THESIS FOR THE DEGREE OF LICENTIATE IN APPLIED ACOUSTICS

Acoustic effect of sound absorbing materials and surfaces in road infrastructure

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CHALMERS UNIVERSITY OF TECHNOLOGY

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Cover:
Examples of surfaces in road infrastructure. Top picture: Concrete supporting wall and noise barrier, bottom picture: walls with claddings of stone gabions.

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Abstract

The most complex road infrastructures are often situated in urban areas which expose hundreds of thousands of people to harmful traffic noise levels. The geometrical complexity and the sound reflecting surfaces of these infrastructures affects the sound propagation. The noise calculation models, input data and evaluation methods may not be sufficient to correctly predict the noise levels spreading over the neighbourhoods.

The aim of this Licentiate thesis was to investigate the acoustic effect of sound absorbing materials and surfaces in road infrastructure. This was done by changing the absorption indices, α, of existing sound reflecting noise barriers at real sites modelled in the Nord 2000 calculation model. The result showed that absorbers reduced the sound levels, but the effects were site dependent. Furthermore, some results of comparisons between measured and calculated sound levels require further studies, in relation to the question if it is necessary to complement the noise prediction method to be able to prove the acoustic effect of changing materials or installing absorbers.

Since absorption data for direct sound field application (in-situ) were lacking for installed noise barriers and walls, they were obtained by sound Reflection Index, RI_Q, measurements using the SOPRA method. This also led to the development of the Direct Field Absorption (DFA) model for evaluating RI_Q measurements, which was tested with promising results. The usage of the DFA model, including other applications of it, will be further investigated in the future work, which goal is to propose a methodology for acoustic planning of complex traffic environments.

Keywords: Road traffic noise, NORD 2000, sound absorption, noise barriers, sound reflection index measurement, SOPRA method, RI_Q , direct sound field, DFA model.

Preface

This licentiate thesis has been carried out at the Division of Applied Acoustics, Department of Architecture and Civil Engineering at Chalmers University of Technology. It is a part of the Industrial PhD project Acoustic planning of complex traffic environments financed by Trafikverket, the Swedish Transport Administration (project nr. 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: Pia Nilsson and Kajsa Ström, and my boss Ingmarie Ahlberg at the Investment department.

I would also like to thank all the knowledgeable and inspiring colleagues at Trafikverket, among them: Maria Luisa Botella, Lars Dahlbom, Rickard Jämtmark, Alf Ekblad, Jennie Hygert, Magnus Källman, Jonas Rajalin and Kjell Strömmer – for invaluable support with information, measurements and ideas! Åke Löfgren, Anna Peetre, Anders Spååls and Van Thai – for the interviews about materials and noise barriers in infrastructure, and for providing examples. Mia Becker, Elin Bylund and Jeanette Svensson – for kindly sharing information from the New Railway projects, which I used as examples at the Inter-Noise 2022 conference. Petter Holmqvist and Magnus Olsson at the Malmö - Lund railway project – for allowing and enabling sound reflection measurements at the construction sites.

I am utterly grateful to the people at the Division of Applied Acoustics, Chalmers, for your excellent support and sharing of your knowledge, time and equipment! First and foremost, to my supervisors Jens Forssén and Wolfgang Kropp and examinator Jens Ahrens, but also to Patrik Höstmad (Signal Processing course!), Astrid Pieringer, Krister Larsson, Fatemeh Dashti, Jannik Theyssen, Leon Müller, Hannes Helmholz, Thomas Deppisch, Elin Hedlund, Nolan Lem and Börje Wijk for patiently helping me with big and small questions.

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A Special Thanks to my colleagues in the working group CEN/TC 226/ WG6 – Road equipment/ Anti-noise devices and the convenors (former and present) Jean-Pierre Clairbois and Massimo Garai, for always answering my questions. I am also much obliged to the people of the SOPRANOISE project, where the Quick SOPRA measurement method was developed, I would not have been able to perform as many reflection index measurements in-situ without SOPRA!

Hopefully, the results of the research project will lead to a better understanding of the acoustics in infrastructure and by this, increase the possibility to lower the traffic noise levels from the biggest and most complex traffic structures and transport hubs, contributing to a better living environment in our cities.

Göteborg, September 2024
Monica Waaranperä

Thesis

This thesis comprises an extended summary (kappa) and the following appended papers and reports.

Paper A Waaranperä M. Why noise control must be considered in the context of sustainable development. *Proc. Inter-Noise 2022*, Glasgow, U.K (2022).

Paper B Waaranperä M, Forssén J, Kropp W. Measurement of sound reflection using the SOPRA method. *Proc. Forum Acusticum* 2023, Turin, Italy (pages 4239-4246) DOI: 10.61782/fa.2023.0855 (2023). https://dael.euracoustics.org/confs/fa2023/data/articles/000855.pdf

Paper C Waaranperä M, Forssén J. 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.apacouts.2024.110251 (2024). https://www.sciencedirect.com/science/article/pii/S0003682X2400402X?via%3Dihub

Report A Waaranperä M. RTN 96 vs. NORD 2000 – a comparison of road traffic noise prediction models (2024).

List of abbreviations and acronyms

AADT
Annual average daily traffic

ABS 16
Skeletal Asphalt (maximum stone size 16 mm)

DL_{Aeq}
Difference between A-weighted equivalent noise Levels (dB)

EEA
European Environmental Agency

EU
European Union

L_{Aeq}
A-weighted equivalent continuous noise levels (dB)

$L_{Aeq,24h}$
24 hours A-weighted equivalent continuous noise level (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)

SMA 11
Stone Mastic Asphalt (maximum stone size 11 mm)

TRV
Trafikverket (Swedish transport administration)

WHO
World Health Organization

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Part I.

I. Extended summary

1. Introduction

1.1. Traffic noise impact

Traffic noise is a particular urban problem which is growing with the increasing urbanisation across the World. Only within the EU countries, more than one hundred million people are exposed to traffic noise levels that are harmful to health [1]. Traffic noise has negative impact on concentration, learning and productivity, impedes relaxation and recuperation, causes sleep disturbance, high blood pressure and increases the risk of cardiovascular diseases and early deaths [2,3]. Furthermore, it is reported that socio-economically weaker groups in society both are more exposed and more vulnerable to environmental noise, with less influence, resources or means to change their situation [1,4]. Environmental noise has economic, environmental and social impacts which are relevant to several of the 17 Sustainable Development Goals of the Agenda 2030 (as discussed in Paper A).

In Sweden, more than two million people are exposed to traffic noise levels above the Swedish guidelines, outside their dwellings [5]. The majority of them live in urban areas which are affected by noise from road traffic, see Figure 1.1.

Figure 1.1: Example of multi-laned road flanked by apartment buildings near a Swedish city centre.

1.2. The PhD project – problem definition

This Licentiate thesis is a part of the Industrial PhD project Acoustic planning of complex traffic environments, which focuses on large scale road infrastructure situated in urban areas. This comprises major road transport systems which often are intricate mixes of road lanes, bridges, supporting walls and columns, noise barriers, portals, road signs etc., forming complex landscapes of thousands of square meters of hard surfaces, see Figure 1.2. In these locations, the noise that is emitted from the traffic is reflected off all the surfaces, which increases the total noise levels that spread over the neighbouring areas where hundreds of thousands of people live and work [5]. Here, the noise is present day and night, all year round, affecting the lives indoors and outdoors.

Figure 1.2: Several levels and dimensions of traffic infrastructure in a Swedish urban area.

Correspondingly, the biggest and most expensive infrastructure projects are often situated in urban areas. The new constructions can change the acoustic conditions, but the noise calculation models, the input data and the evaluation methods may not be of sufficient quality to correctly 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.

Another complication is that the effects of planned noise mitigation measures in such complex settings are not always assessed correctly or by the relevant parameters, consequently, the cost-benefits of reduced noise levels and positive health effects will not be accurately evaluated.

As a further matter, the connection between the equivalent noise levels (L_{DEN} and $L_{Aeq,\ 24\ h}$) used in impact assessments of traffic noise and the level of annoyance can be questioned. A Danish study from 2016 [6], based on a questionnaire with approximately 7000 respondents, showed that road traffic noise from motorways were more annoying than noise from urban roads – at the same L_{DEN} level (dB). In the study it was found that 2-3 times as many people living along motorways report being Highly Annoyed (HA) compared to people along urban roads at the same noise levels. Clearly, there are more factors contributing to the traffic noise disturbance than can be described by the A-weighted equivalent sound levels.

1.3. Objectives of the PhD project

Described above are the reasons for the PhD project, in which it is investigated whether it would be effective and possible to alter the surfaces in road infrastructure to reduce the sound reflections and thus decrease the noise level from the traffic. This is especially concerning geometrically complex settings where the sound propagation can be difficult to predict correctly with existing noise calculation models. One of the research questions is thus if it is necessary to complement the existing noise prediction methods to be able to prove the effect of changing the materials or installing absorbers. The goal is to propose a method to design complex infrastructure with acoustic considerations, which could be a part of planning instructions, e.g., for road authorities.

1.4. Aim and outline of the Licentiate thesis

This licentiate thesis is the stepping stone for the subsequent PhD work. The aim is to investigate the acoustic effect of sound absorbing materials and surfaces in road infrastructure and whether varying impedance and absorption characteristics matter for the resulting sound levels in the vicinity of complex road infrastructures. This comprises:

- Comparison of the available traffic noise prediction models to assess their suitability for the project (summary of appended Report A), Chapter 2.
- Study of acoustic effects of materials and surfaces in road infrastructure, in Chapter 3, including in-situ sound reflection, RI_Q, measurements with the SOPRA method (described in Paper B), and development of a model for assessing the results of RI_Q measurements, the Direct Field Absorption (DFA) model, presented in Paper C.
- Case studies: comparison between calculated and measured sound levels and examination whether different absorption coefficients of the surfaces, e.g., noise barriers, in the road environment affect the calculated noise levels at the receiver positions, see Chapter 4.
- Summary of appended papers A-C, Chapter 5.
- Conclusions, Chapter 6.
- Plans for the future work, Chapter 7.

1.5. Limitations

Road surface is 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 are not examined or measured.

2. RTN 96 vs. NORD 2000 – a comparison of road traffic noise prediction models

This Chapter summarises a study (Report A) of existing traffic noise prediction models in Sweden, specifically concerning the suitability for geometrically complex traffic environments. The study is based on existing publications and discussions with experts of the area.

2.1. Introduction

The purpose of this study is to establish which traffic noise calculation model is the most appropriate for the PhD project Acoustic Planning of Complex Traffic Environments. This is accomplished by comparing the two models that are used for detailed traffic noise calculations in Sweden today and assessing their suitability. The standard model, generally used for infrastructure and building plans, is the Nordic Road Traffic Noise calculation model from 1996, RTN 96 [7], based on a model from the 1970:s. But since more than two decades, another model has been available – the NORD 2000 [8], which is in use in Denmark and Norway (in a modified form). Note that from June 2024, Nord 2000 Road is the standard prediction model for the Swedish Transport Administration, the Nord 2000 Rail will be standard from January 2025.

This study is mainly based on previous comparisons, above all two reports from SP/RISE from 2009 [9] and 2015 [10], and one journal article from 2020 [11]. The noise calculation model for the European noise mapping, Cnossos-EU, is not considered here, since it has already been compared and evaluated, for instance in the aforementioned article [11] and a report [12]. The drawn conclusions of these studies are judged as correct. The primary usage of the Cnossos-EU model is the bigger scale noise mapping within Europe, in accordance with the European Noise Directive, END [13]. The model´s accuracy of the calculated noise levels is reported to be somewhere between that of RTN 96 and Nord 2000, the latter being the most accurate, to a large extent due to the state-of-art sound propagation model and a more realistic source model [12].

2.2. Requirements for the PhD project

The PhD project concerns complex infrastructure, which usually involves motorways and other bigger roads with large traffic volumes in urban settings. For an accuracy of +/- 2 dB (standard deviation), the calculation model must reliably predict situations with:

- Large traffic volume: up to 250 000 veh/24h, as AADT (Annual Average Daily Traffic).
- Urban traffic: often more category 2 vehicles than category 3[1].
- Multiple lanes, 4 or more.
- Multiple sound reflective surfaces, including noise barriers.

[1] In Nord 2000, the road vehicles are sorted into five categories, of which the following three are commonly used for noise calculations: Category 1 = Light vehicles (cars), Category 2 = Medium heavy vehicles, Category 3 = Heavy vehicles. In NMT 96 there are only two categories, Light and Heavy vehicles.

- Multiple noise barriers.
- Varying topography and ground impedance (flow resistivity) between the noise source (traffic) and the receivers.
- Long distance between source and receiver.

2.3. Results and discussion

The result of the study shows that the RTN 96 can only meet two of the requirements, large traffic volume and multiple lanes, while the NORD 2000 seems to manage all, with some reservations concerning situations with more than two parallel noise barriers.

Concerning the last requirement, the RTN 1996 calculation model is valid for a perpendicular distance of 300 m from road, but it is necessary to calculate noise levels at longer distances to accurately identify dwellings and areas where the traffic noise levels exceed the noise limits according to noise guidelines of the Swedish transport administration [14]. For instance, when planning new roads or major reconstructions, all dwellings that may be affected by $L_{Aeq,24h}$ above 55 dB must be mapped and managed in the projects, which may include houses at distances more than 300 meters from the infrastructure.

Furthermore, to be able to analyse the effects of different absorption indices of surfaces in and near the road infrastructure, the results must be presented in one-third octave band values, which is possible with the NORD 2000, but not with the RTN 96.

However, limitations of the NORD 2000 model will be observed during the following work and it will be investigated whether additional methods may be needed to calculate (predict) the noise levels and the effects of various noise reducing measures.

3. Acoustic effect of surfaces in road infrastructure

Chapter 3 comprises a study of the acoustic effect of materials and surfaces in road infrastructure including in-situ sound reflection measurements and development of a model for assessing results of reflection measurements.

3.1. Method

The planned approach for this study was to first map the common construction materials that forms 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. Consequently, in-situ sound reflection measurements were performed to obtain absorption indices (subsequently applied in the calculations of the case studies in Chapter 4). In addition, a model to enable evaluation of the sound reflection measurements in direct sound field, the DFA model, was developed.

3.2. 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 (Figure 3.1), 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.

(a) (b)

Figure 3.1: (a) Concrete and steel motorway bridges over a local street, (b) urban street canyon with supporting walls and noise barriers.

3.2.1. Infrastructure surface materials

Concrete is the most common construction material in complex traffic environments in Sweden. In general, concrete is acoustically hard and sound reflecting, even though there are concrete products with porous layers which might be sound absorbing.

Other surfaces comprise soil or grass on slopes and embankments, and rock cuttings (Figure 3.2 a). 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 [8]. In urban areas other materials can occur, mostly as claddings on concrete constructions or rock. Stone gabions (see Figure 3.2 b), perforated brick and ceramic tiles are examples of materials that are used as claddings, often believed to be sound absorptive or, at least less sound reflective than, e.g., 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.

(a) (b)

Figure 3.2: (a) Concrete and polycarbonate noise barrier on top of rock cutting, (b) claddings of stone gabions on rock cuttings and supporting walls.

3.2.2. Noise barriers

The dominating material in noise barriers in Sweden is wood/timber. Other common types of noise barriers are made of concrete (Figure 3.3.a), perforated metal sheet cassettes, steel mesh elements and transparent plastic or glass sheets (Figure 3.3.b).

Road traffic noise barriers falls under the GPR, the European General safety Product Regulation, meaning that any road noise barrier product sold within the EU market must be assessed and CE marked according to the Product standard EN 14388 [15]. 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 [16] and 2 [17], 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 [18] and

6 [19], for sound reflection and sound insulation under direct sound field conditions, similar to the real situations along the roads, i.e., in-situ.

However, 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 are no acoustic information about them.

(a) (b)

Figure 3 3: (a) Concrete noise barrier with sections of inlayed absorbers, (b) transparent noise barrier.

3.3. Determination of the sound reflective properties of road infrastructure materials

During the inventory of road infrastructure materials, described in Chapter 3.2, it was found that if *any* acoustic data for infrastructure construction materials existed, they had been acquired in laboratories under diffuse sound field conditions in accordance with building acoustics standards [20]. However, measurements of road noise barriers have shown that absorbers function differently in-situ, i.e. in direct sound field [21]. 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 [18], was under consideration when another option was presented, the SOPRA method [22-25], 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 in direct sound field (but not for product qualification).

However, the SOPRA method was not 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 tests 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.

3.3.1. Sound reflection measurements of noise barriers and walls

The sound reflecting properties of five noise barriers, installed along roads or railroads, and three types of walls on train platforms have been measured with the SOPRA method, see Table 3.1. All objects except one were supposed to be sound absorbing, but their effects had not been confirmed after installation or construction. None of the noise barriers have 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) [26], but some 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.

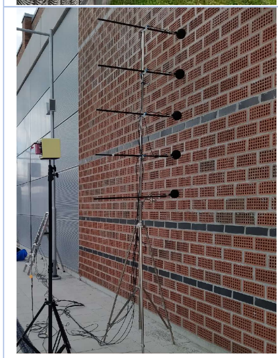
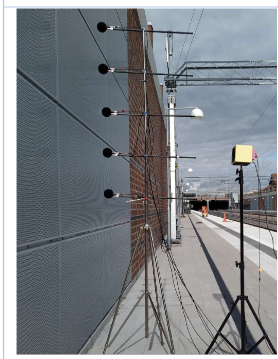
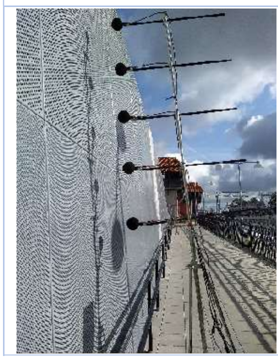
Four of the noise barriers were measured on the backside, i.e. the non-roadside, since the roadsides were not accessible due to heavy traffic and narrow road shoulders. However, the risk of transmitted traffic noise from the roadside must be considered when measuring on the backside. In one of the four 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 measurements are performed as intended, i.e., on the roadside, this should not be a problem as long as there are no other noise source 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., 200-5000 Hz, the absorbing noise barrier section has to be at least 5 m tall, according to [22]. 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 $RI_{Q,(fmin\text{-}5000\ Hz)}$.

The measured noise barriers and walls are presented in Table 3.1 with the calculated single number ratings, DL_{RIQ}, which are summarising their performance when applied to a normalised road traffic spectra [27]. Examples of resulting RI_Q one-third octave band spectra are given in Figure 3.4.

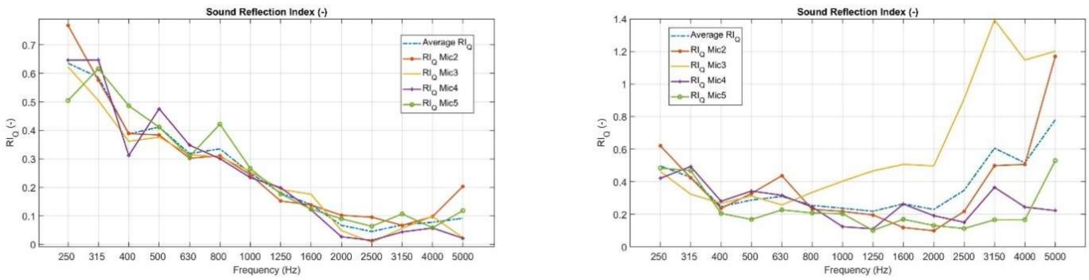
Table 3.1: Overview of measured noise barrier and walls. DL_{RIQ} = Single number rating of the Quick sound Reflection Index, for 200-5000 Hz if barrier height > 5m, for 250-5000 Hz if barrier height is 3-5 m.

	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, m2-m5	$DL_{RIQ,}$ 250-5000 Hz 1.7 - 3.3	
	Reflective Non-roadside (2023-04-12)	Composite board, reflecting (backside of absorbing noise barrier)	3.5	4 mics, m2-m5	$DL_{RIQ,}$ *250-5000 Hz* - 0.6	Absorber on roadside measured in laboratory with the diffuse field method EN 1793-1. DL_{α} =11 dB
	Steel mesh, small panels Non-roadside (2023-08-15 and 2023-10-16)	Steel mesh cassettes, with absorber	4.9	4 mics, m2-m5	$DL_{RIQ,}$ *250-5000 Hz* 1.9 – 3.7	Transmitted noise from road traffic, due to bad sealing between the cassettes?
	Metal cassettes Between railroad and the road. Measured on roadside (2023-08-15)	Metal cassettes with absorber	3.5	4 mics, m2-m5	$DL_{RIQ,}$ *250-5000 Hz* 6.0	Type measured in laboratory with the diffuse field method EN 1793-1, DL_{α} = 12 dB

	Object (Measurement date)	**Type**	**Height (m)**	**Micro-phones**	DL_{RIQ} **(dB)**	**Comments**
	Steel mesh, large panels Non-roadside (2023-08-16)	Steel mesh with absorber	4.0	4 mics, m2-m5	$DL_{RIQ, 250-5000 Hz}$ 5.0	Mic 3 sound refl from border of acoustic panels?
	Perforated brick. Train station (2023-08-23)	Perforated brick wall with absorber	> 5.5	5 mics, m2-m6	$DL_{RIQ, 200-5000 Hz}$ 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, m2-m6	$DL_{RIQ, 200-5000 Hz}$ 5.0	Same absorber behind the surface as the per-forated brick wall on same platform with $DL_{RIQ, 200-5000 Hz}$ 1.3 dB
	Perforated steel with various hole sizes, plastic absorber. Train station (2023-08-24)	Perforated steel plate with absorber. Hole sizes 5, 10 and 15 mm	3.5 +	5 mics, m2-m6	$DL_{RIQ, 250-5000 Hz}$ 5.0	NOTE: used only 4 mics, m2-m5, in the calculation of RI_Q

An example of a resulting RI_Q spectra of a frequently used type of nose barrier, comprised of cassettes of perforated metal sheets filled with an absorber, is presented in Figure 3.4.a, in one-third octave band values. The calculated $DL_{RIQ(250\text{-}5000\ Hz)}$ is 6.0 dB , which is the best result of the measured noise barriers in Table 3.1, but still it is half as much as the corresponding absorption values measured in laboratories, DL_{α}, 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 3.4.b, the RI_Q of one of microphones was “off” 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 bad sealing between the acoustic panels, since the measurements were made on the backside of the noise barrier.



(a) (b)

Figure 3.4: Example of RI_Q spectra of: (a) metal cassette noise barrier, calculated $DL_{RIQ,\ (250\text{-}5000\ Hz)}$ is 6.0 dB, (b) metal mesh noise barrier, calculated $DL_{RIQ,\ (250\text{-}5000\ Hz)}$ is 5.0 dB. In (b), note the anomaly of Mic3, which could be an effect of reflections or bad sealing between the acoustic panels.

For using the measured results of reflection measurements in calculations with the NORD 2000 model, the RI_Q indices are converted into sound absorption coefficients, α, and inserted as one-third octave band values in the noise barrier library of the SoundPLAN calculation software [28].

3.3.2. The Direct Field Absorption (DFA) model

During the in-situ sound reflection measurements, the question arose how the results could be evaluated, especially for on-site constructed noise barriers or other walls where benchmarks didn´t exist. To enable assessment, the Direct Field Absorption (DFA) model was developed and applied to the SOPRA measurement method, which has been 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 on a theoretically derived impedance of the absorber. The DFA-IR:s can be entered to the SOPRA formula to calculate the $DFA\text{-}RI_Q$, 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 3.5. 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.

The DFA model and the methodology for assessing the results of RI_Q measurements will be further investigated in the future work, as well as other possible applications of it. Except for detecting SOPRA measurement anomalies, it may be useful for estimating the RI_Q below the low-frequency limit of in-situ measurements, due to the size of the absorber surface. Also, it might be a tool to predict the performance of new designs of noise barriers (absorbers).

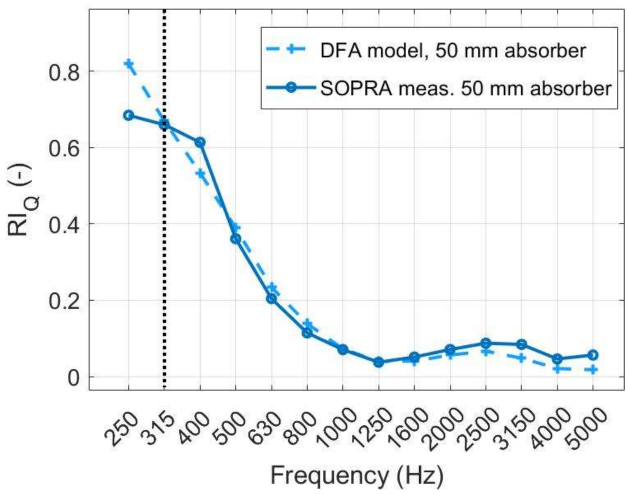


Figure 3.5 Resulting RI_Q one-third octave band spectra of the DFA model and the SOPRA measurement, respectively, of a 50 mm thick absorber. The measurement data is valid from 315 Hz, due to the size of the measured absorber.

4. Case studies

In this Chapter comparisons are made between calculated and measured sound levels at two sites, and it is examined whether different absorption coefficients on noise barriers affects the calculated noise levels.

4.1. Method

A central part of this licentiate thesis is to investigate whether surfaces with varying impedance and absorption characteristics matters for the resulting sound levels in the vicinity of complex road infrastructures. This is achieved through case studies where different absorption coefficients are applied on noise barriers. In the future work it will also be tested on other surfaces. The case studies are based on real sites, where the sound levels have been measured in order to examine if it is possible to reproduce the measured sound levels with calculations, and which parameters or corrections are necessary for aligning the calculated results to the measured ones. Thereafter, the effect of changing the absorption indices of the noise barriers is tested by calculations, regardless of the results of the first point.

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.

Two case studies are presented in this paper, one or two more will be completed in the future work. In the following chapters, the studied sites are presented with the results of the sound level measurements and calculations. Note that the purpose is to compare the results from calculations and measurements, *not* to assess the traffic noise situation in these locations. Moreover, the study focuses on areas close to the roads in order to avoid influence from other noise sources.

4.2. Studied sites

The two studied sites, Sites 1 and 2, are situated in a municipality in the western part of Sweden. A six-lane motorway is dividing the central part of the town. The comparative study of noise measurements and calculations has been performed at two locations: one to the west, north of the motorway and the other to the east, south of the motorway. The distance between the sites is approximately 1 km.

The first site, north of the motorway, is located in a narrow yard between older residential buildings and a 3.7 m tall noise barrier of concrete and transparent polycarbonate elements, see Figure 4.1. and 4.2.

Figure 4.1: Site 1. The studied area seen from the opposite side of the six-lane motorway.

(a) (b)

Figure 4.2: Site 1, the area behind the noise barrier seen from: (a) the west, and (b) the east. The distance between the barrier and the nearest façade is 12 m.

Still on the north side of the motorway, but to the east of the old town centre, a major development is ongoing. In this part, large commercial buildings and a sports arena are placed between the motorway and the new residential houses. Here, a 5.4 m tall noise barrier of concrete and transparent polycarbonate elements is installed along the motorway. The second site is on the opposite side of the new noise barrier, south of the motorway, behind an older noise barrier of concrete and metal sheet elements, 3.0-3.6 m tall (Figure 4.3). The receiver points of Site 2 are located in a small parklike area right behind the noise barrier. The nearest houses of the nearby residential area are located 50 m behind the noise barrier.

Figure 4.3: The second site, behind a 3.0-3.6 m tall noise barrier south of the motorway. Above the barrier, some of the new buildings and the top of the new 5.4 m tall noise barrier north of the motorway can be seen.

4.3. Measurements

Sound level measurements were performed at both sites according to Swedish standard method [29], simultaneously with three microphones at 1, 2 and 4 m height at three distances, 2, 4 and 8 m, behind the noise barrier, see Figure 4.4 and Figure 4.5. At Site 1, additional receiver points were placed 50 m from the noise barrier in the courtyard behind the first row of houses.

The measurements took place in November 2023. The weather was overcast and the temperature -5˚C with a weak wind from north/northeast, i.e., the wind was blowing in the direction from receiver to source on the north side of the motorway at Site 1, which is in conflict with the general requirements of the measurement standard where a weak wind from source to receiver is assumed. But the measurements could still be considered as valid since the receiver positions were so close to the noise source. Though, at the 50 m measurement position in the courtyard there was a bigger risk that the inaccurate direction of the wind could affect the results. Also to be noted is that the ground was slightly covered by fresh snow, but not frozen.

The traffic distribution (vehicle categories) was noted during the measurements and the measured sound levels were adjusted to $L_{Aeq,\,24h}$ with regard to AADT, the Annual average daily traffic, of the year 2022 [30]. In the calculations it was assumed that the road surface was slightly wet and that 10 % of the cars in vehicle class 1 had studded winter tyres.

The measurement results which are relevant for the comparison with calculated sound levels ($L_{Aeq,24h}$ levels and one-third octave bands) are presented in Chapter 4.5.1 for Site 1 and in Chapter 4.5.2 for Site 2.

Figure 4.4: The measurement position 4 m behind the noise barrier at Site 1, north of the motorway (photo: Akustikkonsulten).

Figure 4.5: The measurement position 4 m behind the noise barrier at Site 2, south of the motorway (photo: Akustikkonsulten).

4.4. Modelling and sound level calculations

As previously mentioned, the reason for the case studies is to compare the results from calculations and measurements, *not* to assess the traffic noise levels in the studied locations. The parameters, e.g., weather and road surface corrections, for the calculations were set to simulate the current conditions during the measurements, and thus not according to the standard for calculating L_{DEN} or $L_{Aeq,\ 24h}$ for noise mapping which is based on yearly average traffic and a standardised weather situation [31]. The same parameters were also used for the relative comparisons of sound levels of the present situations and of situations with modified absorption coefficients on the noise barriers at the sites, see chapter 4.6.

The majority of the calculations were single-point calculations at the same receiver positions as where the measurements were carried out. In addition, grid map calculations were performed for both sites and a façade noise map was calculated for Site 1.

4.4.1. Calculation model

The sound level calculations were performed with the calculation model NORD 2000 Road rev. 2006 [8], and with the road traffic source model rev. 2015 [10].

4.4.2. Input data

The studied sites were modelled in the noise calculation software SoundPLAN 8.2 [28], where absorption factors and the impedance class of the present surfaces and areas were as realistically chosen as possible, based on on-site observations. The receiver points were set 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.

Terrain and road model, buildings and noise barriers

The terrain and road model, buildings and noise barriers were extracted from the END noise mapping 2019 of the Swedish transport administration, manually complemented (digitised) with buildings that have been constructed after 2019.

Ground impedance

The ground impedances, relevant for sound absorbing or reflecting effect of the ground, were chosen after visual inspections on the sites. The applied impedance classes are presented in Table 4.1. During the measurements the ground was partly covered by a thin layer of fresh snow but not frozen, the snow was thus not considered to affect the ground impedance.

Table 4.1: Applied impedance classes, from the NORD 2000 model [8]. The higher flow resistivity, the more sound reflecting surface.

Surface	Impedance class	Corresponding flow resistivity, (kPas/m2)
Motorway, dense concrete	H	200000
Roads, parking lots etc.	G	20000
Compacted dense gravel, porous asphalt	F	2000
Compacted green areas, lawns, parks	E	500
Forrest floors, meadows, ballasted rail beds	D	200

Road characteristics

Characteristics of the motorway and connecting lanes included in the calculations, as given below:

- Motorway with 2 continuous lanes plus 1 entrance/exit lane in eastbound direction, hard shoulder, total width approx.15 m.
- Motorway with 2 continuous lanes plus 1 entrance/exit lane in westbound direction, hard shoulder, total width approx.15 m.
- Middle section between eastbound and westbound lanes, approx.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.

The parameters concerning the weather and status of the road surface were chosen after the current conditions during the measurements in November 2023. i.e. (standard values in parentheses):

- Air temperature -5˚C (+15˚C).
- Weak wind, 2 m/s, from north/northwest (used default weather statistics in Nord 2000).
- The Category 1 vehicles that were assumed having studded tyres: 10% (0%).
- The road surface was slightly wet, probability for wet surface condition: 25% (0%).

Traffic volume and distribution over vehicle categories

The traffic data, obtained from Swedish Transport administration [30], are presented in Table 4.2. For Site 1, the traffic data were given for three categories: 1 – cars, 2 – heavy vehicles with 2-4 axles, 3 – heavy vehicles with 4 axles or more. For Site 2, the measured traffic data were only divided in two categories, where the second category represented all heavier vehicles. In the calculations, the Site 1 distribution of Category 2 and 3 vehicles were assumed for both Site 1 and Site 2, as well as for the entrance and exit lanes.

Table 4.2: Traffic volume for each vehicle category according to [31]. The heavy vehicle percentage of the total traffic volume in parentheses (* only one category for both Cat. 2 and Cat. 3 vehicles).

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.	Entrance lane	1470			80 (5.2%)	2022
2.	Mw eastbound	17130			1870 (9.8%)	2022
2.	Mw westbound	17230			1770 (9.3%)	2022
2.	Exit lane	2150			350 (14%)	2022

Speed

The speed limit on the motorway for all vehicle categories is 80 km/h. However, the traffic measurements on the motorway sections indicate that the real average speed is higher, i.e., for Cat. 1: 88-90 km/h and Cat. 2 + Cat.3: 82 km/h. After the first rounds of calculations it was decided to use the measured average speed instead of the speed limit on the continuous lanes of the motorway. The current speed limits of 60 and 80 km/h were kept on the other lanes, i.e., the entrance and exit lanes.

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., no 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.

4.4.3 . Calculation settings

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 points at study Site 1.
- Maximum search radius (distance from source to receiver point): 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.
- Façade noise map: Distance between façade points: 5 m.
- Sound propagation grid map: Grid 3x3 m.

4.5. Comparisons between calculated and measured sound levels

In this Chapter the single-number L_{Aeq} levels and corresponding one-third octave band levels of the measurements and calculations are compared for both sites of the case studies. The objective is to study 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.

4.5.1. Site 1

As a first step, comparisons are made between the measured and calculated single-number equivalent A-weighted (L_{Aeq}) sound levels. The L_{Aeq} results from the calculations and measurements are summarised in Table 4.3 and the differences between the measurement and calculations with different settings are illustrated in Figure 4.8.

Table 4.3: The single-number values of calculations and measurements at Site 1.

Receiver	**Measured L_{Aeq} (dB)**	**Calc. 3 rfl L_{Aeq} (dB)**	**Calc. 4 rfl L_{Aeq} (dB)**	**Calc. 5 rfl L_{Aeq} (dB)**	**Calc. 0.2 dB f-abs L_{Aeq} (dB)**	**Calc. ABS 16, av. speed, 4 rfl, L_{Aeq}(dB)**
mp1_d2_h1	65,1	59,5	60,6	60,7	61,5	64,2
mp1_d2_h2	66,1	61	62,1	62,2	62,8	65,5
mp1_d2_h4	68,2	68,8	69,4	69,4	69,5	72,4
mp1_d4_h1	65,5	60	60,9	61	61,6	64,4
mp1_d4_h2	66,5	61,1	62	62	62,5	65,3
mp1_d4_h4	67,7	65,9	66,6	66,6	66,8	69,8
mp1_d8_h1	65,3	60,6	61,4	61,5	61,9	64,7
mp1_d8_h2	66,7	62,5	63,2	63,3	63,6	66,5
mp1_d8_h4	67,6	65,4	66,3	66,3	66,5	69,5
mp1_d50_h1	50,8	-	-	-	49,8	52,5
mp1_d50_h2	51,7	-	-	-	49,4	52
mp1_d50_h4	52,3	-	-	-	49,8	52,5

After the first round of calculations, the differences between the measured and calculated sound levels at study Site 1 were quite large, the calculated being 1.8 - 5.6 dB lower than the measured levels (except for at mp1_d2_h4), with the largest difference at 1 and 2 m height (see Table 4.3 and Figure 4.8). The actions taken to reduce this gap were: increasing the number of reflections in the calculations, reducing the building façade absorption, changing the road pavement type and applying the measured average speed of the vehicles on the motorway instead of the lower speed limit.

Number of reflections

Increasing the reflection order, i.e., the number of reflections in the calculation settings, from the default value of 3 to 4 increased the calculated sound levels with 0.6 - 1.1 dB. A change from four to five reflections was also tested, but this only added 0 - 0.1 dB to the results while the calculation time increased drastically. The subsequent calculations of Site 1 were therefore made with four reflections.

Building façade sound absorption

Lowering the default value of the façade absorption from 1.0 dB to 0.2 dB increased the noise levels in all receiver positions between the noise barrier and the building. The increase was 0.2 - 0.9 dB, the most at 1 and 2 m above ground, but the calculated levels were still up to 4 dB lower than the measured noise levels.

Road pavement type and vehicle speed

After contact with the maintenance department at the Swedish Transport Administration, it was confirmed that the motorway in question had pavement type ABS 16 which is noisier than the default road pavement SMA 11. The ABS 16 was thus applied in all the following calculations. In addition, the measured average speed on the motorway lanes was entered instead of the speed limit of 80 km/h , which was 88-90 km/h for vehicle category 1, and 82 km/h for vehicles categories 2 and 3. After this, the difference between measured and calculated sound levels was reduced to 0.2 - 1.2 dB, for receiver points at 1 and 2 m above ground, see Table 4.3. On the other hand, at 4 m height, the calculated levels became 1.9 - 4.2 dB higher than the measured, which could be due to a difference between the real and the modelled terrain height, where in reality the microphones at 4 metres are more protected by the noise barrier than the receiver positions in the calculation. This hypothesis was tested by adding receiver points at 3.5 m above the ground, which resulted in a more modest 1.1 - 1.4 dB difference between the calculated 3.5 m levels and measured 4 m levels, see Table 4.4.

Table 4.4: The single-number values of calculations at 3.5 m at Site 1 and the differences between the 3.5 and 4 m calculations, and between the 3.5 m calculations and measurements at 4 m height. Calculations based on ABS 16, average speed and 4 reflections.

Receiver	**Calc. h = 3.5m L_{Aeq} (dB)**	**Diff calc h3.5 - calc h4 (dB)**	**Diff calc h3.5 - meas h4 (dB)**
mp1_d2_h3_5	69,6	-3.8	1,4
mp1_d4_h3_5	68,8	-1	1,1
mp1_d8_h3_5	68,7	-0,8	1,1

Ground impedance

The corrected road paving type and increased vehicle speed also reduced the difference between measured and calculated sound levels in the courtyard behind the first row of houses especially at 2 and 4 m height where the calculated levels ended up being (only) 0.2 - 0.3 dB higher than the measured, instead of 2.3 - 2.5 dB lower, i.e., an increase of 2.6 - 2.7 dB. However, near the ground, at 1 m height, the calculated levels became 1.7 dB higher than the measured, instead of 1 dB lower, which is also an increase of 2.7 dB but not in accordance with the measured value. This could have been due to the choice of ground impedance in the yard (harder/less absorptive than in reality), since the levels were 0.4 - 0.5 dB higher at 1 m than at 2 m for both calculated situations, while the measured level was 0.9 dB lower at 1 m than at 2 m height. Therefore, a test calculation was made with a softer ground factor on the lawn of the courtyard where the microphones were set-up. The ground factor change from Class F, σ = 2000 kPas/m^2 to Class E, σ = 500 kPas/m^2, lowered the levels at 1 and 2 m above ground with 0.1 dB, i.e., to 52.4 and 51.9 dB. At 4 m above the ground the sound levels remained 52.4 dB. On the whole, the ground impedance change did not influence the single-number dB value more than marginally.

Other possible reasons for the difference between calculated and measured L_{Aeq}-values at low height in the courtyard could be the wind conditions in the courtyard during the measurements, and/or multiple reflections taken into account in the calculation of the 1 m measurement position, but not detected in measurement. However, the consequences of overestimating the sound levels by 2 dB in the courtyard are not so severe as underestimating them by 4 dB on the roadside of the houses. Nonetheless, will the measured vs. the calculated sound levels near the ground be observed in the continuing work with case studies.

The effect of different calculation settings at 2, 4 and 8 m distance from the noise barrier is illustrated in Figure 4.7 by a graph showing the difference between measured and calculated sound levels.

Final settings for Site 1

The final settings for Site 1, differing from default or standard values (in parentheses), are as follows:

- Façade absorption 0.2 dB on adjacent buildings (1 dB).
- Number of reflections: 4 (3).
- Speed: Measured average speed, i.e.: Vehicle category 1, 89 km/h, category 2 and 3, 82 km/h (speed limit 80 km/h).
- Tyres, vehicle cat.1: 10 % studded (0 %).
- Road pavement type. ABS 16 (SMA 11).
- Road surface: 25% wet (dry).
- Air temperature: -5˚C (+15˚ C) .

The result for Site 1 with the final settings is presented in Figure 4.8.

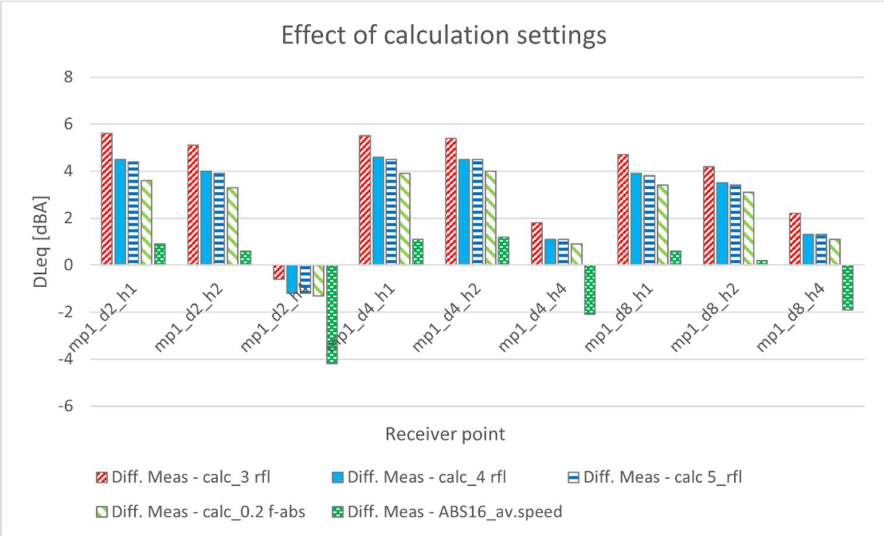


Figure 4.7: The difference between measured and calculated sound levels at Site 1, due to the effect of different calculation settings.

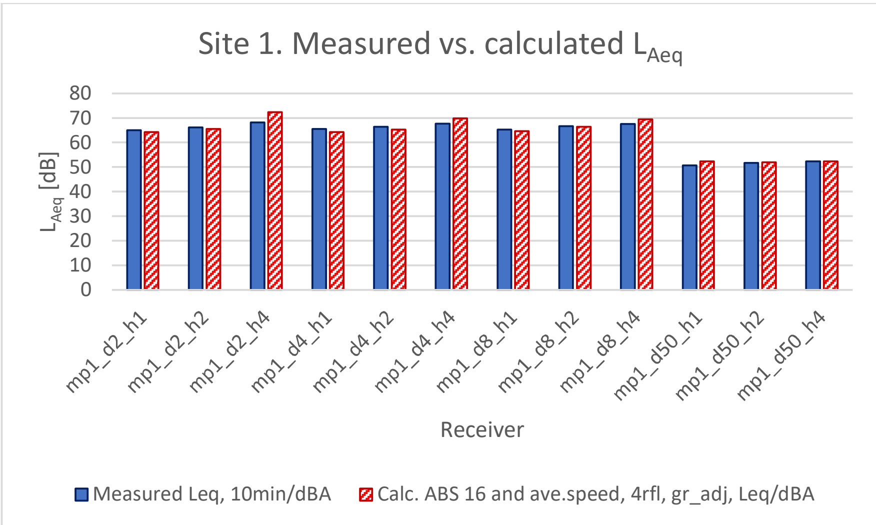


Figure 4.8: Calculated L_{Aeq} values, based on final settings, and measured L_{Aeq} values for receivers at Site 1.

Façade noise map

At Site 1, a façade noise map calculation was performed for the building façades that are closest to the motorway. The distance between the receiver points at the façade was 3 m, and the result, presented in Figure 4.9, was quite as expected: lower noise levels at the lowest floor (effect of both the noise barrier and ground impedance) and also at façades which are shielded by protruding parts of the buildings. The highest levels were found on the top floor.

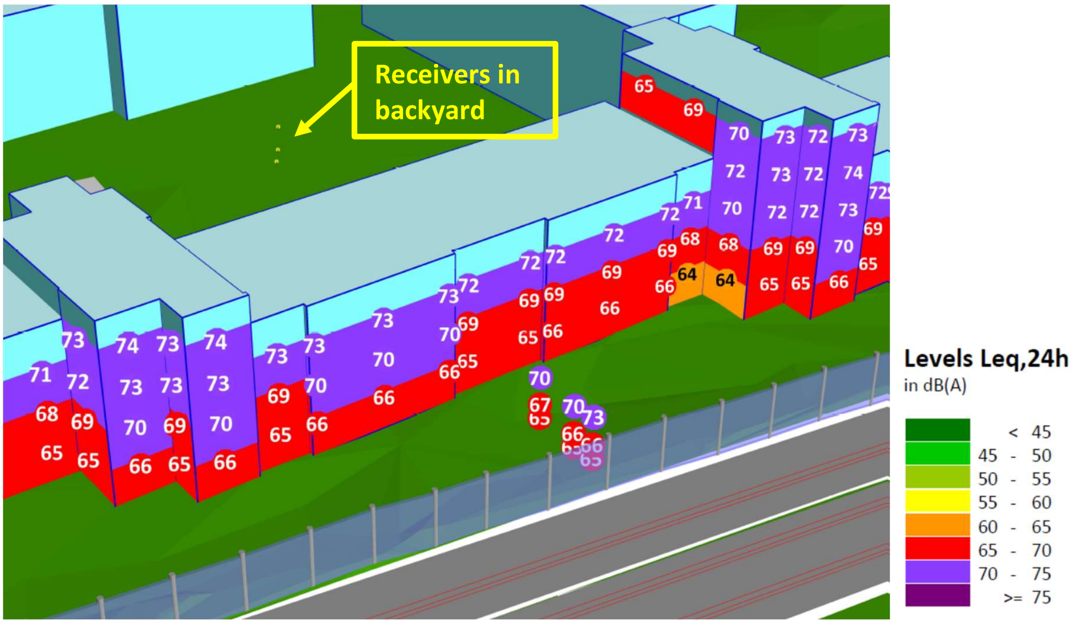


Figure 4.9: Result of the façade noise map calculation at Site 1. The level at the receiver positions of the single point calculations in front of the building are also presented in the figure. Note that the receivers in the backyard, 50 m from the noise barrier, were not included in this calculation.

Grid map calculation

A sound propagation calculation can show how noise barriers or the terrain affect the sound propagation in the model and thus the resulting the noise levels of the studied sites. The higher resolution (smaller calculation grid) the more informative result, but the calculation time increases greatly. Nevertheless, a 3x3 m grid calculation was run over a limited area comprising the locations for the single point receivers at 2, 4 and 8 m distance from the noise barrier, with previously decided final settings and parameters, i.e., ABS 16 road pavement, measured average vehicle speed and reflection depth 4. Calculation height was 2 m above the ground. As for the façade noise map, also here the results were as anticipated, lower noise levels closely behind the noise barrier, and higher by the building façades, the latter due to both noise reflections on the façades and less noise barrier efficiency, see Figure 4.10. Moreover, the grid map results are quite consistent with the 2 m height single point calculations, marked with yellow rings in the figure. In Table 4.5, the single point and grid map levels at the same distances from the noise barrier are compared.

Table 4.5: Calculated single point and grid map levels at 2 m height, for various distances form noise barrier at Site 1.

Distance	Single point (dB)	Grid map (dB)
2 m	65.5	65
4 m	65.3	65
8 m	66.5	66-67

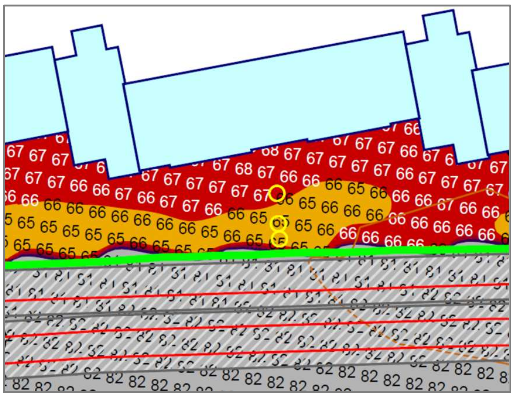


Figure 4.10: The L_{Aeq} result (dB) of 3x3 m grid calculation and the calculation height 2 m above ground. Positions of single point calculations are marked with yellow rings at 2, 4 and 8 m from noise barrier (green line).

Comparison of one-third octave band spectra

Under the assumption that the measurement results are correct, the general tendencies for Site 1, illustrated by the one-third octave band spectra of the "middle" receiver point mp1_d4_h2 (i.e., at 4 m distance from noise barrier and at 2 m height) in Figure 4.11, are that the calculations results in underestimation of the lower frequencies but overestimation of the frequencies above 1 or 1.25 kHz. For mp1_d4_h2 the level difference DL_{Aeq} is 1.2 dBA, which also is the biggest difference between calculated and measured values for Site 1, apart from the 4 m height receivers, see Table 4.7 in Chapter 4.5.3.

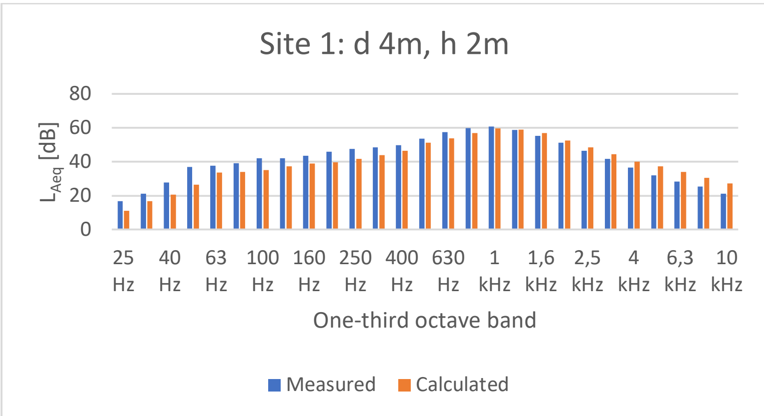


Figure 4.11: One-third octave band spectra for the "middle" receiver point, at Site 1, **mp1_d4_h2,** at 4 m distance from noise barrier and 2 m height. DL_{Aeq} 1.2 dB (L_{Aeq} measured 66.5 dB, L_{Aeq} calculated 65.3 dB).

The receiver point with the biggest DL_{Aeq} (4.2 dB) between calculated and measured values is at the mp1_d2_h4, at 2 m distance from noise barrier and 4 m height, Figure 4.12. It is quite good low frequency match between the measurement and calculation, but the calculation results in much higher values at frequencies above 1000 Hz, where the difference is increasing from 3.8 dB to 18.4 dB between 1 and 10 kHz. At the receiver point with the smallest DL_{Aeq} (0.2 dB) between calculated and measured values, mp1_d8_h2 (8 m distance from noise barrier and 2 m height), Figure 4.13, there are bigger differences at low frequencies than mp1_d2_h4 position, but much smaller differences above 1 kHz, from 0.2 dB at 1.25 kHz to 5.9 dB at 10 kHz.

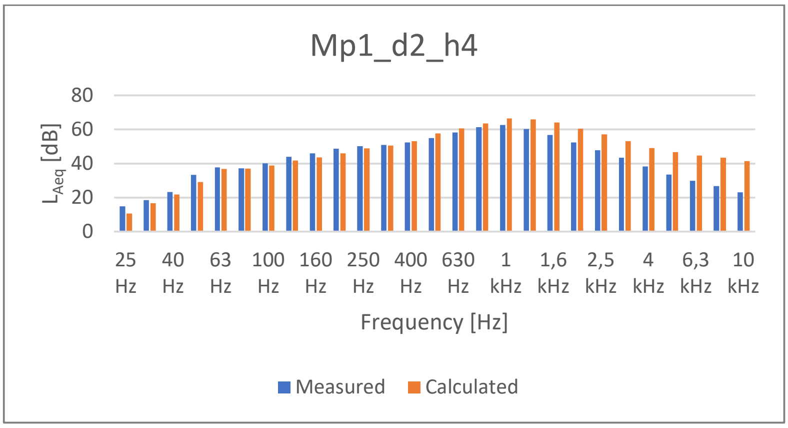


Figure 4.12: The receiver point with biggest DL_{Aeq} difference (4.2 dB) between measured and calculated values, mp1_d2_h4, at 2 m distance from noise barrier and 4 m height (L_{Aeq} measured: 68.2 dB, L_{Aeq} calculated72.4 dB).

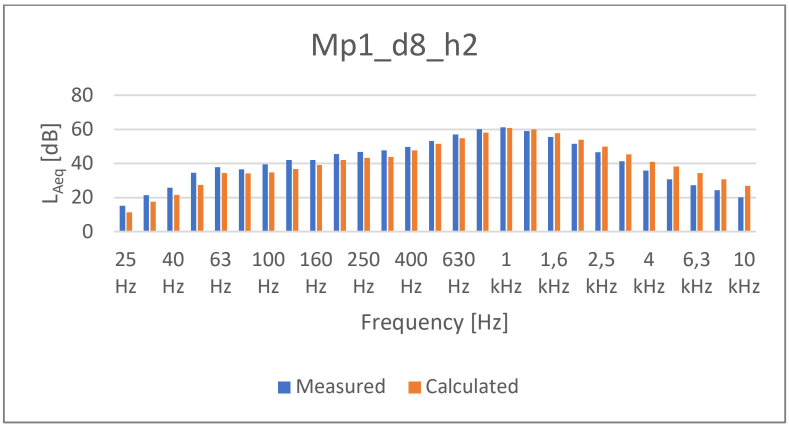


Figure 4.13: The receiver point with smallest DL_{Aeq} difference (0.2 dB) between measured and calculated values, mp1_d8_h2, at 8 m distance from noise barrier and 2 m height (L_{Aeq} Measured: 66.7 dB, L_{Aeq} calculated 66.5 dB).

4.5.2. Site 2

Similar to Site 1, comparisons are made between the measured and calculated single-number equivalent A-weighted (L_{Aeq}) sound levels for Site 2, with glances at the more detailed information in the one-third octave band spectra. The L_{Aeq} results from the calculations, measurements and the differences between them are summarised in Table 4.6, the differences are also illustrated in Figure 4.14.

Table 4.6: The single-number values of calculations and measurements at Site 2, including the differences between the measured and the various calculated levels.

Receiver	Meas. L_{Aeq} (dB)	Calc. SMA 11, v 80 3 rfl L_{Aeq} (dB)	Diff calc (SMA 11/ v 80) - meas	Calc. ABS 16, v 80 km/h 3 rfl L_{Aeq} (dB)	Diff calc (ABS 16/ v 80) - meas	Calc. ABS 16 ave. speed, 3 rfl L_{Aeq} (dB)	Diff calc (ABS 16/ v av.) - meas
mp2_d2_h1	58,7	59,9	1,2	61,8	3,1	62,7	4
mp2_d2_h2	60,3	62	1,7	63,9	3,6	64,8	4,5
mp2_d2_h4	69	72,2	3,2	74,1	5,1	75,1	6,1
mp2_d4_h1	58,7	60	1,3	61,9	3,2	62,9	4,2
mp2_d4_h2	60,5	61,7	1,2	63,6	3,1	64,5	4
mp2_d4_h4	65	67,7	2,7	69,7	4,7	70,6	5,6
mp2_d8_h1	58,3	61,5	3,2	63,4	5,1	64,3	6
mp2_d8_h2	60,1	63,1	3	65	4,9	65,9	5,8
mp2_d8_h4	63,4	66,5	3,1	68,4	5	69,4	6

The first round of calculations was based on the road pavement type SMA 11 (default in Swedish NORD 2000) and the speed limit of 80 km/h for all vehicles. The resulting calculated single number values were then 1.2 - 3.2 dB higher than the measured. The receiver positions with the smallest differences, 1.2 - 1.7 dB, were close to the noise barrier at 1 and 2 m above the ground. The largest differences (approx. 3 dB) were at 4 m height, i.e., above the noise barrier, and at all heights 8 m from the noise barrier.

Number of reflections

Contrary to Site 1, there are no building façades close to the receiver positions at Site 2, instead the area behind the noise barrier is open and relatively flat and the standard number of three reflections should be sufficient for the sound level calculations. However, there is a 5.4 m tall noise barrier on the opposite side of the motorway which reflective effect may contribute to the resulting sound levels at Site 2 (with 3 - 3.6 m tall noise barrier). Therefore, a set of comparative calculations were made with both 3 and 4 reflections, the latter resulted in only 0 - 0.1 dB higher L_{Aeq} levels, so for the subsequent calculations of Site 2, it was decided to continue with three reflections.

Road pavement type and vehicle speed

Adjusting the road surface type (to ABS 16, a noisier type), and applying the measured average speed (from a lower speed limit) only enlarged the difference between the measured and calculated levels, to 4 - 6.1 dB, see Figure 4.14. Due to the "plain" situation, there were not many other corrections to do other than assess and adjust the geographical data and ground impedance, non of which affected the calculated results significantly.

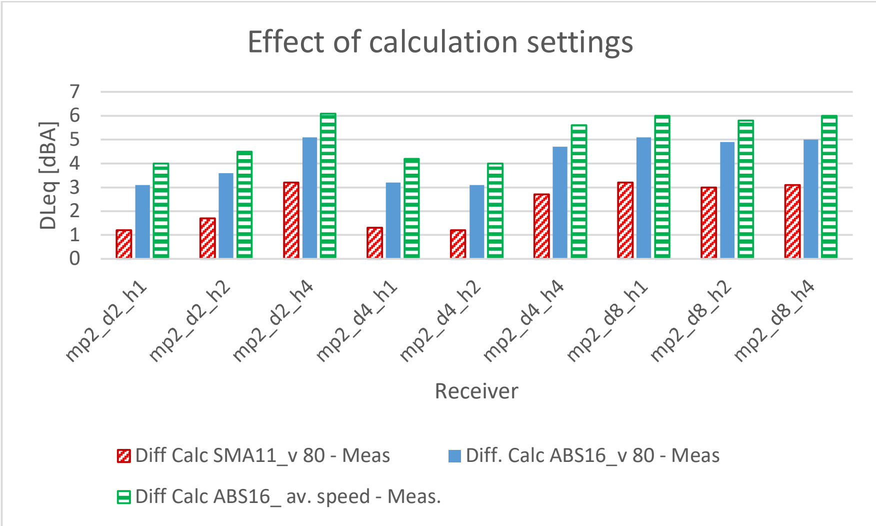


Figure 4.14: The difference between calculated and measured sound levels at Site 2, due to the effect of different calculation settings (all with 3 reflections).

Terrain model

Since the noise barrier at Site 2 has a slightly undulating shape in the horizontal direction, and there are some small height variations in the grassy area behind the barrier, the agreement between the terrain model vs. "reality" was tested by adding receiver points 10 m to the east of the original measurement positions (mp2) in the calculation with ABS 16, v = 80 km/h and 4 reflections. This resulted in 0.4 - 1.9 dB lower L_{Aeq} values at 2 m distance from the noise barrier, i.e., the difference between measured and calculated levels were reduced to around 3 dB at the extra receiver points (mp2e), see Table 4.7. A reduction could also be seen at the other 4 m-height receivers but not at 1 and 2 m height. Thus, the terrain model may be partly responsible for the difference between the measured and calculated sound levels. However, the total differences were still 2.8 - 5.4 dB (based on 80 km/h vehicle speed).

Table 4.7: Comparison of the single-number values of measurements and calculations for the original receiver points (mp2) at Site 2, and calculations for the extra receiver points (mp2e), based on calculations with ABS 16, v 80 km/h, and 4 reflections.

Receiver	**Meas. Mp2 L_{Aeq} (dB)**	**Calc. Mp2 L_{Aeq} (dB)**	**Calc. Mp2e L_{Aeq} (dB)**	**Diff mp2 -mp2e**	**Diff calc mp2e - meas**
mp2e_d2_h1	58,7	61,9	61,5	0,4	2,8
mp2e_d2_h2	60,3	64	63,5	0,5	3,2
mp2e_d2_h4	69	74,2	72,3	1,9	3,3
mp2e_d4_h1	58,7	62	62	0	3,3
mp2e_d4_h2	60,5	63,6	63,8	-0,2	3,3
mp2e_d4_h4	65	69,8	69,4	0,4	4,4
mp2e_d8_h1	58,3	63,4	63,5	-0,1	5,2
mp2e_d8_h2	60,1	65	65,5	-0,5	5,4
mp2e_d8_h4	63,4	68,5	68,4	0,1	5

Grid map calculation

The grid noise calculation that was performed for Site 2 with the quite small grid of 3x3 m revealed that, in the model, traffic noise was leaking in from the east, i.e., after the eastern end of the noise barrier, see Figure 4.15. Since the calculated levels are so much higher than the measured in the receiver positions, incorrect road or terrain height data at that section could be one explanation for the difference.

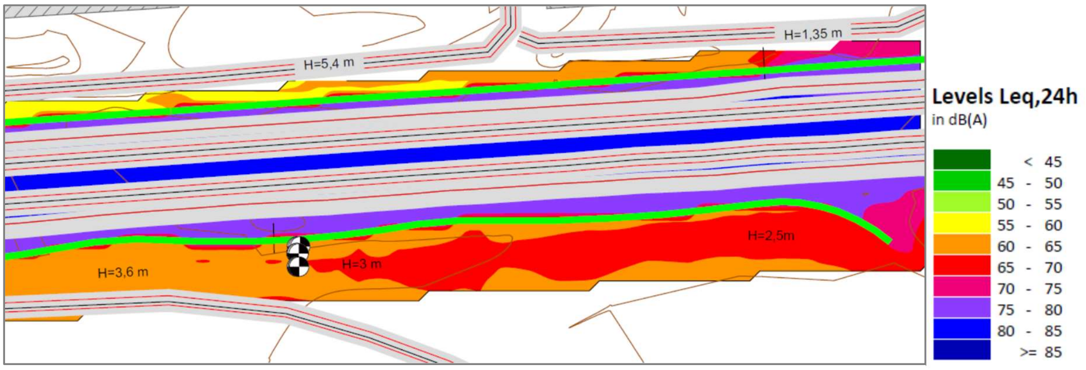


Figure 4.15: Site 2. Grid map calculation with 3x3 m grid, $L_{Aeq,\ 24h}$ at 2 m height. The black-and-white round markers show the single-point receivers at 2, 4 and 8 from the noise barrier (illustrated with a green line). *Note: based on calculations with ABS 16, v 80 km/h, and 3 reflections.*

Measurement conditions

The differences between measured and calculated L_{Aeq} levels may also depend on the situation during the measurements, even though the weather or traffic conditions did not cause any concerns at that time. The measurements and subsequent calculations are to be repeated for both Site 1 and 2 in the future work. Studies of other, comparable sites are also necessary to be able to draw any conclusions about the accurateness of the calculation model and/or the calculation settings.

Final settings for study Site 2

The final settings for Site 2, differing from default or standard values (in parentheses), are as follows:

- Façade absorption: Not relevant (1 dB).
- Number of reflections: 3 (3).
- Speed: Measured average speed: Vehicle category 1—89 km/h, categories 2 and 3—82 km/h (speed limit 80 km/h).
- Tyres, vehicle Category 1: 10 % studded (0 %).
- Road pavement type. ABS 16 (SMA 11).
- Road surface: 25% wet (dry).
- Air temperature: -5˚C (+15˚C).

The results for the single-point receivers at Site 2, i.e., with the final settings are presented in Figure 4.16.

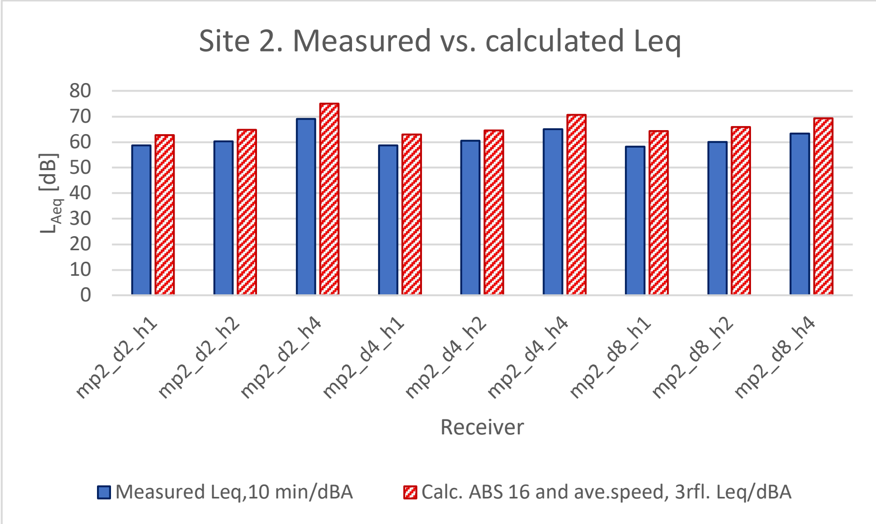


Figure 4.16: Calculated L_{Aeq} values, based on final settings, and measured L_{Aeq} values for receivers at Site 2.

Comparison of one-third octave band spectra

Under the assumption that the measurement results are correct, the general tendencies for Site 2, illustrated by the one-third octave band spectra of the middle receiver point mp2_d4_h2 (i.e., at 4 m distance from noise barrier and at 2 m height), see Figure 4.17, is that the calculations result in underestimation of the frequencies below 250 Hz and overestimation at higher frequencies. This is similar to Site 1 but the overestimation starts already around 500 Hz instead of 1 kHz and is much higher for all receiver positions at Site 2. For mp2_d4_h2 the difference DL_{Aeq} is 4.0 dBA, which is one of the two receivers with the smallest differences between calculated and measured values for Site 2. See Table 4.8 in Chapter 4.5.3.

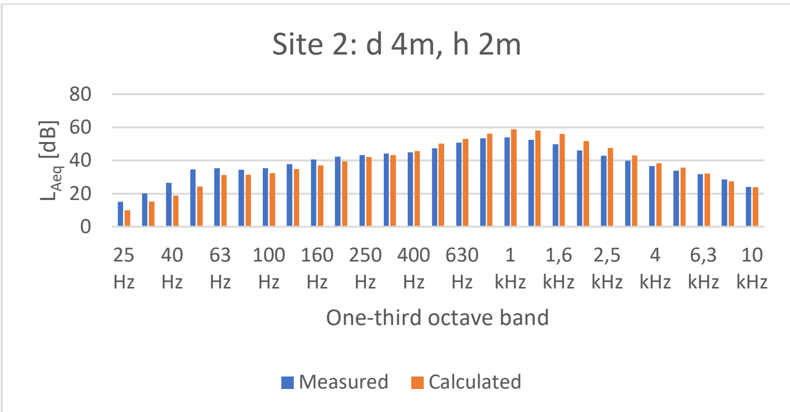


Figure 4.17: One-third octave band spectra for the middle receiver point at Site 2, mp2_d4_h2, at 4 m distance from noise barrier and 2 m height. DL_{Aeq} is 3.1 dB (L_{Aeq} measured 60.5 dB, L_{Aeq} calculated 64.5 dB).

The receiver point with the biggest DL_{Aeq} (6.1 dB) between calculated and measured value is mp2_d2_h4, at 4 m height and 2 m distance from the noise barrier and, see Figure 4.18. There is a quite good low frequency match between the measurement and calculation, but the calculation results in much higher values at frequencies above 315 Hz, the difference is increasing from 1.8 dB at 315 Hz to 12.6 dB at 10 kHz.

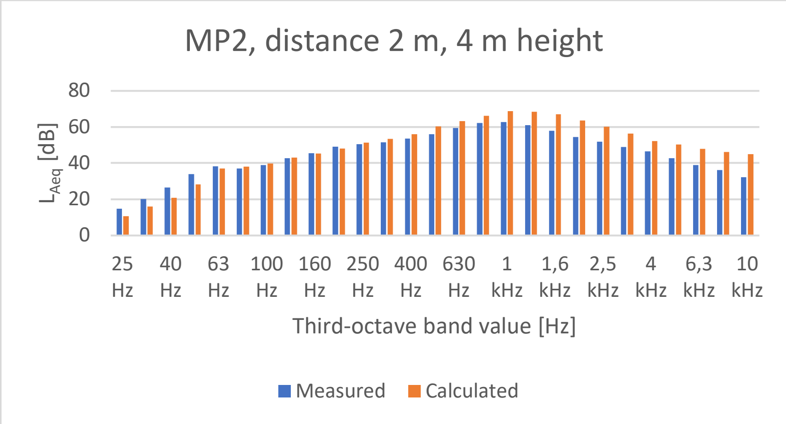


Figure 4.18: The receiver point with the biggest DL_{Aeq} difference (6.1 dB) between calculated and measured values, mp2_d2_h4, at 2 m distance from noise barrier and 4 m height (L_{Aeq} Measured: 69.0 dB, L_{Aeq} calculated 75.1 dB).

4.5.3. Comparison of results for both study sites

Comparing the results of the two study sites, the first observation is that the differences between the measured and calculated levels are much larger for Site 2 than for Site 1. By ranking the absolute values of the differences between measured and calculated L_{Aeq} levels for both sites, see Table 4.8, some patterns appear that might be worth looking into at the continuing work:

- The receiver d2_h4, i.e., at 4 m height and 2 m distance from the noise barrier, is in the bottom of the list in Table 4.7, for both sites (**note b = bottom**). This position is above the noise barrier at both sites, for which the calculated sound levels are much higher than the measured levels.
- The 4 m receiver heights at Site 1 **(note h4),** are the only ones where the calculated levels are higher than the measured ones at Site 1, and also have the biggest difference between measurement and calculations (the measured values at 4 m differs less to the calculated extra receiver points at 3.5 m height, see Table 4.4).
- At Site 2, all the receiver points at 8 m distance are in the bottom of the ranking list, while mp1_d8_h2 and mp1_d8_h1 are in top three of the Site 1 list **(note d8).**

Table 4.8: Ranking of the absolute values of the differences between measured and calculated L_{Aeq} levels for Site 1 (S1) and Site 2 (S2). The calculations are based on ABS 16 and average speed.

#	**S1_Receiver**	**Diff. Meas - Calc** (Abs. value)	**Note**	**#**	**S2_Receiver**	**Diff. Calc – meas.** (Abs. value)	**Note**
1	mp1_d8_h2	(-) 0,2	**d8**	1	mp2_d2_h1	4	
2	mp1_d2_h2	(-) 0,6		2	mp2_d4_h2	4	
3	mp1_d8_h1	(-) 0,6	**d8**	3	mp2_d4_h1	4,2	
4	mp1_d2_h1	(-) 0,9		4	mp2_d2_h2	4,5	
5	mp1_d4_h1	(-) 1,1		5	mp2_d4_h4	5,6	
6	mp1_d4_h2	(-) 1,2		6	mp2_d8_h2	5,8	**d8**
7	mp1_d8_h4	1,9	**h4**	7	mp2_d8_h1	6	**d8**
8	mp1_d4_h4	2,1	**h4**	8	mp2_d8_h4	6	**d8**
9	mp1_d2_h4	4,2	**b, h4**	9	mp2_d2_h4	6,1	**b**

4.6. Test calculations with sound absorbers on noise barriers

In this chapter it is examined whether different absorption indices of the surfaces in the road environment affects the calculated noise levels at the receiver positions. This is done by modifying the existing noise barriers of the sites by changing their absorption indices on one or two sides of the barriers, using some of the absorption data obtained by the in-situ measurements (see Chapter 3.3), but also by removing a sound reflective noise barrier on the opposite side of the road at Site 2.

The same parameters and calculation settings that were used for the comparison of measured and calculated levels in Chapter 4.5 are applied, regardless the fact that the final calculated levels are lower than the measured levels at Site 1 and higher than the measured levels at Site 2. Here, the objectives are the results of the relative comparisons of sound levels of the calculated present situations and of situations with modified absorption indices on the noise barriers.

The following alternatives are tested for both Site 1 and Site 2:

1. Absorbers on the inside of the noise barriers, i.e., the receiver side.
2. Absorbers on the outside of the noise barriers, i.e., the roadside, on both sides of the road.
3. Absorbers on both sides of the noise barriers, on both sides of the road.

For Site 2 also:

4. Absorber on the roadside of the opposite 5.4 m high noise barrier.
5. Alternative without the 5.4 m high noise barrier on the opposite side of road.

Applied absorption coefficients of the noise barriers, according to the following alternatives:

- Present situation, where all noise barriers are sound reflective on both sides, assumed absorption coefficient = 0.01 over all one-third octave band frequencies.
- Noise barrier with sound absorbers on one or both sides (based on absorption coefficients from measurement of a metal cassette barrier, combined with information in a product sheet and complemented with a modest absorption index at frequencies below 200 Hz), see Table 4.9.

Table 4.9: Absorption coefficients for noise barrier with absorber, assumed and measured values from 25 Hz to 10 kHz.

Fc [Hz]/	**25**	**31**	**40**	**50**	**63**	**80**	**100**	**125**	**160**	**200**		**6300**	**8000**	**10000**
Abs.coeff Assumed	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.15	0.2	0.25		0.9	0.9	0.9

Fc [Hz]	**250**	**315**	**400**	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	**4000**	**5000**
Abs.coeff Measured	0.36	0.41	0.61	0.59	0.68	0.66	0.75	0.82	0.86	0.93	0.96	0.93	0.92	0.91

4.6.1. Site 1

The results below are based on calculations with ABS 16 road pavement, average measured speed (89 km/h for category 1 vehicles, and 82 km/h for categories 2 and 3 vehicles), and 0.2 dB façade absorption instead of the default value of 1.0 dB.

Figure 4.19 shows that installing absorbers on both sides of all noise barriers, on both sides of the motorway (abs_all_nbs), gives the highest L_{Aeq}-reduction (1.1 - 2.2 dB) in all Site 1 receiver positions at 2, 4 and 8 m distance from the noise barrier. The best effects are achieved in positions close to the barrier (2 and 4 m) at 1 and 2 m height. In these positions, the second best alternative is absorbers on the inside (receiver side) of the barrier with 0.8 - 1.4 dB sound reduction).

Absorbers on the roadsides only, reduces the sound levels by 0.8 - 1.2 dB. In the receiver positions d4_h4, d8_h2 and d8_h4, it is almost as effective as installing absorbers on both sides of all noise barriers.

The sound levels in the backyard behind the buildings, 50 m from the noise barrier, are only marginally affected by the installation of absorbers on the noise barriers (0- 0.1 dB reduction).

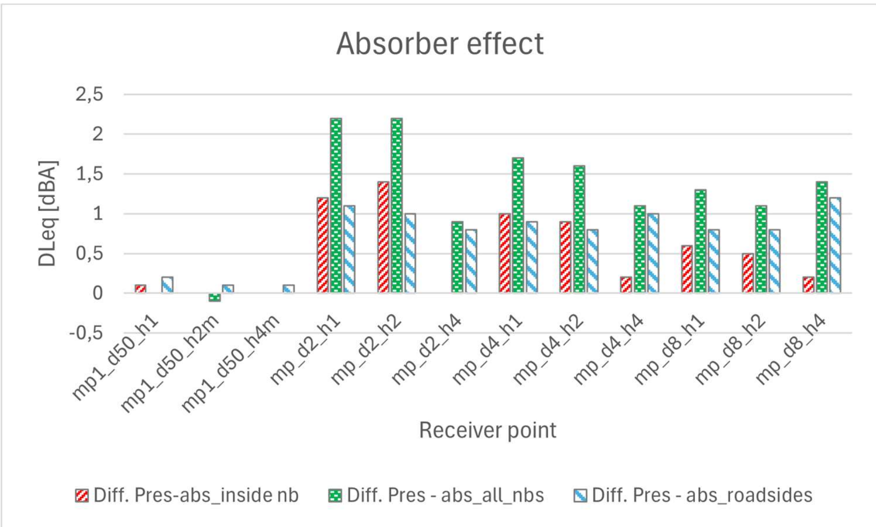


Figure 4.19: Sound reducing effect of different absorber alternatives, compared with present situation, at Site 1 (nb = noise barrier).

4.6.2. Site 2

The results below are based on calculations with ABS 16 road pavement and average measured speed (89 km/h for vehicle category 1, and 82 km/h for categories 2 and 3).

Figure 4.20 shows that installing absorbers on both sides of all noise barriers, on both sides of the motorway (abs_all_nbs), gives the highest L_{Aeq}-reduction (0.9 - 1.6 dB) in all, but one, receiver positions at Site 2. The biggest reductions are at 8 m distance from the noise barrier. Installing absorbers on the roadsides of all noise barriers, or only on the 5.4 m high noise barrier on the opposite side of the motorway, is nearly as good as removing the opposite noise barrier. The reduction is 0.6 - 1.6 dB for those three alternatives and the best effects are achieved at 4 m height and furthest from the noise barrier.

The least effective alternative is installing absorbers on the inside of the noise barrier at the receiver side, which reduces the sound levels with approximately 0.3 - 0.6 dB in positions at 1 and 2 m height close to the barrier (2 and 4 m).

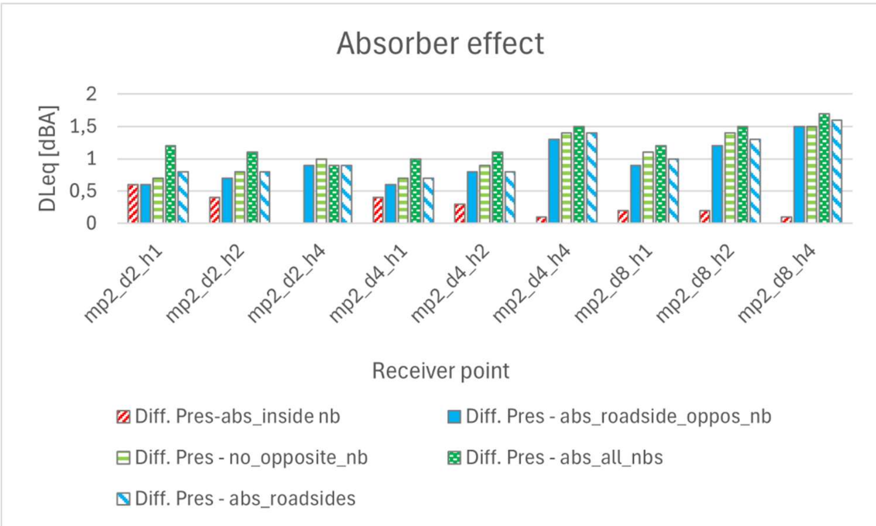


Figure 4.20: Sound reducing effect of different absorber alternatives, compared with present situation, at Site 2 (nb = noise barrier).

4.6.3. Comparison of results for both study sites

At both study sites, the best results of the tests with different absorber alternatives were obtained by installing absorbers on both sides of all noise barriers, i.e., on both sides of the road. However, the top results of the receivers with the highest noise reduction for Site 1 (note **t1**) were at the bottom of the ranking list of Site 2. And vice versa for the top resulting receivers of Site 2 (note *t2*), which were at the bottom of the list for Site 1, see Table 4.10.

At Site 1, the best effect was achieved close to the noise barrier, at 1 and 2 m above the ground. At Site 2, the best effect was furthest away from the noise barrier. Again, as presented in Table 4.8, the d2_m4 is at the bottom of the list for both sites (note **b** = bottom).

One explanation for the almost diametrically opposed top/bottom reduction results could be that Site 1 is in a 12-16 m narrow canyonlike yard between reflecting building façades and noise barrier, i.e., the installed absorbers on the receiver side of the noise barrier at Site 1 reduce reflected sound from the building façades, while Site 2 is located in an open parklike area without any reflecting buildings nearby.

Table 4.10: Ranking of the receiver positions by the noise reduction of absorbers applied on both sides of all noise barriers (nbs). Site 1 (S1) receivers to the left and Site 2 (S2) receivers to the right in the list (calculations based on ABS 16 and average speed).

#	**S1_Receiver**	**All nbs abs, red. (dB)**	**Note.**	**#**	**S2_Receiver**	**All nbs abs, red. (dB)**	**Note.**
1	mp_d2_h2	2,4	**t1**	1	mp2_d8_h4	1,7	*t2*
2	mp_d2_h1	2,3	**t1**	2	mp2_d4_h4	1,5	*t2*
3	mp_d4_h1	1,8	**t1**	3	mp2_d8_h2	1,5	*t2*
4	mp_d4_h2	1,7	**t1**	4	mp2_d2_h1	1,2	**t1**
5	mp_d8_h1	1,4		5	mp2_d8_h1	1,2	
6	mp_d8_h4	1,3	*t2*	6	mp2_d4_h2	1,1	**t1**
7	mp_d8_h2	1,2	*t2*	7	mp2_d2_h2	1,1	**t1**
8	mp_d4_h4	1,1	*t2*	8	mp2_d4_h1	1	**t1**
9	mp_d2_h4	0,9	**b**	9	mp2_d2_h4	0,9	**b**

4.7. Case studies, summary and discussion

4.7.1. Comparisons of calculations and measurements

The comparisons between calculated and measured sound levels at two different sites along the same motorway, about 1 km apart, led to both anticipated and unexpected results. At Site 1, with a canyonlike situation in the narrow yard between the 3.7 m high noise barrier and the 4-5 floor building façades, discrepancies were expected, above all in the lower frequencies, which also showed in the results from the start. However, the differences were not expected to be so big – the measured L_{Aeq} levels were up to 6 dB higher than the calculated levels. Several adjustments had to be done to reduce the gap, the most important ones were to control and correct the road surface type and to apply the measured average speed of the vehicles instead of the lower speed limit). But also to lower the default value of façade absorption from 1 to 0.2 dB and increase the number of reflections taken into account in the calculations (i.e., the reflection depth).

For the second site, the results were more surprising since it is a quite plain situation behind a 3.0 - 3.6 m high noise barrier installed in a narrow parklike area next to a local road, with the nearest building façades at 50 m distance. Here the initial calculated sound levels were about 2-3 dB higher than the measured levels. Adjusting the road surface type (to the present noisier type) and applying the measured average speed (from a lower speed limit) only enlarged the difference, to 4-6 dB. Due to the plain situation, there were not many other corrections to do, other than assessing and controlling the geographical data and ground impedance, non of which affected the calculated results significantly.

By performing a fine, 3x3 m grid noise calculation, it was discovered that, in the model, traffic noise originating from east of the noise barrier was leaking in behind the barrier. One explanation for the difference between the measured and calculated levels could be disagreement between the modelled and the real terrain due to incorrect road or terrain height data at that section. The L_{Aeq} differences at Site 2 may also depend on the measurements, even though the weather or traffic conditions did not cause any concerns at that occasion.

The measurements and subsequent calculations are to be repeated for both sites in the future work. At this stage it is not possible to draw any conclusions concerning the underlying research question whether the prediction model Nord 2000 is calculating the not overly complex conditions of the studied sites correctly, or if other methods are necessary to complement the Nord 2000 calculations.

4.7.2. Effect of installing absorbers on the present sound reflecting noise barriers

The second part of the case study was to test if changing the absorption coefficients of the noise barriers could, theoretically, affect the resulting sound levels at the receiver points. The result was: the more absorbers, the higher the sound reduction. However, there are degrees of effectiveness which are important to consider. The tested alternatives at Site 2 showed that absorbers on both sides of all noise barriers, on both sides of the motorway, gave the biggest sound reduction (up to 1.7 dB), but not far behind were three other options: absorbers on the roadsides, absorber on the roadside of opposite noise barrier only, or removing the opposite side noise barrier.

The least effective alternative at Site 2 was absorbers only on the receiver side of a noise barrier (0 - 0.5 dB noise reduction), but this was the second best option in positions close to the barrier at Site 1 (0.8 - 1.4 dB sound reduction). This may depend on the fact that Site 1 is a narrow yard between the noise barrier and building façades, i.e., with multiple reflections which strengths are reduced by the absorbers on the noise barrier inside. Site 2, on the other hand, is a quite open area, with the nearest building façade at 50 m distance from the noise barrier.

At Site 1, absorbers on both sides of all noise barriers reduced the noise levels with up to 2.4 dB. Absorbers on the roadsides only, reduced the sound levels by 0.8 - 1.2 dB, which at some of the furthest receivers almost was as effective as installing absorbers on both sides of all noise barriers.

5. 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 nr 3 – Good Health and Well-being, nr 11 – Sustainable Cities and Communities and nr 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.

6. Conclusions

The aim of this Licentiate thesis was to investigate the acoustic effect of sound absorbing materials and surfaces in road infrastructure and whether varying impedance and absorption characteristics matter for the resulting sound levels in the vicinity of complex road infrastructures. To do this, some initial steps had to be taken.

First, it was established that the NORD 2000 calculation model for road traffic noise [8] would be the most appropriate of the existing noise predictions models for the sound level calculations of the project, meeting requirements like presenting the results in one-third octave band values so it would be possible to both enter absorption data and analyse the effects of surfaces with different absorption indices. However, limitations of the NORD 2000 model will be observed during the following work since a research question is whether additional methods may be needed to calculate the noise levels and predict the effects of various noise reducing measures in geometrically complex environments.

Second, it became clear that the necessary sound absorption input data for materials in infrastructure hardly existed and was also lacking for the greater part of the installed noise barriers along the roads and rails in Sweden. Thus, this data had to be obtained by measurements, which was achieved with the SOPRA method, a quicker, and in some parts simplified, version of the standard method EN 1793-5 to measure sound reflection in road noise barriers in direct sound field. A substantial part of the work came to concern the study, preparation, execution and evaluation of the SOPRA measurements (presented in the Forum Acusticum conference 2023, see Paper B). Eventually, the sound reflecting properties of five noise barriers, installed along roads or railroads, and three types of walls on train platforms were measured with the SOPRA method, resulting in absorption coefficients to enter into sound level calculations for real sites in the following case studies.

Two case studies have been performed in order to study

1. Differences between calculated and measured sound levels – to examine if it is possible to reproduce the measured sound levels with calculations and which parameters or corrections that may be significant for aligning the calculated results with the measured levels.
2. The effect of installing absorbers on the present sound reflecting noise barriers, regardless of the results of the first point.

The comparisons between calculated and measured sound levels at two different sites along the same motorway, about 1 km apart, led to both anticipated and unexpected results. For the first site, a narrow yard between a noise barrier and building façades, differences between the calculated and measured sound level were expected, but they were surprisingly large – the measured L_{Aeq} levels were up to 6 dB higher than the calculated levels. Several adjustments had to be done to reduce the gap, the most important ones was to control and correct the road surface type and to apply the measured average speed of the vehicles instead of the lower speed limit. But it also helped to lower the default value of façade absorption from 1 to 0.2 dB and increase the number of reflections taken into account in the calculations (reflection depth).

At the second site, a plain suburban situation behind a noise barrier, the results were more surprising. The initial calculated sound levels were about 2-3 dB higher than the measured ones. Correcting the road surface type and applying the measured average speed only enlarged the difference, to 4-6 dB. A 3x3 m grid noise calculation revealed that, in the model, traffic noise was leaking in from east of the noise barrier, which may not be the case in the real situation. This could be due to incorrect road or terrain height data. The differences at Site 2 may also depend on the measurements, even though the weather or traffic conditions did not cause any concerns at that time. Everything considered, at this stage it is not possible to draw any conclusions whether the NORD 2000 calculations of the studied sites are reliable, or if other methods are necessary to complement the Nord 2000 calculations.

In addition, it was examined if different absorption factors on the surfaces (e.g., noise barriers) in the road environment affected the calculated noise levels at the receiver positions. This was done by modifying the present noise barriers of the sites by changing the absorption coefficients on one or both sides of the barriers, but also by removing a reflective noise barrier on the opposite side of the road. The result was: the more absorbers, the higher the noise reduction. However, there are degrees of effectiveness which are important to consider, one solution to reduce noise levels at a certain location may not be optimal for another site down the road.

One of the lessons learnt from all the in-situ sound reflection measurements is, that it is difficult to know if the resulting absorption data is realistic or representative for a certain type of absorber or surface. To be able to evaluate or predict the outcome of direct field sound reflection measurements, the Direct Field Absorption (DFA) model was developed, a time-domain model for the reflection of spherical waves in an absorber-like surface (described in Paper C). The first results are promising, even though the conclusions so far are based on only one kind of absorber. The future work will comprise further studies of the model and other applications for it. Except assessing the results of reflection measurements of an absorber, the DFA model might be used to extrapolate the sound reflection index below the low frequency limit for in-situ measurements. Also, the DFA model might be useful for customising noise barriers, e.g., choose absorber, for specific sites.

7. Future work

The future work comprises the following parts.

Case studies

The case studies presented in this work resulted in some questions that need to be addressed and the sound level measurements at the studied sites have to be repeated – to confirm or re-assess the results of the comparisons between calculated and measured sound levels. Additional measurements and calculations of other sites are needed as well, for instance of locations with absorbers on installed noise barriers. This will include sound reflection *(RI_Q)* measurements of the absorbers on-site.

The objective is to define a method to predict and evaluate the traffic noise levels and other acoustical circumstances in complex infrastructure environments, which may include supplementary calculations and measurements to the calculations with the NORD 2000 prediction model.

DFA model

The developed Direct sound Field Absorption (DFA) model to assess sound reflection measurements in direct sound field, was applied on the SOPRA method with promising results. Additional work is necessary though, e.g., it should be tested on other types of sound absorbing materials.

Also, it will be investigated if the the DFA model can be used to customise noise barriers (e.g., choose absorber) or to predict the performance of new designs of noise barriers, which could be a part of a method to tune the noise reduction, or, to specify the necessary sound absorption in noise barriers or other surfaces to achieve a certain noise reducing effect. This could serve as basis for detailed specifications to manufacturers or contractors of public procurements for infrastructure projects.

Methodology for acoustic planning

The two points above will contribute to the purpose of the PhD project, i.e., to propose a methodology for acoustic planning of complex traffic environments.

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