mp_1d_{50}h_2$	45,9	46,8	50,7	51,6	4,8	4,8
$mp_1d_{50}h_8$	46,6	47,4	51,8	52,7	5,2	5,3

Calculation results, Site 2

At Site 2, the calculated 24-hour equivalent sound levels ($L_{Aeq,24h}$) from November 2023, based on the driving speed limit 80 km/h, are 58–75 dB at the receiver positions in the open area behind the noise barrier, see Table 3.11. The calculated equivalent levels from October 2025, also based on 80 km/h, are 56–74 dB. The table also includes the results of calculations based on average speed instead of 80 km/h. With the higher average speed, the resulting sound levels increase with 0.8–0.9 dB for both years.

Contrary to the results at Site 1, *the calculated sound levels at Site 2 are higher in the 2023 situation than in 2025*, due to the tailwind from source to receiver in 2023 and the headwind in 2025, see Figure 3.11. Though, the differences are smaller in Site 2, only 1.9 to 2.6 dB at the 1 and 2 m positions above ground. Similar to Site 1, the largest differences between the years are found at 4 m height at $mp_2d_4h_4$ and $mp_2d_8h_4$, (5.6–5.8 dB), and the smallest difference in the position $mp_2d_2h_4$, (0.7 dB) i.e., just above

the top of the barrier. The study of the effect of wind direction is further developed in Chapter 3.5.

Table 3.11: The calculated $L_{Aeq,24h}$ at Site 2 based on speed $v=80$ km/h and average speed $av.v=89/82/82$ km/h for the years 2023 and 2025, including the difference between them (note the wind speeds and directions of Nov. 2023 and Oct. 2025).

Receiver	2023 v80, N 2m/s (dB)	2023 av.v, N 2m/s (dB)	2025 v80, SW 4m/s (dB)	2025 av.v, SW 4m/s (dB)	Diff v80 2025- 2023 (dB)	Diff av.v 2025- 2023 (dB)
$mp_2d_2h_1$	58,5	59,3	56,5	57,4	2	1.9
$mp_2d_2h_2$	61,1	61,9	58,7	59,5	2.4	2.4
$mp_2d_2h_4$	74,7	75,5	74,0	74,9	0.7	0.6
$mp_2d_4h_1$	57,8	58,6	55,7	56,6	2.1	2
$mp_2d_4h_2$	59,6	60,5	57,2	58	2.4	2.5
$mp_2d_4h_4$	70,0	70,9	64,2	65,1	5.8	5.8
$mp_2d_8h_1$	59,7	60,5	57,4	58,2	2.3	2.3
$mp_2d_8h_2$	62,0	62,8	59,4	60,3	2.6	2.5
$mp_2d_8h_4$	68,5	69,4	62,9	63,8	5.6	5.6

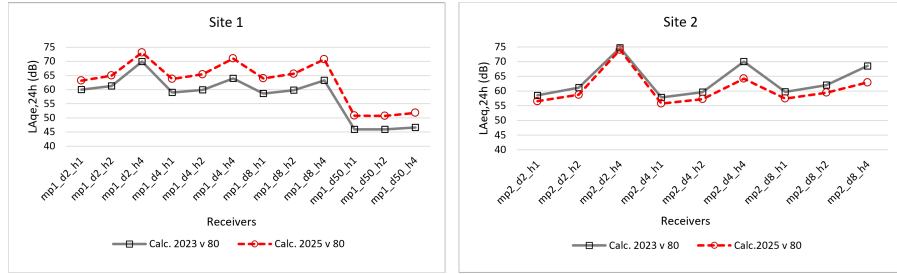


Figure 3.11: Calculated equivalent sound levels, $L_{Aeq,24h}$, 2023 and 2025 at Site 1 (left) and Site 2 (right), based on $v = 80$ km/h.

3.5 Comparison between calculated and measured sound levels

In this section, comparisons are made between the measured and calculated sound levels of study Sites 1 and 2, based on both the previous measurements and calculations from 2023 and the new ones from 2025. In addition, a study of a third site (by a consultant company) is summarised in Chapter 3.6. The objective is to investigate if it is possible to reproduce the measured sound levels with calculations and which parameters or corrections that are significant for aligning the calculated results to the measured ones. Both the speed limit $v=80$ km/h and the measured average speed for each vehicle category (89 km/h for Category 1, 82 km/h for Categories 2 and 3) were used in the calculations.

According to the prescribed traffic noise measurement method in Sweden [27], the measured sound levels during a certain measurement period, dT , is normalised to the volume of traffic of an annual average day, AADT, which enables comparison with the calculations using 24-hour equivalent values, $L_{Aeq,24h}$.

Comparison Site 1

As described in 3.3 and 3.4, respectively, both the measured and calculated sound levels ($L_{Aeq,24h}$) were higher in October 2025 than in November 2023.

Further, in **2023**, in all receiver positions of Site 1 except two, the *measured sound levels were higher than the calculated*, see Table 3.12. Calculations based on the average traffic speed give the best agreement between the measured and calculated noise levels, but still the differences are approximately 2–3 dB in most positions. Both the best agreement and the worst are at 4 m height, the difference at receiver position $mp_1d_4h_4$ is +0.1 dB and at $mp_1d_2h_4$ it is + 5.1 dB.

In **2025**, the *measured sound levels are generally lower than the calculated ones*. The best agreement is between measured levels and calculations based on vehicle speed 80 km/h at 1 and 2 m above ground, the calculated being 0.1 dB higher for all but the receivers $mp_1d_2h_1$ (-0.4 dB) and $mp_1d_8h_2$ (+1.6 dB), see Table 3.13. However, at 4 m height, 2, 4 and 8 m from the noise barrier, the calculated levels are 5–6 dB higher than the measured.

Table 3.12: Site 1, situation 2023 (2 m/s headwind), measured and calculated $L_{Aeq,24h}$ values based on $v=80$ km/h and average speed $av.v=89/82/82$ km/h, and the difference between them.

Receiver	Meas. 2023 (dB)	Calc. 2023 v80, N 2m/s (dB)	Diff calc v80 - meas	Calc. 2023 av.v, N 2m/s (dB)	Diff calc av.v - meas
$mp_1d_2h_1$	62,7	60,0	-2.7	60,8	-1.9
$mp_1d_2h_2$	63,7	61,3	-2.4	62,1	-1.6
$mp_1d_2h_4$	65,8	69,9	4.1	70,9	5.1
$mp_1d_4h_1$	62,6	59,0	-3.6	59,9	-2.7
$mp_1d_4h_2$	63,6	59,9	-3.7	60,8	-2.8
$mp_1d_4h_4$	64,8	64,0	-0.8	64,9	0.1
$mp_1d_8h_1$	62,4	58,6	-3.8	59,5	-2.9
$mp_1d_8h_2$	63,8	59,8	-4.0	60,7	-3.1
$mp_1d_8h_4$	64,7	63,3	-1.4	64,2	-0.5
$mp_1d_{50}h_1$	47,6	45,9	-1.7	46,8	-0.8
$mp_1d_{50}h_2$	48,5	45,9	-2.6	46,8	-1.7
$mp_1d_{50}h_4$	49,1	46,6	-2.5	47,4	-1.7

Table 3.13: Site 1, situation 2025 (4 m/s tailwind), measured and calculated $L_{Aeq,24h}$ values based on $v=80$ km/h and average speed $av.v=89/82/82$ km/h, and the difference between them.

Receiver	Meas. 2025 (dB)	Calc. 2025 v80, SW 4m/s (dB)	Diff calc v80 - meas	Calc. 2025 av.v, SW 4m/s (dB)	Diff calc av.v - meas
$mp_1d_2h_1$	63,6	63,2	-0.4	64,1	0.5
$mp_1d_2h_2$	64,2	65	0.8	65,9	1.7
$mp_1d_2h_4$	66,7	73,1	6.4	74,1	7.4
$mp_1d_4h_1$	63,8	63,8	0	64,7	0.9
$mp_1d_4h_2$	64,5	65,4	0.9	66,3	1.8
$mp_1d_4h_4$	66,2	71.0	4.8	72.0	5.8
$mp_1d_8h_1$	63.0	64	1.0	65	2.0
$mp_1d_8h_2$	64.0	65,6	1.6	66,6	2.6
$mp_1d_8h_4$	65,3	70,7	5.4	71,8	6.5
$mp_1d_{50}h_1$	49,8	50,8	1.0	51,8	2.0
$mp_1d_{50}h_2$	50,3	50,7	0.4	51,6	1.3
$mp_1d_{50}h_4$	51,4	51,8	0.4	52,7	1.3

Figure 3.12 illustrates the variation in $L_{Aeq,24h}$ between receivers and Figure 3.13 shows the differences between the 2023 and 2025 measurements and calculations. The figures include results from calculations based on the standard weather parameters, explained later in this chapter.

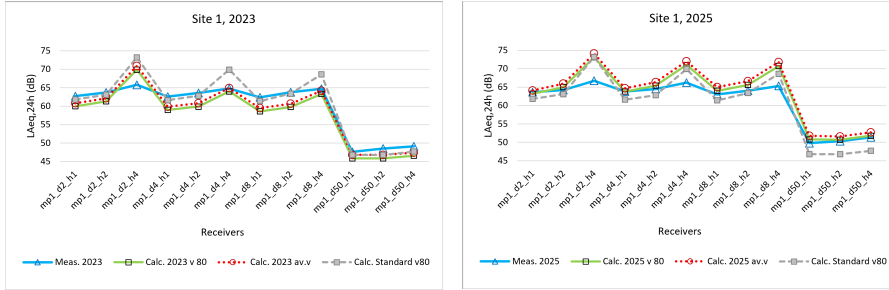


Figure 3.12: Site 1, measured and calculated $L_{Aeq,24h}$, 2023 (left) and 2025 (right). Including calculations based on standard weather parameters and 80 km/h.

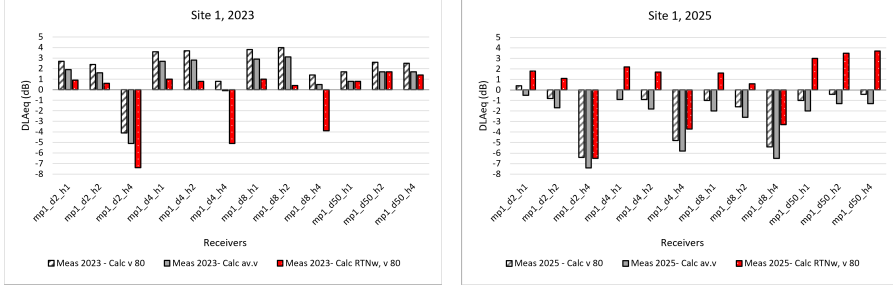


Figure 3.13: Site 1, the difference DL_{Aeq} between measured and calculated sound levels, 2023 (left) and 2025 (right). Including calculations based on standard weather parameters (RTNw) and 80 km/h.

One of the reasons for the quite high calculated noise levels at 4 m height in 2025 (also at $mp_1d_2h_4$ in 2023), could be a difference between the real and the modelled terrain height, where the microphones at 4 m height may be more shielded by the noise barrier in reality than the receiver positions in the model. This was tested by calculating the sound levels for receivers at 3.5 m above the ground which resulted in smaller deviations, of 2.4-3.4 dBA higher levels (with $v=80$ km/h) than the measured levels at 4 m, see Figure 3.14 At $mp_1d_2h_4$ in 2023, the calculated level at 3.5 m (with average driving speed) was the same as the measured at 4 m height.

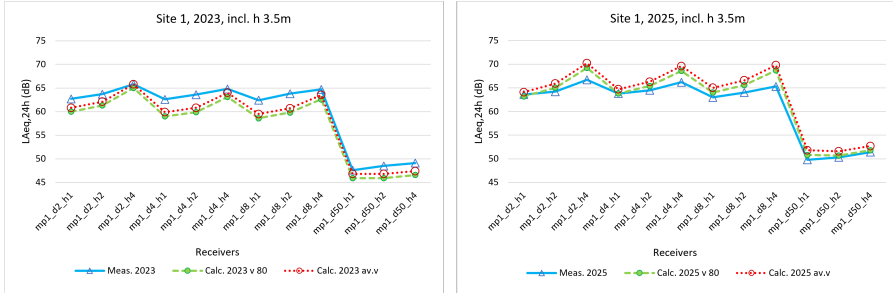


Figure 3.14: Site 1, measured and calculated $L_{Aeq,24h}$, 2023 (left) and 2025 (right), with calculated levels at 3.5 m instead of 4 m height (in $mp_1d_2h_4$, $mp_1d_4h_4$ and $mp_1d_8h_4$).

Comparison Site 2

As described in Chapter 3.3, at Site 2 the *measured* sound levels ($L_{Aeq,24h}$) from 2025 were 2.8–6.1 dB *higher* than in 2023, even though there was a north-western tailwind (from source to receiver) in 2023 and a southern headwind (from receiver to source) in 2025. In comparison, the levels only increased by 0.8–1.4 dB between the 2023 and 2025 measurements at Site 1. Furthermore, the *calculated* levels, based on $v=80\text{km/h}$, were up to 5.8 dB *lower* in 2025 than in 2023 (Chapter 3.4), but this was anticipated due to the different weather conditions.

In **2023**, the measured sound levels behind the noise barrier at 1 and 2 m above the ground were relatively low, around 57–59 dB. Also, in the receiver positions at 4 m above ground, the levels were lower than in Site 1 even though the northern-northwestern wind should have been more “advantageous” for the sound propagation at Site 2. All ***calculated levels were higher than the measured ones***, consequently, the 80 km/h calculations had a better agreement with measured values than the calculations based on average speed. Still, they were 0.7–2.6 dB higher than the measured sound levels at 1 and 2 m height and 6–7.1 dB higher at 4 m above the ground, see Table 3.14.

Table 3.14: Site 2, situation 2023 (2 m/s tailwind), measured and calculated $L_{Aeq,24h}$ levels based on $v=80\text{ km/h}$ and average speed $av.v=89/82/82\text{ km/h}$, and the difference between them.

Receiver	Meas. 2023 (dB)	Calc. 2023 $v=80, \text{NW}$ 2m/s (dB)	Diff calc $v=80 -$ meas	Calc. 2023 $av.v,$ NW 2m/s (dB)	Diff calc $av.v -$ meas
$mp_2d_2h_1$	57,3	58,5	1,2	59,3	2
$mp_2d_2h_2$	58,9	61,1	2,2	61,9	3
$mp_2d_2h_4$	67,6	74,7	7,1	75,5	7,9
$mp_2d_4h_1$	57,1	57,8	0,7	58,6	1,5
$mp_2d_4h_2$	58,9	59,6	0,7	60,5	1,6
$mp_2d_4h_4$	63,4	70	6,6	70,9	7,5
$mp_2d_8h_1$	57,4	59,7	2,3	60,5	3,1
$mp_2d_8h_2$	59,4	62	2,6	62,8	3,4
$mp_2d_8h_4$	62,5	68,5	6	69,4	6,9

The measured sound levels in **2025** were 62.0–70.4 dB. In all receiver positions but $mp_2d_2h_4$ the calculations based on the average speed had the best agreement with measured values, see Table 3.15. However, the **calculated results are 2.5–6.7 dB lower than the measured**, with the largest differences in positions close to the noise barrier. Possible explanations for the rather large differences were examined. First, by increasing the reflection depth in the calculations, i.e., the maximum order of reflection, from the standard 3 to 4. This had small impact on the results, with only 0.1 dB higher level in $mp_2d_2h_4$. Thus, it was decided to continue with three reflections for the Site 2 calculations.

Table 3.15: Site 2, situation 2025 (2 m/s headwind), measured and calculated $L_{Aeq,24h}$ values based on $v=80$ km/h and average speed $av.v=89/82/82$ km/h, and the difference between them.

Receiver	Meas. 2025 (dB)	Calc. 2025 v80, S 2m/s (dB)	Diff calc v80 - meas	Calc. 2025 av.v, S 2m/s (dB)	Diff calc av.v - meas
$mp_2d_2h_1$	63,4	56,5	-6,9	57,4	-6
$mp_2d_2h_2$	64,3	58,7	-5,6	59,5	-4,8
$mp_2d_2h_4$	70,4	74	3,6	74,9	4,5
$mp_2d_4h_1$	62,7	55,7	-7	56,6	-6,1
$mp_2d_4h_2$	64,7	57,2	-7,5	58	-6,7
$mp_2d_4h_4$	67,6	64,2	-3,4	65,1	-2,5
$mp_2d_8h_1$	62	57,4	-4,6	58,2	-3,8
$mp_2d_8h_2$	64,2	59,4	-4,8	60,3	-3,9
$mp_2d_8h_4$	66,6	62,9	-3,7	63,8	-2,8

Figure 3.15 illustrates the variation between the 2023 and 2025 measurements and calculations. The figure includes results from calculations based on the standard weather parameters, explained in the following section.

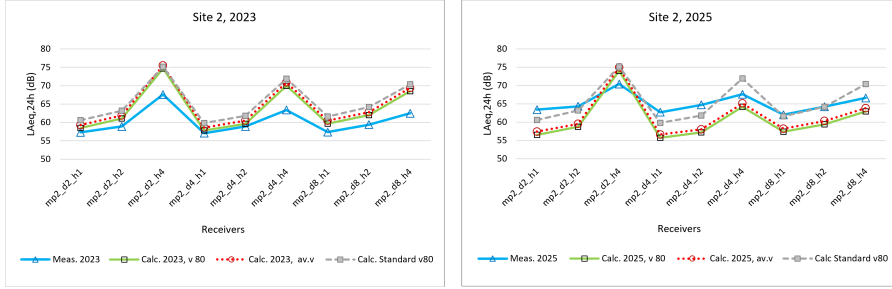


Figure 3.15: Site 2, measured and calculated $L_{Aeq,24h}$, 2023 (left) and 2025 (right).

Next, the traffic in a local street was taken into consideration for the **2025** calculation. The street is situated approximately 15 m from the noise barrier, i.e. south of the receiver positions at Site 2. Since there was no official AADT for this part of the street, a 24-hour traffic was derived from the number of passing vehicles that were counted during the sound level measurement periods in 2025 (see Table 3.2). Thus, the inserted traffic data for the local street were 8088 AADT with a vehicle distribution of Category 1: 96.5%, Category 2: 1.5% and Category 3: 2.1%. The speed limit 60 km/h was applied for all vehicle categories.

The contribution from the local traffic increased the calculated sound levels with up to 5 dB and, except at $mp2d2h4$, the gap between the calculated and measured sound levels was reduced to 0.4–1.7 dB, see Figure 3.16 and Table 3.16. Figure 3.17 illustrates the difference, DL_{Aeq} , between measured and calculated equivalent sound levels with $v=80$ km/h and measured average speed, with motorway traffic only or including traffic on local street. (Note: The local traffic was not counted in 2023.)

Table 3.16: Site 2, Measured and calculated $L_{Aeq,24h}$ values with $v=80$ km/h and measured average speed on motorway. Last two columns show result from calculations including traffic on local street. Situation 2025, with 2 m/s wind from south at measurement occasion and calculation.

Receiver	Meas. 2025 (dB)	Calc. 2025 mv, v80, (dB)	Calc. 2025, mw, v80, +local (dB)	Calc. 2025, mw, av.v, (dB)	Calc. 2025, mw, av.v, +local (dB)
$mp_2d_2h_1$	63,4	56,5	61,9	57,4	62,2
$mp_2d_2h_2$	64,3	58,7	63,4	59,5	63,7
$mp_2d_2h_4$	70,4	74,0	74,3	74,9	75,2
$mp_2d_4h_1$	62,7	55,7	61,0	56,6	61,3
$mp_2d_4h_2$	64,7	57,2	62,7	58,0	63,0
$mp_2d_4h_4$	67,6	64,2	66,7	65,1	67,2
$mp_2d_8h_1$	62,0	57,4	62,4	58,2	62,6
$mp_2d_8h_2$	64,2	59,4	64,3	60,3	64,6
$mp_2d_8h_4$	66,6	62,9	66,7	63,8	67,1

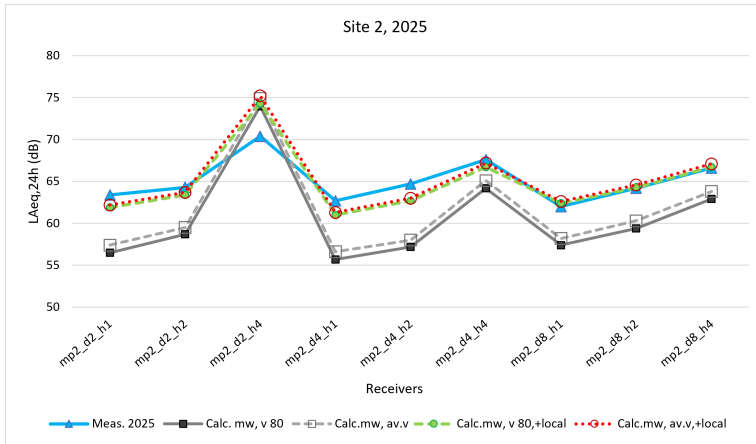


Figure 3.16: Measured and calculated $L_{Aeq,24h}$ levels with $v=80$ km/h and measured average speed, with motorway traffic only or including traffic on local street. Situation 2025, with 2m/s wind from south at measurement occasion and calculation.

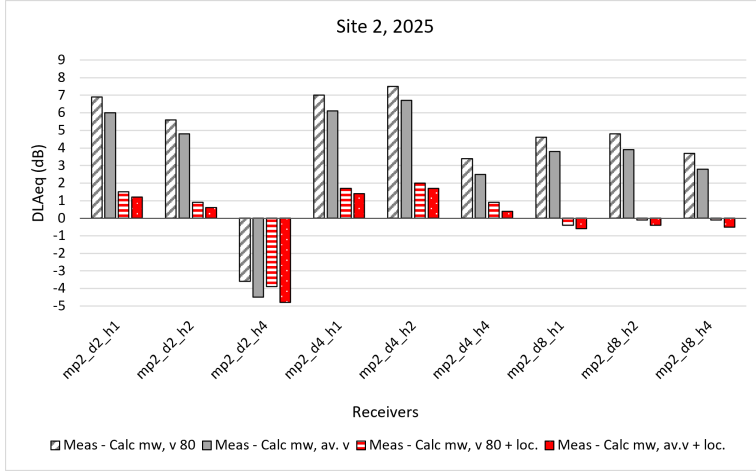


Figure 3.17: Site 2, 2025. The difference DL_{Aeq} between measured and calculated equivalent sound levels with $v=80$ km/h and measured average speed, with motorway traffic only or including traffic on local street.

The results above indicate that the local traffic contributed to the total sound levels during the measurements in 2025. This was further confirmed by studying the source contribution table from the SoundPLAN calculations, included in Table 3.17, where the contribution to the noise level by the local road is given explicitly. The largest source contribution came from the local street in all receiver positions except for $mp2d2h4$, i.e., above the top of the noise barrier where the contribution from the motorway (all lanes) were 9–10 dB higher than the traffic noise from the local street.

Table 3.17: Site 2, situation 2025. The calculated source contribution from traffic in local street and on motorway (mw), respectively. Src contr=source contribution .

Receiver	Calc. 2025, mw, v80, +local (dB)	Src contr. v80 local str (dB)	Src contr. v80 mw (dB)	Calc. 2025, mw, av.v, +local (dB)	Src contr. av.v, local str (dB)	Src contr. av. v, local str (dB)
$mp_2d_2h_1$	61,9	58	51	62,2	58	52
$mp_2d_2h_2$	63,4	59	53	63,7	59	54
$mp_2d_2h_4$	74,3	59	68	75,2	59	69
$mp_2d_4h_1$	61,0	57	50	61,3	57	51
$mp_2d_4h_2$	62,7	58	52	63,0	58	53
$mp_2d_4h_4$	66,7	60	58	67,2	60	59
$mp_2d_8h_1$	62,4	58	52	62,6	58	53
$mp_2d_8h_2$	64,3	60	54	64,6	60	55
$mp_2d_8h_4$	66,7	62	57	67,1	62	58

Standard weather conditions

The weather conditions according to the instructions for Swedish Nord2000 calculations [10] has been tested in calculations for both Site 1 and Site 2. With the standard weather settings, a 1.5 m/s wind with downward refraction from source to receiver is assumed for all receiver positions. The results are combined with the 2023 and 2025 calculations in Figure 3.18. All calculations are based on the 80 km/h speed limit.

In the front yard of Site 1, ($mp_1d_2h_4$ excluded), the standard weather conditions give 2–6 dB *higher* sound levels than the weather of 2023 with headwind (2 m/s from north), and 1–3 dB *lower* than 2025, with a stronger tailwind (4 m/s from SW). In the backyard of Site 1 the standard weather setting results in 1 dB higher levels than the 2023 weather, but 4 dB lower levels than the 2025 weather. In Site 2, the standard weather always results in higher sound levels than the actual weather situation during the two measurement occasions.

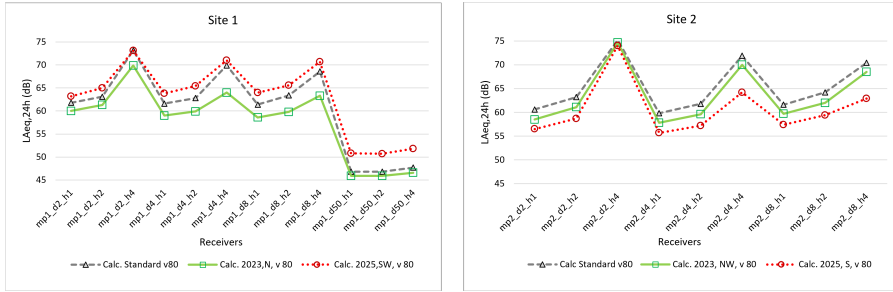


Figure 3.18: Calculated $L_{Aeq,24h}$ based on standard weather conditions and conditions during measurements in 2023 and 2025 respectively. Site 1 (left) and Site 2 (right).

Except for $mp_2d_2h_4$, the standard weather gives around 2 dB higher levels compared to the 2023 situation, with tailwind (2 m/s from NW) and 4-8 dB higher levels than situation 2025, with headwind (2 m/s from south). In the positions right above the noise barrier tops at both sites, $mp_1d_2h_4$ and $mp_2d_2h_4$, the different weather conditions do not affect the results more than marginally.

Observations, Sites 1 and 2

Site 1: Height variations between the real and modelled terrain might be one reason for the quite large difference between calculated and measured sound levels at 4 m height, 2 m from the noise barrier.

Site 1: In Site 1, the best fit between calculated and measured results was achieved with calculations based on average driving speed in 2023 (though with a weak headwind) and with 80 km/h in 2025 (with tailwind). The standard weather conditions represent the situation in the narrow front yard fairly well, but might need consideration in the backyard (with seating area and playground) since the standard weather resulted in 4 dB lower levels than the actual weather situation in 2025 with only slightly stronger tailwind from the road.

Site 2, 2023: The gap between measured and (higher) calculated sound levels after adjustments for weather conditions were still 0.7–2.6 dB, a difference for which an explanation could not be found, except for a possibility of a measurement or post-processing flaw.

Site 2, 2025: To align the calculated sound levels with the (higher) measured levels, the most significant actions were to include the contribution from the noise of the traffic in the local street at the receiver side of the noise barrier, use the average speed on the motorway traffic and apply the actual weather conditions.

Sites 1 and 2: In both sites, the calculated sound levels at d_2h_4 are always higher or much higher than the measured levels. Possibly, the direct sound levels in positions just above noise barriers are overestimated in the calculations.

3.6 Site 3

A consultant company performed both the sound levels measurements and calculations for Site 3. The approach of this case study was slightly different than for Sites 1 and 2. Since the existing noise barriers at Site 3 were assumed to have some sound absorbing or scattering effect on the noise from the road traffic, this was tested by applying different absorption coefficients (i.e., reflection loss $DL\alpha$ in dB) on the barriers in the calculations. The calculated results were then compared with the measured sound levels. The consultant report is summarised in this chapter.

General description

The neighbourhood of the third study site resembles the one of Site 1 in many ways. To begin with, they are both divided by a 6-lane road with noise barriers and have 3–5 storeys apartment buildings parallel to the road. The distance between the building façades behind the receiver positions is 12–15 m at Site 1 and 16 m at Site 3. However, Site 3 is more urban and densely built than Site 1, with houses and small local streets closely to both sides of the road, see Figure 3.19, while the opposite side of the road at Site 1 is comprising a parallel street and an open park-like landscape with the nearest buildings at least 50 m from the road. The speed limit is 80 km/h at Site 1 and 60 km/h at Site 3. The AADT is ca 80 000 at Site 1 and 167 000 at Site 3. The vehicle distribution at Site 3 was nearly identical to the distribution at Site 1, i.e., Category 1 (passenger cars) 95%, Category 2 (medium heavy vehicles with 2–4 axles) 1% and Category 3 (heavy vehicles with 4 axles or more) 4%.

Similar to Site 1, there are noise barriers with varying design on both sides along an approximately 1 km stretch of the road. The existing noise barriers by the studied receiver positions of Site 3 are 3–3.5 m tall, comprising concrete sections with a corrugated surface on the roadside and cement-bound wood-wool absorbers on the receiver side, see Figure 3.20. The concrete noise barrier is interrupted every 50 m with 3 m wide sections of transparent polycarbonate.



Figure 3.19: View over the 6-lane road at Site 3, flanked by noise barriers and apartment buildings. The receiver positions for the measurements and calculations are situated further down the road on the left hand side.



Figure 3.20: The noise barrier at Site 3. To the left, corrugated concrete surface on the roadside (photo: Akustikkonsulten), to the right, wooden slats with cement-bound wood wool panels (photo: author).



Figure 3.21: Measurement positions at Site 3, to the left $M_1 16m$, between the noise barrier and house facade, to the right $M_2 16m$ between the house gables (photos: Akustikkonsulten).

Measurements and calculations

The sound level measurements at Site 3 were performed in November 2025 in accordance with the Swedish standard method [27]. The receivers were distributed along two “lines” perpendicular to the noise barriers. The line 1 receivers were positioned between the noise barrier and a building façade, 2, 4 and 16 m from the noise barrier. The second receiver line continued between the gables of two houses, where the line 2 positions were 2, 4, 16, 26 and 37 m from the noise barrier, see Figure 3.21. The measurements were carried out with three microphones simultaneously at 1, 2 and 4 m height above the ground for each distance. The receiver positions in the tables, graphs and texts are denoted as the following examples: $M_1 2m@1m$, meaning measurement line 1, 2 m from noise barrier at 1 m height, and $M_2 37m@4m$, meaning measurement line 2, 37 m from the noise barrier at 4 m height.

The measurement time periods, dT , were 10 minutes in the early afternoon during a weekday. The traffic volume and distribution (vehicle categories) were noted during the measurements and the obtained sound level data were delivered as equivalent levels for the measurement time $L_{Aeq,dT}$ as well as normalised to equivalent 24-hour levels $L_{Aeq,24h}$. The latter was based on 24-hour traffic estimated from the traffic volume during the noise measurements since official traffic data was not available for this stretch of road. The 24-hour traffic was 167 000 vehicles, with a vehicle distribution comprising 95% Category 1, 1% Category 2 and 4% Category 3. This traffic data was input to the sound level calculations in SoundPLAN 9.1 with the Nord2000 road noise

model [9]. The speed limit 60 km/h was set on all lanes except for the lane closest to the receiver side, where the speed was estimated to 30 km/h due to a traffic congestion at the time of the measurements.

The other parameters were also chosen according to the conditions during the measurements. The weather was partly cloudy, the temperature +10°C and the 3 m/s wind came from south-west, i.e., a tailwind in the direction from source to receiver. The relative humidity was 80% and the air pressure 1013 hPa.

The applied ground impedance classes and corresponding flow resistivity [9] for the surfaces were: Class G (20 000 $kPas/m^2$) for roads and pavements, class F (2 000 $kPas/m^2$) for gravel surfaces and Class E (500 $kPas/m^2$) for lawns and parks etc. The road surface was DAC 16.

Façade reflection loss and reflection depth

The effect of reflection loss in the building façades was tested by applying 0.2 dB or 1 dB (standard) reflection loss, ($DL\alpha$), with three and six reflections in the calculation settings. The difference between 1 dB or 0.2 dB reflection loss in the façade ($DL\alpha$) was of little significance in the present case, 0–0.3 dB except in the calculation positions 26 m and 37 m from the noise barriers (i.e., between the gables of two buildings) where the difference amounted to 0.3–0.5 dB. If the number of reflections was increased from 3 to 6 in the calculation setting, the sound levels in these points became up to 1.5 dB higher, regardless of whether the façades had 0.2 dB or 1 dB reflection loss.

Results

Since the existing noise barriers at Site 3 were assumed to have sound absorbing effect on the noise from the road traffic, this was tested by applying different absorption (i.e., reflection loss $DL\alpha$) on the barriers in the calculations. The calculated results were then compared with the measured sound levels.

The tested $DL\alpha$:s were 1, 4 and 8 dB, applied as single-number values, either on the roadsides only or on both sides, of the noise barriers at both sides of the road. According to the report, the application of absorption to the roadsides gave none, or very little, effect on the calculated $L_{Aeq,24h}$ noise levels (for all $DL\alpha$ values). The best agreement with measured sound levels was obtained with 4 dB sound absorption on both sides of the noise barriers, see Figure 3.22.

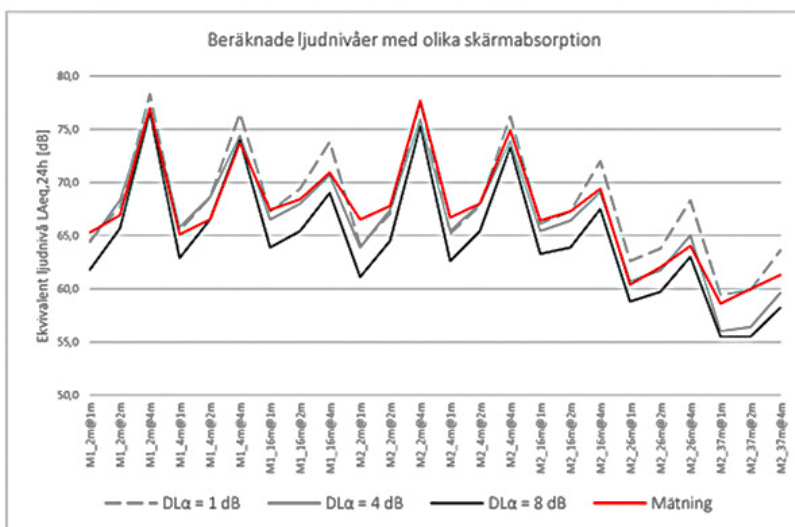


Figure 3.22: Site 3. Calculated sound levels with different noise barrier absorption, $DL\alpha$, compared to measurement results (red line). For each case, the same absorption is applied to both sides of the noise barriers (Figure: Akustikkonsulten).

Tables 3.18 and 3.19 present the calculated and measured equivalent sound levels. The calculations are based on $DL\alpha = 4$ dB on both sides of the noise barriers, reflection loss 0.2 dB in building façades and the reflection depth for the calculations is set to 3.

Table 3.18: Site 3, receiver line 1. Calculated and measured $L_{Aeq,24h}$ (dB) and the difference between them. Calculations with $DL\alpha = 4\text{dB}$ on both sides of noise barriers, reflection loss 0.2 dB in building façades, reflection depth=3.

Receiver	Meas. $L_{Aeq,24h}$ (dB)	Calc. $L_{Aeq,24h}$ (dB)	Diff. Meas-calc (dB)
$M_1 2m@1m$	65,3	64,4	0,9
$M_1 2m@2m$	66,9	68,3	-1,4
$M_1 2m@4m$	77,0	77,0	0,0
$M_1 4m@1m$	65,1	65,8	-0,7
$M_1 4m@2m$	66,5	68,6	-2,1
$M_1 4m@4m$	73,7	74,4	-0,7
$M_1 16m@1m$	67,4	66,5	0,9
$M_1 16m@2m$	68,4	68,0	0,4
$M_1 16m@4m$	70,9	70,7	0,2

Table 3.19: Site 3, receiver line 2. Calculated and measured $L_{Aeq,24h}$ (dB) and the difference between them. Calculations with $DL\alpha = 4\text{dB}$ on both sides of noise barriers, reflection loss 0.2 dB in building façades, reflection depth=3.

Receiver	Meas. $L_{Aeq,24h}$ (dB)	Calc. $L_{Aeq,24h}$ (dB)	Diff. Meas-calc (dB)
$M_2 2m@1m$	66,5	63,9	2,6
$M_2 2m@2m$	67,8	67,4	0,4
$M_2 2m@4m$	77,7	76,0	1,7
$M_2 4m@1m$	66,7	65,4	1,3
$M_2 4m@2m$	68	68	0,0
$M_2 4m@4m$	74,9	73,9	1,0
$M_2 16m@1m$	66,4	65,4	1,0
$M_2 16m@2m$	67,3	66,4	0,9
$M_2 16m@4m$	69,4	69,1	0,3
$M_2 26m@1m$	60,4	60,7	-0,3
$M_2 26m@2m$	62	61,7	0,3
$M_2 26m@4m$	64,0	65,0	-1,0
$M_2 37m@1m$	58,6	56	2,6
$M_2 37m@2m$	60,0	56,4	3,6
$M_2 37m@4m$	61,3	59,6	1,7

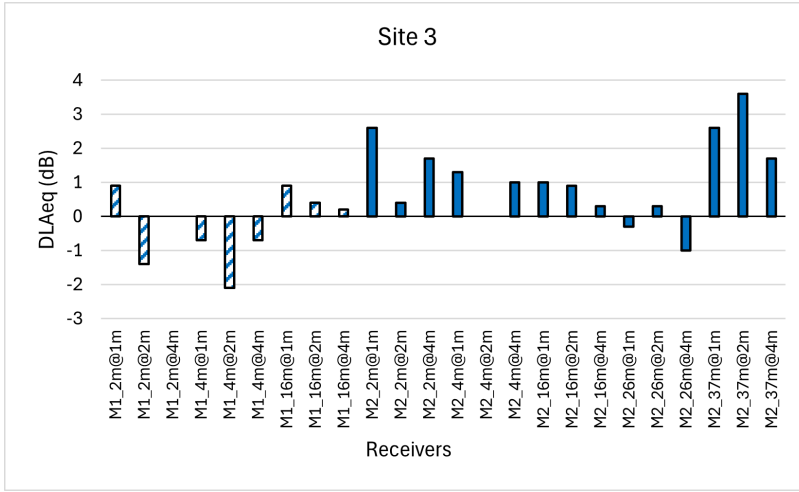


Figure 3.23: Site 3, the difference between measured and calculated $L_{Aeq,24h}$ (dB). Calculations with $DL\alpha = 4$ dB on both sides of the noise barriers and reflection loss 0.2 dB in building façades, reflection depth = 3 (Striped columns = receiver positions along measurement line 1, full columns=receivers along measurement line 2).

Along measurement line 1 the difference between calculated and measured sound levels vary, the largest difference are at 2 m height for both $M1_2m@2m$ and $M1_4m@2m$, where the calculated levels are 1.4–2.1 dB higher than the measured ones, see Figure 3.23.

Along the second measurement line, the measured levels are 0–3.6 dB higher than the calculated in all receiver positions except $M2_26m@1m$ and $M2_26m@4m$. This can be partly explained by background traffic noise that could not be excluded from the measurements. The largest differences are found at all three heights of $M2_37m$, i.e., furthest from the road and between the house gables. However, if the number of reflections is increased from 3 to 6 in the calculation settings, the calculated sound levels in these positions will be up to 1.5 dB higher, i.e., narrowing the gap between measured and calculated sound levels.

The results above were obtained with 4 dB sound absorption on both sides of the noise barriers. However, it is likely that the corrugated side of the concrete noise barriers (on the roadside) has lower sound absorption than $DL\alpha = 4$

dB. Moreover, calculations with absorbers on the roadsides only, had none or very small effect on the resulting L_{Aeq} levels compared to a situation without absorbers on the noise barriers. Whereby no indication on the real absorption of the noise barriers can be given, unless measured with an in-situ sound reflection measurement method, e.g., according to the standard test method EN 1793-5, [15], or by the SOPRA method, as described in Chapter 2.

3.7 Conclusions from the case studies

Drawn conclusions of the three case studies are presented in this section, followed by suggestions for improving noise assessments in Chapter 3.8.

Calculations vs. measurements

All sites: The meteorological parameters should be as similar as possible in the SoundPLAN calculation settings as during the measurements for better agreement between measured and calculated sound levels.

Site 1: Concerning sound reflections, both the reflection depth and the building façade absorption may be important. At Site 1 it was a better agreement with zero or very low reflection loss (0.2 dB) in the façade than with the default value of 1 dB. Increasing the reflection depth from 3 to 4 reduced the difference between calculated and measured levels. However, further increasing the number of reflections did not increase the noise levels more than marginally, e.g., 6 reflections gave 0.1 dB higher levels in a few receiver positions at a higher computational cost. See also the comment about reflection depth of Site 3 below.

Site 2: Including traffic in the local street in the calculation resulted in better agreement with the measured levels, since the local traffic was concluded to be the dominating source of the total sound levels in all receiver positions except $mp_2d_2h_4$.

Sites 1 and 2: The calculated sound levels in positions $mp_1d_2h_4$ and $mp_2d_2h_4$, i.e., above the top of the noise barriers, were remarkably higher than the measured ones.

Site 3: Calculations with AADT based on traffic volume during the measurements gave a better agreement with the measured sound levels than official AADT (Sites 1 and 2).

Site 3: 4 dB absorption on roadsides as well as receiver side of noise barriers in the calculation resulted in the best agreement with measured levels - even though the roadside surfaces of the existing noise barriers probably did not have that high absorption. For establishing the absorption of the installed noise barriers, in-situ sound reflection measurements would be necessary, e.g., according to the standard test method EN 1793-5, [15], or by the SOPRA method, as described in Chapter 2.

Site 3: Concerning reflection depth, a higher number of reflections in the

calculation setting reduced the gap between the measured and the calculated noise levels in position M_237m , i.e., between two house gables. With the standard 3 reflections, the calculated levels were up to 3.6 dB lower than the measured. With 6 reflections, the calculated sound levels in these positions increased by 1.5 dB.

Effect of wind and other weather conditions

The weather conditions, mainly the wind direction, had a strong impact on the calculated noise levels in Sites 1 and 2, and therefore a separate study of the effect of the wind direction was conducted. Here, the results are exemplified by the calculations based on the 2025 situation at Site 2, with a 2 m/s wind blowing from the north (tailwind) or south (headwind), compared with the standard weather settings based on the RTN96 weather according to [10], with a 1.5 m/s downwind towards the receivers (the receivers at Site 2 are south of the motorway). The calculations have been performed with both 80 km/h and the average measured speeds 89/82/82 km/h. Only traffic on the motorway was included in the calculations.

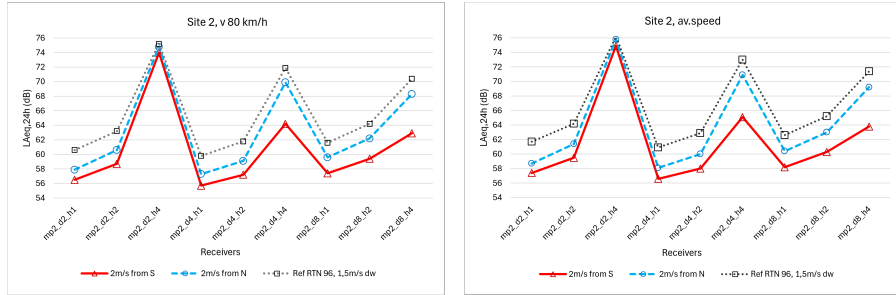


Figure 3.24: Calculated $L_{Aeq,24h}$ based on $v=80$ km/h (left) and average speed (right) with different weather conditions.

The results are presented in Figure 3.24. In all positions, the RTN96 weather results in higher levels than a manually set wind in a perpendicular direction from the road to the receivers (i.e., tailwind). In Site 2, the noise levels are 1.4–2.7 dB lower with 2 m/s wind from north than with the RTN96 weather.

It can be noted that, temporary weather conditions are not suitable for

evaluation of the traffic noise in relation to noise limits, nor for noise mitigation plans. For this, statistically more representative weather data should be applied (which is also recommended for the END noise mapping [9]). If such statistics are lacking or not available for some reason, it is recommended (in Sweden) to instead use the aforementioned standard weather parameters from the old Nordic Road noise traffic model [10]. However, it should be recognised that the calculated $L_{Aeq,24h}$ results based on the standard weather could both over- and underestimate the noise level in specific sites, which can lead to erroneous decisions about noise mitigation actions.

3.8 Suggestions for noise calculations

Based on the conclusions of Chapter 3.7, this part contains some suggestions for improving noise calculations and evaluations.

Weather condition: In general, actual weather statistics is recommended for assessing noise levels and planning noise mitigation measures. If this is not available for the area in question, the weather settings according to the national guidelines (e.g., [10]) should be used. For local noise action plans, the local weather conditions could be studied for different times of the day and also for different times of the year, to find critical situations that could be the basis for the noise calculations and subsequent dimensioning of the noise mitigation measures. This could be very specific, e.g., for schools or park areas it could be checked whether the input of wind directions and wind speed during daytime (or certain time of year) give results which differ from the results of calculations with average or standard weather.

Traffic variation: study the available traffic data for the particular site or road stretch. If large variations during day and night times are common, consider using other data than 24-hour average AADT as input, to simulate the noise situations during certain times, e.g., daytime levels when planning noise mitigation for recreation areas, school yards, parks etc., or nighttime levels for reducing annoyance and sleep disturbance indoors. This also includes variations in average speed, which might be higher at times outside of the rush-hours.

Other noise sources: Check if other noise sources in the vicinity can contribute to the noise level at the receiver positions, e.g., visit the site and assess the sound ambient. If it is not possible to find data for other noise sources, like

traffic data for local streets, consider noise measurements. The knowledge of other noise sources is important for the planning of noise mitigation measures, especially for the use of absorbers.

Façade reflection loss: In Nord2000/SoundPLAN, a default value of 1 dB reflection loss is assumed for all building façades. In order to minimize the risk of underestimating the noise level, consider reducing the reflection loss in façades close to outdoor areas where the noise levels may be affected by multiple sound reflections.

Reflection depth: The recommended minimum reflection depth for detailed noise calculations in Nord2000/SoundPLAN is 3 reflections. Test if the number of reflections should be higher for sites with hard and presumably sound reflecting surfaces. See also "Canyon-like sites".

Canyon-like sites (e.g., Site 1 and 3): assess the reflection depth of the calculations, whether the standard value of 3 is enough or if a higher number of reflections should be applied to avoid the risk of underestimation of the noise levels as well as the effect of absorbers (on noise barriers).

Evaluate calculated noise levels in certain receiver positions critically, e.g., relating to the receiver positions just above the line of sight of the noise barriers in Sites 1 and 2. One cause for questionable results could be differences between the heights in the digital terrain model and the real terrain.

Measurements: Preferably, perform validating sound level measurements under conditions according to the standard method, i.e., with a weak tailwind from source to receiver. If not possible, evaluate the effect of the weather situation for the receiver positions, e.g., by comparing the results of calculations with tailwind and headwind (see also section about weather conditions above).

3.9 Uncertainty

For moderately complex terrains or terrains with screens and wind speeds up to 5 m/s, the uncertainty of the sound propagation model of Nord2000 has been validated to 1 dB within 400 m distance from the noise source, and 2 dB for 400–1000 m distance [34]. Except for the sound propagation model, several other factors contribute to the total uncertainty of a sound prediction method. For Nord2000, according to [9], the combined standard uncertainty comprises the uncertainty of the source noise emission, the sound attenuation during

propagation (transfer function), the vehicle speed and the traffic intensity and distribution over the vehicle categories. With the default values, for a distance shorter than 100 m from the noise source and a vehicle speed of 80 km/h, the standard uncertainty is 1.5 dB. (In addition, the final result depends also on the quality of the data and the execution of the calculations, e.g., settings, [35].)

The uncertainty of the results of road traffic noise measurements depends strongly on the weather and traffic conditions during the measurement periods. If the specifications in the Swedish standard measurement method for road noise [27] are fulfilled, the uncertainty is estimated to 3 dB in positions close to the road. According to the standard, the equipment and measurement chain stands for 1.5 dB of the total uncertainty.

CHAPTER 4

Acoustic effect of absorbers

In this chapter it is examined whether different absorption indices on road noise barriers can affect the traffic noise levels in urban settings. This is done by modifying the existing noise barriers in the calculation models of Sites 1 and 2 in Chapter 3 and

- test different absorber applications on the noise barriers in three different situations, Chapter 4.1,
- test different absorber types on the barriers in Site 1, Chapter 4.2.

In addition, a model for Boundary Element Method calculations has been adapted to validate the results from Nord2000 calculations with absorbers on noise barriers, Chapter 4.3.

Parts of Chapters 4.1 and 4.2 were included in a presentation at the BNAM conference 2026 (Paper E).

4.1 Effect of absorber location

Situations and receiver positions

The study was performed on three situations based on Sites 1 and 2, presented in Chapter 3. For Site 2, two sets of traffic noise calculations were performed, the first with traffic on the motorway only and the second including traffic in the local street. As described in Chapter 3, the two sites are located along a motorway flanked by noise barriers on both sides. Site 1 is situated in a 12–15 m narrow yard between a residential building and a 3.7 m tall noise barrier. The noise barrier on the opposite side of the motorway is approximately 3 m tall. Site 2 is behind a 3.0–3.6 m tall noise barrier in a strip of vegetation next to a local street. The nearest buildings are more than 50 m away from the barrier on the receiver side. At Site 2, the noise barrier on the opposite side of the motorway is 5.4 m tall. All noise barriers are made of hard, sound reflecting materials like concrete, transparent sheets or metal panels. Schematic figures of the sites are presented in Figure 4.1.

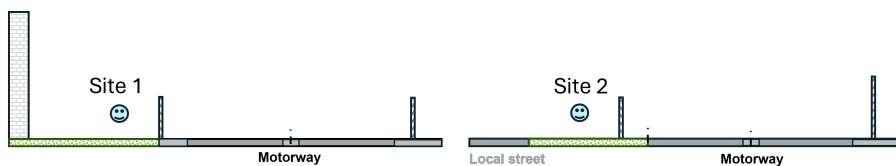


Figure 4.1: Sketches of Site 1 (left) and Site 2 (right). (Figures not to scale.)

The calculations were performed for single point receivers. In both sites, the receiver positions were at 1, 2 and 4 m height at three distances, 2, 4 and 8 m behind the noise barrier. The receiver positions in the following text, tables and graphs are normally denoted as $mp_{1,2}$ (measurement position), d_{xm} (distance) and h_{xm} (height), mp or mp_1 for Site 1 and mp_2 for Site 2.

Input data and calculation settings

The geographic data of Sites 1 and 2 in Chapter 3 were used for this study, including the digital model of the terrain, roads, buildings and existing noise barriers, as well as the ground impedance classes, see Figures 3.9 and 3.10. The AADT (Annual Averaged Daily Traffic) on the motorway was 76 000 in

total (both directions) distributed over three vehicle categories: Category 1 (passenger cars) 94.5 %, Category 2 (medium and heavy vehicles with 2-4 axles) 0.9 % and Category 3 (heavy vehicles with 4 axles or more) 4.6 %. The 80 km/h speed limit was used as driving speed for all vehicle categories. For the local street at Site 2, the AADT was 8 100 vehicles with 96.5% of Category 1, 1.5% of Category 2 and 2.1% of Category 3 vehicles. The driving speed was 60 km/h.

The motorway has three lanes in each direction with a 3 m hard middle section. At Site 1, there are hard shoulders on both sides of the motorway, all the way to the noise barriers. At Site 2, there is a strip of vegetation between the safety rail and the noise barrier on the side closest to the receiver, but not at the opposite side of the motorway. The total width between the noise barriers is approximately 33 m at both sites. The local street is a 2-lane road with hard shoulders and a total width of 8 m. The road surface type DAC 16 was assumed for both the motorway and the local street.

The standard weather conditions, according to[9], [10], were applied, including wind speed 1.5 m/s with a downwind direction from source to receiver, air temperature +15 °C, relative humidity 70 % and air pressure of 1013.3 mbar.

The remaining calculation settings were identical to the ones of the test case studies in Chapter 3, e.g., reflection depth (4 for Site 1 and 3 for Site 2) and 0.2 dB façade absorption on buildings at Site 1.

Absorber application

Three alternative absorber applications were tested for both sites: on the roadside of the noise barriers on both sides of the motorway, on the receiver side (only the barrier close to the receivers) and on both sides of the noise barriers on both sides of the motorway (the maximum absorber alternative), see Figure 4.2. In addition, for the situation with only motorway traffic at Site 2, two other options were tested concerning the noise barrier on the opposite side of the road: absorber on the opposite noise barrier only and removing the opposite barrier, see Figure 4.7. The one-third octave band absorber indices of the mineral wool cassette was used, see Chapter 4.2. The resulting noise levels from each alternative were compared with the reference situation without absorbers, i.e., with sound reflecting noise barriers.

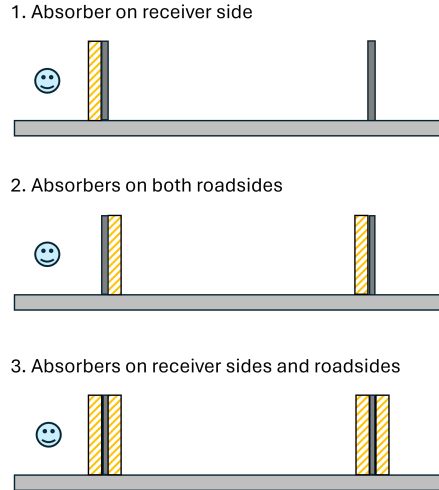


Figure 4.2: Studied absorber positions on the noise barriers. (Figures not to scale).

Result, Site 1

The result for Site 1 is presented in Figure 4.3. The calculated A-weighted 24-h equivalent noise level, $L_{Aeq,24h}$, in the receiver positions with *sound reflecting barriers* were between 61.9 and 73.2 dB in Site 1. The highest noise levels were at 4 m above the ground, i.e, above the noise barrier height. In the other positions the sound levels varied between 62 and 64 dB.

For all receiver positions, the largest difference in noise reduction between the absorber alternatives and the reference situation was obtained with the maximum absorber alternative, with up to 2.6 dB lower noise level, see Figure 4.4. The second best alternative at Site 1 depended on the receiver position. Close to the noise barrier at 1 and 2 m height, the absorber on the receiver side of the barrier gave up to 0.6 dB higher noise reduction than the absorbers on the roadsides, but further from the barrier and at 4 m height, the roadside absorbers were the better of the two options.

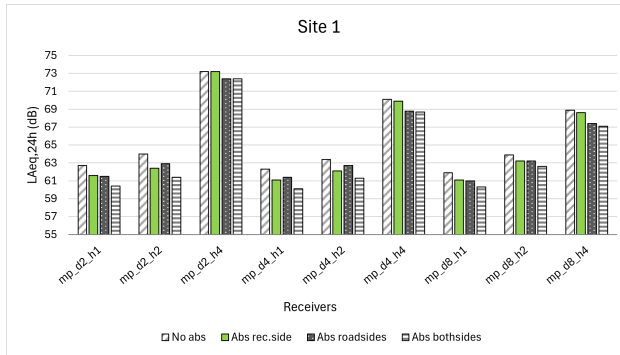


Figure 4.3: Site 1, $L_{Aeq,24h}$ in the receiver positions of Site 1, with reflecting noise barrier and with the alternative absorber applications.

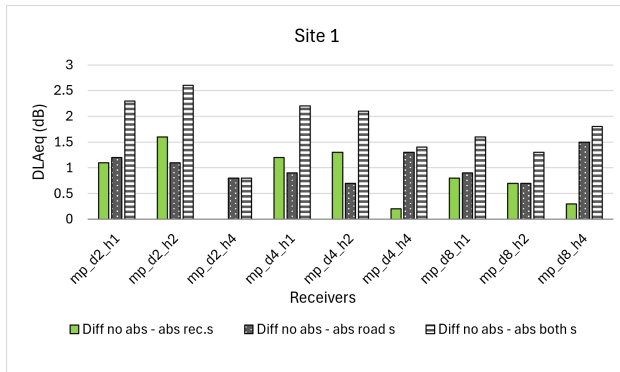


Figure 4.4: Site 1, the difference in noise reduction DL_{Aeq} (dB) between situation without absorbers and with different absorber applications on the noise barriers.

Result, Site 2

Two situations were studied in Site 2, the first with traffic on the motorway only and the second including traffic in the local street, which is situated on the receiver side of the noise barrier, as presented in Figure 4.1. The calculated A-weighted 24-h equivalent noise level, $L_{Aeq,24h}$, in the receiver positions with sound reflecting barriers were between 60.6 and 75.2 dB with motorway traffic

only, and 63.1–75.4 dB when the noise from the local traffic was included in the calculations, see Figure 4.5 and Table 4.1. In both situations, the highest noise levels are at 4 m height, where the local traffic increases the noise level by 0.2–1.0 dB. At the receiver positions 1 and 2 m above the ground the total sound levels are 2.4–3.3 dB higher when the local traffic is included in the calculations.

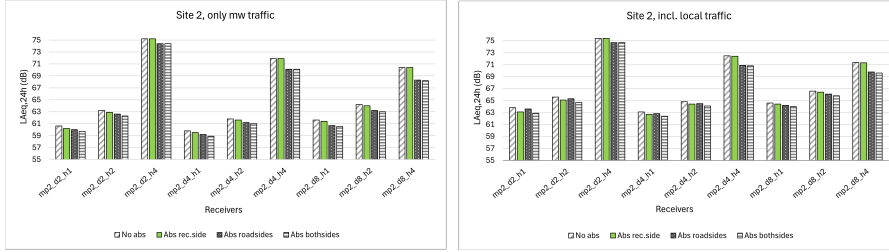


Figure 4.5: $L_{Aeq,24h}$ in the receiver positions of Site 2, with reflecting noise barrier and with the alternative absorber applications. For situation with motorway traffic only (left) and for situation including local traffic (right).

Table 4.1: Site 2, the calculated equivalent A-weighted sound levels $L_{Aeq,24h}$ with and without the local traffic, and the difference DL_{eq} between the levels.

Receiver	Incl. local tr $L_{Aeq,24h}$ (dB)	Excl.local tr. $L_{Aeq,24h}$ (dB)	Diff Incl-excl. local tr. (dB)
$mp_2d_2h_1$	63,8	60,6	3,2
$mp_2d_2h_2$	65,6	63,2	2,4
$mp_2d_2h_4$	75,4	75,2	0,2
$mp_2d_4h_1$	63,1	59,8	3,3
$mp_2d_4h_2$	64,8	61,8	3
$mp_2d_4h_4$	72,5	71,9	0,6
$mp_2d_8h_1$	64,6	61,6	3
$mp_2d_8h_2$	66,6	64,2	2,4
$mp_2d_8h_4$	71,4	70,4	1

As for Site 1, the maximum absorber alternative results in the highest noise reduction compared to the reference situation, with up to 2.2 dB lower noise levels for the situation with only motorway traffic and 1.8 dB lower levels

when including the local traffic, see Figure 4.6. But contrary to Site 1, the largest reduction is at the positions furthest from the noise barrier.

The second best option for the case with only motorway traffic was the alternative with absorbers on the roadsides. In contrast to Site 1, absorbers on the receiver side of the noise barrier gave very little effect in all receiver positions (0–0.4 dB). However, when noise from the local traffic is taken into account, absorbers on the receiver side were better than the roadside absorbers in positions close to the noise barrier and at 1 m and 2 m height.

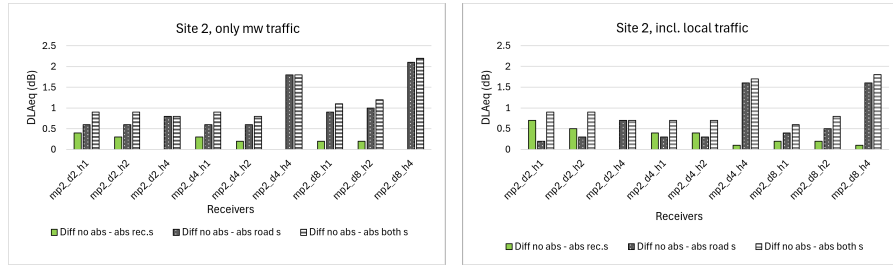


Figure 4.6: Site 2, the difference DL_{eq} in noise reduction DL_{eq} (dB) between situations without absorbers and with different absorber applications on the noise barriers.

For the situation with only motorway traffic at Site 2, two additional options were tested concerning the 5.4 m tall noise barrier on the opposite side of the road: (1) absorber on the roadside of the opposite barrier (but not on the barrier on the receiver side) and (2) removing the opposite barrier. The alternatives are illustrated in Figure 4.7. The results, presented in Figure 4.8, show that the two additional alternatives improved noise reduction by 0.5–2.1 dB compared to the situation without absorbers on the noise barriers, and are in general as effective as installing absorbers on the roadsides of all noise barriers. Furthermore, these three alternatives are as good as the maximum alternative at 4 m height.

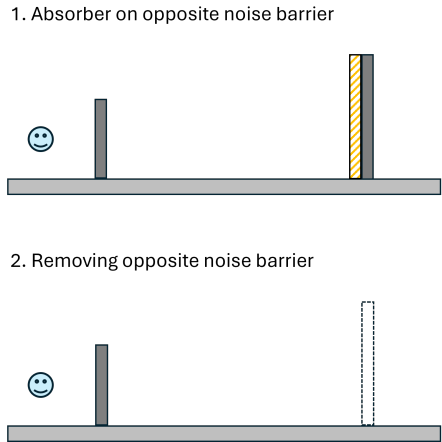


Figure 4.7: Additional alternatives at Site 2. *Figures not to scale.*



Figure 4.8: Site 2, the difference in noise reduction DL_{eq} (dB) between situation without absorbers and with different absorber applications on the noise barriers, including the additional alternatives.

Conclusion about absorber location

Absorbers on noise barriers reduce the traffic noise levels, but the effect of the various absorber locations is strongly site dependent. What may be a good choice for one site may not be the best option for another site, even if it is along the same road.

4.2 Effect of absorber type

In this chapter, the effect of different absorption indices on noise barriers has been studied. Four different absorber or noise barrier types were tested on the existing noise barriers at Site 1: perforated metal cassette with mineral wool, porous concrete, LDPE foam panel and cement-bound wood wool sheets, presented in Figure 4.9. The absorbers' single-number absorption values RI or RI_Q (i.e., reflection index in direct sound field) vary from 3.9 dB to 6.0 dB, see Table 4.2. The absorption data for three of them originate from (own) SOPRA RI_Q measurements (Chapter 2.3). The fourth absorber has been measured by a certified test facility according to the standard EN 1793-5 for declaration of RI [15]. All four absorber types were tested on the three alternative absorber applications described in 4.1, i.e., on the receiver side (only on the noise barrier closest to the receiver), on the roadsides and on both sides of the noise barriers.



Figure 4.9: The absorber and noise barrier types: perforated metal cassette with mineral wool (top left), porous concrete (top right), LDPE foam panel (bottom left) and cement-bound wood wool sheets (bottom right).

Table 4.2: Applied absorber types, single-number values RI or RI_Q and frequency range of measurement. The thickness refers to the absorber layer/panel or total absorber thickness in noise barrier construction (*Assumed thickness).

Absorber, thickness	Method	RI/RI_Q (dB)	Freq.range (Hz)	Comment
Mineral wool in metal cassettes, 50 mm*	SOPRA	6.0	250–5000	Roadside
Porous concrete, 70 mm	SOPRA	5.6–5.9	250–5000	In factory yard
LDPE, Low-density polyethylene foam, 40 mm	EN 1793-5	4.9	200–5000	Test facility
Cement-bound wood wool, 20 mm + 50 mm* min.wool	SOPRA	3.1	250–5000	Older noise barrier

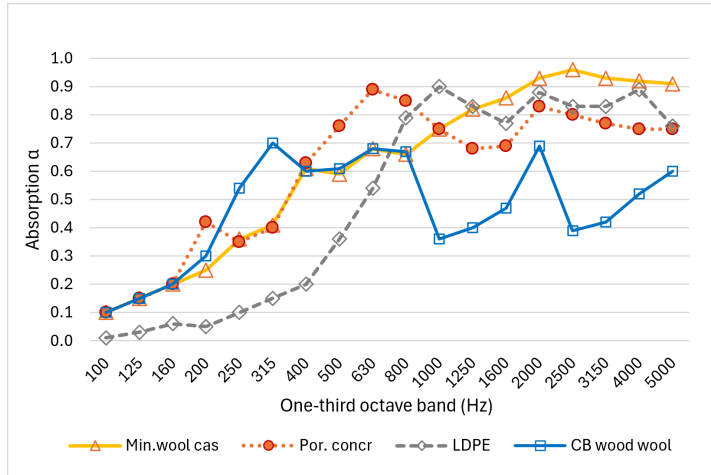


Figure 4.10: Absorption spectra for the tested absorbers. (Note: the valid frequency ranges of the measurements are shown in Table 4.2).

The one-third octave band absorption spectrum of each absorber type, Figure 4.10, was inserted into the SoundPLAN noise barrier library and subsequently chosen for the different absorber applications. Absorption values

outside of the valid frequency ranges of the measurements have either been very moderately guessed or extrapolated for the noise calculations in SoundPLAN (with frequency range 25–10 kHz), e.g., for the mineral wool cassette absorber, see Table 4.6.

Results

The three alternative absorber applications show similar results concerning the effect of the different absorber types and will here be represented by the results from the alternative with the largest noise reduction, i.e., with absorbers on both sides of the noise barriers. To begin with, the results are in agreement with the corresponding alternative in the previous chapter, 4.1, i.e., the best noise reducing effect of applying the absorbers is found at the receiver positions 1 and 2 m above ground, 2 and 4 m from the noise barrier, see Figure 4.11. The least effect of the absorbers was in the position just above the top of the barrier, i.e., at 4 m height, 2 m from the noise barrier in $mp_1d_2h_4$.

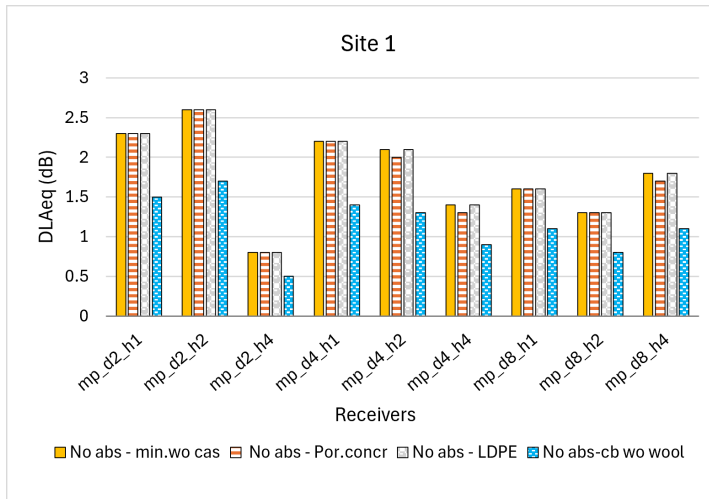


Figure 4.11: The difference in noise reduction DL_{Aeq} (dB) between situation without absorbers and with different absorber types applied to both sides of the noise barriers at Site 1.

The absorber type with the lowest absorption value (cement-bound wood

wool, RI_Q , 3.1 dB) also gave the least noise reduction (0.5–1.7 dB), whereas the other three absorbers resulted in up to 0.9 dB better noise reduction (0.8–2.6 dB), see Table 4.3. There was no, or very little, difference between the results of these three absorbers, even though their RI or RI_Q varied from 4.9 to 6.0 dB.

Table 4.3: The calculated $L_{Aeq,24h}$ without absorbers and with different absorber types applied to both sides of the noise barriers at Site 1. Last column shows the difference DL_{Aeq} between the cement-bound wood wool and the other absorbers.

Receiver	No abs (dB)	Por. concr (dB)	LPDE (dB)	Min. wool cas (dB)	Cb wood wool (dB)	DL_{Aeq} Cbw - others (dB)
$mp_1d_2h_1$	62.7	60.4	60.4	60.4	61.2	0.8
$mp_1d_2h_2$	64.0	61.4	61.4	61.4	62.3	0.9
$mp_1d_2h_4$	73.2	72.4	72.4	72.4	72.7	0.3
$mp_1d_4h_1$	62.3	60.1	60.1	60.1	60.9	0.8
$mp_1d_4h_2$	63.4	61.4	61.3	61.3	62.1	0.7–0.8
$mp_1d_4h_4$	70.1	68.8	68.7	68.7	69.2	0.4–0.5
$mp_1d_8h_1$	61.9	60.3	60.3	60.3	60.8	0.5
$mp_1d_8h_2$	63.9	62.6	62.6	62.6	63.1	0.5
$mp_1d_8h_4$	68.9	67.2	67.1	67.1	67.8	0.6–0.7

The results on the frequency spectra have also been studied, demonstrated in the following examples from the receiver positions $mp_1d_2h_1$ and $mp_1d_2h_2$ (close to the noise barrier), $mp_1d_4h_2$ (in the middle) and $mp_1d_8h_4$ (closer to the building façade than to the noise barrier). The single-number noise levels, *without absorbers* on the existing noise barriers, are for the first three receivers 62.7–64.0 dBA and for $mp_1d_8h_4$ 68.9 dBA, see column “No abs” in Table 4.3. Accordingly, the corresponding one-third octave band spectrum of receiver $mp_1d_8h_4$ is above the three others’ spectra in Figure 4.12.

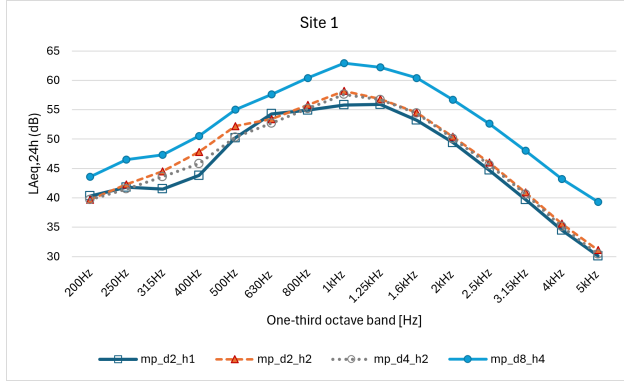


Figure 4.12: One-third octave band spectra at four of the receivers of Site 1 with sound reflecting noise barriers, i.e., without absorbers.

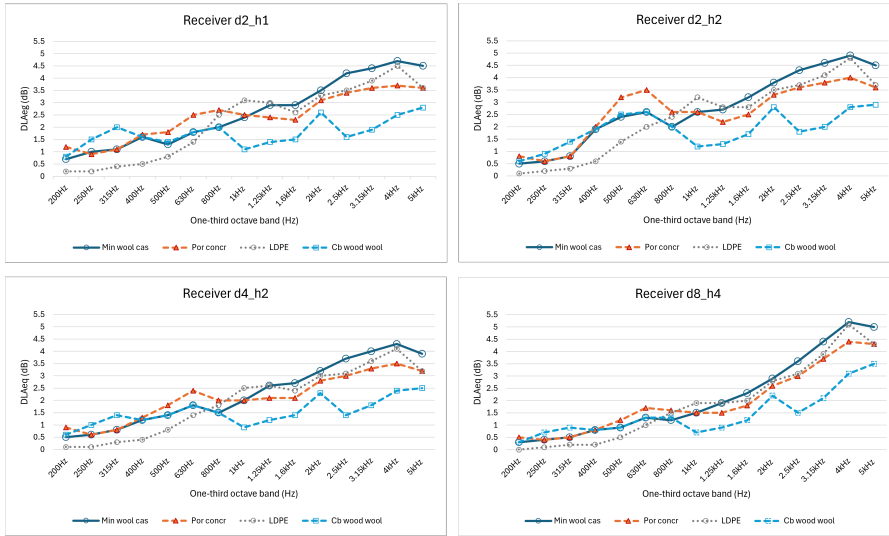


Figure 4.13: The difference in noise reduction DL_{Aeq} (dB) between the situations without and with different absorber types applied to both sides of the noise barriers. Examples of one-third octave band spectra from receiver positions $mp_1d_2h_1$ (top left), $mp_1d_2h_2$ (top right), $mp_1d_4h_2$ (bottom left) and $mp_1d_8h_4$ (bottom right).

In Figure 4.13, the results of applying absorbers on both sides of the noise barriers are presented for each of the four receivers as the difference in noise reduction, DL_{Aeq} (dB), compared with a reflecting noise barrier. These graphs show that different absorber spectra (Figure 4.10) result in different noise reduction spectra, even if the single-number values of the noise reduction, DL_{Aeq} , are the same. Furthermore, the cement-bound wood wool with 0.6–0.9 dB lower DL_{Aeq} than the other three tested absorbers, has some advantage in the lower frequencies and is as good or better than the mineral wool cassette up to 800 Hz. The mineral wool cassette has the best DL_{Aeq} in the higher frequencies, above 1250 Hz, and the light-weight LDPE is the second best above 800 Hz but has the lowest noise reduction at lower frequencies. The heavy and thick porous concrete has a strong noise reduction in the 400–800 Hz range.

What also can be observed, is that the effect of the absorber type implementations varies with the distance from the noise barrier and height above ground, e.g., the largest reduction of low-frequency noise is found close to the noise barrier, at the receiver positions $mp_1d_2h_1$ and $mp_1d_2h_2$.

Conclusion about absorber type

From this study it can be concluded that different absorber types result in different calculated noise level reductions. If only considering the single-number values, three of the tested absorbers gave equally good sound level reductions DL_{eq} even if their RI or RI_Q varied between 4.9–6.0 dB. But if the effect of different absorber types is studied on the spectrum level, there are variations which might be important to consider for certain locations, e.g., in narrow spaces between building facades and noise barriers where there might be a strong low-frequency content in the noise.

Note, the number of measured samples of each absorber or noise barrier type in this study is too small to draw any general conclusions about the possible sound absorbing performance of the materials.

4.3 Validation using the Boundary Element Method

Introduction

When noise mitigation measures are considered, the most important question to answer is what noise reducing effect they would have, concerning both the reduction as single-number equivalent levels, DL_{Aeq} , and the changes in the frequency spectra (e.g., in one-third octave bands). The decisions are usually based on results from calculations, in Sweden with the Nord2000 model, however, it is not until the measure is taken, i.e., when the noise barrier has been built, that the accuracy of the predicted results can be controlled by measurements.

Previous parts of this thesis have concerned the effect of sound absorbing materials and surfaces in urban road infrastructure, focusing on sites where hard, sound reflecting noise barriers already exist. The effect of different absorber applications on the existing noise barriers (on the road side, receiver side or both sides of the barrier) has been calculated with the Nord2000 model in SoundPLAN and conclusions have been drawn: (1) The effect of the location of an absorber is site dependent (see 4.1) and (2) Different absorbers give different results (see 4.2).

Here, the Boundary Element Method (BEM) is used to validate results obtained by the Nord2000/SoundPLAN calculations, specifically concerning the effects of installing absorbers on sound reflecting noise barriers. This is done by comparing the resulting insertion loss, IL, from a reflecting noise barrier with the IL from a sound absorbing noise barrier.

The Nord2000 road noise prediction method

The Nord2000 road noise prediction method [9] has been the prescribed road and railway noise calculation method in Denmark since 2007 and for the Swedish Transport Administration since 2024. The Nord2000 method includes source models for road and rail traffic in one-third octave bands from 25 Hz to 10 000 Hz. For the road noise model, the traffic is divided into three vehicle categories (Category 1 - passenger cars, Category 2 - medium or heavy vehicles with 2-3 axles and Category 3 - heavy vehicles with 4 axles or more). The sources are set at three heights above the road surface: 0.01 m

for the tyre-road noise for all three vehicle categories, 0.30 m for the propulsion noise of cars and 0.75 m for the propulsion noise of medium and heavy vehicles. The sound propagation model [31], [36] is based on geometrical ray theory and contains algorithms for computing one-third octave band sound attenuation along the path from source to receiver, taking into account the terrain shape and the acoustic impedance of the ground type. The calculation of screening is based on geometrical theory of diffraction and the effect of ground and barrier surface is modelled using a Fresnel zone weighting [31]. Downward or upward refraction is modelled by using curved sound rays following circular arcs with the curvature depending on the sound speed profile and the location of the source and the receiver (Note: not modelled in BEM.).

The Nord2000 model is implemented in the SoundPLAN noise prediction software [25], including the eight ground impedance classes defined in Nord2000. Absorption coefficients, in one-third octave or octave bands, for noise barriers can be inserted into the SoundPLAN absorption library. In the software, the absorption coefficients for fibrous porous materials can also be calculated from the effective flow resistivity, σ , of the material.

The 2.5D BEM

To evaluate the results from the Nord2000 calculations of the situations in this study, the 2.5D Boundary Element Method (2.5D BEM) is applied (in MATLAB). The 2.5D BEM models a point source based on a 2D geometry (x and z coordinates, see Figure 4.16) that is assumed to be constant in the y -direction, creating a 3D approximation. This approximation does not require a full 3D model, which reduces the computation time. The transform from a 2D to a 3D solution is described in, e.g., [37] and an example of the application of the transformation for BEM can be found in [38].

The used BEM model for this study originates from previous work by Forssén and van der Aa, e.g., [38]. The adaptations of the model are made by Forssén and the author. The situation without noise barrier, i.e., with hard ground only, is calculated analytically with source strength according to the Nord2000 model.

Test situations

The insertion loss, IL, is the sound level difference at the receiver position without and with noise barrier (i.e., before and after installing a noise barrier). The single-number IL uses A-weighted traffic noise levels. For the BEM evaluation of the Nord2000/SoundPLAN results concerning the effects of installing absorbers on sound reflecting noise barriers, the resulting insertion losses from the two methods are compared in terms of the differences between the single-number insertion losses of a reflecting noise barrier and of a sound absorbing noise barrier, as $D_{IL} = IL_{nb,refl} - IL_{nb,abs}$. Spectral comparisons are also made. For $IL_{nb,abs}$ there are three alternative absorber applications, see Figure 4.14:

- On the roadside
- On the receiver side
- On both sides of the noise barrier

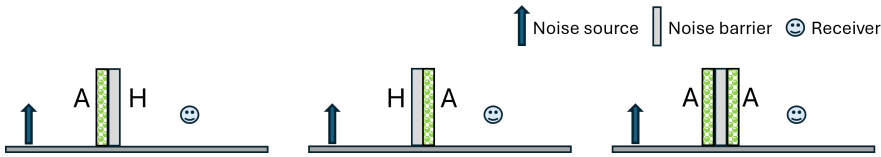


Figure 4.14: Alternative absorber applications on the noise barrier, on the roadside, on the receiver side and on both sides. A = absorber, H = hard surface.

Two situations are studied, Situations 1 and 2, all based on simplifications of study Site 1 (3.2) illustrated in Figure 4.15, 1a: Hard ground and hard noise barrier, 2a: Hard ground, hard noise barrier and a 20 m tall building façade 14 m from the noise barrier (the façade is assumed to have 0 dB reflection loss). The three alternative absorber applications are tested on both situations.

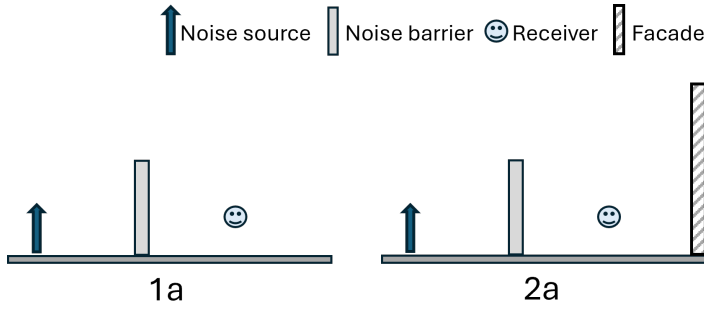


Figure 4.15: Studied situations: 1a. Hard ground and hard noise barrier, 2a. Hard ground, noise barrier and façade.

Geometry

In this study, the 2D BEM models of the two situations comprise the source, receiver and noise barrier positions defined by their x (horizontal) and z (vertical) coordinates, see Figure 4.16. The horizontal plane $z=0$ represents the hard ground and the vertical plane at $x = x_{façade}$ represents the building façade in Situation 2, 14 m from the noise barrier. These planes are given a reflection factor of 1, i.e., they are assumed to be fully reflective, as is the ground between the noise barrier and façade, and are modelled in BEM as symmetry planes, see Figure 4.16. However, for the comparison of the results from Nord2000/SoundPLAN and BEM calculations, the corresponding 3D model of Site 1 in SoundPLAN must be simplified. Thus, the terrain and road surface height was set to 0 m, the building was slightly adjusted to be parallel to the noise barrier and the noise barrier was extended by 200 meters so that the diffracted sound contributions from the vertical edges of the barrier would be negligible compared to the diffraction of the top of the barrier, see Figure 4.16.

Furthermore, the building height was increased to 20 m in order to simulate the conditions in the BEM model of Situation 2 where the façade is represented by an infinite symmetry plane. The reflection loss in the façade was set to 0 dB, to match the equivalent of the reflection factor in the BEM model.

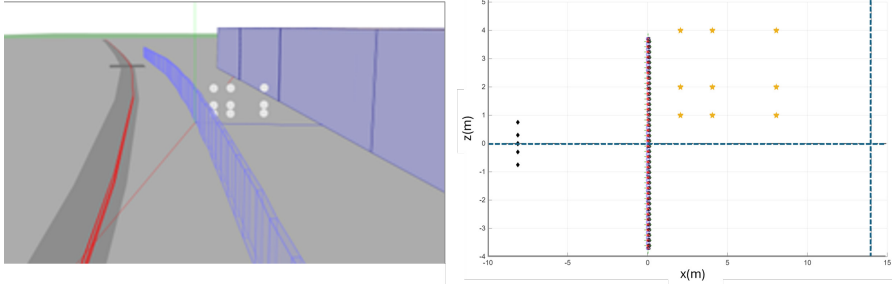


Figure 4.16: To the left: the SoundPLAN model of Situation 2, with a building to the right of the receiver positions (white dots). To the right: the BEM model of the sources (black rhombi), receivers (yellow marks) and noise barrier in both situation 1 and 2. The image x -plane for the hard ground and the image z -plane for the building façade (in Sit.2) are illustrated by the dashed lines.

Input data

The following input data have been used in the SoundPLAN and BEM calculations.

Traffic: AADT 16 443 (one lane, same direction), distributed over three vehicle categories: Category 1: 94.5%, Category 2: 0.9%, Category 3: 4.6%. Speed for all vehicle categories, $v=80$ km/h. The traffic noise sources were positioned according to the Nord2000 model, with the following height above the road surface for the vehicle categories:

- Tyre/road, all vehicle categories: 0.01 m.
- Propulsion noise, Category 1 : 0.3 m.
- Propulsion noise, Categories 2 and 3: 0.75 m.

All noise sources were placed 1 m to the right of the vehicle centre in the driving direction (in accordance with Nord2000 standard [9]). The centre of the vehicles was assumed to be in the middle of the road lane, which had a width of 3.75 m. The total horizontal distance between the emission lines (of the three traffic noise sources) and noise barrier was 8.25 m. The road surface type was SMA 11.

Ground impedance: for the hard shoulder surface between the noise source and the noise barrier on the roadside and for situations with hard surface on receiver side, in SoundPLAN: $\sigma = 20\,000\text{ kPa s/m}^2$, in BEM: reflection factor 1 on hard ground (and hard façade plane).

Noise barrier dimensions: height 3.7 m, thickness 0.025 m was assumed in the BEM model, approximating the fixed width *thin barrier* in SoundPLAN.

The meteorological parameters in SoundPLAN were set as far as possible in accordance with the neutral weather conditions for the BEM calculations, i.e., with no wind and no turbulence, see Table 4.4. The other parameters in SoundPLAN were in accordance with the Swedish instructions for Nord2000 calculations [10].

Table 4.4: : Weather conditions in SoundPLAN. *The turbulence parameters for wind (Cw^2) and temperature (Ct^2) were set as small as possible in SoundPLAN, i.e., close to zero.*

Parameter	SoundPLAN
Temperature	+15°C
Rel.humidity	70%
Air pressure	1013.3 Pa
Wind	0 m/s
Turbulence param, Cw^2	0,0001 $m^{4/3}/s^2$
Turbulence param, Ct^2	0,0001 K/S^2
Wind direction	Downwind (src-> rec)

Calculation settings in SoundPLAN and BEM

The calculations in SoundPLAN and BEM were performed with the settings presented in Table 4.5.

Table 4.5: Settings for calculations in SoundPLAN and BEM model.

Parameter	SoundPLAN	BEM
Reflection order	6	"Unlimited"
Reflections in facades	Included	Included
Facade absorption	0 dB (no refl.loss)	0 dB
Max. search radius (dist. fr source to rec.)	300 m	Sources along 600 m road is included
Max. refl. dist. to rec.	200 m	N/A
Max. refl. dist. to source	50 m	N/A
Allowed tolerance for each source contribution	0.1 dB	N/A
Ground effect from road surfaces	Yes (lane width 3.75m)	Hard ground
Single point calculations, propagation	Calculate refl. of assigned façade, and ignore standard dependent correction	Receiver points defined
Frequency range	25-10 000 Hz	25-5 000 Hz

Absorber

The characteristics of a 100 mm thick mineral wool panel with a flow resistivity, σ , of 22.5 kPas/m² was used as absorber in both SoundPLAN and BEM. For SoundPLAN, the sound absorption data, see Table 4.6, had been obtained by sound reflection index (RI_Q) measurements and inserted into the SoundPLAN noise barrier library for use in the calculations. The RI_Q results had been verified by DFA, the Direct-field absorption model, DFA (see Chapter 2), using the Miki impedance model for porous absorbers [39]. The Miki impedance model was also applied in BEM, where the flow resistivity is input for determining the impedance Z of the absorber.

Table 4.6: Absorption coefficients for the absorber: assumed (*) and measured values, in one-third octave bands from 25 Hz to 10 kHz

Fc (Hz)	25-80	100	125	160	200	250	315	400	500	630
Abs	0.1*	0.11	0.22	0.32	0.61	0.61	0.72	0.78	0.82	0.84
Fc (Hz)	800	1k	1.25k	1.6k	2k	2.5k	3.15k	4k	5k	6.3-10k
Abs	0.86	0.87	0.90	0.93	0.94	0.95	0.97	0.97	0.98	0.98*

Frequency range

About the frequency range, the upper frequency limit of the BEM calculations is quite important since it largely affects the computation time, which increases strongly with frequency. In Nord2000, the standard range for the $L_{Aeq,24h}$ calculations is 25 Hz–10 kHz. Since this is about evaluation of Nord2000/SoundPLAN results, the resulting single-number values from SoundPLAN have been calculated for two shorter ranges, 25 Hz–5 kHz (medium range) and 25 Hz–2.5 kHz (short range) and compared with the full range values, see examples from Situations 01 and 1a in Figure 4.17. The largest differences, 0.10–0.13 dB, are found between the full and short range levels for the situations 01 and 02, i.e, without noise barriers. For all alternatives with noise barriers, the differences are lower than 0.06 dB. The differences between the full and medium frequency range levels were smaller than 0.02 dB in all situations (Sit.1 and Sit.2). Thus, the results from calculations in the full frequency range in Nord2000/SoundPLAN should be comparable to the results from calculations in the medium, or even short, range in BEM.

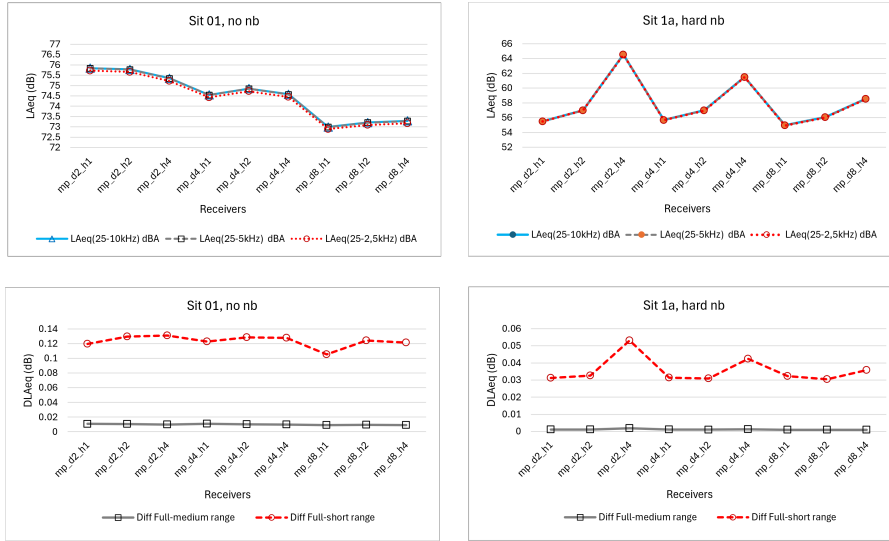


Figure 4.17: SoundPLAN equivalent levels, L_{Aeq} , (top figures) and the difference DL_{Aeq} between them (bottom figures), calculated over three frequency ranges for situation 01 without noise barrier and situation 1a with hard, sound reflecting noise barrier.

Results

First, the sound levels without noise barrier in Situation 01 and 02, i.e., the reference situations, are calculated in SoundPLAN and with the BEM model. Then the insertion loss is calculated for all noise barrier alternatives, i.e.,

- With hard, sound reflecting noise barrier (Sit.1a and Sit.2a).
- With absorber on the roadside of the noise barrier (Sit.1b and Sit.2b).
- With absorber on the receiver side of the noise barrier (Sit.1c and Sit.2c).
- With absorbers on both sides of the noise barrier (Sit.1d and Sit.2d).

Reference Situations 01 and 02, without noise barriers

In the receiver positions of Situations 01 and 02, i.e., without noise barrier, the L_{Aeq} values calculated in SoundPLAN are 71.1–73.9 dB in Situation 01 and

72.7–74.5 dB in Situation 02. The corresponding levels in BEM are 71.5–74.0 dB in Situation 01 and 74.2–75.1 dB in Situation 02. In general, the BEM L_{Aeq} values are higher than the results from SoundPLAN. The SoundPLAN levels differ between -0.7 and +0.2 dB from BEM in Situation 1 and are 0.5–1.8 dB lower than the BEM levels in Situation 2, see Figure 4.18.

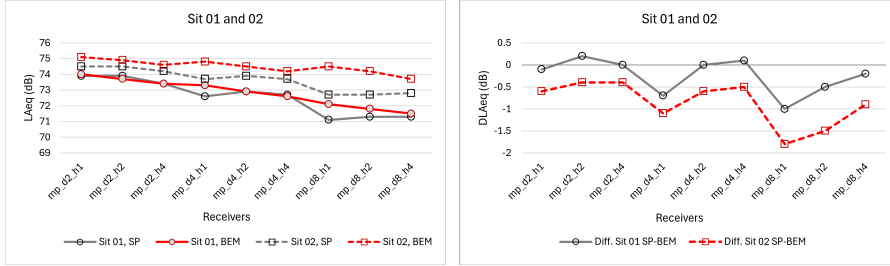


Figure 4.18: Sound levels L_{Aeq} for the reference situations 01 and 02, without noise barriers, calculated in SoundPLAN (SP) and BEM (left side), and the difference DL_{Aeq} between the SP and BEM levels (right side).

Situation 1, insertion loss

The insertion losses (IL) for the different absorber alternatives (Sit.1a–Sit.1d) are presented in Table 4.7. The table includes results from both Nord2000/SoundPLAN and BEM. The introduction of the 3.7 m tall hard noise barrier, i.e., Situation 1a, reduces the L_{Aeq} sound levels in all receiver positions by approximately 10.9–20.3 dB in SoundPLAN and 9.6–17.9 dB in BEM. Then the absorber implementations increase the insertion loss further, by 0.2–1.8 dB in SoundPLAN and 0.9–6.2 dB in BEM, see Figure 4.19. SoundPLAN always calculates higher IL of the screen itself, while BEM mostly results in higher effect of the absorbers (except for positions at 2 m distance from noise barrier in Sit.1b and 4 m above ground in Sit.1c). According to both the SoundPLAN and BEM calculations, the largest insertion losses are found close to the noise barrier at 1 and 2 m above ground (receivers d_2h_1 , d_2h_2 , d_4h_1 and d_4h_2) where Sit.1d with absorbers on both sides of the noise barrier results in the highest noise reduction. The second best alternative, above all in positions close to the noise barrier, is Sit.1c with absorbers on the receiver side.

Table 4.7: Insertion loss (IL) for different absorber alternatives (Sit.1a–Sit.1d) calculated with SoundPLAN or BEM.

Receiver	1a SP (dB)	1a BEM (dB)	1b SP (dB)	1b BEM (dB)	1c SP (dB)	1c BEM (dB)	1d SP (dB)	1d BEM (dB)
$mp_1d_2h_1$	20.3	17.9	21.0	20.2	21.4	22.6	22.1	24.1
$mp_1d_2h_2$	18.9	16.1	19.5	18.4	19.7	19.9	20.3	21.8
$mp_1d_2h_4$	10.9	09.6	11.2	11.0	11.2	10.5	11.5	11.7
$mp_1d_4h_1$	18.9	18.3	19.5	20.2	19.6	21.0	20.2	22.5
$mp_1d_4h_2$	18.0	16.8	18.5	18.7	18.5	19.1	19.0	20.7
$mp_1d_4h_4$	13.4	12.5	13.7	13.8	13.6	13.4	14.0	14.5
$mp_1d_8h_1$	18.1	17.6	18.6	19.2	18.6	19.2	19.1	20.7
$mp_1d_8h_2$	17.4	16.8	17.9	18.4	17.9	18.3	18.3	19.7
$mp_1d_8h_4$	15.0	14.1	15.4	15.5	15.3	15.1	15.6	16.3

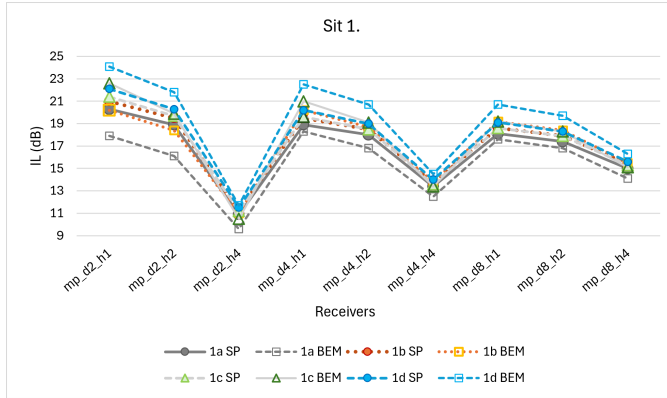


Figure 4.19: Insertion loss (IL) for different absorber alternatives (Sit.1a–Sit.1d), calculated with SoundPLAN and BEM.

The calculated absorber effect according to the SoundPLAN and BEM results, expressed as the difference D_{IL} between the single-number insertion losses from a reflecting noise barrier and from a sound absorbing noise barrier i.e., $D_{IL} = IL_{nb,refl} - IL_{nb,abs}$, is illustrated in Figure 4.20 for Situation 1.

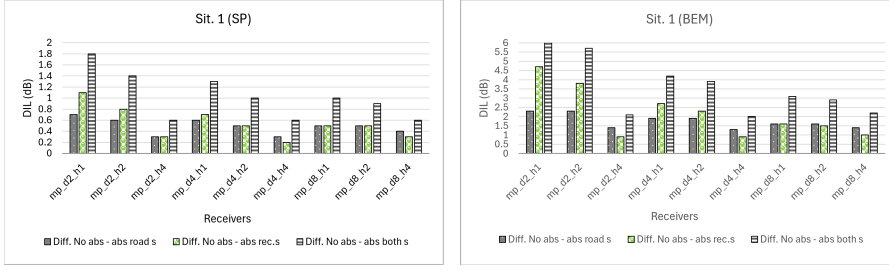


Figure 4.20: The differences D_{IL} between IL from a reflecting noise barrier (No abs) with the IL from a sound absorbing noise barrier, ($IL_{nb,refl} - IL_{nb,abs}$), the SoundPLAN results to the left and BEM results to the right (note the different scales of the figures).

Situation 2, insertion loss

The insertion losses (IL) for the different absorber alternatives (Sit.2a–Sit.2d) are presented in Table 4.8. The table includes results from both SoundPLAN and BEM. The 3.7 m tall hard noise barrier, i.e., Sit.2a, reduces the sound levels, L_{Aeq} , in all receiver positions by 11.5–18.4 dB in SoundPLAN and 10.3–14.8 dB in BEM, see Figure 4.21. Then the absorber alternatives increase the insertion loss further, by 0.2–2.3 dB in SoundPLAN and 1.2–8.0 dB in BEM. As in Situation 1, SoundPLAN always calculates higher IL of the screen itself (Sit.2a), while BEM results in higher predicted effect of the absorbers in all but two receiver positions for Sit.2c and in all receivers for Sit.2d. However, contrary to Situation 1, here SoundPLAN calculates an effect of absorbers on the roadside, Sit.2b, which is higher than the result from BEM. According to both the SoundPLAN and BEM calculations, the largest insertion losses are found at 1 and 2 m above ground, the closer to the noise barrier the better the noise reducing effect. At 4 m height, the largest IL is found 8 m from the barrier, which is closer to the building façade than the noise barrier. Sit.2d, with absorbers on both sides of the noise barrier, results in the highest noise reduction. The second best alternative is Sit.2c, with absorbers on the receiver side.

Table 4.8: Insertion loss (IL) for different absorber alternatives (Sit.2a–Sit.2d) calculated with SoundPLAN or BEM.

Receiver	2a SP (dB)	2a BEM (dB)	2b SP (dB)	2b BEM (dB)	2c SP (dB)	2c BEM (dB)	2d SP (dB)	2d BEM (dB)
$mp_2d_2h_1$	18.4	13.6	19.0	15.1	20.1	20.4	20.7	21.6
$mp_2d_2h_2$	17.5	13.3	18.1	15.2	19.0	19	19.5	20.5
$mp_2d_2h_4$	11.5	10.3	11.8	11.7	11.7	11.5	12.0	12.6
$mp_2d_4h_1$	17.7	14.8	18.2	16.1	18.9	20.3	19.5	21.6
$mp_2d_4h_2$	17.1	14.4	17.6	15.8	18.2	18.7	18.7	20.1
$mp_2d_4h_4$	13.8	12.8	14.1	14.1	14.0	14.3	14.4	15.3
$mp_2d_8h_1$	16.9	14.5	17.4	15.8	18.0	18.9	18.4	20.3
$mp_2d_8h_2$	16.3	14.8	16.8	16.2	17.4	18.5	17.8	19.8
$mp_2d_8h_4$	15.1	14.1	15.5	15.4	15.4	15.9	15.7	17.0

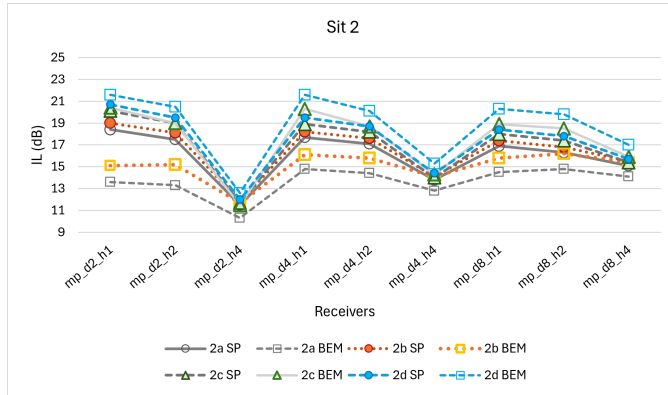


Figure 4.21: The Insertion loss IL for different absorber alternatives (Sit.2a–Sit.2d), calculated with SoundPLAN and BEM.

The calculated absorber effect according to the SoundPLAN and BEM results, i.e., the difference D_{IL} between the single-number insertion losses IL from a reflecting noise barrier and from a sound absorbing noise barrier, is presented in Figure 4.22 for Situation 2.

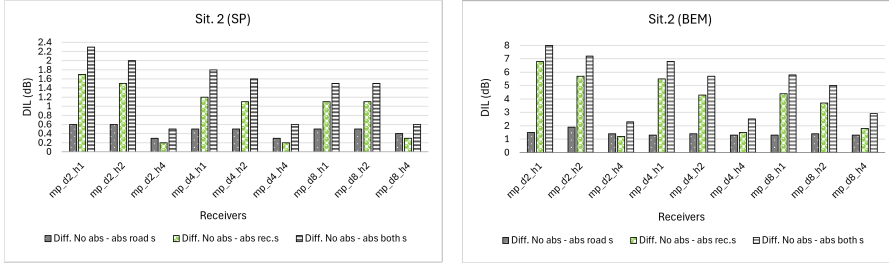


Figure 4.22: The differences DIL between IL from a reflecting noise barrier (no abs) with the IL from a sound absorbing noise barrier, ($IL_{nb,refl} - IL_{nb,abs}$), the SoundPLAN results to the left and BEM results to the right (note the different scales of the figures).

Discussion about BEM for Nord2000 evaluation

Beginning with the situations 01 and 02, i.e., without noise barrier, the SoundPLAN levels differ between -0.7 and +0.2 dB from BEM in Situation 01 and are 0.5–1.8 dB lower than the BEM levels in Situation 02, see Figure 4.18. The reason for the differences in sound levels from the two models is presently unknown, but may be related to the modelling of the source extension along the road and to the modelling of the interference between direct and ground reflected sound.

However, for this study, the more important question concerns the calculated absorber effect, expressed as the difference, DIL , between the insertion loss from a reflecting noise barrier and the insertion loss from a sound absorbing noise barrier i.e., $DIL = IL_{nb,refl} - IL_{nb,abs}$. As presented in Figure 4.20 for Situation 1 and Figure 4.22 for Situation 2, the graphs from Nord2000/SoundPLAN and BEM show a similar pattern over receiver position. According to the results from both models, all absorber alternatives increase the insertion loss of the noise barrier, but the BEM results are considerably higher, especially for the alternatives with absorber on the receiver side or absorbers on both sides of the noise barrier. The differences in DIL between the SoundPLAN and BEM are illustrated in Figure 4.23.

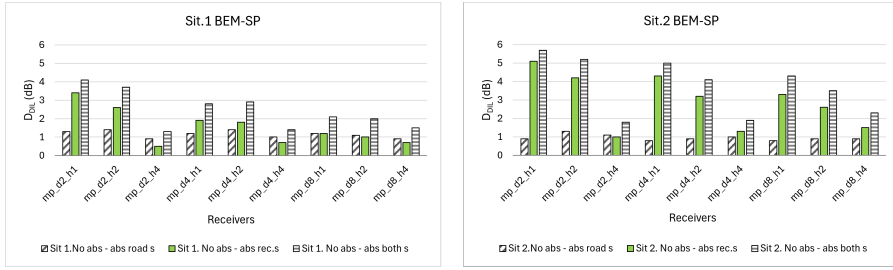


Figure 4.23: The differences between the DIL s from BEM and Nord2000/SoundPLAN, for the alternatives in Situation 1 (to the left) and in Situation 2 (to the right).

There are some possible explanations for the larger predicted absorber effect in BEM. The largest differences between the Nord2000 and BEM DIL results are found at positions near the noise barrier and close to the ground, where the grazing angle of the diffracted path is small (compared to the angle for the receivers higher up and further away from the noise barrier). The smaller the grazing angle of the diffracted sound path, the larger the effect of absorbers, which might be better estimated in the wave-based BEM model than in Nord2000. For instance in Situation 1, in Figure 4.24 for position $d2h1$, i.e., 2 m from the noise barrier and 1 m above the ground, the IL curves of BEM increase more than the Nord2000 (SP(n2kr)) curves in frequencies above 315 Hz in Sit.1c and Sit.1d (with absorbers on the receiver side and on both sides of the noise barrier). While in position $d2h4$, at the same horizontal distance from the barrier but 4 m above the ground, the differences between the IL results from BEM and Nord2000 are much smaller in Sit.1c and Sit.1d, see Figure 4.26. The corresponding sound levels (SPL) for the absorber alternatives of the two positions, calculated with BEM, are presented in Figures 4.25 and 4.27. By comparing those figures it is clear that both the screening effect of the noise barrier, as well as the difference between the sound levels of the absorber alternatives, are greater at 1 m height than at 4 m height.

4.3 Validation using the Boundary Element Method

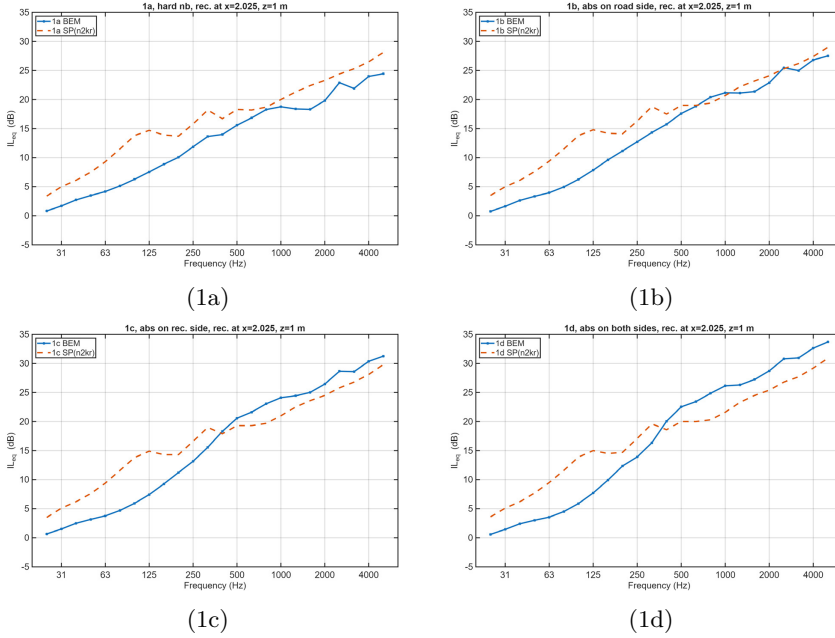


Figure 4.24: The IL:s from Nord2000/SoundPLAN and BEM, for Sit.1a–Sit.1d, at $d2h1$, i.e., 2 m from the noise barrier and 1 m above the ground.

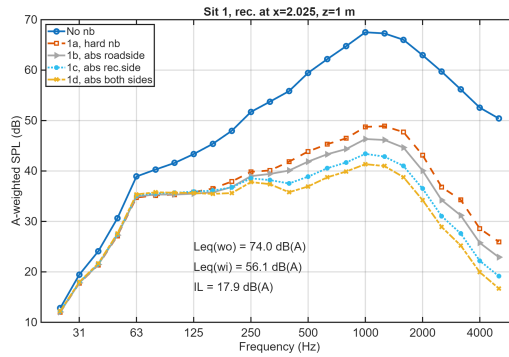


Figure 4.25: The sound pressure levels calculated with BEM, for Sit.1a–Sit.1d, at $d2h1$, i.e., 2 m from the noise barrier and 1 m above the ground.

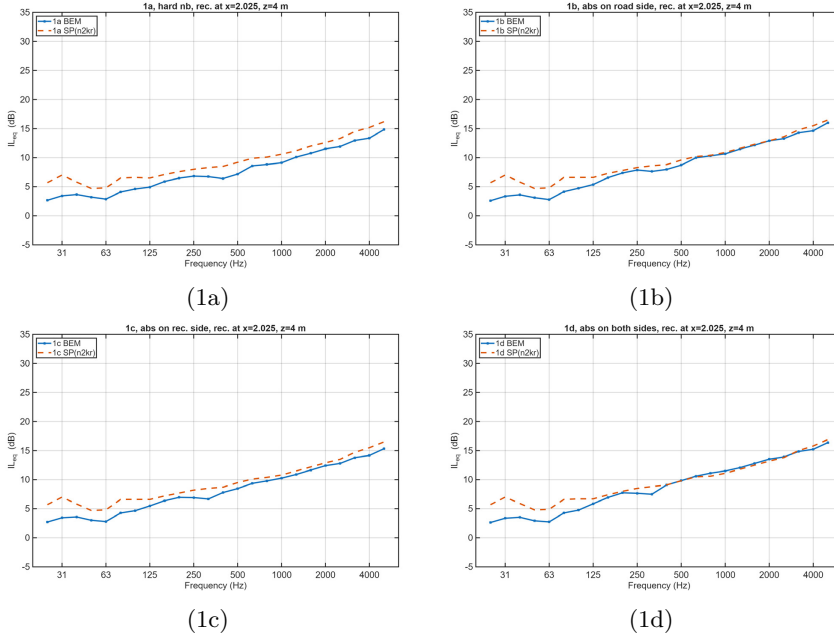


Figure 4.26: The IL:s from Nord2000/SoundPLAN and BEM, for Sit.1a–Sit.1d, at $d/2h/4$, i.e., 2 m from the noise barrier and 4 m above the ground.

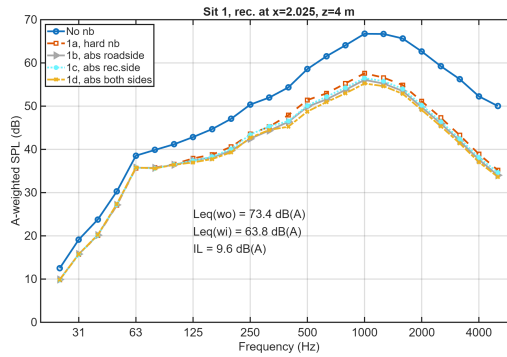


Figure 4.27: The sound pressure levels calculated with BEM, for Sit.1a–Sit.1d, at $d/2h/4$, i.e., 2 m from the noise barrier and 4 m above the ground.

Further, in the spectra of the *DIL*:s for the receiver position of Situation 2, there are significant dips and peaks in the curves from BEM while the Nord2000 curves are smoother, see Figures 4.28 and 4.30. The dips and peaks are corresponding with peaks and dips in the BEM plots of the sound pressure levels in 4.29 and 4.31, and are strongest for the noise barrier alternatives without absorber (Sit.2a) or with absorber on the road side of the barrier (Sit.2b).

In this case, the explanation could lie in how interference from reflections affects the models, particularly the interference due to reflections in vertical surfaces, which is taken into account in the BEM but not in the Nord2000 model where only energy addition is used (though the interference from reflections in the ground is included in both models). In Situation 2, with two opposite vertical surfaces which can give rise to a standing wave, and a hard, reflecting ground in between, an absorber on one of the vertical surfaces reduces the strength of the sound reflections and thus the interference in the BEM model. The phenomenon of standing waves or strong interference is not included in Nord2000, which could imply that the effect of absorbers on the receiver side is underestimated by the model.

At positions near the ground, like *d2h1* and *d8h1*, the strong dips and peaks of the BEM curves in Sit.2a (no absorber) and Sit.2b (absorber on the roadside) are reduced in Sit.2c (absorber on receiver side) and Sit.2d (absorber on both sides), see Figures 4.28 and 4.30. Further, note that there is very little effect of the absorbers on the roadside, above all in *d2h1*, i.e., where Sit.2b nearly has the same IL as Sit.2a, and Sit.2d (absorber on both sides) only slightly improves the IL of Sit.2c (absorber on the receiver side).

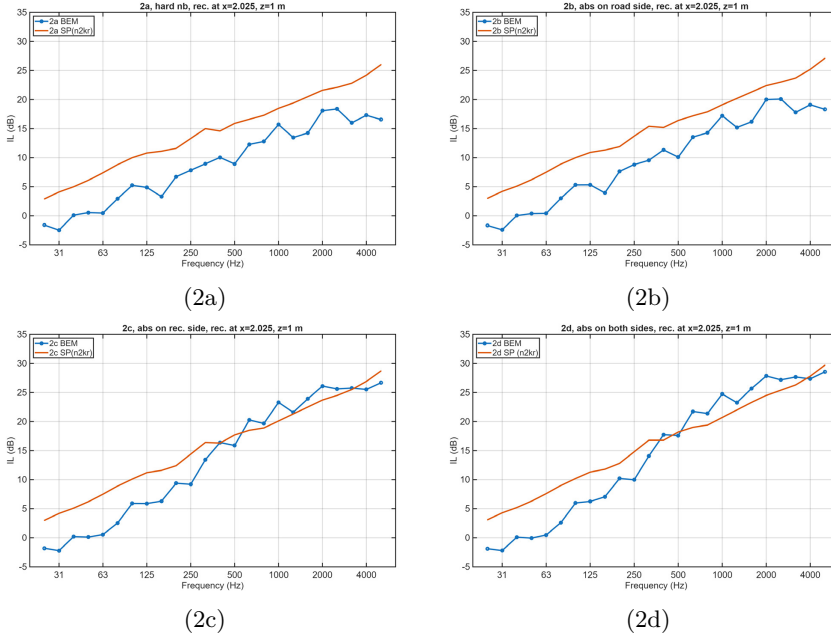


Figure 4.28: The IL:s from Nord2000/SoundPLAN and BEM, for Sit.2a–Sit.2d at $d2h1$, i.e., 2 m from the noise barrier and 1 m above the ground.

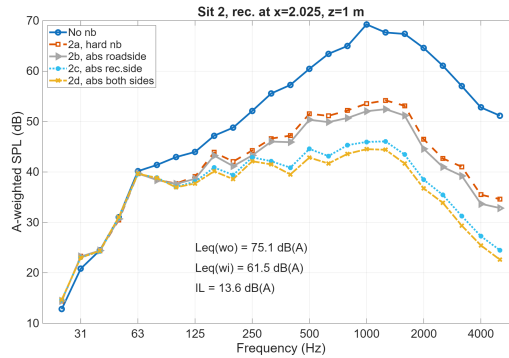


Figure 4.29: The sound pressure levels calculated with BEM, for Sit.2a–Sit.2d, at $d2h1$, i.e., 2 m from the noise barrier and 1 m above the ground.

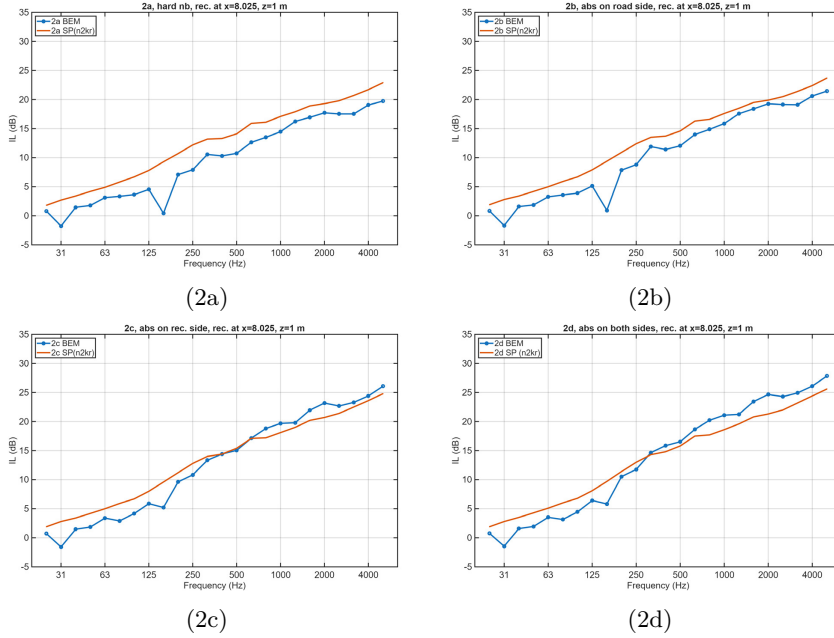


Figure 4.30: The IL:s from Nord2000/SoundPLAN and BEM, for Sit.2a–Sit.2d at $d8h1$, i.e., 8 m from the noise barrier and 1 m above the ground.

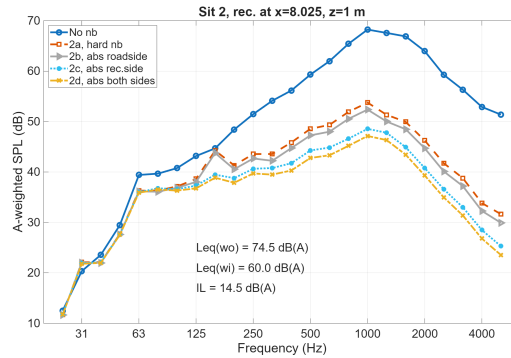


Figure 4.31: The sound pressure levels calculated with BEM, for Sit.2a–Sit.2d, at $d8h1$, i.e., 8 m from the noise barrier and 1 m above the ground.

CHAPTER 5

Discussion

Originally, the name of this PhD project was "Tools for acoustic planning of complex traffic environments". Since then, the project developed in a not so straight direction as planned in 2019 when it was proposed, and the title has been changed. Still, one could say that the original title covers the results of the work, if considering the results as *tools*.

To begin with, "Complex traffic environments" soon became defined as urban large-scale road infrastructure, since it is in urban environments the complexity exists, in the sense of multiple sound reflections occurring between hard surfaces near traffic noise sources, often in combination with noise barriers. One of the tools originates from the comparison between measured and calculated sound levels of three urban sites along large and busy roads: as suggestions for improving the results of sound level calculations with the Nord2000 model, specifically for urban environments.

The key tool for the whole project, would be the use of the SOPRA method for obtaining absorption data for surfaces in road infrastructure [19]. The method is a simplification of the test standard EN 1793-5 [15] for in-situ sound reflection index (RI) measurements of road noise barriers, applied for declaration of sound absorption performance of noise barrier products. The

quicker SOPRA method was studied, tested and eventually used for eleven different measurements of absorbers, noise barriers as well as other walls in infrastructure, nine of them in-situ, resulting in quick sound reflection indices RI_Q in one-third octave bands to use for prediction of absorber effects with the Nord2000 model.

Furthermore, the Direct Field Absorption (DFA) model for evaluating the RI_Q was developed. It has also been confirmed that the DFA model can be used for estimating the obtained RI_Q below the low-frequency limits of the measured surface. (The applicability of the DFA-model is currently limited to fibrous porous materials like mineral wool.)

The final tool is the proposal to optimize the use of absorbers on road noise barriers by studying the effect of their position (e.g., on roadside or on receiver side of noise barrier) and their absorption coefficients. The study has shown that the effect of absorbers is strongly site dependent, and that different absorbers give different sound reduction, especially if assessed on the spectrum levels.

What was not expected in the original plan for the project, was finding cause for suggesting further research and possible development of a model applicable to situations with multiple reflections with resonant behaviour. When the results from Nord2000 calculations of absorber effect was evaluated by using the Boundary Element Method (BEM), the purpose was to confirm that the Nord2000 did not overestimate the sound reducing effect of applying absorbers, above all in positions where doubts could be expected (i.e., on the receiver side of a noise barrier). However, the BEM results indicate that Nord2000 may underestimate the absorber effect, *especially* when applied on the receiver side in a site with multiple sound reflections between the noise barrier and other vertical surfaces.

Note that all three tools are necessary for acoustic planning of urban infrastructure. To be able to calculate the effect of absorbers, absorption data for direct sound field conditions is a prerequisite, and to evaluate the effect of absorber implementation more accurately, the parameters and settings in the calculations might need to be adjusted, compared to standard settings and parameters. To optimize the absorber effect, alternative absorber positions should be studied, and the choice of an adequate absorber for the treatment of the noise in a specific site can be facilitated by calculations.

Now, the ambition for future work is to apply these tools for acoustic plan-

ning of noise mitigation plans and infrastructure projects. Hopefully, in future projects, we will be able to answer the question "Would it be worth the cost, time and effort to replace a hard, sound reflecting surface (Figure 5.1) with a sound absorbing surface (Figure 5.2)?"



Figure 5.1: Would it be worth the cost, time and effort to replace hard, sound reflecting surfaces....



Figure 5.2: ... with sound absorbing?

CHAPTER 6

Summary of appended papers

Paper A: Why noise control must be considered in the context of sustainable development.

More than 100 million Europeans are exposed to traffic noise levels that can be harmful to health, which places traffic noise as the second largest environmental cause of health problems in Europe. Environmental noise has economic, environmental and social impacts which affects nearly all of the 17 Sustainable Development Goals, SDGs, of the Agenda 2030.

In this paper an example from Sweden is presented, where the Swedish National Transport Administration has based the goals of new railway line projects on the Agenda 2030, applying the SDG Compass methodology. Traffic noise is considered a key factor and noise from both the new planned railways as well as the present national rails and roads are taken into account, motivated by targets within the SDG No.3 – Good Health and Well-being, No.11 – Sustainable Cities and Communities and No.15 – Life On Land. In the paper it is argued that these could be complemented with targets within the 10th SDG, Reduced Inequality, since several studies have shown that socio-economically disadvantaged groups may be both exposed to higher levels and be more vulnerable to environmental noise.

Paper B: Measurement of sound reflection using the SOPRA method.

A method was needed for in-situ measurements of sound reflection of installed noise barriers and other surfaces in road infrastructure. This paper describes the examination of the quick method, a.k.a. the SOPRA method, for measuring the Quick Sound reflection Index RI_Q , of road noise barriers in direct sound field, i.e., in-situ. This comprised preparation, equipment, execution and post-processing of the measurement data. The result led to the decision to use the SOPRA method to measure the RI_Q of noise barriers as well as other surfaces and materials in road infrastructure.

Paper C: Time-domain model of spherical wave reflection in a flat surface with absorber character – application to the SOPRA measurement method.

Restricted access or time on-site by the roads and also limited surface sizes to investigate may make it difficult to assess the results of reflection index measurements. This paper presents a time-domain model for the reflection of spherical waves in an absorber-like surface in direct sound field, the Direct Field Absorption (DFA) model, developed for enabling evaluation or prediction of the reflection measurement results. The paper describes the DFA model and the methodology for the evaluation, presented with an example of application to the SOPRA quick method to measure the Quick Sound reflection Index, RI_Q . The first results are promising, albeit based on only one type of absorber. The DFA model will be further studied in the continuing work, including the possible use for estimating the RI_Q below the low frequency limit of a measured object, i.e., when it is physically impossible to measure. Another application of the DFA model could be design of noise barriers (i.e., absorbers) intended for a specific site.

Paper D: Modelling of spherical wave reflection on an absorbing flat surface considering its finite size – Application to traffic noise barriers.

In this paper, the Boundary Element Method is used for examining the possible use of the Direct Field Absorption, DFA, model for estimating the sound reflection indices RI_Q below the low frequency limit of an absorber surface measured with the SOPRA method. The low-frequency limit of in-situ SOPRA measurements depends on the size of the measured object, e.g., a noise

barrier. The DFA model calculates the reflection index of an infinite area, meaning that the comparison with the SOPRA- RI_Q only can be considered valid for the same frequency range as the measured absorber area. Thus, its applicability for calculating the reflection indices at low frequencies for finite sized surfaces, larger than the measured area, was tested by using BEM. The RI_Q s for a measured absorber surface and an enlarged absorber were calculated with the BEM model and compared with the DFA extrapolation below the low-frequency limit of the SOPRA measurement. The BEM- RI_Q for the enlarged surface showed a good agreement with the DFA- RI_Q for two absorber thicknesses. This confirms the validity of using the DFA modelling at lower frequencies to predict the sound reflection performance of larger surfaces than measured, at a lower computational cost than the BEM application.

Paper E: Application of absorption data from SOPRA sound reflection index measurements in Nord2000 road noise calculations – results from a case study.

This paper presents the results from a case study where the absorption data in one-third octave band values were applied on noise barriers in Nord2000/SoundPLAN models of real sites for road noise calculations. The existing noise barriers in the locations are made of sound reflecting materials like concrete and polycarbonate. Three alternative absorber applications were studied: on the roadside, on the receiver side and on both sides of the noise barriers. Absorption data from four types of absorbers were used on all three application alternatives. The tested absorber types were mineral wool, LDPE (low-density polyethylene) foam, porous concrete and cement-bound wood wool. It was concluded that absorbers reduce the noise levels, but the effect of the application is site dependent. Further, the different absorber types of the study result in different noise level reductions, above all if considering the resulting one-third octave band spectra, but not so much in single-number values.

Conclusion and Future Work

7.1 Conclusion

In this PhD project it was investigated if it is necessary to adjust or complement the Nord2000 road noise prediction method to assess noise situations in urban areas close to large-scale road infrastructure more accurately and be able to prove the effect of installing absorbers or changing the acoustic characteristics of materials or surfaces in the constructions of the infrastructure.

The first part was examined by comparing measured and calculated sound levels in three urban locations with varying complexity. The results of the comparisons were the bases for suggestions to improve road traffic noise predictions. For sites with several sound reflecting surfaces, one of the first recommended actions would be testing the reflection depth in the calculation settings to see if a higher number of reflections increase the calculated noise levels and thus should be used in the calculations.

Other parameters to consider, assuming that the geographic data is accurate, are weather and traffic conditions. It is suggested to examine if there are major variations in weather and traffic, compared to the standard meteorological parameters and available traffic data, which may be important to

take into account for noise assessments and for the planning of noise reducing measures.

A prerequisite for the second part of the PhD project, the acoustic effect of sound absorbing materials in road infrastructure, was available absorption data to use in calculations. Since it was discovered that absorption data for materials in infrastructure hardly existed and was also missing for most of the installed noise barriers along roads and railways in Sweden, this had to be determined by measurements. This evolved to a third part in the PhD project, comprising studying, preparing, performing and evaluating the method for measuring the sound reflection index of road noise barriers in-situ, i.e., in direct sound field, which was performed with the SOPRA method. Except for producing valuable measurement data, experience has been gained of a method for measuring sound reflection in surfaces in-situ, useful for noise barriers and other surfaces.

The obtained absorption indices, in one-third octave bands, were used in the noise mapping software SoundPLAN with the Nord2000 model to calculate the effect of applying absorbers on the existing noise barriers in the models of test cases 1 and 2. Both the placement and the type of absorber were investigated.

The studies showed that: (1) Absorbers reduce the traffic noise levels and can be particularly useful for attenuating reflected sound in locations where multiple reflections occur. (2) The effect of absorbers is site dependent and may vary along the same road. Therefore, it is suggested to identify typical areas along a road when planning noise mitigation measures and for each of them investigate the effect of plausible alternatives for absorber applications. (3) Different types of absorbers result in different noise level reductions, which may not be very evident if only single-number values are considered. But if the effect of different absorber types is studied on the spectrum level, there are variations which might be important to consider for certain locations, e.g., in narrow spaces between building facades and noise barriers with a strong low-frequency content in the noise.

Furthermore, an evaluation of the Nord2000 results by using a Boundary Element Method, BEM, indicates that Nord2000 may underestimate the effect of absorbers on noise barriers, especially for situations with multiple reflections between the noise barrier and other vertical surfaces.

7.2 Future work

The title of this thesis, *The effect of sound absorbing surfaces for acoustic planning of road infrastructure*, implies that the results are considered a platform for continuing the work towards a methodology for acoustic planning of road infrastructure.

There are both specific and general areas for further studies and development. One specific topic concerns the last paragraph of the Conclusions: the indication that the Nord2000 model may underestimate the effect of absorbers in certain situations. This should be investigated more closely and if found justified, efforts could be made on development of the Nord2000 (and possibly other noise mapping models) in this respect.

Another suggestion for future research is how other hard surfaces (than noise barriers and building facades) in infrastructure environments could be considered in the noise prediction models. For instance, to examine if it could be possible to change the absorption indices of undersides and lateral sides of long bridges overspanning local streets and how the effect of such sound absorbing surfaces could be taken into account in the noise predictions. A fundamental question is whether there are any realistic possibilities for changing the properties of the surfaces in constructions. Therefore, a future research study should be conducted in collaboration with specialists of that field, e.g., bridge constructors, infrastructure planners and architects.

For a positive development in practice, some further steps must be taken. To succeed with the implementation of acoustic planning within road planning and design, engineers, architects, planners and acousticians from academy, industry and public sectors need to be involved.

Finally, environmental noise control is a question of health, an issue with severe social and economic consequences if ignored. We, who work in the transport and urban planning sector, have the knowledge and the responsibility to contribute to better and healthier living environments in our cities.

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