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Management of a ground-borne noise prediction methodology for railway traffic in tunnels

Master's thesis in the Master's Programme Sound and Vibration

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Cover:
Shows classical railway modeling. Models are useful when trying to understand how things work, regardless if it is trains or ground-borne noise. Source: Wikimedia Commons.
Department of Architecture and Civil Engineering
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ABSTRACT

The purpose of this thesis was to understand how a new prediction methodology for ground-borne noise should be maintained and continuously updated. The scope included ground-borne noise from trains in tunnels and focused on the predictions to fulfill the requirements for the post-construction phase. Research questions were formulated and they were as follows: What new data should be added to the methodology? What are the risks when managing the methodology? What strategy should be used to ensure a successful management? The method was composed of a literature review, case studies, interviews and a numerical analysis. In total, 22 respondents were interviewed.

The results from the case studies demonstrated that under-ballast mats are common and that assumptions related to the foundation differ between projects. However, assumptions used when obtaining the ground-borne noise level in a room are similar. In Sweden, the same noise criteria have been utilized in practice. The results from the interview sessions demonstrated that more information regarding the coupling between the tunnel and the building is needed. Also, the contribution from railway components can be added to the implemented model. Measures should not be added to the implemented model since it could alter the creativity during development. However, a default value for an under-ballast mat can be added. Advantages with the methodology is that it contains a great deal of data, a detailed literature study, includes the uncertainties and that it is transparent. The source strength in the model was developed using data from two specific tunnels.

One identified risk is that the model might not make sufficient predictions for cases with significantly different conditions. Another risk is that it stagnates when it is no longer maintained. To ensure a successful management, a reference group is needed that can discuss it. The process of using the methodology and the implementation of the model should be further explained in a step-by-step user guide. New measurements are required and results from other methods, such as specific transfer functions can be used.

The numerical part demonstrated for a specific case that no measures on the track are needed for dwellings situated further than 100 m away from the tunnel when passenger trains are investigated. For freight trains, the same distance must exceed 200 m. A difference of 5 dBA exists between results from the implemented model and results from the EIA (Environmental Impact Assessment) in the Lärketorpet project. Important for fulfilling the criteria is that an upgraded rail structure is used. This will mitigate the ground-borne noise levels. Future studies could focus on comparing numerical results from other projects and investigate ground-borne noise in the construction phase.

Keywords: Ground-borne noise, under-ballast mat, tunnel, environmental impact assessment.

Förvaltning av en stomljudsmodell för tåg i tunnlar
Examensarbete inom masterprogrammet ljud och vibrationer

Carl Höjdefors

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SAMMANFATTNING

Examensarbetet har haft som syfte att undersöka hur en ny metodik för att beräkna stomljud från tåg i tunnlar kan förvaltas och uppdateras. För att svara på syftet användes tre frågeställningar: Vilken ny data behöver tillföras metodiken? Vilka risker finns det när metodiken ska förvaltas? Hur bör metodiken förvaltas på ett effektivt sätt? Examensarbetet avgränsades till tunnelprojekt och till driftfasen. Metoden bestod av en kvalitativ del och en kvantitativ del. Den kvalitativa delen omfattade en litteraturstudie i form av fallstudier och intervjuer. Totalt intervjuades 22 respondenter från olika områden. Fallstudierna omfattade närläsning av projektrapporter, miljökonsekvensbeskrivningar och lokaliseringsutredningar. Slutligen genomfördes en numerisk analys bestående av en undersökning av den implementerade modellen i Excel.

Resultaten från fallstudierna visade att ballastmattor är en vanlig åtgärd och att antaganden rörande grundläggningen skiljer sig. Däremot är antaganden gällande beräkningen av stomljudsnivåerna likartade. Dessutom har samma riktvärde för stomljud varit praxis i de flesta projekt i Sverige. Resultatet från intervjuerna visade att mer kunskap relaterad till överföringen mellan tunneln och huset behöver tillkomma. Spårdetaljer kan läggas till i den implementerade Excelmallen. Åtgärder bör inte läggas in i den numeriska versionen eftersom det kan förändra kreativiteten, men ett standardvärde för exempelvis en ballastmatta kan läggas till för att underlätta vid bedömningen av stomljudsnivåerna. Fördelar med metodiken är att den innehåller mycket data, hanterar osäkerheterna väl, har en genomarbetad litteraturstudie och att den är transparent.

Risker när metodiken ska förvaltas är att den inte är anpassad efter verkligheten och att resultaten inte stämmer med mätdata. En annan risk är att metodiken stagnerar när de ansvariga inte längre fortsätter att utveckla den. För att metodiken ska förvaltas på ett effektivt sätt bör en referensgrupp bildas som kan diskutera den. Sedan bör den implementerade modellen förklaras i ett tillhörande dokument. Fortfarande krävs lokala mätningar och en jämförelse med andra metoder, som specifika överföringsfunktioner för att öka kunskapen. Resultaten från den numeriska delen i en specifik fallstudie från Lärketorpet i Trollhättan visade att bostäder som ligger 100 m från tunneln när passagerartåg passerar klarar riktvärdet. För godståg måste samma avstånd överstiga 200 m. En skillnad på 5 dBA existerar mellan resultaten från miljökonsekvensbedömningen och den implementerade modellen. Centralt är att en nyare banuppbyggnad används för att uppnå låga stomljudsnivåer. Framtida studier kan fokusera på att jämföra resultat från andra projekt eller på att undersöka stomljud som uppstår under konstruktionsfasen till följd av borrning och sprängning.

Nyckelord: Stomljud, ballastmatta, tunnel, miljökonsekvensbedömning

Contents

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Carl Höjdefors

Notations

dB	Decibel
EIA	Environmental impact assessment
FEM	Finite element method
IL	Insertion loss
LVT	Low-vibration track
SEA	Statistical energy analysis
SPL	Sound pressure level
TDOK	Trafikverket's governing documents
TGM	Tunnel boring machine
UPS	Under-sleeper pads
VL	Vibrational level

1 Introduction

The introduction will present the background, the purpose, the definitions, the goals and the scope. Ground-borne noise is important since it has an effect on human health and this will motivate this study which is now described in the background.

1.1 Background

Vibrations that occur when trains are passing through tunnels can cause ground-borne noise in nearby dwellings. Ground-borne noise can be disturbing and must therefore be investigated (for more on vibrations and ground-borne noise, see chapter 3.3). The ground-borne noise level is often provided with information on what time weighting setting has been used. There are two time weighting settings named "FAST" and "SLOW". The setting FAST means that the integration time for the sound pressure level meter is shorter. Therefore, the sound only needs to be steady for 125 ms for the device to capture the amplitude. For the setting SLOW, the integration time is 1 s. [1]. Different countries have different limit values for ground-borne noise in dwellings. For example Norway has 32 dBA (FAST) as a standard value while Finland has 35 dBA (SLOW) [1]. Great Britain's target value is 40 dBA (SLOW) and Austria has 45 dBA (the integration time is unknown) during the day and 40 dBA during the night. These mentioned values above are the maximum values, but the equivalent level is also important to consider since how often trains arrive can have an impact [1]. The maximum value only considers the contribution from single train passages. For example, the equivalent value in Germany is between 35 dBA–40 dBA during the day and between 25 dBA–30 dBA during the night [1]. The day is defined as the time from 6 am to 10 pm and the night is defined as the time from 10 pm to 6 am [1].

In Sweden, there are no limiting values that are used for the entire country rather, project values are used for ground-borne noise from railway passages [1]. The limit value for ground-borne noise that has been recommended by Trafikverket is a maximum value of 32 dBA (FAST) [2]. In a report published by the UIC (International union of railways), it is described that the equivalent limit values can vary between 35 dBA to 40 dBA during the day. At night, the limit can vary between 25 dBA to 30 dBA. According to the report, the ground-borne noise levels for trains in tunnels are often presented as the maximum values and they are in the range of 25–30 dBA [3]. These limit values are based on regulations on environmental noise. It should be noted that when A-weighting is used, the values can become small since ground-borne noise is of low frequency character [3]. Important aspects for understanding ground-borne noise is for example input data on the bedrock properties, the building type and the track geometry [3]. The guidelines recommend that since this approach takes time, it is beneficial with a prediction methodology [3]. This prediction methodology should be able to handle the input data that changes for each location depending on where the railway will be built [3].

At Chalmers University of Technology, such a prediction methodology for ground-borne noise has been developed by Fatemeh Dashti [4]. The methodology is developed for three stages in the process: the localization stage, the planning stage and the construction stage [4]. By incorporating a statistical approach and geological considerations for the Swedish rock conditions, the methodology provides new perspectives. Therefore, the methodology is more accurate for the Swedish conditions. It is stated in the PhD thesis that the methodology should be practical, include the necessary parameters and be easy to update [4]. By adding new existing data, the methodology can become even more accurate [4]. For it to function more effectively, all the different stakeholders need to cooperate. This is something that is mentioned several times in a recent report [3]. Only by taking into account the important guidelines, the results from the experts working in the field and the opinions from the residents is it possible to find sustainable solutions [3]. These solutions need to be cost beneficial and effective over time [3]. For this to become a reality, the new prediction methodology must be managed in the same way, independently on who the stakeholder is.

The question that remains is now how it can be maintained and what is missing in the methodology so that it can be used by all different stakeholders? The subject for this master's thesis is therefore how this new prediction methodology can be maintained.

1.2 Purpose and definitions

The purpose of the thesis is to investigate how a methodology can be maintained and continuously updated. Here, a distinction must be made between the terms "model" and "methodology". The word "model" refers to the equations that forms the basis for calculating ground-borne noise. The concept of "methodology" refers to the whole process of using such a model. Here, the three stages (the localization stage, the planning stage and the construction stage) are included in the methodology. The methodology takes into account what extra measurements should be made and how the results can be applied. How data should be acquired and processed is another important aspect.

The thesis will only investigate the role of the methodology. This includes understanding what other fields should be included. Another important aspect is to give insight into how issues related to ground-borne noise can be introduced in the process. The idea is then that the methodology will be more accessible for the stakeholders. Hopefully, this will enable better collaboration between the different stakeholders at Trafikverket. Improved collaboration can lead to more efficient decision making in the future. Another goal is that the results will become useful in the practical planning process and not just be a theoretical discussion. Still, the thesis will focus on the overall methodology process and will not focus on a single tunnel project. An objective is that the results should be practical. Overall comparisons to other countries, such as Norway or Finland could still be made. To include other countries will provide insight into what challenges exist in other cities.

In order for the purpose to be fruitful, it is divided into a number of research questions. They are as follows:

1. What new data should be added to the methodology?
2. What are the risks when managing the methodology?
3. What strategy should be used to ensure a successful management?

1.3 Goals

The objectives of this master's thesis were:

1. Provide guidance on how the methodology can be implemented in practice

2. Give insight into how the new prediction methodology for ground-borne noise can be further developed.

This thesis project was planned together with Trafikverket. It was therefore of uppermost importance that the result that this thesis presented were meaningful for Trafikverket.

1.4 Scope

This thesis will investigate the management of a methodology adapted to predict ground-borne noise from railway traffic in tunnels. Information and details from railway lines without tunnels, so-called surface lines have as far as possible been excluded. In some cases, it is impossible to completely separate tunnel lines and surface lines. Tunnels can for example exist as a part of a surface line. Project areas with loose soil have been excluded because Dashti's engineering methodology is adapted to the bedrock conditions that exist in Sweden. The bedrock conditions can of course vary greatly between areas, but by only including projects built on crystalline rock, it becomes possible to compare case studies with the methodology.

Management is in this thesis defined as the operational decisions to maintain and continuously update the methodology. Management is therefore viewed as a direct approach in which actions are formed [5]. The risks that are mentioned in the second research question can also be formulated as challenges. The strategy that is mentioned in the third research question is defined as organizational structure. This organizational structure can be defined as expectations and rules for how a task should be performed and who should be responsible [5]. The name "Trafikverket" will be used rather than "The Swedish Transportation Agency" (often referred to as STA). This is because "Trafikverket" is more common in many of the reports. Names of mentioned cities have not been translated, but their original spelling remains. Project names have been translated into English since many infrastructure projects have names that describe the project and only having the Swedish project name could create confusion.

1.5 Limitations

The scope described how the subject of the thesis was defined. A section related to the scope is the section on the limitations. The limitations are as follows:

- The purpose was investigated by simulations, no measurements in existing tunnels were conducted
- Many calculations for ground-borne noise can be found, indicating that the specific assumptions must be known in great detail as to be able to compare numerical results
- Not many studies exist on ground-borne noise, which means that it can be a challenge to compare results from this thesis with results from other studies
- The available data, in the form of project reports, can sometimes be difficult to find

Another limitation that must be mentioned is that this thesis explores the technical details. Laws were not be studied in much detail. Even if laws and regulations have an impact on the management of a methodology, focus will still be on the technical aspects of the ground-borne noise methodology. The legal process with procurements and decisions cannot fully be ignored, but will not be reflected in neither the research questions nor in the interview questions. Possibilities and challenges can still be governed by laws and regulations and this is important to keep in mind. These limitations will be further discussed in section 2.5 when the method approach for the thesis is presented. With this being mentioned, it is now time to present how this purpose can be understood.

2 Method

This chapter will describe the method part. The method was based on a literature review, a qualitative approach and a quantitative approach. Apart from describing the overall approach, this method part will describe how the more detailed approach worked. The method section will start with a general description.

2.1 General description

The method can be divided into the literature review, the interview session and the numerical analysis. The interview session corresponds to the qualitative part, while the numerical analysis corresponds to the quantitative part. A numerical simulation was utilized to understand how the new methodology functioned. The numerical simulation consisted of using the implemented version in Excel and the process is described more thoroughly later. The qualitative approach consisted of several interviews with experts from numerous fields. These experts or respondents were representative because they had a deep understanding of the subject and experience from projects where ground-borne noise had been a key aspect. There were a variety of respondents meaning that their expertise could range from example geology and geotechnics to city planning, railway mechanics and even public health.

A number of interview questions were asked to each and everyone of the respondents. The interview questions were both descriptive and analytical. It was of interest to see if the respondents could name other fields that were to be be investigated in this thesis. The respondents gave their opinion on how this prediction methodology could be implemented and also what they thought was missing. The interviews were held in Swedish. The answers were later transcribed and translated into English. All interview answers were translated by the author. Quotes were used because they are important for conveying opinions and descriptions. The equipment was the audio recording app in the mobile and some of the interviews were held on Teams and these interviews were not recorded. The interview questions together with the answers can be found in the Appendix. This interview part will be described in section 2.3. The method part started with a literature review.

2.2 Literature review

The literature study was composed of three parts. The first part included information about how a tunnel can be built and general information about railway traffic. The second part included information about vibrations and ground-borne noise. The third part concerned the management of a methodology and the focus was on methodologies in infrastructure projects. The literature review presented results from similar studies. Public policy documents and data from projects are two important sources, together with articles and technical reports. A special category were the environmental impact assessments. An environmental impact assessment (EIA) contains information on how a project impacts the environment by investigating the impact of several areas, for example air quality, water management and acoustics. The main criteria for exploring a project in the thesis was that the project had much available information. An argument for primarily utilizing freely available documents is that a similar work in the future would then have access to the same information. The geology played a part; all projects had to have the same type of rock class and soil type. This was to ensure that it would be possible to compare the projects. Both completed projects and ongoing tunnel initiatives were included, as long as the geological conditions were similar. The projects became a basis for conducting the case studies. One project with its EIA and other documents formed a case study and information on how ground-borne noise was described and analyzed in a case study was important for interpreting the qualitative part and the quantitative part. The case studies then created the context for the other parts.

The sources for the literature review related to vibrations and ground-borne noise were mostly articles and technical reports. Documents that are publicly available were preferred. The sources were reliable because the authors often had a great deal of experience from their research field. Articles and technical reports could however be very detailed and not all information was relevant for this thesis. Articles and technical reports are written for a specific project and are therefore not updated once the project is over. This means that some information sometimes was irrelevant depending on how old the article or technical report was. It became necessary to use and compare many articles and technical reports to achieve the correct conclusions. Finally, not all articles or reports were written for the Swedish conditions. Even if this thesis investigated the management of a methodology from a general perspective, the results were based on facts from Swedish projects. When reading articles and technical reports, it became necessary to keep in mind what information can be useful in a Swedish context. In some cases, the reports were provided by the respondents. In that case, the link to that specific report couldn't be found, but the reference is described in the reference list. All references are listed in the reference list at the end of this thesis.

2.3 The interview session

The so-called research interview consists of seven steps. The process that the interview session follows can be seen in Figure 2.1. The steps in the interview session are [6]:

1. Thematizing
2. Designing
3. Interviewing
4. Transcribing
5. Analyzing
6. Verifying
7. Reporting

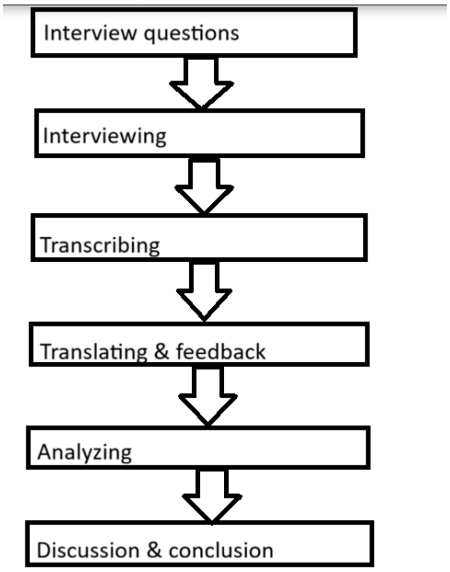

Figure 2.1: Shows the important steps when defining the method for qualitative part

The first step, thematizing, included to reflect on the purpose of the interview. The overall theme of the interview session were conceptualized in this step. One way to do this was to connect the purpose to the interview session by having the purpose as the theme [6]. This is the designing phase where the interview questions were formulated [6]. Later, the interview phase began. After the interviews had been conducted the answers are transcribed and analyzed according to the purpose. During the verifying phase, the results were generalized so that they could be reported which is the final step [6]. When the findings were reported, the ethical considerations are very important [6] and the ethical aspects are described in section 2.3.5, "Ethics". Step 3 (interviewing), step 4 (transcribing) and step 5 (analyzing) require some more detailed information.

2.3.1 Interviewing

The interview session

The interview part starts with some preparations. First, the topic of the research must be identified. The research questions need to be deconstructed into interview questions [7]. Then, the time and place must be decided. Equipment such as a recording device is brought to the interview room and the setting shall be quiet. The interviewer gives some general information and after that, the real interview starts [7].

To interview experts from different fields is something that can provide much information from a single meeting. Bill Graham states in his book [7] that experts tend to have information that hasn't been published. They also have a great deal of experience from their involvement in all kinds of projects. Through these projects they have developed knowledge that is of a more practical nature and not pure academical [7]. The interviewer creates a setting that is focused by having good eye contact with the interviewee. The interviewer should be clear about what the purpose of the interview is and should listen attentively [6]. Facial expressions or body language are equally important as having structured interview questions [6]. The interview questions should be simple and lead to the answer of a certain research questions, but interview questions can be introductory, specifying, direct or indirect [6]. The interviewer is responsible for changing theme and to ask follow-up questions. Follow-up questions are important when discussing complex topics or when critical questions need to be asked. These questions are needed to reach an analytical depth [6]. Before and after the interview starts, a briefing or reflection can be useful. This reflection enables for a moment of summarizing what questions will be asked and what can be developed in future interviews [6].

Even if the interviewer has structured questions, there is a need to be aware of what can make the interview stagnate. It can happen that the interviewees feel that they talk too much. The interviewer then has the opportunity to encourage them to continue by concentrate more on the answers [7]. A solution that can be used is to ask for examples which helps the interviewees formulate their thoughts or to summarize their answers. Keywords can be an effective tool to get both fruitful answers and to let the interviewees know where to continue [7]. It is difficult to decide how many interviews that are necessary. After some interviews, the answers will no longer expand the knowledge and the answers will appear the same and interviews are time-consuming [7].

Interview techniques

There are many interview techniques and they all serve different purposes. Well-known interview techniques are the unstructured interview, the semi-structured interview, the video interview and the elite interview. Group interviews are another category, but that type of interview was not used in this thesis [7].

The unstructured interview is characterized by the fact that it is the interviewee which determines the direction of the interview. The main purpose is that the interviewee will have the possibility to inform the interviewer about a certain subject [7]. The interviewee can feel more comfortable when the interview questions aren't predefined. The structure can be achieved later by categorizing the interview answers. The semi-structured interview on the other hand, combines the flexibility from the unstructured interview with a structure in order to efficiently collect data. The features of the semi-structured interview are that the questions are the same, the questions are evaluated after every session, that follow-up questions are used and that all the interviews takes the same amount of time [7]. What makes the interview technique flexible is that open questions can be used and that leading questions can be utilized [7].

The video interview has an advantage compared to other interview techniques that are not face to face which is that it is possible for the interviewee to react directly to a question [7]. The disadvantage is that the body language completely disappear. This requires more from the interviewer because the interviewer must now focus more on interpreting the interviewee. However, it opens up for the possibility to interview people in other regions or even countries [7]. Interview techniques not only depend on the structure of the interview, but also on the interviewee. A special case is when interviewing experts. An expert has special knowledge within a specific field [7]. They often have more knowledge on the specific subject than the interviewer and they are also aware of what a fruitful interview questions is. Interviewing experts will however lead to access to detailed information, access to unpublished information and provide the interviewer with in-depth knowledge [7].

2.3.2 Transcribing

The transcribing process takes most time of all the steps when conducting interviews. Transcribing is the process in which the face-to-face interview becomes a clear text. To do this isn't easy and some decisions must be made. A problem is that much of the meaning can disappear when spoken language is transformed into text. All semantic phrases will disappear [7]. It is hard to convey the interviewees feelings or their facial expressions that carry much meaning [6]. There are no real guidelines when transcribing apart from that it is important to be coherent. However, the transcriber affects the character of the text. This means that the reliability can be discussed depending on the quality of the transcriber [6]. Syntax and semantics are used to generate a good translation. A solution to avoid misunderstandings is to use back-translation where the text is translated back into the original language during the translation process [8]. For the validity, it is best if the transcription is adapted to the research purpose [6]. Ethics is included in the transcription process because sensitive details must be changed or reformulated [6]. The interviewees must also have the chance to review the transcribed version to ensure that the translation has been successful.

The transcribed text contains the interview questions, what the interviewee has said and the follow-up questions. It must be clear what is what. If possible, pauses and answers that aren't easy to interpret are marked in the text. The transcription is to be done as soon as possible, so that no details are forgotten [7]. A certain system with symbols have been developed to aid the interpretation when reading transcribed interviews [9]. This technique was developed by researchers from the discipline of conversation analysis. It should be mentioned briefly because it has prolonged the development of transcription techniques that are very detailed [6]. The one who is acclaimed for developing this transcription system is Gail Jefferson who suggested this system in 1965. Jefferson's system was new because it captured how something was said [9]. His transcription system is based on three main principles. Numbered lines are used so that the conversation can be followed and symbols are used to show other behavior. The third principle is that the conversation should transcribed as authentically as possible. Some of the symbols used can be seen in table 2.1. Conversation analysis describes the practices and actions during interactions. This approach is a useful method when studying the everyday conversation or social interactions between professionals. By studying the social interaction underlying structures can become visible [10]. Conversation analysis can be a suitable tool when analyzing courtroom discussions or the interaction between a doctor and a patient [10]. Before conversation analysis was developed, interaction was only viewed as a consequence of language, society or culture [10].

Table 2.1: Shows some of the more common symbols when transcribing interviews

Symbol	Meaning
=	Direct reply without silence in between
?	Strongly rising intonation
,	Slightly rising intonation
((text))	Describing something that happens outside of the interview
[text]	Overlapping talk
-	Cut-off
(text)	Uncertain interpretation

There are also symbols for describing laughter or aspiration. Even if this method is very detailed, some researchers claim that it is too detailed and creates less space for the analysis [9]. Others claim that the system isn't standardized compared to the phonetic alphabet. The transcription can be difficult to read and might only be useful when studying language. However, the system enables for interpretation of the conversation through the transcripts [9]. The system used for transcribing found in conversation analysis inspired the system used in this thesis.

2.3.3 Analyzing

After the material has been transcribed it must be analyzed. In this section, qualitative content analysis, argumentation analysis, analysis focused on the meaning and analysis focused on the language are presented. Meaning condensation is the last technique that will be presented.

Analysis techniques

Regardless of what method is chosen, it is common to divide the transcribed words into categories and analyze them separately. This approach is called coding. The categories should be descriptive and form the basis of what is denoted as qualitative content analysis [7]. Categories will after some time make it clear what is important in the interview. The transcription will include everything and creates an overview. It is however the categories that will highlight what parts of the transcribed interview that are interesting. The interesting parts remain as a corner stone for reaching nuanced conclusions. In content analysis, the categories are not connected to external factors, but rather to the interpretations within the text. This means that the categories can only be used to determine what interpretations are convincing enough. Conclusions are only based on the categories [8]. The categories themselves are only tools, so for the actual analysis a new method must be used [8]. In content analysis the categories are often quantified and the distribution of different categories is analyzed with statistical tools [8].

Apart from qualitative content analysis, argumentation analysis is another analysis technique [11]. The purpose of the argumentation analysis is to reconstruct the arguments, value the argumentation and to investigate if there are any flaws in the argumentation. Reconstructing the position and the arguments are important, as is identifying the counter arguments [11]. The argumentation analysis is very structured and is both descriptive and analytical. The arguments are reconstructed and the researcher can comment the arguments. This makes argumentation analysis a dynamic analyzing technique [11]. The problems with argumentation analysis is that it is difficult to reconstruct the arguments as they were intended to be read. Another challenge is that arguments can be unclear which makes it difficult to follow the argumentation [11].

Two other related approaches must also be described: analysis of the meaning or analysis of the language [6]. Both approaches can of course be combined. Analysis with its focus on meaning incorporates an approach where statements from the interviewees are encapsulated. The interviewer tries to formulate the statements so that they express a core meaning. Hermeneutics is a special variant of meaning analysis, where the context or the tradition that a text belongs to says much about its content [6]. Analysis with its focus on language uses individual words as a base for the analysis. It can for example be how grammar is used [6].

Analysis based on the sender, the recipient and the interpreter

A text or material can be analyzed with a focus on who the sender is [12]. In this analysis, the context is assumed to significantly affect the content. The idea is to analyze what purpose the creator of the material has. A core theme is to not attach the reader's own ideas into the material, the reader should process the material in a neutral manner [12]. At the same time, it is always so that the context in which a specific material exist, is primarily a context. Variations exist and having knowledge on the context is not the only necessary aspect. The main reason to analyze the material based on the recipient is because material has a certain audience [12]. The devised audience affects what the material contains and what the sender would like the recipient to learn by studying the material. This is not the only present aspect; the expectations that the recipient has will also affect the interpretation of the material [12]. Analysis with a focus on the interpreter highlights the knowledge that each reader has and how this reader affects the interpretation. What the reader already knows about the subject will determine the interpretation [12].

Meaning condensation

Meaning condensation is an approach where the meanings that the interviewees express are reassembled as short formulations. The idea with meaning condensation is to see the so-called meaning units in a text and try and grasp what theme they represent. These smaller parts can then be analyzed [13]. The most well-known condensation analysis was developed by the researcher Giorgi in 1975 [13]. The condensation analysis can be said to exist by combining five different steps [13]. The first step involves reading the interview material to understand the context. After that, the meaning units of the text are identified. Then, each meaning unit is categorized with a theme term. Later, the meaning units are evaluated and connected to the purpose of the study. The last step is when the themes are connected to create a summarized version of the interview [13].

2.3.4 The interview approach in the thesis

The interview session followed the same structure as was explained. Follow-up questions were very important, both for clarifying and for encouraging the interviewees to explain certain topics. The experts had different backgrounds and worked in a variety of fields. The interview questions couldn't therefore be identical because the interviewees all had different backgrounds. All interview questions did however relate to the research questions that were formulated above. The interview questions can instead be found in the Appendix along with the answers from every single interviewee. In this thesis, the semi-structured interview technique was chosen. The main reason was that it, as was described above, enables for a flexible interview while creating structure in the interview answers. Some of the interviews were video interviews and then the techniques from the video interview were applied. Some of the experts were specialists, but others were generalists so techniques from the elite interview were not needed at every occasion. This means that the semi-structured interview was the most common technique.

The interviewees were chosen in a specific manner. First, a general list of interviewees were provided by the supervisors. These interviewees were contacted. Not everyone on this list could be present during the interview session. This created a shortage of respondents. The solution was to ask the interviewees if the could recommend someone. The next approach was to contact experts that had been part of large infrastructure projects. The idea was to include respondents from public agencies, consulting firms and from academia. Finally, this resulted in 22 interviewees. To summarize, the interviewees were chosen because they had been working with ground-borne noise or tunnels. The interview questions could for example be:

1. What is your background?
2. What other experts do you need to cooperate with?
3. What kind of infrastructure projects have you worked with?
4. Are you familiar with the new prediction methodology for ground-borne noise?
5. How do you work with ground-borne noise in a typical project?
6. What information is needed in order to work with ground-borne noise?
7. How are problems related to ground-borne noise being investigated after the project has finished?
8. What measures are most effective or most common in Sweden?
9. What makes it difficult to work with ground-borne noise?
10. How should a new prediction methodology be managed?
11. What risks exist when a methodology is managed?

The interview questions presented above are questions that were frequently asked, but more specific questions could also be of interest. Not all respondents could answer all questions. Examples of this is that not all respondents had ideas on how the methodology could be managed. The semi-structured interview technique contains some common traits. The aspect that the same type of questions were used couldn't always be applied. Here, the method that this thesis is based on diverts on one point from the path outlined by the semi-structured interview technique. The other parts, that the interview questions were evaluated, the use of follow-up questions and the having a uniform time for each interview remained. It is not enough with a carefully planned interview technique, the answers must be ordered. This leads to the transcribing part.

The transcribing process started by transcribing the recorded excerpts. During the interview, notes were taken, but it became hard simultaneously ask questions, listen and write. Another challenge was that the interviews were conducted in Swedish, but the material had to be translated into English. After that, the transcribed and translated interview was sent back in the form of a brief report to the respondent. The interviewee had the time to read through the transcribed and translated answers and add comments. This created a meaningful dialogue in which more information was generated. The symbols presented above for transcribing conversations in conversation analysis were not implemented, but this thesis work was inspired by the symbols. Numbered lines were not used because the order of the questions were of no importance, but as with the transcribing symbols, numbered lines inspired the structure. The transcribing symbols found in the transcribed documents in the thesis can be seen in table 2.2. The symbols used when quoting parts from the transcribed interviews can be seen in table 2.3.

Table 2.2: Shows the symbols used for transcribing interviews

Symbol	Meaning
Q	Question
A	Answer
[text]	Comments

Table 2.3: Shows the symbols used when quoting

Symbol	Meaning
"text"	Citation
[...]	Break between or after a quote

For the analysis, the same procedure with meaning condensation that Kvale described was utilized in this thesis. The interview answers were studied and categorized with the help of meaning condensation and some patterns turned out to be more important than others. Not all answers from the interview questions were analyzed. Answers that created patterns or indicated certain contradictions were included. The patterns were explored with meaning condensation and therefore more information could be found and key points from each interview answer was formalized into statements. Themes essential for understanding the interview answers were:

- The contributing perspective
- The critical perspective
- The collaborative perspective

The contributing perspective answers the question "What new data should be added to the methodology? The critical perspective will answer "What are the risks when managing the methodology?". The contributing perspective answers the final research question "What strategy should be used to ensure a successful management?" The contributing perspective contains reflections on what fields are crucial when working with ground-borne noise, what data should be added to the methodology, the importance of criteria and measures. The critical perspective presents challenges and advantages with the methodology. The collaborative perspective connects all research question by considering the strategy when managing and keeping the methodology relevant. It also reflects on the how the ground-borne noise issue can be solved in the future.

Each theme that had been formed by using meaning condensation could then be studied as smaller units. Similarities and differences between these units from each interviewee were compared. This comparison formed the basis of the analysis. Results from previous research studies were integrated into the analysis, which made it possible to see the interview answers in a larger context. Together, the comparisons created outlooks and possibilities and challenges of the methodology emerged. Since the thesis is based on interviews and not on surveys, the categories described in the section on content analysis will not be quantified. They will however still be used to more easy interpret the answers. Argumentation analysis could have been utilized in this thesis since the interviewee's in many occasions presented arguments for certain assumptions in an engineering context. The reason why argumentation analysis was not introduced in this thesis was because the interviewee's rarely had an explicit position. Instead, the thesis used an approach that more resembles the one used in analysis of meaning. The language and the choice of words of course played a part, but it was not the specific words that were interesting. Instead, it was the message that the interviewee conveyed that was in focus. An analysis of the meaning of words is an approach that is more linked to research within the field of social sciences, so it wasn't the correct choice of method in this case. Only using meaning condensation is only a method of analyzing parts of a text. It is also needed with an analysis technique that can filter the answer from the setting and context created by the interviewee and the interviewer.

For this thesis, an analysis based on the sender was most relevant. That is because it is the sender, or the interviewee's that are in focus. It will of course be important to understand how the interviewer contributes to the setting with a pre-understanding, but the emphasize is on what the interviewee's mention during the interview session. The interviewees mentioned details which needed certain knowledge. At that point, the context actually made a difference. In the same way, the interpreter's perspective must be considered. The analysis was then a combination of an analysis with a focus on meaning, with an analysis based on the sender. Analysis with a focus on the meaning with analysis with a focus on the sender was applied to the text excerpts sorted out by the meaning condensation technique. The analysis part can be summarized as:

- The transcribed interview material was studied
- The material was categorized by investigating existing patterns
- Meaning condensation was applied in order to find the core parts of the excerpts
- Analysis with a focus on the meaning and on the sender was applied to filter out the context created by the sender
- Results from other studies were compared with statements from the excerpts

Not all material could be used directly because there were sometimes sensitive project details that were specific for a certain project. The ethical part played an important role in this case.

2.3.5 Ethics

The ethical aspects are very important in this case because interviews are a major part of the thesis. The Swedish Research Council has published a codex called "Good Research Practice" [14]. The council emphasize that it is always necessary with an ethical reflection that focuses on the upcoming problems. Four steps are used as guidelines [14]:

- Understand the specific circumstance and its problems
- Identify alternative measures
- Analyze the different alternative measures with respect to their values and risks
- Compare the alternative measures

The steps mentioned above must be combined with the legal framework and also with the important interests. An important interest is the protection interest which means that those who are involved in research must be protected [14]. This interest has more influence on the research procedure than other interests, for example the interest to contribute to important findings [14].

A special case that is related to personal data is the discussion on GDPR (General Data Protection Regulation) [14]. GDPR was passed by the European Parliament and is in use by several organizations since 2018 [15]. The Swedish Parliament has passed a law stating that all parts of GDPR doesn't have to be followed (articles 5–30 and 35–50) if the purpose is pure academical. GDPR doesn't have to be followed if it would indicate a deviation from "The Freedom of the Press act" or "The Fundamental Law on Freedom of Expression" [16]. However, the regulations governing the protection of each person's identity is still valid [16]. GDPR applies when personal data is being processed. Personal data can for example be a person's name or social security number, but it can also be audio recordings [14]. Something is considered as personal data when it can be used to identify a person despite that other information is needed for the identification [14]. The GDPR puts certain demands on the processing of the personal data. Some of these key points are [14]:

- The researcher must be able to show that GDPR is followed and how
- No more data is to be processed than needed
- Protecting action, such as pseudonymisation shall be used
- There must be a specific purpose for processing the data
- The GDPR must justify the processing of the data
- The personal data that is presented must be accurate
- The data can't be stored longer than necessary

With the ethical guideline and the protection interest in mind, is it possible to discuss the ethical aspects of the thesis. The ethical aspects must be considered both before, during and after the interviews. The interview questions should be open questions, so that each expert will be able to give an honest and comprehensive answer. During the interview the answers must be written down or recorded. Then, the formulations that each interviewee gives are correct. At the same time, the information from the answers must be processed in such a way that the respondents can remain anonymous. After the interviews, the answers must be processed so that sensitive details from current projects aren't revealed. After every interview, the respondents had the possibility to review their answers and make changes if necessary. One ethical perspective is that there exists a feedback process which creates an open atmosphere. This feedback process enables transparency which is important for the quality of the answers. Review and discussion of the answers are also necessary when it comes to the language aspect because the interviews had to be translated from Swedish to English. A feedback session avoids any misunderstandings that can't be avoided by only having access to the recorded interview. The GDPR are essential for creating a good ethical context. The interviewees were informed how the data will be handled and processed. They needed to give their consent before the interview started. It is also important to inform that the data (i.e. audio recordings) will be deleted after the processing has finished. The final answers will however remain in the final thesis, but it will not be possible to get access to the recordings.

In this ethical context, quotes are interesting. It will be difficult to ensure complete confidentiality, but the use of pseudonyms or initials can be a solution when using quotes [17]. Pseudonyms and initials could potentially be a problem when the interviewees want give specific comments. The interviewer must therefore decide what quotes should be used [17]. This creates another potential problem which is related to power. The interviewer creates the interview situation which means that the direction of the interview is already determined by the interview questions. The interviewee could feel that the discussion isn't open and that some subjects remain untouched during the interview [17]. In the end, ethics in research interviews depends on the context. Sensitive themes require more preparations to ensure privacy and confidentiality [17].

The biggest ethical problem was how to include the interviewees opinions, but still provide a confidential experience. The opinions brought an analytical depth, but only if the sensitive information was kept confidential. Using the steps provided by the Swedish Research Council gave insight into how ethical issues can be handled. The process of anonymization became important. As mentioned above, it can however lead to a weaker analysis section in the report since the expert's answers can't really be compared. At the same time, to ensure confidentiality has a higher priority than to achieve fruitful results and that is why the confidentiality is prioritized.

2.3.6 The interviewees and their background

The interviewees all had different backgrounds and this had an impact on how they viewed the methodology. In total, 22 people were interviewed. Some interviews were physical and others were held online. The online interviews were not recorded. Each interview was approximately 45 minutes to 1 hour long. The interviewees are denoted as respondents in the following chapter. They are named respondent 1, respondent 2 and so on depending on when the interview was scheduled. Respondent 1 was interviewed first. The background of each respondent, listed 1–22, is summarized as:

1. Civil engineer, works as a specialist within vibrations and ground-borne noise for a public agency
2. Civil engineer, works as a consultant within acoustics
3. Civil engineer, works as a consultant within acoustics
4. Civil engineer, works as a researcher within sound and vibration
5. Engineer, works as a consultant within acoustics
6. Civil engineer, works as a consultant within acoustics
7. Civil engineer, works as a consultant within acoustics
8. Health inspector, works as environmental coordinator for a public agency
9. Health inspector, works as an analyst for a public agency
10. Civil engineer, works a consultant within acoustics
11. Civil engineer, works within a committee
12. Civil engineer, works with product development for sound and vibration
13. Civil engineer, works as a project manager
14. Civil engineer, works as a specialist within sound and vibrations for a public agency
15. Land surveyor, works as a covener for a public agency
16. Geologist, works as specialist within vibrations and ground-borne noise for a public agency
17. Civil engineer, works as a consultant within sound and vibration
18. Civil engineer, works as an environmental expert within the public sector
19. Risk manager, works as a licensee for trams within the public sector
20. Engineer, works as specialist within sound and vibration for a public agency

21. Engineer, works as a researcher
22. Civil engineer, works as a project manager for a public agency

All of the respondents have great knowledge of vibrations and ground-borne noise. The majority are engineers and in the Appendix,where the transcribed interviews can be found, it can be seen that many have worked with larger infrastructure projects. The respondents work as public officials, consultants and researchers. There is a variety of fields which shows the plurality. Almost all respondents were aware of the new prediction methodology, but not everyone were familiar with it. Those who were familiar with it had either read the PhD thesis, contributed with data, been involved in the discussions or a combination of all three.

2.4 The numerical simulation

The numerical simulation is the last part of the method. The implemented model can be found in Excel and it is newly developed.

2.4.1 The implemented model

As mentioned, the numerical simulation used the new prediction methodology. This provided insight into how flexible the methodology was to use in a real world application. It also enabled for an understanding on how much the results differed between the methodology and the final result in a project. For the numerical simulation, the project in the city of Trollhättan was used. The main reason is that it is a smaller project which will make it easy to find the correct data (see section 3.4.6 for more information on this project). Another reason is that a smaller project contains less variables than a larger project. The numerical simulation is entirely based on Fatemeh Dashti's model, and in specific, the version of the model implemented in Excel.

The procedure consisted of using the case study to retrieve the correct variables. The documentation from the project Lärketorpet in Trollhättan was used. The sources, in the form of reports were studied. Not all necessary information could be found, for example detailed information on the track type. Parameters related to the track type, the train type and the train speed are important for the generating the ground-borne noise. The implemented model in Excel have some parts that cannot be changed and parts that can be changed. The methodology uses a reference speed for determining the correction factor for the train speed. The reference speed changes with the track type and the train type and can be seen in table 2.4. The parameters to be changed were:

- Speed of the P-wave (m/s)
- Distance between the tunnel wall and the dwelling (m)
- Loss factor (-)
- Train speed (km/h)
- Train type (passenger or freight)
- Track type (modern or old)
- Building floor (0–7)
- Building type (concrete structure or unknown)

The parameters that were kept unchanged and which therefore remained constant were:

- The reference distance from the center of the track, which is 4.2 m
- The reference train speed, which depends on the track type and the train type

Table 2.4: Shows how the reference speed varies with track and train type

Track	Train	Reference speed
Old	Passenger	80 km/h
Modern	Passenger	160 km/h
Old	Freight	50 km/h
Modern	Freight	90 km/h

The implemented model provided useful information both for the location stage and for the planning stage. Calculations for the construction stage are not to be found in the Excel sheets. The implemented version of the model can be seen in Figure 2.2. For the location stage, a single value is given, both the LASmax and LAFmax values. For the planning stage, the methodology presents the values in one-third octave bands. The frequency range is from 20 Hz–1000 Hz. These values are LASmax values. By using the implemented model, it also becomes possible to get a specific value on what attenuation is required, so that the LAFmax noise criteria is not exceeded. Information on the uncertainty is available both for the single decibel values and for the results in one-third octave bands. The mathematical formulations that the implemented model is based on are explained in section 3.4.1.

Table 1: Input Data			
Track and Train information			
Track type	Train type	Train Speed (km/h)	Train speed_ref (km/h)
Old	Passenger	160	80
Propagation path			
R (m)	R_ref (m)	η	C_p (m/s)
25	4.2	0.01	3000
Floor term			
	Building type	Floor above basement	
	Concrete	0	

Figure 2.2: Shows the implemented version of the model in Excel.

In documents from the project, the planning of the dwellings is described. Along the main street, 2-4 storey residential buildings are planned [18]. Dwellings located next to local roads will have 2 floors. Some residential buildings could even have 8 floors. The terrain map states that dwellings situated 25 meters from the railway tunnel are in focus for a risk analysis during construction work on the tunnel wall [19]. This could indicate that a residential house has approximately 2 floors and that the house closest to the tunnel is located 25 meters from the tunnel wall. For the room, the room volume is assumed to be 30 cubic meters, the floor is assumed to be 12 square meters and the RT is assumed to be 0.5 s. The absorption area is assumed to be 9.6 Sabine square meters.

Later, the loss factor, the distance, the train speed and the building floor were changed to simulate different scenarios. Changes in the loss factor represents the quality of the rock. Good rock quality means a lower loss factor. In the same way, the structure of the rail represents two cases: an old track and a modern track. The old track is based on the Gårda tunnel, while the modern track is based on the track from the Åsa Tunnel. The terms "old" and "modern" are somewhat misleading because it does not refer to the maintenance of the track. The terms rather refer to what track structure was used. The numerical process is summarized in Figure 2.3. After the parameters had been changed to simulate different scenarios, the data was exported to MATLAB and plotted. The plotted data presented the ground-borne noise levels with time weighting setting SLOW. The plotted data made it possible to analyze trends and compare the parameters, but the data from the EIA is provided as single values.

Findings from the numerical simulation had a direct connection to the qualitative results. Comparison of the numerical results from the implemented methodology and the EIA also gave insight into how the qualitative conclusions could be interpreted. Thoughts on how assumptions differ in the numerical case were necessary to incorporate in the discussion on the methodology.

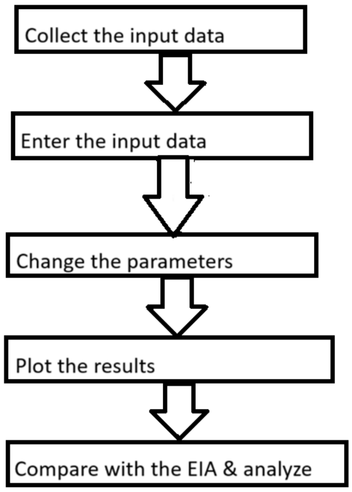

Figure 2.3: Shows the numerical procedure.

2.5 Methodology discussion and sources of error

Sources of error for the qualitative part

Finally, it could be worth to mention some alternative method approaches. The research interview as a method is appropriate because the interviewee's thoughts can be understood, but it is time-consuming and that's why it isn't suitable as a research method that require large samples [6]. Results from interviews tend to be hard to conceptualize into a general pattern compared to results from big surveys [7]. The interviewer must later make a choice of what is relevant to use in the result section. This means that the results are biased and depend on the interviewer's subjective decision from the transcribed material [7]. A questionnaire survey could have been used instead. Questionnaire surveys are flexible, doesn't require transcription and can reach a large number of respondents [7].

If questionnaire surveys were used, a larger sample could have been acquired which would generate more reliable results. There is a risk that the results become less reliable if it is hard to see general trends in the data. A middle way could have been to combine interviews with results from surveys. Then, the opinions from the experts could have been complemented by conclusions from survey data.

As was stated above, the analysis were based on an approach that focus on the meaning. Another approach that was mentioned was related to the study of the language itself. Since this thesis analyzed technical terms and the management of a methodology, a study of the specific terms could have been useful. An analysis of the terms used by the interviewees could have enabled for a more complex analysis by analyzing what the specific technical terms mean and what the use of those words can say about the management of the ground-borne noise methodology. For this thesis, the message that the interviewees want to convey was studied instead.

This thesis was not based on site visits. When ground-borne noise is discussed, an idea could have been to actually visit ongoing railway projects where the methodology was used. Site visits could have enabled for a more real-world interpretation of the methodology. An example of this is that interviews with the project managers and engineers were an option to truly understand how the methodology is managed in the practical applications.

Sources of error for the numerical part

For the numerical simulation part, a FEM (finite element method) software could have been used. Since the interview sessions required much time and effort, there was not much time to develop a model in FEM. However, a FEM model of a railway tunnel could have produced important findings on the parameters that affect the propagation of ground-borne noise. Examples are the influence of rock formations and several geological layers. The numerical simulation instead focused on the application of the methodology and this distinction is important to emphasize.

As described, the numerical part consisted of comparing the results from the implemented model with results from a recent project. This meant that the assumptions and data had to be similar. It is quite difficult to interpret an EIA (environmental impact assessment) for a project and directly understand what assumptions were used. Most assumptions in the EIA were well-defined, but others were more unclear. Examples of sources of error that affected the results were [20]:

- The frequency range in the EIA does not correspond to the frequency range in the implemented model. The frequency range in the report was 13 Hz–562 Hz.
- A part of the line had an installed ballast mat
- The measured reference distance from the tunnel can be different
- In the EIA, both time-weightings SLOW and FAST were used. The time-weighting settings are described in the literature review.

These aspects make comparisons laborious. Therefore, single values were convenient to use when comparing results from the EIA with results from the implemented model. The results provided in one-third octave bands were necessary for analyzing different parameters, but could not really be used when comparing data from the project. It would have been interesting to plot the ground-borne noise levels from an EIA with the levels from the implemented model, but that was unfortunately not the case. Measurements were not included and as with the site visits, measurements could have enabled for more realistic comparisons. Conducting measurements in a tunnel would have excluded some of the sources of error connected with interpreting a railway plan. However, there are safety aspects with visiting a tunnel. It can also be difficult to get access to a tunnel section and to perform measurements.

2.6 AI tools

The use of AI tools is very limited in this thesis. AI tools have been used to find errors in the LaTeX file. Examples are how to include new paragraphs or changing the font of the text.

3 Literature review

This literature study will explain some aspects for understanding the management of a prediction methodology for railway traffic in tunnels. The literature study is divided into different segments: what characterizes railway traffic in tunnels, what vibrations and ground-borne noise are and how methodologies are managed in infrastructure projects. It will however start with a brief section on acoustical concepts. Some of the concepts can be recognized in the new prediction methodology and it is then interesting to present some of them.

3.1 Acoustical concepts

Simplified, sound is the sensation that the human auditory system experiences when particles are oscillating [21]. Sound can be defined as the variations around the static pressure. These oscillations require a medium, e.g. air. Oscillating particles create a motion and it is this motion that is perceived as sound. The motion is often referred to as a wave and it has a direction of propagation and a speed (for a more detailed description of different waves, see section 3.3, "Vibrations"). Temperature and the character of the medium are two aspects that can impact the speed of a sound wave. The speed of sound increases with increasing temperature. Another aspect is how the pressure fluctuates and this can be understood by the quantity frequency. One quantity that is connected to the frequency is the time period that describes the time it takes for an oscillation to be completed, i.e. the time period. Lastly, the wavelength must be mentioned. It describes the length of the wave in space. The wave speed, the frequency and the wavelength are defined in equations 1–3 and their descriptions can be seen in table 3.1.

$$c = f\lambda \tag{1}$$

$$f = \frac{1}{T} \tag{2}$$

$$\lambda = \frac{c}{f} \tag{3}$$

Table 3.1: Shows the quantities found in equation 1–3 and their descriptions

Quantity	Description	Unit
c	Speed of sound	m/s
f	Frequency	Hz
λ	Wavelength	m
T	Time period	s

Since the sound pressure can be described as a function of time, it is often interesting to try and illustrate this. The problem to be aware of is that the sound pressure fluctuates. This means that if a time average is made, it would be zero due to the fluctuations. To solve this situation, the rms value is introduced. The rms-value stands for the root mean square value and the starting point is to take the average value of the squared sound pressure for a given time interval [21]. The rms value can then be obtained by using the equation:

$$\tilde{p} = \sqrt{\frac{1}{\Delta t}\int_{t_0}^{t0+\Delta t} p^2(t)dt} \tag{4}$$

Table 3.2: Shows the quantities found in equation 4 and the descriptions

Quantity	Description	Unit
$\tilde{p}$	rms value of the sound pressure	Pa
p	sound pressure	Pa
t_0	starting time of the integration	s
Δt	integration time	s

From equation 4 above, it can be seen that as the integration time (Δt), approaches infinity, the rms value will reach a constant value [21]. The rms value is practical to extract information from, but it can be hard to interpret. That is why, during the 20th century, the level concept has been developed. A level is a quantity that is based on a logarithmic approach. The unit of the sound pressure level is decibel (dB). For expressing the level, a reference value is needed and this reference value is chosen to 20 micro Pascal. This reference value corresponds to the lowest sound pressure that can be perceived at 1000 Hz [21]. A measurement system for measuring the sound pressure level often has a setting named FAST or SLOW. The setting depends on how quickly the device respond to changes in the surrounding sound pressure [21]. The setting called FAST is said to more resemble how humans react to sound, while the setting called SLOW is more convenient when interpreting the result. The setting SLOW is more suitable when measuring stationary sounds, an example is traffic noise [21]. The integration time for FAST is 125 ms and for SLOW it is 1 s. An integration time is needed in order for the instrument to capture the amplitude. According to research studies, humans can actually perceive the amplitude with a duration of 50 ms–100 ms [1]. The quantities for calculating the sound pressure level can be seen in table 3.3. The sound pressure level can be expressed as [21]:

$$L_p = 10\log_{10}(\frac{\tilde{p}^2}{p_{\text{ref}}^2}) \tag{5}$$

Table 3.3: Shows the quantities found in equation and 5 and their descriptions

Quantity	Description	Unit
L_p	Sound pressure level	dB
p_{ref}	Reference value for the sound pressure	Pa
$\tilde{p}^2$	Squared rms value of the sound pressure	Pa

Apart from showing the sound pressure level as a function of time, a signal can also be described by using the frequency. One way to do this is to either use one-third octave bands or octave bands [21]. These are filters that have a lower and an upper frequency limit. The distance between the lower and upper frequency limit is called the bandwidth. One octave band is composed of three one-third octave bands and an octave is simply a doubling of the frequency [21]. As sound is described as a function of frequency or time, a graphical representation gives information of how the sound pressure level varies.

However, it can sometimes be advantageous to represent the total sound pressure level for an entire band. The summed up sound pressure level is given by equation 6. The unit of the total sound pressure level is also dB. The total sound pressure level is obtained by adding the sound pressure levels with respect to the energy.

$$L_{p,\text{tot}} = \log_{10}(\sum 10^{\frac{L_p}{10}}) \tag{6}$$

Another quantity that is mentioned in the literature is the is acoustic power (the unit is Watt, W). Sound doesn't generate that much power and an example of this acoustic power is that a orchestra generates about 20 W. In physics, the energy is always conserved, so the acoustic power that is generated by a source is conserved in the sound wave. Damping however, transfers the acoustic energy into heat. The sound pressure level is also reduced as the distance from the source increases, which occurs because the sound energy is distributed over a wider area [21]. The power can also be expressed as a level quantity, the sound power level. The unit is also dB. Related to this quantity is the acoustic power per square meter or the intensity. The quantities needed for calculating the sound intensity are presented in table 3.4. The sound intensity for a plane wave or a spherical wave can be expressed by [21]:

$$I = \frac{\tilde{p}^2}{\rho c} \tag{7}$$

Table 3.4: Shows the quantities found in equation 7 and their descriptions

Quantity	Description	Unit
I	Sound intensity	W/m^2
c	Speed of sound in air	m/s
ρ	Density of air at 20 degrees	kg/m^3

As mentioned, the sound pressure level of a source varies with distance. That is because the sound intensity decreases with the distance. Sound sources are characterized as either point sources or line sources and this characterization depends partly on how the sound pressure level changes as the distance from the source increases [21]. Very simplified, the point source can be compared with a radiating sphere and the line source can be compared with a radiating cylinder. For point sources, the sound pressure level decreases with 6 dB when the distance is doubled. In the same way, the sound pressure level for a line source decreases with 3 dB when the distance is doubled [21]. Knowing how sound distributes is important for describing how the sound pressure level decreases. As was stated above, measuring community noise can sometimes be difficult because the sound pressure level varies with time. An average of the sound energy is therefore made and this sound pressure level is called the equivalent level [21]. Another way to formulate is that the equivalent level is a constant level that has the same sound energy as a sound that varies with time during a certain period of time [21]. The quantities needed for calculating the equivalent sound pressure level are found in table 3.5. The equivalent level can then be expressed as [21]:

$$L_{\text{eq}} = 10 \log_{10}(\frac{1}{T} \int_0^T 10^{\frac{L_p}{10}} dt) \tag{8}$$

Table 3.5: Shows the quantities found in equation 8 and their descriptions

Quantity	Description	Unit
L_{eq}	Equivalent sound pressure level	dB
T	Time period	s
L_p	Sound pressure level	dB

Another concept that often is mentioned the maximum level which is the maximum sound pressure level at a time period [21]. It is common to either present the equivalent or the maximum levels. For road traffic noise, the equivalent level is most useful [21]. For ground-borne noise, the maximum level is preferred and this will be explained later in the thesis.

Sound is not only phenomena, but also a property that affects humans. Sound with a frequency between 20 Hz–20000 Hz can be perceived by humans [21]. This range is dependent on age and individual differences exist. The sensitivity of our auditory system is clearly frequency dependent. The subjective feature can be visualized with the help of the equal loudness contours. One interesting remark is that two sounds will not be perceived as equally loud if they have the same value in dB, but have different frequencies. The situation is actually even more complex because the perception of sound isn't always logarithmic [21]. An increase of the sound level by 10 dB will make it to be perceived twice as loud. However, this is not valid for low sound pressure levels. For creating clarity, the weighting curves are nowadays a good option. By having these curves, the gap between the sound pressure level that can be measured and the human subjective experience have been bridged [21]. The weighting curves can be compared to a filter and there are many different filters. The most well-known filter is the A-weighting procedure in which the contribution from the lower frequencies on the sound pressure level is reduced. The A-weighting can be obtained by adding a constant to the sound pressure level in each one-third octave band or octave band [21]. The reduction is highest for the frequencies 20 Hz–200 Hz. By using the A-weighting procedure, the values more correspond to how the human auditory system perceives a sound [22].

The total A-weighted sound pressure level can be obtained by using equation 6 above, adding the A-weighted sound pressure level values. When the sound pressure level of two equally strong sources is added, the resulting sound pressure level will increase with 3 dB. Adding the sound pressure levels in this way is only acceptable if the sources are uncorrelated. That two sources are uncorrelated means that they are independent from each other [21]. When A-weighting is indicated, it is denoted as dBA or sometimes as dB(A) in the literature. It should be mentioned that A-weighting is not always the most suitable operation, the used filter must be adapted to the situation. Another type of filter is the C-weighting procedure that is useful for sounds with a great deal of high frequency content [21].

The primary function of human hearing is to decode information in speech. Human speech usually lies in the range of 60 dBA–65 dBA [21]. A hearing loss in the high frequency part is more severe than a loss in the low frequency region. Speech intelligibility can also be changed by the effect of masking. This concept illustrates the complexity of sound. Masking means that one sound can mask another sound, making one sound dominate over another. A low frequency sound is better at masking human speech than a sound with high frequency content [21]. Sound's effect on human health should always be considered and this aspect is critical for places used for sleep and rest. The perception of sound primarily depends on the frequency, the strength of the sound and the duration of exposure. Subjective experiences, the attitude to the specific sound and if it is commonly associated with the surroundings are impacting the perception [22]. Sounds of a more low frequency character are perceived as more disturbing [22].

Sound transmission in dwellings has received much attention and many studies have contributed to the understanding of how buildings and rooms impact the sound quality. Sound in for example an appartment can be divided into two categories: airborne sound and structure-borne sound [23]. The airborne sound is transmitted in the air and for traffic noise, the source is noise from the vehicles or the tyres, while the structure-borne sound is transmitted through solids. The medium for airborne sound is the air itself and the medium for structure-borne sound are solids [23]. The radiator for airborne sound due to traffic noise is in this case often tyres or sirens [24]. The radiator of structure-borne sound is vibrating surfaces [23]. The theme of this thesis is ground-borne noise and that noise category will be described in another chapter, but already here, it should be stated that the source for ground-borne noise is rolling noise or noise generated by the wheel and the rail [25]. The efficiency of a radiator is given by the radiation factor [24]. The quantities needed for calculating the radiation efficiency can be seen in table 3.6.

$$\sigma = \frac{W_{\text{rad}}}{\rho c S \tilde{u}^2} \tag{9}$$

Table 3.6: Shows the quantities found in equation 9 and their descriptions

Quantity	Description	Unit
W_{rad}	Radiated sound power	W
p	Density of air at a temperature of 20 degrees	kg/m^3
c	Speed of sound in air at a temperature of 20 degrees	m/s
S	Area of a building element	m^2
$\tilde{u}^2$	Squared surface average of the vibration velocity	m/s
σ	Sound radiation factor	-

When the sound has reached the room, it will slowly decay over time. A quantity that is very useful in this case is the reverberation time. The reverberation time is defined as the time it takes for the sound energy to decrease with 60 dB [21]. The reverberation time can be obtained by using Sabine's formula. This formula is explained in equation 12 and the quantities are presented in table 3.7. Sabine's formula can only be used when the sound field is diffuse. A sound field is considered as diffuse when the density of the energy is the same in a room. It can also be mentioned that the propagation has the same probability independent of the direction [24]. A reverberation time of 0.5 s is a standard value for rooms [24]. The absorption area and the reverberation time are mentioned is because these quantities are necessary for understanding how the vibrational level is converted into ground-borne noise level [4].

$$T_{60} = 0.16\frac{V}{A} \tag{10}$$

Table 3.7: Shows the quantities found in equation 10 and their description

Quantity	Description	Unit
T_{60}	Reverberation time	s
V	Room volume	m^3
A	Absorption area	m^2

The sound power expressed above can also be expressed as a level quantity [22]. The reference value for the sound power level is 1 pico Watt and the quantities needed for calculating the sound power level are presented in table 3.8. The distance and the design of the room will impact the sound propagation. The sound power level is independent of where the source is placed, so values for the sound power level are often preferred to present [22]. However, the sound power level cannot be measured by devices and then it must be calculated from the sound pressure level. The sound pressure level can be calculated if the sound power level is known together with knowledge about the area which the sound power is distributed over [22]. The relation between the sound pressure level and the sound power level can be formulated as in equation 14 [22]. The quantities in equation 14 are described in table 3.9.

$$L_w = 10\log_{10}(\frac{W}{W_{\text{ref}}}) \tag{11}$$

Table 3.8: Shows the quantities found in equation 11 and their descriptions

Quantity	Description	Unit
L_w	Sound power level	dB
W_{ref}	Reference value for the sound power	W
W	Sound power	W

$$L_p = L_w + 10\log_{10}(\frac{1}{4\pi r^2} + \frac{4}{A}) \tag{12}$$

The quantity,r, is the reverberation radius. At short distances from the source, the direct sound will be more significant than the reverberant sound. As the distance from the source increases, the reverberant or the sound that is reflected, will be more significant. The total sound level perceived by a resident, is the sum of the direct sound and the reverberant sound. These properties for the room will not be explored further, but this information is important for understanding how the room affects the sound distribution.

Table 3.9: Shows the quantities found in equation 12 and their descriptions

Quantity	Description	Unit
L_w	Sound power level	dB
r	Reverberation radius	m
A	Absorption area	m^2
L_p	Sound pressure level	dB

There are strict regulations on how high the sound pressure level can be in a dwelling. In Sweden, the noise requirements for dwellings are called "the minimum requirements". They have been developed by the National Board of Housing and are part of the building regulations [23]. Dwellings should be constructed so that the exposure to noise is minimized. Homes shall also be designed so that the noise transmission in an existing or adjacent dwelling is limited [23]. This means that there are requirements or noise criteria on the sound pressure level regarding the airborne sound and the impact sound in a dwelling. Regulations also include details on the upper limit for the equivalent and maximum levels for road traffic noise. Noise criteria are always discussed as A-weighted values since the A-weighting better resembles how humans perceive sound [21]. There are noise criteria for the ground-borne noise level that will be presented below [1]. Ground-borne noise can be more difficult to mitigate compared to airborne noise and knowledge on the source properties are essential. Since the source and the track are connected, it is preferred to gather information on the track and how it together with the wheel can generate vibrations that lead to noise [25].

3.2 Railway traffic in tunnels

The geological milestones of Sweden can be divided into three parts: the precambrian crystalline rocks, a sedimentary cover and the Caledonides [26]. The Swedish bedrock is composed of primary rock that is approximately 600 million years old. The layer beneath this primary rock is hard and is suitable to use when building tunnels. Knowledge about the rock conditions are primarily used to construct tunnels. The layer beneath this primary rock is hard and is suitable to use when building tunnels. Knowledge about the rock conditions are primarily used to construct tunnels [27]. Tunnels do not only enable for road and railway traffic, but are also used for transporting and delivering storm water, drinking water and energy. Separate rock chambers are used as storage facilities for oil and heat. They can be used as reactor chambers or as shelters during times of crisis [27]. Trafikverket manages 285 tunnels and 178 of these are railway tunnels. Most of the tunnels are constructed of rock, but some are concrete tunnels. The tunnel is inspected every second year and the risk of rockfalls and crack formations are investigated [28].

Building a new tunnel often starts with a pre-study. Many perspectives are integrated in order to get an initial view of the situation. It can for example be lab test results, photographs from site visits or reading previous measurements on the rock quality. All this information should provide useful information that will help when assessing the cost, security, time for building the tunnel and potential risks to the environment. After this initial phase, the project development begins [27]. At this point, more substantial field measurements are conducted. This is because the rock quality will impact heavily on the technical conditions and the cost of a tunnel. Every section of the terrain is investigated which gives a total view on what rock chambers are critical. Administrative and legal documents are written, results from calculations are presented and finally cross-sections are published. The project then enters a building phase. This phase contains many stages, but some of them are probing, grouting, tunnel blasting and lining [27]. Installation of fans and other services are of course needed afterwards before the tunnel can be opened for traffic. This is what happens when the tunnel enters the maintenance phase where additional measurements of the rock conditions are needed [27].

The building phase of a new tunnel can in more detail be described by the steps drilling, charging, blasting, unloading, scraping and reinforcement [29]. This is an example of a method and others exist. Before the drilling begins, injection is initiated which is when cracks in the mountain are filled. By doing this, water cannot flow through the cracks and effect the tunnel drilling process. Cement and water are pumped through the cracks and they are sealed as the cement starts to react. The tunnel holes are later drilled and filled with explosive charges. By having a carefully monitored explosion, the rock can be processed without impacting the sensitive areas. The remaining rock segments are removed and can sometimes be used in the construction process as building material. A hydraulic machine is used in a process called scraping and at this point most of the tunnel has been constructed [29]. The conditions are now suitable for the step where the tunnel walls can be designed. Bolts are hammered into the rock wall and a concrete solution is sprayed on the wall. An inner ceiling is fastened on the rock wall and the described steps are repeated for all tunnel corridors and the tunnel is then ready to be opened for railway traffic [29]. Figure 3.1 shows the dimensions of a typical tunnel.

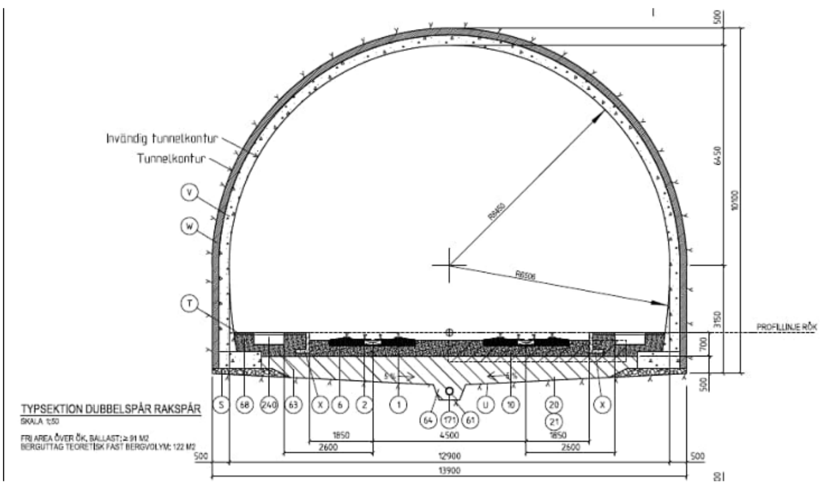

Figure 3.1: Shows a typical tunnel for a double-track railway. The image has been published with permission from Trafikverket. The original image can be found in the report TSS NGJ 4.1. The image has been replicated in [30].

When a train is moving on a rail, rolling noise can occur. Neither the rail nor the wheel of the train have surfaces that are smooth. When these surfaces move against each other, rolling noise is generated [25]. Surfaces that aren't even and contribute to the rolling noise can be described with the term roughness. When this roughness excites the rail and the wheel a displacement is created which in turn creates dynamic forces [25]. Dynamic forces make the structures vibrate which can radiate sound. The vibrating rail is greatest in the low frequency spectrum, while the wheel vibrates the most at the high frequencies. Rolling noise is then a result of the interaction between the rail and the wheel [25]. Both components are needed to generate noise, but depending on the situation the rail or the wheel can be more dominant [25]. In more detail, the rail and the wheel can be represented by two systems that are connected. The contact spring can be introduced as a new system that connects the rail and the wheel [25]. The interaction force is determined by the roughness and the mobilities from the rail, wheel and the contact spring [25]. At the resonance frequencies of the rail and the wheel, the systems will be more sensitive to excitation because the mobility is high [3]. Figure 3.2 shows a train and its components.

Figure 3.2: Shows a train with wheel and rail. Source: The author.

3.3 Vibrations and ground-borne noise

It is this excitation from the wheel and the rail that causes vibrations and vibrations that travel through the ground and into buildings can be disturbing. A distinction must be made between the vibrations that can be felt and the vibrations that lead to ground-borne noise [31]. Vibrations that can be perceived occurs from trains and can be felt in a building. They do not lead to noise inside an apartment. These vibrations require loose soil and are in the frequency range 1 Hz–80 Hz. The vibrations that give rise to ground-borne noise cannot be perceived and are in the frequency range 50 Hz–200 Hz. For vibrations to result in ground-borne noise, a hard soil type is needed [31].

There are three main types of waves that often are mentioned when ground vibrations are discussed [3]. One such wave type is the S-wave (also known as shear waves). S-waves have a direction that is normal to the direction of propagation. Here, it is the local particle motion that is normal to the direction of propagation. These waves can't propagate through gases or liquids [32]. They are also transversal with wave speeds of 30 m/s–500 m/s [3]. On the other hand, the P-wave (also known as pressure waves) is a longitudinal wave with a long wavelength [3]. The P-wave has the highest velocity of all the waves. The movement of the local material particles is parallel to the direction of the propagation [32].

The wave type that is most important is the Rayleigh wave. The reason why they are important is because they do not decay with distance for a line source if material damping is neglected [3]. Rayleigh waves are generated if the medium is bounded and has a free surface. The wave propagates forward, but also perpendicular to the propagation direction. The wave propagation of the local particles can be described as elliptical [3]. The depth is important for how far the Rayleigh wave can travel. Firstly, the wave speed will increase with the depth, but at a depth corresponding to two wavelengths, the speed will be greatly reduced. Secondly, the wave amplitude will start to increase and reach the highest value approximately when the depth corresponds to 0.2–0.6 wavelengths. When the depth corresponds to 1.3 wavelengths, the value of the wave amplitude is very small [32].

That the wave amplitude can decrease with distance is well-known. Also, damping will reduce the amplitude [3]. For a soil, situation is more complex because several layers exist in the ground, making it necessary with field work for knowing the soil properties

[3]. For example, a more stiff soil layer can reflect the waves [3]. Between the ground layers, there is often ground water as well. Water can reflect incoming waves [3]. Since this thesis will explore ground-borne noise that is generated by vibrations in rock, it is not necessary to describe all relations for soil and damping. The wave speed can be widely different. The P-wave speed for clay ranges from 1000–2500 m/s and for granite it is 5500–5900 m/s. The S-wave speed for clay is 400 m/s–1000 m/s. The wave speed depends on the saturation rate and an example of this is that for an unsaturated sand, the P-wave speed is 200 m/s–1000 m/s, while for a saturated sand, the same number is 800 m/s–2200 m/s [33]. The rock type has a big impact on the wave speed, both for the P-wave speed and for the S-wave speed [33]. The wave speeds for the wave types are presented in table 3.10.

$$C_S = \sqrt{\frac{G}{\rho}} \tag{13}$$

$$C_P = \frac{E(1-\mu)}{\rho(1-2\mu)(1+\mu)} \tag{14}$$

$$C_R = \frac{0.862 + 1.14\mu}{(1+\mu)} C_S \tag{15}$$

Table 3.10: Shows the quantities found in equations 13–15 and their descriptions

Quantity	Description	Unit
C_S	Velocity of the S-wave	m/s
C_P	Velocity of the P-wave	m/s
C_R	velocity of the R-wave	m/s
G	Shear modulus	Pa
ρ	Density	kg/m^3
E	Elasticity modulus	Pa
μ	Poisson's ratio	-

Density, porosity, anisotropy, temperature, texture, rock type and water content are aspects that can change the propagation properties [32]. The water content has already been mentioned, but as the density increases, the velocity will also increase. Increased velocity can be observed as well when the porosity decreases. Anisotropy means that a material has different properties depending on the direction [32]. An example of the effect of anisotropy is how cracks can decrease the velocity depending on how the cracks are situated. How cracks and joints effect vibration velocity is also a product of the joint itself: its length, contact area, content, if it's filled or not and its mechanical stress [32]. The picture of how joints effect propagation velocity is therefore complex which is important to keep in mind. Generally, cracks will attenuate an incoming wave and at the same time reflect a part of the energy. The remaining energy will be transmitted [32].

The geometrical attenuation of the vibration can be estimated by using Lamb's equation, see equation 16. Table 3.11 shows the quantities from this equation. The constant m, is a geometrical coefficient and depends on if the source is characterized as a point source or as a line source. The value of this constant will depend on if the wave is a P-wave, a S-wave or a Rayleigh wave. The damping coefficient is frequency dependent and loose soils, like clay, will attenuate the amplitude more than bedrock. For clay, the damping can range from 0.1–0.3 and for bedrock the same number is smaller than 0.003 [4]. From a distance, r_1, from the source, a vibration amplitude is measured. This vibration amplitude is denoted as $\hat{v}$.

$$\hat{v} = \hat{v_1}(\frac{r_1}{r})^m e^{-\alpha(r-r_1)} \tag{16}$$

Table 3.11: Shows the quantities found in equation 18 and their descriptions

Quantity	Description	Unit
v	Vibration amplitude	mm/s
$\hat{v_1}$	Measured vibration amplitude	mm/s
r_1	Distance from the measured amplitude	m
r	Distance from the vibration source	m
m	Geometrical attenuation coefficient	-
α	Loss factor of the rock or soil	1/m

In this thesis, it is however ground-borne noise that is in focus. The vibrations are mentioned here because they carry the energy that causes ground-borne noise. This ground-borne noise is perceived as a low frequency noise. As with noise criteria, countries tend to have certain definitions on the frequency limit. In Sweden, ground-borne noise is defined as a low-frequency sound that is generated by vibrations within the range 50 Hz–200 Hz [30]. However, as will become evident later in this thesis, it can be wise to include even higher frequencies, up to about 1000 Hz [4].

Ground-borne noise is expected to become a growing concern in the future when more railway lines are being developed [25]. Ground-borne noise is generated when the building structure is beginning to vibrate. The mass and stiffness of the building elements have an influence on how big these vibrations become. For example, a wall panel can cause noise in a room if it is starting to vibrate. The properties of the room will also have an effect on the ground-borne noise [3].

3.3.1 Noise criteria for ground-borne noise and health aspects

It is difficult to provide a total overview of the noise criteria because many different noise criteria exist. It doesn't help that countries have chosen their own noise criteria which makes comparisons a hard task [3]. A project named the RIVAS project has suggested some noise criteria for ground-borne noise and vibrations. Table 3.12 shows these values and is inspired by the one found in [3]. Note that the maximum values are based on the time-weighting setting FAST and that the equivalent levels are based on an average of 24 h.

Table 3.12: Shows target values for both ground vibrations and ground-borne noise

Max (vibration)	Eq (vibration)	Max (ground-borne noise)	Eq (ground-borne noise)
0.1 mm/s	0.028 mm/s	38 dBA	32 dBA

The Public Health Agency of Sweden has released an excessive guideline on noise inside dwellings [34]. Ground-borne noise is interpreted as low frequency noise and noise criteria exist for every one-third octave band which can be seen in table 3.13. The noise criteria for every one-third octave band is the equivalent level in dB. The table is based on the one found in [34]. Later in the thesis, the ground-borne noise level values will be denoted with either LPAFmax or LPASmax. The first term refers to the maximum A-weighted ground-borne noise level with time-weighting setting FAST. The second term relates to the maximum A-weighed ground-borne noise level with time-weighting setting SLOW.

Table 3.13: Shows the noise criteria for low frequency noise published by the Public Health Agency

Frequency band (Hz)	Tolerated value (dB)
31.5	56
40	49
50	43
63	42
80	40
100	38
125	36
160	34
200	32

Both Sweden and Norway uses the same type of noise criteria which is a 32 dBA maximum value with time-weighting FAST. For the Norwegian case, the noise criteria is based on a survey from 2003, when it was concluded that 32 dBA was appropriate [1]. In Finland, 35 dBA maximum value is used, but with the time-weighting SLOW. When measurements are needed, the standard deviation is used which means that the final value is the average value of the maximum values in dB. In Norway, it is more common with calculations of the ground-borne noise levels than with measurements [1]. Target values are vital for bridging the gap between the engineering discipline of acoustics and the society. However, the impact of ground-borne noise is better understood by observing the effects that ground-borne noise has on human health.

The World Health Organization (WHO) states that noise affects the health of residents when the A-weighted maximum value with time-weighting setting FAST of 32 dB is exceeded [35]. In a study, 23 people were exposed to ground-borne noise in a sleep laboratory. The participants spent five nights in the lab and one night served as an acclimatization session. The second night in the lab was used as a control sessions, which meant that the participants weren't exposed to any ground-borne noise. The following nights exposed the participants to different noise levels. Ground-borne noise levels of 35, 40 and 45 dB (maximum values with time-weighting setting FAST) were simulated by playing recordings of train passages [36]. Each night included one of the above mentioned ground-borne noise levels. For each night, 32 passages were used and the time between each passage was 5–25 minutes. The speed of the trains were always exceeding 150 km/h. By using polysomography (PSG) and surveys, it was possible to analyze the sleep of the participants [36].

Both the effect of the total exposure and the effect of single passages were analyzed. The main results were that the results are similar to studies focusing on airborne noise. The results were similar when comparing the effect of noise on the heart rate for the same A-weighted values [36]. At 45 dB there is a clear effect on the sleep, but at 35 dB the effect is not significant. The results from the surveys demonstrated that the participants don't feel affected when the ground-borne noise level is 35 dB. However, as it it increases to 40 dB and 45 dB there is a disturbance in the sleep quality [36]. The sleep disturbance when exposed to a ground-borne noise level of 35 dB is minor, for 40 dB it is moderate and for 45 dB it is very clear. It was not possible to say anything on what the chance is for a participant to wake up due to exposure from ground-borne noise. The findings rather related to an increase in the heart rate during a sleep session [36].

3.3.2 Measures at the source

For avoiding the harmful effects described in section 3.3.1, measures must be used. Measures for ground-borne noise exist at three typical levels: measures at the source, along the transmission path and at the receiver [3]. Most of those measures will be mentioned below together with their reduction in dB. When comparing how effective a measure is, the concept insertion loss is practical. The insertion loss consists of measuring the difference in dB before and after the measure has been implemented. In the following tables, the insertion loss will be denoted as IL [37]. When installing measures, numerous aspects will influence how effective the measure is. The temperature, the train speed and the track configuration will influence the measure. Different rail systems can be present depending on the country and this will have an effect. All rail components will interact which can make it hard to compare measures since both the train speed, the status of the track and the wheel/rail interaction impacts the results. Still, choosing a soft rail pad is the most effective decision [37].

The dB-values refer to the reduction for ground-borne noise and not for vibrations. To give a cost estimate for all the measures is possible, but since that information is mostly based on estimates, it is not presented below. The values for the mitigation are sometimes presented as A-weighted values and sometimes the report only mentions "dB". Firstly, measures can be placed at the track and at the vehicle (or bogie). Defects of the track and badly maintained ballast can give rise to vibrations. It is therefore important to maintain acceptable quality of the track. Improvement of the track can give a reduction of 6 dB [3]. The quality of the wheel is another contributing factor of the vibrations. The driving component in the form of the locomotive can be changed so that its suspension is improved. This can give a reduction of up to 12 dB [3]. Measures for the track are for example resilient blocks which gives a reduction of 13 dB. The embedded rail is a solution where the rail is embedded in a concrete slab and this gives a reduction of 2.5 dB [3].

Secondly, ballasted lines often have under-ballast mats installed. Under-ballast mats serve two purposes: to stabilize the ballast and to mitigate vibrations on the tunnel wall [3]. For an under-ballast mat, the stiffness plays an important part and Figure 3.3 shows an elastic mat for a surface line. From Figure 3.3 it is not clear how the mat is installed and it is possibly also effective for airborne noise. A soft mat which shields the ballast can actually cause resonances. The under-ballast mat must be optimized and a reduction of 5 dB is expected up to 20 Hz, but the reduction can be greater above 20 Hz. Another common measure are the under-sleeper pads (or UPS). To be effective, UPS need a low dynamic stiffness, but the static stiffness must at the same time be in the same range. UPS are better for the higher frequencies (above 30 Hz) and can actually create amplification in the lower frequency region. Even if UPS are good for ground-borne noise, they can increase the problems related to airborne noise that is radiating from the sleepers. A reduction of 8–20 dB is estimated for straight ballasted tracks with heavy sleepers [3]. For lines without ballast, slab tracks can be used. The rail is then fixed in blocks, mounted on a concrete slab. A cheaper option is under-sleeper mats. A mat is embedded in the slab and each sleeper is connected to this mat. A reduction of 6 dB has been observed, but in some cases even 15 dB. One last important solution for surface lines is column stabilization. Column stabilization means that concrete pillars are inserted into soft ground. The mitigation option is not possible in rock, so it will only be mentioned briefly here. Data for the reduction in dB is hard to find, but vibrations seem to decrease with 45% with distances up to 60 m from the track [3].

Thirdly, measures in tunnels include the floating slab track in tunnels. The slab and a suspension together become a mass spring system. Here, the ratio between the mass of the train and the mass of the slab is something that will determine how effective this particular measure is. A reduction of 20–26 dB has been estimated, but the economic cost is high. Therefore, the floating slab track should be a last option when every other option has failed [3].

Figure 3.3: Shows a ballast mat that is used as a mitigation strategy close to the source. Note that this is a surface line. Source: Wikimedia Commons.

3.3.3 Measures at the transmission path

Measures at the transmission path are not so relevant for tunnel lines, but are more effective for surface lines with loose soil. These measures concern different kinds of barriers. There is a great deal of creativity in this case and both air, water, concrete or an elastic mat can serve as barriers. The idea is that this ditch, with its lower stiffness, will block the vibrations. An example is that a trench is constructed. That trench can be filled with water that blocks the incoming waves. Sheet piled walls is a more active solution that has the same purpose as if a ditch would be used. [3]. All barriers must however be deep enough (at most 10 m) as to avoid diffraction. The literature mentions a reduction of 2 dB for filled trenches and between 2–6 dB for unfilled trenches. A ditch filled with water can give a reduction of 3 dB, this requires that the ditch is at least 2 m deep. The use of barriers require space which always isn't available. This means that there must be a space between the rail and the dwelling. Also, existing water pipes can be an obstacle when planning a line of trenches [3].

3.3.4 Measures at the receiver

When measures at the receiver are discussed it is often measures at the building. These kinds of measures are often hard to implement. It is recommended that measures at the receiver is made during the construction stage and not afterwards [3]. Close to the foundation, an elastic layer can be installed that will act as a shield. A reduction of 2-6 dB is estimated. Another solution is to use piles that makes the ground floor more stiff. If the floor is made out of wood, additional beams can be added. A reduction of 2–6 dB has been estimated, but some sources even mentions reductions as large as 20 dB [3]. The most effective measure at the receiver is to install special resilient bearings. It works for all different kinds of buildings, as long as the foundation is strong [3]. It is a popular strategy for buildings that have an underground railway line below the foundation. A reduction of 20 dB–26 dB is estimated [3]. To install measures at the receiver is not that expensive compared to installing the measures in the transmission path. Measures at the receiver can however be viewed as controversial since the consequence is that the daily life is interfered when elastic layers, more stiff floors, beams or bearings are installed in a dwelling where people reside [3].

In a report from Trafikverket, it is emphasized that the function of noise criteria for ground-borne noise is to protect the dwellings and keep them as places of sleep [2]. Annoyance from ground-borne noise must also be considered during daytime or when other building types are planned. Measures for ground-borne noise must be integrated into the city planning discussion as soon as increased traffic can become a problem during the night [2]. In the report, it is also stated that measures in the infrastructure are difficult to apply after the construction has been finished. That is why measures for ground-borne noise must be implemented when the construction or foundation works begin [2].

3.4 Management of engineering methodologies

3.4.1 Dashti's prediction methodology for ground-borne noise

As was mentioned in the background, a new prediction methodology has been developed for Trafikverket by Fatemeh Dashti from Chalmers University of Technology. The prediction methodology will in this thesis mainly serve as a background for the numerical part that will be presented later. It is now time to try and understand this methodology in much greater detail [38].

The purpose of Dashti's PhD thesis was to create a methodology for ground-borne noise. The methodology was aligned with Trafikverket's projects and was limited to ground-borne noise in tunnels [4]. The intention was that the model would include the major aspects, be practical and that there should also exist a possibility to change parameters in the model [4]. As mentioned in the introduction of this thesis, the methodology encompasses the localization stage, the planning stage and the construction stage. The model is suited for bedrock and Dashti states that the methodology require the following assumptions for the input data:

- A bedrock with no cracks
- A rigid building foundation
- A furnished room

The methodology is adapted to dwellings situated on bedrock. The model uses a statistical approach instead of utilizing safety factors. This approach require that the data is representative and that normal distribution is valid. Earlier methodologies have relied more on safety factors. The downside of using safety factors is that they might lead to conservative values that are not realistic [4]. A new approach was to use the standard deviation, this is explained in the PhD thesis. The uncertainty is included by adding a value equal to two times the standard deviation to the studied average value [4]. Applying a statistical approach during the processing of the measurement data made it possible to include all train passages. This resulted in a new situation because 95% of train passages could be incorporated into the presentation of the data [4].

The method that is mentioned in the PhD thesis is based on both measurements and numerical simulations. For example, accelerometers were placed in tunnels to measure vibrations. The correction factor for train speed together with the correction factor for track type were used to prolongate the further development of the model [4]. The model is valid in the frequency range 20 Hz–1 kHz, but it works best for vibrations with a frequency of up to 500 Hz [4]. Measurements were initiated in a nearby tunnel. The tunnel had a double-track system and a ballasted track [4]. Accelerometers were placed both at the tunnel wall and on the sleepers. An issue was to find rock section stable enough to mount measurement equipment on. The solution was to utilize a hammer to find rock with suitable quality [4]. A speed radar was installed that could measure the speed of the trains, this included trains passing in both directions. In total, 930 train passages were noted by the device during three days in April of 2021. Both freight train passages and passenger train passages were captured by the speed radar [4]. Data from measurements inside tunnels were advantageous used to get new data. Hydraulic shakers and hydraulic hammers generated vibrations in a part of The West Link tunnel and served as a vibration source [4].

Apart from direct measurements inside tunnels, additional measurements were planned to investigate the decay effect. Seismometers were placed over a 40 m strip of land. These measurements conducted in 2021 were followed by measurements inside the dwellings [4]. A transfer function was utilized to illustrate the coupling between the tunnel wall and a building. The next step was to use available data from Carlbergsgatan 13 and Hillgatan 10 in order to examine the relationship between vibrations of the floor and the ground-borne noise. Here, both the vertical and the horizontal vibration were compared [4]. In order to examine how building floors affected the results, measurements were conducted at Övre Fogelbergsgatan 1 in 2022. The dwelling had a bedrock foundation and The West Link was constructed nearby which provided a realistic noise scenario. Machinery in the form of a hydraulic hammer was used for the new measurements. As the hydraulic hammer began to operate, vibrations were captured by seismometers. Measurements with a hydraulic shaker were also conducted [4].

Data from measurements were also used to try and understand how trains could be characterized; sound sources can be defined as point sources or line sources. Freight trains have properties that make it convenient to characterize them as point sources since single bogies can act as a dominant source. Passenger trains often act as line sources. The situation is more complex because separate parts of the train and features of the track can indicate radiation properties that are more commonly observed in point sources [4]. Results from the field measurements were later used to define the source term and the correction terms that the methodology is based on. The results from all different measurements were gathered to create a source term and several correction terms. Conclusions from other models were studied to fine-tune the contributing terms. Measurement results could verify reliable values for several of the correction terms [4]. However, for understanding the wave propagation a numerical simulation had to be done.

The numerical simulation was based on the finite element method, which is commonly referred to as FEM. The purpose of the simulation was to understand how rock formations affect the vibration and to understand what difference the tunnel shielding effect made [4]. The numerical simulations also served as an indication whether or not passenger trains and freight trains could be seen as a point sources or as line sources. The FEM simulations were not integrated into the final model, but they gave useful information on how the transmission could be interpreted [4]. The FEM simulations were based on both a 2D and a 3D case. An important assumption was that the bedrock layer was infinitely large and that that wave reflections next to the boundaries could be neglected. The solution was to introduce an impedance matching approach [4]. In order to understand if a train could be characterized as a point source or as a line source, the vibrations along a train were utilized, with a focus on bogies. This gave information on how the vibrations were attenuated as the distance increased [4].

The simulated vibrations were tested for both a half-space tunnel and a full-space tunnel [4]. The results were analyzed in one-third octave bands with frequencies from 10 Hz up to 1 kHz. The depth of a tunnel and the distance were important aspects to consider [4]. Simulations in 2D and 3D provided similar results with respect to the vibration pattern. The smaller tunnel shows fluctuations above the tunnel and no simple existing pattern at 1000 Hz [4]. Dashti concludes that the tunnel has the ability to block some of the vibrations. At most, the tunnel can create a reduction of 10 dB. This reduction is less at low frequencies. When discussing reduction in vibration levels it is important to keep in mind that wave interference causes variations in this pattern [4].

The results also showed that the vibration energy is focused below the tunnel. Above the tunnel, the vibrations are reduced, but this also depends on the direction of propagation [4]. Dashti demonstrates that bedrock zones can reduce vibrations as wave reflections occur at the source side of the rock. Deeper tunnels create less reduction after the bedrock zone. This increase can be as great as 5 dB [4]. When analyzing if the trains could be characterized as point sources or line sources, the results demonstrated that the attenuation pattern corresponded to a decrease of 6 dB when the distance was doubled. This was true for distances less than 10 Hz and greater than 100 m. For distances of 10 m–100 m, the pattern is more close to 5 dB per distance doubling [4].

As was explained in the PhD thesis, single bogies from a freight train can dominate because of a freight train's uneven loading. Passenger trains normally exhibit a uniform pattern, but Dashti state that the irregularities of the track can change this. Assuming a reduction of 3 dB for a doubling of the distance is not realistic, but assuming a reduction of 6 dB is not correct either [4]. All information from the numerical simulations was vital for understanding the effects that the rock had on the propagation, for example the damping. Together with conclusions from measurements and other data, it was possible to provide a new methodology [4].

This new prediction methodology is helpful when a new railway tunnel is localized, planned and constructed. The model also creates the possibility for the engineering team to include specific data from the local tunnel project. The methodology works for both passenger trains and freight trains. In the PhD thesis, it is stated that future studies could include the effect that different mitigation strategies have at the receiver, for example steel springs in dwellings. Today, the model can be used to see where measures are needed, but mitigation options can't be added as input to the implemented model. Measures are however included in the correction term related to the track, $\Delta L_e(\text{treatment})$. Dashti also state that future studies could provide more detailed information on how geological zones impact the propagation of the vibrations [4]. By conducting more measurements, even more data will become available. This leads to a situation where the model becomes more accurate and reliable when uncertainties are eliminated. More data is therefore needed from other tunnels [4].

The methodology is formulated as a set of equations that can be used to calculate the ground-borne noise sound pressure level in a dwelling [38]. The vibration level on a floor can be expressed as in the equation below and the quantities are presented in table 3.14:

$$L_{\text{VASmax}} = L_{\text{eASmax}} + \Delta L_{\text{s}} + \Delta L_{\text{g}} + \Delta L_{\text{f}} + \Delta L_{\text{b}} + \Delta L_{\text{corr}} \tag{17}$$

Table 3.14: Shows the quantities found in equation 17 and their descriptions

Quantity	Description	Unit
L_{VASmax}	Maximum vibration level for a floor (ref. 50 nm/s)	dBA VL
L_{eASmax}	Maximum vibration level (ref. 50 nm/s)	dBA
ΔL_s	Correction term for the train speed	dB
ΔL_g	Correction term for the distance attenuation	dB
ΔL_f	Correction term for the coupling related to the foundation	dB
ΔL_b	Correction term for the attenuation for building floors	dB
ΔL_{corr}	Correction term for other aspects	dB

The unit of the source term, including the correction terms are dB. There are uncertainties for both the source term and the correction terms. The source term and the correction term for the train speed have clear differences in the uncertainty depending on the frequency. This uncertainty is then frequency dependent. A combined uncertainty for all terms and for all frequencies, ranging from 20 Hz–1 kHz, is 14 dB for freight trains and 10.5 dB for passenger trains [38]. The first term is the source term. The vibrations that forms the basis of this source term are preferably measured in three positions on the wall. The vibrations are measured 1.5 meters above the railhead and a reference distance of 4.2 meters is used. A-weighting is applied and the maximum vibrational levels are processed with the time-weighting SLOW. By using the vertical vibrations, the same direction is used as the applied force to the wheel and rail has. The source term is expressed as in [38] and the quantities are presented in table 3.15:

$$L_{\text{eASmax}} = L_{\text{eASmax}}(\text{train}) + \Delta L_{\text{e}}(\text{track}) + \Delta L_{\text{e}}(\text{treatment}) \tag{18}$$

Table 3.15: Shows the quantities found in equation 18 and their descriptions

Quantity	Description	Unit
L_{eASmax}	Maximum vibration level (ref. 50 nm/s)	dBA
$L_{\text{eASmax}}(\text{train})$	Max vibration level in ref. position, direction & track	dBA
$\Delta L_e(\text{track})$	Correction term for other track types	dB
$\Delta L_e(\text{treatment})$	Correction term for track treatments	dB

The second term is the speed correction factor and this factor is quite complicated to describe. It changes with increased train speed as can be seen for the speed categories 80 km/h–160 km/h, 160 km/h–240 km/h and 240 km/h–320 km/h. The quantities are presented in table 3.16. For train speeds higher than 320 km/h, the correction factor is zero [38]:

$$20\log_{10}(\frac{v}{v_{\text{ref}}}) \tag{19}$$

$$10\log_{10}(\frac{v}{v_{\text{ref}}}) \tag{20}$$

$$18\log_{10}(\frac{v}{v_{\text{ref}}}) \tag{21}$$

Table 3.16: Shows the quantities found in equation 19–21 and their descriptions

Quantity	Description	Unit
v	Train speed	km/h
v_{ref}	Train reference speed	km/h

An interesting thing occurs as the train speed increases. Some of the energy is transferred to the higher frequency bands because of the roughness properties of the rail and the wheel. It is well-known that higher damping can be found in these higher frequency bands. There is also a weaker coupling for the higher frequencies when vibrations are travelling from the ground and into the building [38]. The speed correction term can be expressed as in equation 22 when the roughness is considered. What occurs is that the roughness of the rail and the wheel will lead to a shift in frequency. This leads to a situation were more energy is shifted to higher frequency bands, in this case the one-third octave bands. Without explaining all the details, the equation can be described as an adaptation of the HS2-model. For more information on the HS2-model, see the section 2.4.2 below. For more information on the equation, see the cited paper [38]. The quantities for calculating the speed correction term are presented in table 3.17.

$$\Delta L_{\text{s}}(f) = R_{\text{eff}}(\lambda, v_2) - R_{\text{eff}}(\lambda, v_1) \tag{22}$$

Table 3.17: Shows the quantities found in equation 22 and their descriptions

Quantity	Description	Unit
ΔL_s	Correction term for train speed	dB
R_{eff}	Effective roughness	dB
λ	Roughness wavelength	m
v_2	Vibration spectrum of the train speed	m/s
v_1	Scaled vibration spectrum for a train speed	m/s
f	Frequency	Hz

The second correction term is the distance correction term and [38] and the quantities for this correction factor are presented in table 3.18.

$$\Delta L_g = -10\log_{10}(\frac{R}{R_{\text{ref}}}) - 10log(e^{-2\pi f\eta(R-R_{\text{ref}})/cp}) \tag{23}$$

Table 3.18: Shows the quantities found in equation 23 and their descriptions

Quantity	Description	Unit
ΔL_g	Correction term for distance attenuation	dB
R	Distance from the track	m
R_{ref}	Reference distance	m
f	Frequency	Hz
η	Loss factor for the material	-
c_p	P-wave speed in the ground	m/s

The third correction term, ΔL_{f}, includes the loss for the foundation [38]. It is often assumed to be zero, which indicates that vibrations aren't blocked at any point, rather the coupling is substantial. It can exist variations and this is something that is seen in the measurements and the assumption that the loss due to the foundation can be zero is always an assumption on the safe side [38].

The fourth correction term, ΔL_{b}, concerns the contribution from building floors. The frequency doesn't seem to effect the correction term of building floors. This correction factor is set to 2 dB, so a reduction of 2 dB for each building floor is expected [38]. As is the case for all the above mentioned correction factors, this correction can vary. For concrete buildings, measurements indicate 2 dB with a standard deviation of 1 dB for each building floor [38]. The quantities related to the correction term for the building floors is presented in table 3.19.

$$\Delta L_b = \Delta L_{\text{bf}} + \Delta L_{\text{bA}} \tag{24}$$

Table 3.19: Shows the quantities found in equation 24 and their descriptions

Quantity	Description	Unit
ΔL_b	Correction term for building floors	dB
ΔL_{bf}	Building floor attenuation	dB
ΔL_{bA}	Building floor amplification	dB

The fifth correction term,ΔL_{corr} is not described that much. It is however mentioned that it incorporates other factors that cannot be captured with a correction term for speed, distance and the coupling at the foundation or building floor. Examples are treatments, bedrock zones or other track types [39]. With all the correction terms assembled, it is possible to calculate the ground-borne noise level in a room due to vibrations from trains in a tunnel. The necessary quantities for calculating the ground-borne noise level are presented in table 3.20. The sound pressure level can then in turn be expressed as [38]:

$$L_{p,\text{ASmax}} = L_{\text{VASmax}} + 10\log_{10}(\sigma_S) + 10\log_{10}(\frac{4S}{A}) \tag{25}$$

Table 3.20: Shows the quantities found in equation 25 and their descriptions

Quantity	Description	Unit
$L_{p,\text{ASmax}}$	Maximum sound pressure level	dBA
L_{VASmax}	Max vibration level, ref. 50 nm/s	dBA
σ_S	Radiation efficiency	-
S	Area of the radiating surface	m^2
A	Equivalent absorption area of the room	m^2

The sound pressure level in the room can be estimated when not that much data is available. About 3 dB is added to account for sound radiation from surfaces in the room. The equation presupposes a reverberation time value of 0.5 seconds, a value of the radiation efficiency that is 1 and a floor area that is 10 m^2. The approximate value for the ground-borne noise level when the maximum vibration level is known can be expressed as [38]:

$$L_{p,\text{ASmax}} \approx L_{V\,\text{ASmax}} + 10 \tag{26}$$

The quantities above were seen in table 3.20. Equation can be used during the location stage, when there is a lack of specific information [39]. The vibration level uses the reference value of 50 nm/s and it should be noted that it relates to the maximum vibration of the floor. the sound pressure level uses a reference value of 20 micro Pascal [39].

3.4.2 Other methodologies for ground-borne noise

Many stakeholders, companies and researchers have developed their own prediction methodologies for ground-borne noise. A prediction methodology does not exist without its specific context. Therefore it can be interesting to study other methodologies for understanding more on what forms a specific methodology.

A well-known methodology that also has been useful for creating the new prediction methodology is the HS2 model, it can be seen in equation 27. This model was created in the United Kingdom and is actually based on a previous model [4]. Approximately 3000 measurements were conducted and the train speed was at most 300 km/h. The HS2 model can handle a maximum train speed of 360 km/h [4]. The result is provided in one-third octave bands and the frequency range is limited to 16 Hz–250 Hz. In this model, the vibration level is determined by the effective roughness that is speed-dependent. The spectrum of the vibration can be calculated by scaling the vibration spectrum of another train speed [4]. The HS2 model is worth mentioning because its speed dependence model has been integrated into the new prediction methodology [4].

There are also other models that are used to convert the vibration level on a floor to a ground-borne noise level. The researcher Kurzweil has presented a model for expressing the ground-borne noise level [4]. This model is mainly focused on trains in the metro. The vibration level in a room is acquired by using the acceleration of the tunnel wall and add correction factors to this value for the acceleration. The A-weighted sound pressure level in a dwelling can be calculated by manipulating the vibration level in a room which gives the result in octave bands [4]. The correction factors are including attenuation for the soil and the rock. The two remaining correction factors in Kurzweil's model include the coupling loss and the attenuation in the building [4]. Equation 28 shows the core part of Kurzweil's model and the quantities can be seen in table 3.21.

$$L_a = L_{a,wall} - C_g - C_{gb} - C_b \tag{27}$$

$$L_p = L_a - 20\log_{10}(f) + 37 \tag{28}$$

Table 3.21: Shows the quantities found in equation 27–28 and their descriptions

Quantity	Description	Unit
L_a	Vibration level in a room	dB
$L_{a,wall}$	Acceleration of a metro tunnel wall as the train passes	dB
C_g	Correction factor for soil attenuation	dB
C_{gb}	Correction factor for coupling loss	dB
C_b	Correction factor for building attenuation	dB
L_p	A-weighted ground-borne noise level in a room	dBA

3.4.3 Trafikverket, ground-borne noise and building processes

Trafikverket has a routine when a project is developed and implemented. The overall routine consists of three stages: governance, leadership and operational procedures [40]. The leadership stage can be divided into a planning phase, an implementing phase and a closing phase. The operational procedures can be divided into a planning phase, a pre-construction phase, a construction phase and a closing phase. The operational procedures include milestones that must be solved [40]:

- Building permit
- Responsibility for the working environment
- Managing contracts
- Project specific demands
- Traffic impact
- Environmental impact
- Land management
- Information and communication processes
- Implementation contracts
- Project handover

These demands are only examples and there are more demands within each milestone. The process is more described in the project planning documents and in other governing documents. The routine is showed in Swedish in Figure 3.4. The planning procedure of a new railway must not only be governed effectively, but also meet the requirements that are found in Trafikerket's environmental policy. The environmental regulations must be addressed throughout the project. According to the Swedish Environmental Code, the shoreline and the natural environment shall be protected. Measures that will impact the nature and wildlife must be discussed. The Swedish Environmental Code is always addressed when new measures are planned [41].

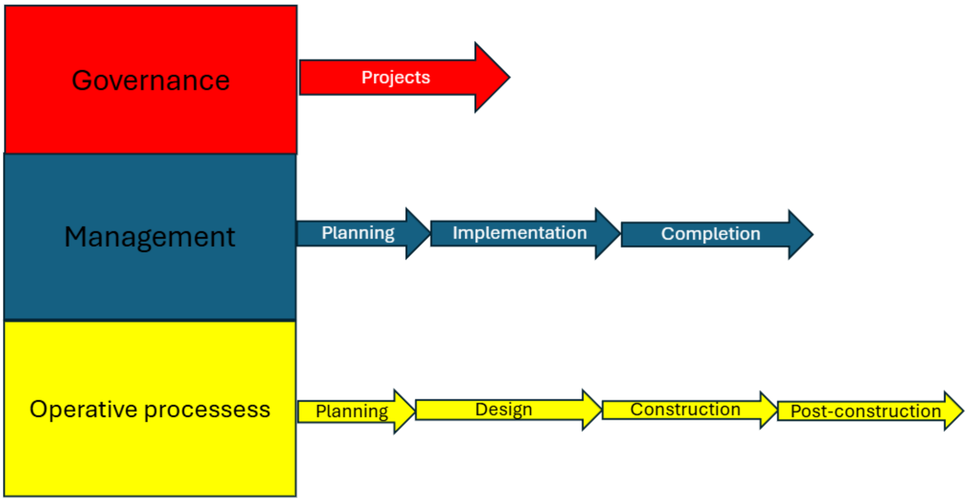

Figure 3.4: Shows the routine that Trafikverket follows. Source: The author. The image is inspired by the one found in [40].

The process of building a new railway follows the same procedures as the ones described for tunnels above. One concept that is distinctive is to involve the residents in the planning process. This is often referred to as consultation [41]. The consultation continues until the planning process is reviewed. During a consultation session, opinions are gathered and discussed. The idea is that the residents should have the opportunity to influence the planning process. Land owners and other stakeholders can also be a part of the consultation. For larger projects, the municipality and traffic planners are often contacted. The consultation can exist in the form of meetings or telephone surveys. Different projects have different ways of inviting to the consultation sessions and the consultation sessions are often adapted to the specific project. Information must however be updated and available [41].

In a summarizing document, information about the consultations are presented together with the opinions from the involved participants and stakeholders. The procedure is activated when a new railway line is built or rebuilt. Reconstruction is included in these stages, but measures that aren't too complex are not considered as a part of this new construction stage [41]. As a result, small measures do not require an activation of the planning procedures. As soon as measures are discussed, four steps can be used as a helpful guideline. The first step is to reconsider if measures are needed and how they will impact the surroundings. The second step recommends that the measure is optimized, so that the existing infrastructure is integrated. The third step is the rebuilding stage and the measure isn't meant to drastically change the existing infrastructure. The fourth and final step is the building stage and this step is only considered if larger changes are needed [41].

Within Trafikverket there has been a discussion on how to manage specific demands for ground-borne noise. A project named "G4" suggested that the a common target value would be introduced for the new railway lines that are being built [42]. Railway projects have had noise criteria that differed depending on the project. These noise criteria are aimed at certain building types, such as hospitals or schools. For example, ground-borne noise values in a specific project can be presented. When the railway line Göteborg-Borås is discussed, 33 dBA (maximum value with time-weighting setting SLOW) is used for dwellings and 35 dBA (maximum value with time-weighting setting SLOW) is used for schools. What will become apparent later when examples from case studies are provided is that both time-weighting settings can be used depending on what the project leaders find appropriate. It is possible to follow parts of the discussion through a presentation.

In that presentation, three objectives are presented [42]. These objectives are: in what building types, except for dwellings, can ground-borne noise be perceived? How should these building types be categorized? What quality shall these target values represent and how can the target values be connected to regulations in The Swedish Environmental Code? It is also discussed if the noise criteria for certain building types can be a combination of noise criteria for airborne noise and ground-borne noise. The presentation ends with some concluding remarks [42]. In the presentation, it was also stated that for dwellings, the value is more strict and for other building types the target value should be a recommendation. Guidelines will be written to ensure that it will be easy to interpret the recommendations for specific building types [42].

The discussion that lead to the recommended value of 32 dBA (maximum value with time-weighting setting FAST) was based on measurements, research results from studies on sleep disturbances, data from The Noise Commission and established routines [43]. The argument that was used during the discussion in 2020 was that the concepts A-weighting and maximum value seemed appropriate. The time-weighting FAST was used because it corresponds to how people perceive sound. The value was also considered to be a reasonable value in terms of sleep disturbances and it was used in many projects for the time being. Finally, the value was judged to be possible to achieve in future projects [43]. It was already stated that the noise criteria for ground-borne noise indicates a higher environmental assessment than for airborne noise. The authors of the report discuss that it would require substantial change to adjust the airborne noise demands to fulfill the same demands for ground-borne noise. Measures for airborne noise are more easily implemented and mitigation strategies for ground-borne noise must therefore be more robust [43].

The process of developing a new noise criteria was commented in a newsletter written by the Noise Commission in Stockholm [44]. The newsletter includes a short section which highlights the development of a new prediction methodology at Chalmers University of Technology. At the time of the publication in April 2021, the noise criteria was completely new. It is mentioned that a local noise criteria or a criteria connected to projects were widely used before that. Before the noise criteria of 32 dBA was discussed, a value of 30 dBA with time-weighting SLOW was used instead. A noise criteria of 30 dBA with time weighting SLOW corresponds to a noise criteria of 32 dBA with time weighting FAST [44]. The difference between the two time-weighting settings is approximately 2 dB–3 dB. However, by reading Dashti's PhD thesis, it becomes more convincing that the difference between FAST and SLOW is 3 dB and not 2 dB. The data from the measurements that Dashti performed more point to a difference of 3 dB [4]. The process of developing a new noise criteria for ground-borne noise started in 2015. Numerous research projects started as was described above [44]. In the numerical calculations in this thesis, the difference between the time-weighting settings SLOW and FAST is defined as difference of 3 dB.

3.4.4 Theories on project management in infrastructure projects

In order to understand how a new prediction methodology can be managed, it is vital to understand how a project is influenced by methodologies. This section will present some findings from research studies that will later be used to place the results from this thesis in a larger context. Recently, researchers at Stockholm University have studied Trafikverket and how the organization functions. The researchers have published four reports that focused on Trafikverket's governance. The first report is a pre-study. The theme of the following three reports is strategy, risks and collaboration & shared view. The authors of the reports have studied the entire organization that Trafikverket is composed of.

The first part is quite extensive. The report identifies three themes that characterizes Trafikverket. The authors of all reports have in common that they have interviewed team leaders from many sectors within Trafikverket [45]. The first part focuses on the overall strategy that Trafikverket uses in order to become a more practical and effective organization. The results from the first part is that Trafikverket has a great need to prioritize. Two type of strategies are required: one overall strategy and one narrow strategy, that informs how the team leaders can organize the projects. The overall strategy can be seen as a tool for evaluating the transport goals. Both the overall strategy and the narrow strategy are needed in the organization. They can however work against each other and that can be an issue [45]. One challenge is to merge the overall strategy with the more narrow strategy and the solution is to have planning documents. At some point, the shift between the overall strategy to the narrow strategy will become unclear. This indicates a less effective organization and the solution is to enable for better communication between the team leaders and the public officials. The next challenge is that Trafikverket is a vast and complex public organization. Strategies tend to be forgotten together with policy documents and guidelines. The efficiency of the overall strategy is therefore reduced [45]. Complexity can lead to chaos which in turn can make the working process less transparent. The solution is to simplify the strategy and to make sure that this simplification remains at all levels [45]. Uncertainties are inevitable in a big organization, but order is preferred and clarity is something to work for. The first part ends with a discussion on the importance of professional judgments.

Public officials play a key role in making decisions. As the professional judgments gains more legitimacy, public officials have greater possibilities to extend the strategy to semi-structures in Trafikverket [45]. The second part is interesting because it investigates tensions within a public organization. The context that a public organization is a part of makes it hard to apply the same strategy that is used in private companies [46]. This context is important to understand when change is needed. The authors of the report are adding another conclusion, that the strategy must be reviewed. Every strategic guideline is to be reviewed depending on how it effect the overall strategy. As an example, it's not only the budget that is to be reviewed, but also the consequence that every strategic action creates [46]. A solution is to evaluate the strategic action with the concepts long-term perspective, short-term perspective, holistic view, complexity, proactivity and reactivity. The concepts are not fully defined in the report. They are however, suggested as components that can make it easier to decode why the strategy isn't working [46]. The third part only studies the interaction between Trafikverket and private companies. The third report demonstrates that collaboration is indeed necessary [47]. Efficient collaboration can be achieved with transparency and understanding. The objective is that goals are reached and at the same time, a diversity of tasks and targets are integrated into the bigger picture [47].

Numerous researchers have studied the phenomena when a methodology is adapted. Daniel Ekström researches how integrated project teams can be used as a tool to share knowledge during the design phase in bridge constructions [48]. One main conclusion from Ekström's work is that the bridge construction process demands communication between all the stakeholders. Mutual understanding is a key feature that is vital that everyone engage in. Another feature is that all stakeholders can act in each others context [48]. An example of this is that a contractor can be interested in the design process of a new bridge. The contractor and the structural designer need to find an approach from which they can work together. Together, they will form a team where everyone has a certain responsibility. This must happen at an early stage which is not common at the moment [48].

The result that collaboration is vital has been identified in other studies. A study that focused on social ties in construction projects demonstrates that the interchange between the formal and informal connections are important [49]. It is therefore, not only the contract, but also the social ties that are important [49]. This result was presented in an article written by Anna af Hällström and others [49]. Another perspective is found by Klara Granheimer, Per Erik Eriksson and Erika Hedgren. In a paper they highlight that every stakeholder has different expectations. The article's main purpose is to understand how engineering consultants, sub-consultants and clients relate to innovation in projects [50]. They conclude that a public client is ready to engage in the project, but can be unwilling to make some of the changes. The client's perspective is short-term and the sub-consultant has a long-term perspective [50]. The sub-consultants use information from many sectors to enhance their current project [50].

It is not only the expectations that matter, but the organizational strategy also need to be considered. The authors Susanna Hedborg, Emilia Nilsson Vestola and Anna Kadefors have investigated the strategic project management and especially for inter-organizational projects with a public client [51]. A main result is that the strategy discussion moved from the public client to a contractor. This marks a shift in the strategic responsibility from the public stakeholder to the client and the solution is for the public client to focus on the transformation process. Only then will it be possible to change strategy [51].

A different perspective is provided by Anna-Therése Järvenpää, Johan Larsson and Per Erik Eriksson [52]. They have interviewed both clients and contractors in the construction sector. The study shows the relationship between control mechanisms and innovation. Once again, inter-organizational structures have been used as a framework. By studying contracts, it became possible to analyze several case studies. The public client that was studied was Trafikverket. An important result is that the innovation possibilities will depend on what type of control mechanisms is used. The implementation of output control promotes innovation, while process control might discard the innovation changes. Successful innovation can be achieved by utilizing output control instead of process control. A result is also that social control can strengthen the cooperation, as long as the public client is an active stakeholder [52]. The process control is connected to the bureaucratic system with governing rules. The output control is connected to the dynamic changes of the market where competition determines the outcome. Social control is connected to a certain group where for example values are one aspect [52].

Previous studies exemplifies how management in a public client context can be understood. The framework is either based on expectations, the current strategy or a control mechanism. Together with Ekström's study, in which a team's quality is highlighted, a more clear picture emerges. All studies have the same purpose, to understand management in the construction sector and what role different stakeholders have. These perspectives mainly investigate the circumstances from within the construction sector. Something that plays a part is public value. This indicates a shift towards the legitimacy of a public stakeholder where the organization structure alone cannot explain the management process. How a public organization relates to external stakeholders, outside of the industry can mirror its function.

The scholar Mark Moore developed a theoretical framework for understanding public value [53]. This framework is conceptualized within the so-called strategic triangle. Three components are creating the strategic triangle: the public value, the operational capability and the authorizing environment. The level of operational capability can indicate if the project is realistic [53]. The authorizing environment will indicate if the project is established by the stakeholders. The public value and the operational capability can be said to be the base of the strategic triangle and the authorizing environment is the top of the triangle [53]. It can be used in the public sector to navigate between different strategies and to evaluate policies [53]. Other theories for the public sector exist and it can be worhwile to give a short introduction to some of those theories.

There is a very detailed book on theories for the public sector [5]. The book explores several interesting topics, for example how the public sector is organized, how a public organization functions, what goals are important and how a public organization is governed. The book discusses how a public organization can be changed and how the results of those organizations can be measured [5]. The most relevant sections of the book are the chapters on the application of organizational theory, leadership and change within a public organization. Public organizations are special and this is due to the fact that they have a mandate from the people. Laws and regulations put pressure on public organizations, so the market is not defining how a public organization behaves, but rather the legal procedure. All public organizations must engage in numerous tasks at the same time, making the situation more complex. An example of this is that a public organization can be both a contractor, a client, and stakeholder [5].

Two perspectives are the instrumental perspective and the cultural perspective. An organizational perspective permeates the book and can be viewed as a lens in which all themes in the book are observed. The instrumental perspective emphasize that organizations are only an instrument for achieving major goals. A resultsoriented approach characterizes the instrumental perspective. An example of the instrumental perspective is that many public organizations are dominated by a bureucratic structure. This bureucratic structure uses routines, division of tasks and hierarchy to establish the organization [5]. The cultural perspective on the other hand, emphasizes the cultural context and its values. The values are not predetermined, but develop over time. Most public organizations are service-oriented, serving the public by offering protection, information or healthcare. This requires an organization that symbolizes openness. The cultural perspective can be used to explain why organizations persist. A common organizational culture creates a sense of belonging and reduces tensions. The instrumental perspective can be connected to the cultural perspective, provided that values can lead to greater productivity [5]. An organizational culture can be an underlying rulebook and this creates smooth transitions. Increased legitimacy is another effect of a developed organizational culture. One risk is that the organizational culture creates behvaiors in a team that isn't productive or even unwanted [5].

The instrumental perspective and the cultural perspective can be applied to discussions on leadership and leadership styles. Leaders who use the instrumental perspective are eager to implement decisions and the tools they use are routines and processes. Leaders who use the cultural perspective tend to argue that it is necessary to be an idealist and tools are values, education and to enable for cooperation within the organization [5]. All public organizations are special because they are more governed by regulations and there are demands from the public that must be assessed. Apart from these two perspectives, the book presents leadership styles. Examples of leadership styles are leaders that are characterized by either their ability to influence, motivate, protect or support the officials. To be a leader is not only to govern, but also to initiate change. A concept that is related to change is coordination. Change within a public organization demands efficient coordination between managers and officials (vertical coordination). Public organizations might need to cooperate with other government agencies which can require specialized departments (horizontal coordination) [5]. Change can be the result of a decision or occur in separate departments. According to the instrumental perspective, change is surrounded by regulations and procedures. Goals and regulations create change and that's why it is so important to work with structural processes. The first task is therefore to introduce groups that works with the development of a new structure. This group can establish a repository of knowledge with guiding documents [5].

The cultural perspective instead identifies norms as the driving component for the process of reforming a public organization [5]. A new idea can be discarded if it is very different from the expectations that managers and officials have. Norms are slowly and steadily replaced and this is identified as change. Change within a public organization can only be successful if this change has legitimacy. This can be achieved by taking advice from other organizations or by being inspired by change in other countries. Another approach is to decide to initiate an investigation that symbolizes unity. Regardless of what perspective is used to analyze change, most dynamic processes will benefit from participants who feel involved in the dialogue [5].

Methodologies are frequently discussed as a main topic at acoustic conferences. In 2010, the international congress on acoustics was held in Sydney. The researcher Dave Davis's contribution was an article on the different prediction methods for ground-borne noise [54]. In his article, Davis differentiates between four methods: numerical methods, empirical methods, theoretical methods and field measurements. The author describes how vibrations give rise to ground-borne noise and how the models can be expected to behave. Davis concludes that no method is better than any other. The source, the soil and the phase which the project has entered will decide what method is most appropriate [54]. Combining methods is an option and this is required during the planning phase. The suggestion is to use numerical methods to model the vibrations and a theoretical method to capture the ground-borne noise levels [54].

With this perspective in mind, detailed case studied can be explored. Projects from both Finland, Norway and Sweden will be studied. All projects can be seen in Figure 3.5. Most of the Swedish projects are located in the Western part of Sweden where the rock conditions are similar which makes comparisons realistic. The case studies will begin with a description of some projects in Finland and Norway and will end with some Swedish projects.

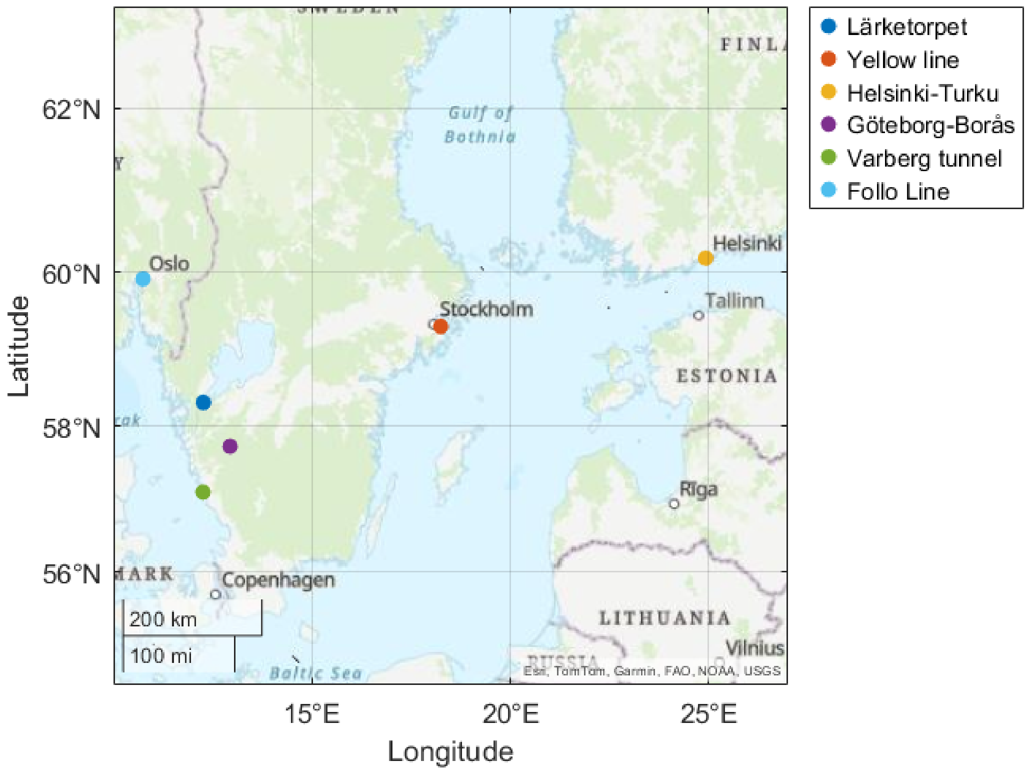

Figure 3.5: Shows the location of the studied projects. Source: The author.

3.4.5 Case studies in Finland and Norway

The Helsinki–Turku railway line

Finland has several ongoing railway tunnel projects. There is a report on ground-borne noise (VTT2468), but it is only available in Finnish. However, an abstract is available in English [55]. The report claims that it is necessary to develop a guideline. The proposed limiting values are 30 dBA for properties that are used for sleep, 35 dBA for working environments and 25 dBA–30 dBA for buildings that require certain conditions. For surface lines, a ground-borne noise limiting value can be exceeded with 5 dB. These values are maximum values where the time-weighting setting SLOW has been used [55]. The reports also explains that the values for ground-borne noise is lower than for air-borne noise. That is because when comparing the same A-weighted sound level, ground-borne noise is perceived as louder than broad band noise [55]. For urban planning, a guide is presented. It consists of three levels and the first level investigates the distance dependence for ground vibrations. The second level include the factors along the propagation path and a curve is used for estimating the vibration by viewing it as a function of distance. An average vibration in the room is given by adjusting this curve and factors such as soil type will here have an impact. The ground-borne noise level can then be obtained by adjusting the curve again by using new factors and the result is an A-weighted curve. The third level describes the measurement procedure when investigating ground-borne noise issues. Measures are also described [55]. One aspect that should be mentioned is that the report gives a concluding remark, that assessment guidelines can be reviewed depending on the situation. Local circumstances could therefore be taken into account in the ground-borne noise assessment [55].

An example is appropriate in this case for illustrating how a policy is used in practice. The newly planned railway line between Helsinki-Turku is an excellent example [56]. The purpose with that project is to connect two big city regions. Apart from a shorter commuting time, the railway line will increase the competitiveness, expand the business interest in the region and enable for more opportunities for the tourism sector [56]. New railway sections will have trains with a train speed of 200 km/h. The environmental impact assessment (or EIA) gives a clue on how ground-borne noise has been assessed. The EIA is presenting two alternatives, named A and B. Option A can be described as a double line next to the existing line for the section Salo-Kuppis. Option B includes an expansion close to Pikis. This expansion is combined with three other expansions for the route Salo-Åbo and option B is after that merged into option A. Option A will be 55 km long and option B will be 51 km long. The options are compared with option 0+ which is the current railway line, but with some extra measures [56].

According to the EIA, both options will result in the same consequences with respect to ground-borne noise. Some locations will experience higher ground-borne noise levels, but compared to the current situation the properties that are exposed to high ground-borne noise levels is assumed to decrease. The EIA uses the guidelines from [55] and follows the limiting value from that policy. Neither option will result in substantial ground-borne noise levels. The overall conclusion is that the consequence will be minor negative. At some parts of the line, the consequence is better. All corridors have been reviewed and their consequence related to the effect of ground-borne noise is presented for both options. These consequences will not be analyzed in this thesis since both options meet the requirements. Correction factors are important to understand in this case.

The EIA does not present the calculation procedure, but comments what correction factors are used. The correction factors can be seen in table 3.22 and are taken from [56]. The value 0 or -15 for the correction factor "Location of the line" depends on if it is a surface line (0 dB) or a tunnel line (-15 dB). The values -50, -35 or -20 depends on if the soil is soft (-50 dB) or hard (-35 dB). The value -20 is used when the soil is neither soft, nor hard which means that the soil is composed of a rock section [56]. The EIA states that it is a difficult task to precisely predict the propagation properties. Small changes in the soil conditions could change the final wave speeds. Further more, building types can redirect the waves, depending on the material of the foundation. Material radiate sounds differently which is yet another uncertainty [56].

Table 3.22: Shows the correction factors for the railway line Helsinki-Turku

Type of correction	Value in dB
Isolation of the track	0
Railway line	0
Location of the line	0 or -15
Foundation	0
Properties of the train	0
Resonance in the building	6
Transition to sound pressure level	-28
Safety margin	6
Properties of the soil	-50, -35 or -20

In the report, it is mentioned that no official limiting value exists, but VTT2468 provides useful values as a starting point [56]. The EIA comments how specific values are used. Dwellings are assigned the value 30 dB or 35 dB (35 dB for surface lines). The same values are recommended for hospitals. Offices and shops have been assigned the value 40 dB or 45 dB. Concert halls are found in the broader range, somewhere between 25 dB–30 dB. The overall recommended value is still the maximum value of 30 dBA or 35 dBA, both with time-weighting SLOW and this value is based on when annoyance from residents occur [56]. Measures for the railway line Helsinki-Turku are discussed very briefly. Data on the insertion loss are not presented for any of the corridors [56]. The measures mainly [56]:

- Special changes in the foundation of the track
- Elastic mats that reduce vibrations

The Follo Line in Norway

Norway can also be studied and a large project is the Follo Line. Measures are described in a railway plan. The measures are needed and the consequence can be severe if no measures are installed. For buildings that are reached by considerably high ground-borne noise levels, more measures can be considered. It is stated that many risk factors are eliminated when the foundation of the tunnel is maintained. The railway line will be able to be constructed and ground-borne noise issues will not stop the planning of the project. This will lead to a completely new opportunity to expand the railway network as the capacity increases [56].

In Norway, the institution named "Statens Vegvesen" is responsible for the roads and it also supervise the road sector in Norway. Standardization is another responsibility for Statens vegvesen. One of the interesting documents is the national policy for transportation [57]. It is a very detailed report that explores all aspects of noise in living environments. For this thesis, the chapter on railway noise is most relevant. To enable for better communications, some railway connections need to be developed. At the same time, the number of departed trains has increased. It is then necessary with a strategy for the railway sector in Norway [57]. Bane NOR is responsible for the railway network in Norway. Norway is an interesting country to study because about 700 tunnels can be found in the country [58]. One example of a new railway and tunnel project is the Follo Line in Oslo. It is a part of the InterCity plan for Norway that connects the region around Oslo. This will develop the suburbs and areas outside of Oslo. At the same time, the expansion of the InterCity project with 25 new railway stations will lead to a more modern railway [58]. The core of the InterCity project is the Follo Line which is 22 km long. The Follo Line consists of a new double track between Oslo and the station at Ski. A 20 km long tunnel is connecting the south-eastern part of Oslo with the city of Ski [58].

The EIA for the Follo Line is available in Norwegian. The noise criteria in Norway is the LAFmax value of 32 dBA, but public agencies have decided to implement measures when 30 dBA is exceeded [59]. It is noted that no official guideline exists for ground-borne noise in Norway. As the Follo Line was planned, it became apparent that the line would have a huge impact on the local infrastructure [60]. As the railway line Gardermobanen was constructed, a specific methodology was created. The idea with the methodology is to calculate the ground-borne noise level for an old tunnel, without any measures. Results from the actual project in the form of ground-borne noise levels and measures are added to the old tunnel. This gives an approximation of the present case [59]. Not many details are discovered by reading the EIA, but it is mentioned that the foundation, the design of the tunnel, the rail type and the location of the rooms for rest and sleep are factors to consider. Apparently, it was common that some dwellings close to the line were situated just above ground. The existence of ground-level appartments meant that measurements had to be conducted in nearby basements. A safety margin of 3 dB was added to dwellings which weren't located close to the ground. A larger safety margin was added if the building was constructed on loose soil. Measures are designed for the worst case scenario and not all properties will in reality have the same problem with ground-borne noise. Measures according to the EIA include [59]:

- Under-ballast mats
- Isolation layers
- Soil reinforcement
- Installation of springs in buildings

Sections of the line that are just meeting the criteria should be studied carefully. More measurements must be planned for those sections. No information is provided on how big the insertion loss will be, but the measures will make it possible to not exceed the noise criteria [59]. For the construction phase, the structure-borne noise levels from the tunnel boring machine (TBM) were simulated and measures had to be made. For example, 50 meters away from the TBM the structure-borne noise level was calculated to be at least 40 dB and possibly even higher. In those cases, the residents were given the chance to stay at a hotel [60].

Many years before the construction of the line began, a conference paper was published that suggested a new type of measure [61]. The idea was to investigate how to simulate the structure-borne sound for a double-track railway. A hydraulic machine fastened to a wagon generated vibrations and the transfer vibrations were recorded. This was done in a tunnel and the noise level was also recorded in dwellings above the tunnel. The distance between the tunnel roof and the houses was not large, almost never greater than 2 meters [61]. Small explosive charges were later detonated in the tunnel in order to verify the results. The results could be used to understand what measures can be effective. The main conclusion is that one effective measure was to combine an under-ballast mat with a layer of crushed stone particles that was approximately one and a half meters thick.

The stone layer was effective without the under-ballast mat [61]. This indicates that a combination of measures can be an alternative approach.

3.4.6 Case studies in Sweden

Sweden has published a guideline for assessing noise problems in urban contexts. This document mentions several strategic aspects that are relevant for airborne noise, but not that much is mentioned about ground-borne noise [62]. The final chapter of the document stipulates some topics for vibrations and ground-borne noise that could be explored further. For ground-borne noise those are a cost optimization for measures and the development of a ground-borne noise model. Moreover, it is here that the limiting value for ground-borne noise is described. The authors of the report states that a commission currently is working on more guidelines for ground-borne noise [62].

As an example, the new train line between the cities of Göteborg and Borås can be examined [30]. The train line has been analyzed in several reports. It will be a part of the main line that connects Stockholm and Göteborg. The new line will enable for a faster journey between the capital and Göteborg, improve the communications to the airport at Landvetter and also connect the cities in the western part of Sweden. The line between Göteborg and Borås is 60 km long. The construction of the line was expected to start 2025–2027 (at the moment, the line is not under construction) and the analysis use the year 2040 as a start year for the analysis [30].

In the documents, it is mentioned that Trafikverket has used a methodology that has been been the methodology of choice for several projects in Stockholm. The methodology builds on calculations and measurements that are used to get a value for the ground-borne noise level inside a dwelling [30]. The assumption is that the track is old, that the rock in the tunnels are homogenous and free of cracks. For estimating where measures are needed, the reports looks at the consequences of ground-borne noise. The consequence can be found by combining the sensitivity of an area with its effect [30]. Categorization of different corridors depending on their consequence is a part of the environmental impact assessment. Sensitivity can be classified into high sensitivity, moderate sensitivity and low sensitivity. High sensitivity means that the area isn't affected by noise at the moment. The area would be perceived as more vibrant if the noise levels start to increase [30]. The effect is defined in the report as the number of dwellings that will have ground-borne noise levels above 32 dBA before measures have been implemented [30]. The effect can either range from high, medium, low or insignificant. For Göteborg-Borås, each corridor has been investigated [30]. The methodology used in this project is based on correction terms. The correction terms of interest are correction terms for the source, the track, the speed of the train, the building and a specific correction factor for the distance to a building.

The new metro line in Stockholm

Another example from a large city is the new metro line in Stockholm (also referred to as "The Yellow Line"). Älvsjö in Stockholm is a new station that will be the subject of a new metro line [63]. The ground-borne noise model used is, as in the case with Göteborg-Borås, a combination of calculations based on the theory and formulas that arise from the measurements (a so-called semi-empirical methodology). This methodology is called FUT [63]. The model uses assumptions from an earlier model from 1975, but it formulates new assumptions. About 2 dB has been reduced as the ground-borne noise continues to travel up in the dwelling. Also, 11 dB has been added to adjust for the sound radiation inside the dwelling and to have a safety margin [63]. The safety margin is 5 dB in this case. The purpose of the report is to give an overview of the area and provide insight into how measures can be used. The report observes that when the train passes a switch, the ground-borne noise level can increase with 7 dB [63]. It is stated that the exact measures can differ from what is now suggested. Still, measures that gives a 10 dB reduction are needed almost everywhere, but at switches, reductions of 20 dB are needed. There will be enough space for 50 mm material of some type within the rail [63]. The main solution is to add a rubber layer or an elastomer. When the reduction needs to be greater than 20 dB, the thickness of the rubber layer can increase and the concrete slab can be heavier [63].

Similarly, the metro segment at Nacka uses the same semi-empirical model [64]. For this part of the metro line, some modifications have been made to the original model. The approach this time is to adjust for multi-story buildings by adding 3 dB for each floor, however this is not done in the final result section [64]. The theoretical framework is based on findings by the researcher Kurzweil presented in section 3.4.2. These findings have been complemented with results from measurements. Vibrations were measured at a tunnel wall. Different correction factors are used for the train speed, the geometrical damping and the material damping. The material damping was identified through measurements and is adjusted for in every octave band. Lastly, the vibrational level was calculated for every octave band. After that, an A-weighting procedure is performed. A safety margin of 3 dB has been added at the end. The calculation method is described more detailed in the report. The setting SLOW is used together with a distance correction term, a rock correction term due to damping and a correction term for the transition between the rock and the building foundation [64]. As far as measures are concerned, no distinction has been made for existing and new dwellings since they should both be able to meet the restrictions. A mentioned measure is the elastic interlayer or an under-ballast mat [64]. The report concludes that the predicted values probably are higher than the real values because the assumptions are rather conservative [64].

The Varberg tunnel

Another example that originates from the western part of Sweden is the tunnel in Varberg. The process of building the new tunnel began in 2019 and the tunnel was opened in 2025. The main goal was to establish the city of Varberg as a vibrant city, make the connections more efficient and to make the railway section more safe [65]. The tunnel became 2.8 km and the tunnel is located below the city of Varberg. The double-track railway is composed of a nine km long track between Varberg and Hamra. At the same time a construction of a new station began. This new station is situated 200 m from the old station [65]. Ground-borne noise was naturally considered. The condition was that the ground-borne noise level was to be lower than 35 dBA (maximum value with time weighting slow). Measures for reducing the levels to 30 dBA (maximum value with time-weighting SLOW) can be accepted if the cost is reasonable. Measures need to be introduced since all parts of the tunnel in Varberg will experience larger values than what is recommended [66].

Vibration and ground-borne noise measurements were conducted at several positions along the line. Measurements related to the construction phase utilized a TBM as source, while train passages were used for the measurements aimed at understanding noise propagation in the planning phase. These results were combined with data on the rail type, train type, soil condition and train speed. The vibrational level was measured in three basements and the ground-borne noise level in a dwelling was then based on that number [67]. The dwellings targeted for measurements were chosen so that they had the same soil conditions. They also had to be situated close enough to the railway track and include dwelling sites both on the surface and at railway cuttings. The EIA for the project in Varberg presents examples of ground-borne noise levels for some of the sites in the city and how these vary depending on the train type and building floor [67]. For the post-construction phase, the ground-borne noise related problems assumed to be minor or in worst case cause a moderate risk with measures in place [67]. An interesting observation in the case of the EIA belonging to the Varberg tunnel is that objective-specific noise criteria have been suggested for dwellings, schools and hospitals. For dwellings, hospitals and hotels, 35 dBA is suggested. Schools and offices were assigned the value of 40 dBA [67]. This is an explicit example where a differentiation exists for different building types.

Measures for ground-borne noise in the project in Varberg are relevant along the whole line. The insertion loss ranges from 10 dB–20 dB depending on what section of the line is studied [67]. Without any measure, the project value of 35 dBA was estimated to be exceeded by 20 dBA for dwellings situated directly above the tunnel. A floating slab track is described as the most effective measure. Resilient rail pads are other examples, but they are not seen as effective as the floating slab track [67]. When measures are installed, the noise criteria of 35 dBA will not be exceeded and this is valid across the whole line. However the rail must be maintained from time to time in order to achieve the best result [67]. The last project is also from a nearby city, Trollhättan.

The project Lärketorpet in Trollhättan

The objective of the project in Trollhättan was to provide the right conditions for expanding the district of Lärketorpet [68]. The district will become more sustainable with zero-emission buildings and by minimizing excavations in the area. Details on the possibilities of developing the area were published in 2008. The comprehensive plan was published in 2013 and was followed by a detailed development plan in 2016. This detailed development plan explains that the strategy is to connect the infrastructure in the city of Trollhättan and the railway tunnel is included in this strategy [68]. The ground-borne noise situation was analyzed for the nearby tunnel. Measurements were planned in 2017 and vibrations were measured in rock sections as for train passages. These vibrations were later used to estimate the ground-borne noise levels. A noise criteria of 30 dBA was chosen [68]. According to the report, the ground-borne noise levels are lower than expected. As usual, the ground-borne noise level is calculated by using a presumed vibrational level on the floor. It is mentioned that the ground-borne noise levels can vary depending on the type of foundation and building. The geological conditions can also have an impact on the levels, but this is not viewed as a problem since the geological conditions are the same for the district [68]. One explanation to why the ground-borne noise levels are unexpectedly low is that the geological conditions are promising or that the railway track is maintained [68].

For the project in Trollhättan, a separate ground-borne noise investigation was made. At this time, the noise criteria LAFmax of 32 dBA had not been introduced, so the project used another criteria. Noise criteria that were common to use in other projects were

LASmax of 30 dBA for dwellings, hospitals and hotels [20]. A LASmax value of 38 dBA was recommended for offices and schools. According to the building permit, the ground-borne noise level in a dwelling from a tunnel couldn't exceed the LASmax value of 35 dBA [20]. Later in the document, it becomes clear that the LASmax value of 30 dBA was used. The methodology in the Trollhättan project is semi-empirical. The initial calculations resulted in ground-borne noise levels in the range of 19 dBA–46 dBA. These calculations assumed train speeds of 100 km/h, 160 km/h and 200 km/h. The train type is probably passenger trains [20].

The vibrations were measured at a maximum distance of 100 meters from the center of the track. Two measurements sessions were scheduled in 2017, one for the 28th of April and another one for the 10th of May [20]. After the vibrations had been registered, the data was analyzed in order to identify real train passages. The time signal was analyzed in the frequency domain and the measurements results could then be used to generate the ground-borne noise level. As input parameters, the reverberation time was chosen to be 0.5 s, the radiation factor was assumed to be 1 and the height of the room to be 2.8 m. The main formula that is used combines information on the acoustic power from a vibrating floor with the expected sound pressure in a room. Theoretical results from Kurzweil were mentioned as one step to convert vibrations to a ground-borne noise sound pressure level in a room. Radiation from the walls and the roof was neglected, as was the shape of the room [20]. The calculated values from the project report, based on details from site visits, can be seen in table 3.23. The table is based on the one found in [20] and the LASmax values are valid for the ground floor [20]. It can be seen that the values range from 19 dBA to 46 dBA.

Table 3.23: Shows the calculated values for the project in Trollhättan. The number in the parenthesis is the vertical distance from the rail to the house

Train speed (km/h)	Distance to the house (m)	LASmax value (dB)
160	0 (25)	45
200	0 (25)	46
160	0 (35)	42
200	0 (35)	43
200	25 (25)	41
200	25 (35)	41
200	50 (25)	39
200	50 (35)	38
200	100 (25)	33
200	100 (35)	33
200	150 (25)	30
200	150 (35)	30
200	200 (25)	27
200	200 (35)	27
200	500 (25)	19
200	500 (35)	19

The final result from the new report is that the ground-borne noise levels are below 30 dBA. This result represents a shift, as the previous result was higher. The new result is even below 22 dBA. There is a big difference between the initial calculations and the results and the combined value of the results was 27 dBA [20]. One aspect to consider is that many of the dwellings used for measurements experienced internal disruptions. It is not exemplified what these other vibrations are, but they apparently affected the results. Therefore, there exists sources of error. Another aspect is that the tunnel section used for measurements already had an under-ballast mat installed [20]. The ground-borne noise level in the apartment above became 20 dBA. In the report it is therefore stated that the ground-borne noise levels in other buildings along the line could be higher. This is the only time where measures are mentioned and it is possible that the low ground-borne noise levels won't make measures necessary [20].

4 Results & Analysis

The result section presents all results from the case studies, the interview sessions and from the numerical analysis. The results from every part are summarized at the end. Remarks from previous studies will be discussed together with the results from every perspective.

4.1 Comparing case studies in Sweden, Norway and Finland

From the study of all EIAs, it becomes apparent that differences exist depending on the project, but when comparing the final values, the projects are quite similar. The noise criteria value LAFmax of 32 dB is merely a recommendation. The noise criteria for the railway line Göteborg-Borås, the metro in Stockholm, the tunnel in Varberg and the tunnel in Trollhättan can be seen in table 4.1. For the Varberg project, it should be noted that different values were considered depending on the economic cost. Measures that yielded 30 dBA were considered if the cost was tolerable. Since the LAFmax value of 32 dBA corresponds to a LASmax value of 35 dBA, the same noise criteria has been used in practice. Different projects in Sweden has then been using about the same noise criteria, indicating that the project plans relies on the same criteria. This confirms that even if assumptions can be different, the same result is reached. Measures for each project are seen in table 4.2.

Table 4.1: Shows the noise criteria for some projects in Sweden

Göteborg-Borås	Stockholm metro	Varberg tunnel	Trollhättan
LAFmax 32 dBA	LAFmax 32 dBA	LASmax 35 dBA	LASmax 30 dBA

An aspect to keep in mind is that the values listed in the tables could be changed. As the project entered other phases, new values for the measures could have been more relevant. Many available values come from railway plans which often serve as a first estimate when the tunnel line is planned.

Table 4.2: Shows active ground-borne noise measures for the projects

Project	Measure	IL (dB)
Göteborg-Borås	UPS, Ballast mats	8–10 or 18–20
Stockholm metro	Rail pads, Low-vibration track, Mats	10–20
Varberg tunnel	Booted sleeper blocks, Floating slab track	10–15
Trollhättan	Ballast mat	N/A

The suggestion of using UPS (under-sleeper pads) in the project Göteborg-Borås gives an insertion loss of 8 dB–10 dB, while ballast mats gives 18 dB–20 dB. In the same way, the under-ballast mats corresponds to a more advanced measure compared to the low-vibration track (LVT) measure in the Stockholm metro project. The EIA for the project in Varberg recommends booted sleeper blocks and a floating slab track is deployed if necessary. No measures, except for under-ballast mats were reported from the project in Trollhättan. This concludes that the insertion loss is somewhere 10 dB–20 dB and a reduction of more than 20 dB is seldom needed. The need for installed measures will not be the same across the line, some parts will not need additional measures. Rail pads are an effective measure, as are under-ballast mats or similar mats for the rail. The measures are related to the source-characteristics and nothing is mentioned about measures for the propagation path. This concluded that measures at the source and for the rail are most relevant when solving ground-borne noise problems in the field.

Measures are vital for having control over the ground-borne noise situation. The use of measures makes it possible to advance further in the construction work. Many of the neighborhoods couldn't have been planned if measures weren't in place. All case studies demonstrate that measures are needed. Even if the type of measure is very different from project to project, an insertion loss of more than 20 dB is uncommon. The project Göteborg-Borås needs more robust measures. This can be explained by the fact that the project is more extensive, with vast stretches of land that must be protected. Other projects, such as the project in Varberg, need different solutions. This is the case with the floating slab track. In Stockholm, as many as three different measures are planned. An explanation to this is that dwellings are situated directly above the line, compared to the railway line Göteborg-Borås. Under-Ballast mats are a reoccurring measure that is mentioned in two of the three projects. Under-ballast mats are a standard measure. That under-ballast mats are a common option means that these type of options are reliable and that they will become important for the methodology.

The approach to ground-borne noise is dependent on the assumptions. Of course, it will never be the case that one methodology is independent from another. The major equations are often borrowed and further developed in a new methodology. What can be observed is that most of the projects in Sweden use a semi-empirical model. In all projects, vibrations are measured in a tunnel and at ground surfaces. Regardless of what methodology is used, the case studies show how initial measurement functions as a starting point. These vibrational levels are later used for calculating the ground-borne noise level in an adjacent room. There is then a common reference frame for converting the vibrational level to a sound pressure level in a room. This similarity arise from a common use of Kurzweil's equation. This equation govern the transition from vibrational level to sound pressure level. This could explain why the results in the end are almost the same.

It can even be the case that assumptions differ within the same project. The separate metro sections in Stockholm applied the same methodology, but the assumptions regarding the influence of building floors differed. A difference could also be found in the choice of safety margin. The assumptions are then connected to the coupling between building and the rock. Safety margins are therefore a necessary trait in order to avoid miscalculations. There is therefore a great deal of flexibility to address the ground-borne noise issue. The lack of a common standard requires that each project has their own assumptions despite the fact that the noise criteria are similar.

In section 3.4.5, the Norwegian and Finnish strategies were presented. The noise criteria for the project centered around the train line between Helsinki-Turku are shown below. The noise criteria for the Norwegian project named The Follo Line can also be seen in table 4.3. A similar trend as in Sweden can be seen here, namely that in practice, approximately the same noise criteria are used. The difference is in what time-weighting is used.

Table 4.3: Shows the noise criteria for a Norwegian and a Finnish project

The Follo Line	Train line Helsinki-Turku
LAFmax 32 dBA	LASmax 30 dBA

Table 4.4: Shows active ground-borne noise measures the a Norwegian and a Finnish project

Project	Measure	IL (dB)
The Follo Line	Ballast mat, isolation layers, soil reinforcement, springs	N/A
Railway line Helsinki-Turku	Foundation reinforcement, damping mats	N/A

It can be seen from table 4.4 that under-ballast mats are commonly used. The trend of using under-ballast mats can be observed in Sweden, Norway and Finland. One difference from the projects in Sweden is that the Follo Line project contains steel springs in the dwellings. Normally, only measures at the source are proposed. The insertion loss is not presented in the EIAs, but from the Swedish projects, it is possible to make an initial assumption. The under-ballast mats will possibly give an insertion loss of 10 dB. Another difference is that the projects in Norway and Finland more explicitly mentions measures for reinforcing either the soil or the foundation. These types of measures could have been included in the projects in Sweden, but they are not mentioned. A final difference exist between the calculation procedures. In Sweden, the vibrational level is measured and the ground-borne noise level is calculated. In Norway, a reference tunnel case is used and that reference case serve as a tool for simulating the ground-borne noise. The Finnish project does not mention anything about the exact calculation procedure, so it is hard to know if any differences are similarities exist.

The comparison of EIAs between the countries in Scandinavia gives information on how future measures can be applied. In Norway, the new type of ballast layer was tested and this was described in section 3.4.5. The experimental solution with a new ballast layer can be tested in Sweden if other solutions are too costly. In Finland, the methodology in use is described in a document and this is an aspect that might inspire the Swedish procedures. For the future development of the methodology, the Swedish engineers can perhaps be inspired by the methodology in Finland and especially how it has different levels of suggested solutions depending on what information is available. The analysis of this is that it is important to have a dialogue between the Scandinavian countries to exchange data and ideas on engineering procedures. Because of the fact that these Scandinavian countries have almost the same geological conditions, it is possible to compare results and share data between many tunnel projects. Finland and Norway also have several ongoing tunnel projects that can create cooperation, for example how data can be exchanged. The outlooks provided by the Norwegian and the Finnish perspectives will be visible also in the results from the interview sessions.

4.2 Management of a ground-borne noise methodology: The contributing perspective

The following sections will present and analyze the interview answers. Quotes and summaries of the interview answers are provided. The full interview answers, with all respondents, can be found in the Appendix.

Data required in the new prediction methodology

A question that arises is what data or documentation are needed in order to work effectively with ground-borne noise. The respondents were many times asked to give examples of what data that could be added or what input they need in their daily work. Ground-borne noise requires cooperation between many fields. The examples are as follows:

- Public health
- Geology/geotechnology
- Railway mechanics
- Construction engineering
- Environmental engineering
- Cultural environment

Many other examples exist[1], but these are the most common examples from the interview answers. Constructing a tunnel demands cooperation and the tunnel construction work itself consists of many steps. Trafikverket cooperate with consultants, public agencies and legal authorities. As was described in the theory part, the public can also contribute through consultation sessions. If one perspective should be considered as more important, it is the geological and geotechnical perspective. Because the foundation creates conditions for the wave propagation, the foundation is critical. The foundation is emphasized in the interview answers. Many ideas on important input exists, but the foundation and the geology seem to be more present than other perspectives in the interview answers. The foundation and the geology is therefore a key aspect. This indicates that the foundation needs to be more studied in the methodology.

Respondent 11 puts emphasize on the geology which is seen in the following quote. "More information on the loss factor could be beneficial, for example how the geological parameters impact the loss factor." Respondent 1 comments on how an understanding of the transmission path is helpful when asked what more information is needed. "It can be how the model functions and also what is happening along the way". When asked what is need in order to work with ground-borne noise, respondent 6 mentions the foundation and the coupling. "How the building is connected to the bedrock and the coupling through the foundation are the most important aspects." Respondent 3 mentions the geology together with the source strength in the following citation. "The source strength is the most important one. However, local differences will always be present when constructing a railway line. For Sweden, I don't believe that the differences will vary that much as we have almost the same geology everywhere. Still the geology will have an impact and it is important to know the geological conditions." The foundation is partly mentioned by respondent 12. "Parameters that should be incorporated are the

[1]Other examples are land acquisition, traffic planning, project management and tunnel excavation

stiffness of the foundation, the loss factor and the properties of the elastic layer under the actual load in track." The track and the rail are also mentioned by expert 17. "[...] more aspects should be added, for example the contribution from switches."

The analysis of this is that the correction factor related to the foundation can be improved. In this case, both the foundation for the rail and the coupling between the rock and the building are mentioned. The geology is connected to both the rail and the coupling between the rock and the building and determine both these aspects. For a future development of the methodology, discussions can continue on how the foundation next to the rail can be modeled. The coupling can between the rock and the building can be explored in the implemented methodology with new building types.

Other aspects that could be discussed further are how measures can be implemented in the methodology. Several respondents agree upon the fact that all parts should be open to change. This means that it must be possible to change all correction factors. Respondent 11 reflects upon what should be possible to change in a methodology. "All parameters should be flexible so that they can be changed as long as it can be explained in the methodology[...]." Respondent 14 argues for the same thing. "It must be possible to change everything." Measures are not viewed as an aspect that is to be fixated into the methodology. Respondent 13 highlights that measures shouldn't necessarily be a part of the methodology, even if it might have its advantages. Respondent 11 also note that measures can be difficult to include since numerous products exist on the market and the engineer must be able to choose between different measures in a methodology. These ideas can be read in the full answers in the Appendix. At the same time, some of the respondents argue for the fact that measures actually could be needed directly in the methodology. An example is found in the interview answers from respondent 3. "For a new methodology to be introduced, it can be beneficial to explain how measures can be included and what limits there are."

Some aspects are clearly defined which enables for transparency and this will be discussed later on in the chapter "Management of a ground-borne noise methodology: the critical perspective". From the quotes above, it becomes evident that defined variables shall be possible to change. For efficient use of the methodology, variables must be defined, but aspects must be discussed so that the methodology can be adapted to the specific project. In the PhD thesis, Dashti stated that measures was one thing that could be added later on. There is some indication in the interview answers that measures could be necessary to add. From the interview answers, it seems that all core parts of a methodology must be flexible. This means that it might not be best to include measures. As Dashti stated, the methodology can be complemented with measurements. This is also an example that the methodology must be flexible. The respondents point out that it must be possible to revise the methodology at every stage and this could include new data from measurements. This means that measures are not ideally included since it wouldn't be flexible to introduce measures in the implemented model that later need to be changed. An example is that multiple products exist and it would be too complex to include all these variations. The analysis of this is that measures might not be added to the implemented model, but a standard value for an under-ballast mat can be relevant. Under-ballast mats are not mentioned in the interview answers as something that should be added, but one result from the case studies was that under-ballast mats are preferred in Sweden. The results from the case studies can therefore be used to provide guidance on how the methodology can be developed. Since measures are included in a correction term, it is more a question of including predefined measures or adding common measures in the implemented model. EIAs and railway plans do not only require precise documentation on the ground-borne noise levels, but also an idea on where to place robust measures. However, installing a measure can be a complex procedure, which means that measures best are included when estimating the results, but not as a main part of the implemented model. As the respondents have mentioned, there are many products that exist on the market. An analysis of this is that implementing measures in the implemented model could in fact stop the creative process of developing new products. Unlike the measures, one aspect that cannot be changed is the noise criteria that are used for evaluating the measured or calculated ground-borne noise levels.

Objective-specific and daytime noise criteria

All ground-borne noise levels from all projects are evaluated with the noise criteria, most commonly a value that corresponds to the LAFmax value of 32 dBA. Here, no trend can be observed in the interview answers how that criteria is used. Some respondents claim that the value is relevant and applicable, while others argue that it is too strict. Human health is one aspect which makes the noise criteria relevant. All respondents mean that protecting resident's health shall be prioritized. Some of the respondents believe the criteria to be too strict when new sites are developed. They still argue for the necessity of the noise criteria and it is only by having a determined value that residents can be protected from the harmful effects. In the long-term, residents can develop an increased risk of mortality. Strokes and heart attacks are the most severe consequences of high exposure due to ground-borne noise. Noise in general also has these long-term effects. The main argument as to why the noise criteria is strict is because it makes it hard to build in new areas. Despite the fact that ground-borne noise can have consequences on human health, not many residents are exposed to ground-borne noise. Instead, it is the airborne noise which most people are exposed to. This can be read in several interview answers. For airborne noise there are more criteria, adapted to specific contexts. This brings forward a similar theme: if object-specific noise criteria are to be developed.

Section 4.1 described how objective noise criteria are assigned to infrastructure projects. Once again, some respondents claim that new criteria could be necessary. Examples of specific buildings that could be in focus for an objective-specific noise criteria are hospitals and schools. Others mean that more criteria aren't needed because ground-borne noise is not as important as airborne noise. The fact that airborne noise has motivated the decision enforce the noise problem in legal documents is mainly because it is a greater problem than ground-borne noise. The only demand that can be found in the technical report from Trafikverket in Swedish is the LAFmax value of 32 dBA. More values, both equivalent and maximum, are found for airborne noise. The airborne noise regulations also differ between activity during the daytime and during the night. As a result, there are noise criteria for airborne noise for different parts of the day. Introducing objective-specific noise criteria for schools and hospitals was discussed in the early stage at Trafikverket when the LAFmax value was regulated. It is unclear why the discussions stopped, but this marked the end of that perspective.

Objective-specific noise criteria could become a tool for new infrastructure projects when a part of the tunnel is situated near sensitive areas. Some of the respondents believe object-specific noise criteria to be useful. Respondent 6 thought that they could be considered. "Yes, it is always necessary to see if the noise criteria can be evaluated".

On the other hand, some of the respondents also identifies the problematic side of the objective-specific noise criteria. One respondent mention that building types with different noise criteria can't be upgraded. A quote from respondent 18 illustrates this and also shows how closely connected noise issues are to city planning. "On the other hand, having object-specific noise criteria means that an office can't be upgraded to a residential building." This is one example of when the use of objective-specific noise criteria becomes problematic. Objective-specific noise criteria could, according to the respondents, be an effective tool for new scenarios. Respondent 18, once again comments on this. "It would be beneficial to have these objective-specific noise criteria. This of course still means that there must be the same quality despite the type of building. Different demands can make it more convenient for the developer as it can be a challenge to have the same demands that we have for residential buildings on all building types".

These objective-specific specific noise criteria are not the only criteria mentioned in the interview answers. The daytime regulations are also mentioned as seen in the following quote by respondent 15. "We would like to know what the situation is for the day. Disturbances occur during the day as well[...]The number of passages and how the annoyance can be described are two examples of what I would like to know more about, especially for the daytime." Respondent 8 also comments the use of a daytime criteria. "It is possible to investigate if this criteria should be in use during daytime, especially when there is increased traffic."

By having noise criteria that are adapted for the day, it will be more easy to interpret the ground-borne noise levels and connect these to an EIA. Only having demands for the night is problematic because the ground-borne noise levels are dependent on the train capacity. The train capacity, i.e. the variation of the train passages, changes during the day, evening and night. Having criteria for the day would enable for an improved planning process and lead to the investigation of more realistic scenarios. At the same time, developing both objective-specific noise criteria and daytime criteria is demanding. It requires time and effort and in the end, it might not be worth the time to develop these specific criteria. A tunnel project has other parameters that need more focus. Also, discussing noise criteria is not really a part of the scope of this thesis, even if it is an interesting theme. The noise criteria became a relevant theme because projects had previously used different criteria. Therefore it was interesting to analyze how criteria impacts the noise assessment. If object-specific noise criteria and daytime criteria should be developed can't really be decided in this thesis, more data is needed. Despite this, the discussion can continue.

Relevant measures for ground-borne noise

From the interview answers, it can be read that measures are seldom reviewed after the project has finished. All respondents say that it's very rare to return to a project to conduct extra measurements. A common opinion is that it is only when complaints are received that the measures are reviewed and that measures at the source are the best alternative. The respondents emphasize that it is very hard to implement measures afterwards. A quote from respondent 1 illustrates this well. "[...]we are good at implementing measures in the tunnels, but its unsure exactly how good we are." Respondent 10 shares the same view. "Feedback only reaches us if we have residents that complain." As for the case studies, an under-ballast mat seem to be a common measure. Respondent 20 mentions this type of mitigation strategy. "Ballast mats are a common option. For most tunnels, ballasted mats are a choice." Other examples that are mentioned by other respondents are under-sleeper pads (UPS) or LVT (low-vibration track). An example of how measures can affect each other comes from respondent 12. "It is important to remember that all parts of a system will interact and therefore the subgrade must be considered to make sure that the correct solution is chosen[...] As an example, by using the correct combination of elastic system with UPS and ballast mat, a ballast depth of 300 mm could potentially be reduced to 150 mm without loss of function and without a quicker deterioration of the track system, which is something that is being investigated in other jurisdictions."

The analysis of this is that the solution is to install more measures than needed and this can imply that the ground-borne noise levels might be lower in reality. To be on the safe side, robust measures are installed. A tunnel with continuous traffic makes maintenance of the installed measure inconvenient. This leads to a situation where the measures must be easy to repair and that it is difficult to evaluate projects after the tunnel has been constructed. However, there are many different measures that can be placed close to the source. Examples mentioned in the interview answers above were LVT, UPS or under-ballast mats. Both the case studies and the interview answers imply that under-ballast mats are used in numerous projects.

A trend that the respondents observe is that in Sweden, ballasted tracks are common and so it will also be in the future. This is a cost-effective, yet reliable option. The economic aspect will despite this remain. The following quote from respondent 13 exemplifies how crucial the cost is. "We don't want to make measures that are too costly. The most convenient solution is a ballasted track system without any measure." Respondent 3 explains the situation. "If the railway line is already in operation, it can be hard to implement measures. Measures can also be expensive. If we reach precisely below the target, it's good. If we are too good at mitigating ground-borne noise, then we have a project that is overdimensional. It can be beneficial to have a project that is overdimensioned if the background noise level is problematic." Respondent 6 comments on how complaints and measures are connected. "Usually, it is only when a problem occurs that measures are evaluated. There are some exceptions where extra measurements have been arranged without there being an initial problem." Respondent 12 refers to a specific standard where most measures are described. For a reduction of 10 dBA, under-ballast pads can be an option and for an insertion loss of 25 dBA or more, a mass-spring-system, which in this case is symbolized by concrete slabs on springs, is the best choice. Respondent 19 explains what measures can be used for trams in cities. "We have slab tracks and rubber materials. Using materials that can mitigate vibrations is a relatively new thing, but it is not always clear what measures can be used in different cases."

Respondent 15 reasons on the fact that the economic cost is substantial and this means that many interests must be compared with the economic aspect. Railway lines are mentioned as features that dominate the landscape which can change the soundscape. Respondent 15 also comments on another type of measure; that the acquisition procedure can be applied for specific properties. "We also have the ability to acquire a property by applying the right of acquisition. That is more common than expropriation. What motivates a property acquisition is the health aspect." Respondent 15 also explains that it can be even more difficult to create a balanced soundscape at the countryside. "Often it can be difficult to implement measures against ground-borne noise. At the countryside, it can be even more challenging to create a good environment. Since this environment is undisturbed, the introduction of a train line or a tunnel creates an imminent change in the landscape."

The quotes and examples above signify how the economic cost is apparent in most projects. The analysis of this theme is that complaints can make it necessary to review an installed measure, but it is seldom the case. All aspects need to be considered before the tunnel is constructed because it is a complex task to change measures afterwards. At the same time, the experience from the residents must be included in the assessment. Complaints are therefore important for understanding what tunnel lines need extra measures. A tunnel is a huge change in the landscape and the disturbances from ground-borne noise can be challenging. That is why many fields must cooperate and acousticians must know how the tunnel will impact the landscape.

4.3 Summary of the contributing perspective

The contributing perspective provided results concerning what data can be added to the methodology. Answers from the respondents showed that fields such as public health, geotechnics, railway mechanics and others are important when determining the ground-borne noise levels. The answers also showed that ground-borne noise measures are only installed before the tunnel is completed and that complaints are quite rare. There is no clear trend that the noise criteria should change or that other criteria should be developed. The LAFmax value of 32 dBA is viewed as a safe value and sometimes it is mentioned as an obstacle when building. All respondents agree that protecting residents is the strongest argument for keeping the noise criteria.

What can be seen is that most respondents say that more information on the transmission from the rail foundation is needed. More information regarding the transmission from the rock and into the building, i.e. the coupling is also needed. The geological conditions must be studied in greater detail since their are very important for the transmission. In the implemented model, rail components, e.g. switches can be added. At the moment, measures are a part of the methodology, but there is also a discussion if they shall be added to the implemented version. Some of the respondents would like to see measures since it would be an effective tool when planning. On the other hand, introducing measures could determine what measures to use which could make the creative process cease. The recommendation from the analysis in this thesis is that measures shouldn't be included in the implemented version. However, a standard measure, such as an under-ballast mat could be an idea. That is because the under-ballast mat is the measure of choice in most projects.

4.4 Management of a ground-borne noise methodology: The critical perspective

Challenges with the new methodology

Many of the respondents are aware of the new prediction methodology for ground-borne noise. Some have reviewed the PhD thesis, some have contributed with their advice and others have received data from the project. There are also some respondents that have never heard of the methodology. The respondents that are familiar with the methodology can in some cases explain what they think are the challenges and advantages with the methodology. This brings forward a critical perspective with many insights. Firstly, it should be noted that not all respondents have studied the methodology and only some could give information on the challenges and advantages. Secondly, the challenges that the respondents mention are challenges and not disadvantages.

The methodology has some challenges that the respondents mention. The challenge is that a methodology can't capture all the transmission factors. Expert 4 explains this. "The challenge is that the reality is always more complex and it can be a difficult task to capture all the aspects in one methodology." The consequence that a methodology cannot capture everything is that more data is needed. Respondent 17 would like to see more data. "One challenge is that few tunnels are studied[...]" Expert 11 also comments on this. "Data from more tunnels is needed[...] It would be good to plot the results from for several sites and compare."Respondent 12 identifies a need to include the foundation and this relates to the fact that the foundation is important for the coupling. "A disadvantage is that the foundation of the track does not seem to be included in enough detail."

Using correction factors, which the new prediction methodology relies on, is not the only approach that exists. Respondents mention transfer functions as an alternative. Respondent 17 gives an example of how transfer functions can be used as an alternative approach. "Transfer functions could be more in focus, so that we know how the tunnel is excited by the vibrations." Respondent 14 also mentions transfer functions as a choice of method. "One example could be transfer functions. They can be measured as well as simulated, but correction factors can be good to get a first estimate." That several different methods can be used is apparent. Respondent 21 explains how hard it can be to capture everything by only using numerical simulations. It is important to emphasize that models are just models which means that they only illustrate what happens in the real world. A combination of several numerical approaches can be advantageous, respondent 21 mentions in the interview answers how FEM can be combined with SEA (statistical energy analysis).

Comparing assumptions is one way of investigating the uncertainty. Respondent 21 states that ground-borne noise can be difficult to model due to the uncertainties. Modeling the transmission from the tunnel and to the building is described as especially challenging. That is why there is a need for more measurements. All respondents would like to see more measurements. For example, respondent 1, 7 and 11 state that more knowledge is needed and this knowledge can only be achieved by measuring. Respondent 16 has an example on how the rock can be examined, to decrease the uncertainties. "Seismic method (refraction seismic) can be used to estimate the bedrock seismic velocity. This might be helpful when assessing ground-borne noise issues. Typically, the seismic velocity is lower in crushed rock and higher in intact rock." Respondent 14 comments on what more is needed to know about ground-borne noise. "We know how waves propagate in solids, how they enter buildings and lead to noise. It could be beneficial to know more about soil wave propagation properties. It can for example be wave propagation in a two-phase materials or wave propagation in random media[...]." Respondent 19 explains that more data is needed in general and what the challenge can be when working with data from tunnels. The quote is unrelated to the new methodology and more concerns the general approach. "In most cases, the measurement results from one tunnel cannot be transferred to another. Tunnels can have been constructed in many different ways and this means that we must use a cluster analysis."

The analysis of these parts is that the use of transfer functions isn't exactly mentioned as a challenge compared to the methodology, but it is quite a different perspective. It should be noted that the correction factors found in the prediction methodology are actually based on transfer functions. However, the use of specific transfer functions could become an even more explored option in the future and this option shall be analyzed and discussed. When analyzing how a methodology can be integrated and adapted into a project, other approaches must be reviewed. The conference paper from Davis highlighted that a combination of approaches for ground-borne noise could be effective [54] and the interview answers also point in that direction. Specific transfer functions could be more studied which would lead to new insights into how the transmission works. Rock is a material that doesn't behave as other materials, for example steel. In the literature review, it was described how rock formations could redirect the incoming wave and also attenuate it, making predictions difficult. This uncertainty requires more input data in the form of new measurements.

More measurements can focus on the rock and its properties. At the moment, there are no indications that public agencies or consulting firms devote a great deal of time into understanding the transmission effects of the rock. These kinds of seismic measurements mentioned by the respondents can be introduced. This is motivated by the fact that the foundation has been identified as critical and knowing more on the transmission effect is always interesting. The PhD thesis that contains the prediction methodology ends with a section that invites the reader to complement the methodology with measurements, new data or numerical results. When exploring the methodology, specific transfer functions can't be forgotten. Rather, specific transfer functions are to be present when processing the data together with other approaches. As the respondents have stated, specific transfer functions could still be in focus despite that the methodology can deliver robust results. Even if the methodology has been created with a specific purpose, results from other methods can be discussed and analyzed. Comparing approaches requires that the methodologies are open for discussion. This leads to a perspective on the transparency, which is viewed as a major advantage.

Advantages with the new methodology

One theme that is mentioned by many respondents is the transparency of the methodology. The transparency is a strong advantage of the methodology and it is mentioned that thanks to the transparency, it is now possible to understand all steps of the calculation procedure. From an engineering perspective, it would lead to a better reliability of the results as the procedure gains more legitimacy. Likewise, the methodology is praised for having presented new measurement data. An example comes from respondent 11. "As the methodology was developed, new measurements were conducted. This data is excellent and will be of very good use." Other measurement data was incorporated in the methodology, but substantial new data was continuously added. As was described in the chapters above, an ambitious measurement plan was launched and resulted in interesting findings. The respondents who had heard about the methodology said that the data was vital. The measurement campaign that the methodology is based on, was noted by the respondents. As can be read in the interview answers in the Appendix, the new data has lead to the possibility to create new methodologies and standards in some of the other Scandinavian countries. Examples of this come from respondent 11 and 20. By using data from existing tunnel projects, the methodology becomes realistic since it is adapted to the context. Another advantage is that this methodology is adapted to the geology that exists in Sweden, which respondent 1 points out. "The advantage that the model from Chalmers has is that it is adjusted for the Swedish soil conditions." Other advantages that the methodology has is the literature study that is very detailed. Respondent 17 comments on this. "An advantage with the methodology is that the literature review is substantial and very well written." The approach to use the standard deviation to access the uncertainty is another example. Respondent 4 mentions this. "It is transparent with the uncertainties." The transparency is however mentioned by most respondents.

Respondent 4 also mentions the transparency as an advantage."It[the advantage] is the transparency[...]" Respondent 3 agrees on this fact. "The model is transparent and I hope that this will lead to a more uniform working process." Respondent 6 also mentions the transparency as a main advantage that the methodology has. "It's good that the methodology is transparent and has a more clear structure." That the transparency can lead to a better comparison of products is an aspect that respondent 12 points out. "It is good that the methodology connects results and data from other projects. The results from the methodology can be used as a guidance. This is especially important since it must be easy to compare different calculation results during procurement." Transparency is also something that respondents would like to see in the technical reports in a project, for example how parameters are defined and what assumptions are used. Respondents 18 and expert 20 talks about this and this can be seen in the interview answers when they are asked on what input is needed. Respondent 14 comments the role of the transparency when asked what makes it difficult to work with ground-borne noise. "We also need to have a structured working process to coordinate relevant engineering disciplines. If a comparison is made to structural engineering, transparency is required throughout the verification process, starting with a design basis. For noise and vibration problems, it is not uncommon to work with black boxes. This creates problems, without transparency it is virtually impossible to review a design solution."

At this point, it can be relevant to compare results from this thesis with results from other studies, presented in section 3.4.4. That transparency is important is highlighted in several recent studies that were presented in the theory part. The transparency is linked to improved communication. Therefore, the result from the interviews is similar to Ekström's result [48] that communication is needed. Since the methodology is transparent it will enable for engineers from different fields to understand the result. This also is something that Ekström emphasizes [48], that different stakeholders engage in other fields than their own. This transparency will then lead to more efficient collaboration. However, the results by af Hällström et al. , regarding interchange between the formal and informal connections [49] can't be verified in this case. Rather, it seems that the openness provided by the transparency leads to a greater legitimacy.

This increased legitimacy doesn't seem to be impacted by how the information is communicated, so if the contact is formal or informal doesn't seem to be important. Neither the the result from Granheimer, Eriksson and Hedgren [50] can be verified. Their conclusion, that a public client is unwilling to change and that the client has a short-term perspective, cannot be observed. It might be the case that the bureaucratic structure can indicate a tendency towards a less efficient decision making. A consulting firm could in some projects have a short-term perspective as they have a budget for a project and might not be involved in all stages. However, even if there can be a tendency towards inefficient decision making and the use of a short-term perspective, the interview answers actually indicate the opposite. Trafikverket, as a public client, demonstrates an ability to change as the methodology was reviewed in many occasions. From all stakeholders, consultants and agencies, there is an ambition to work with ground-borne noise issues in a long-term perspective.

The transparency can be linked to what Moore described as the strategic triangle [53]. Here, public value is one of three main themes. Public value is as equally important as the operational capability and the authorizing environment. The respondents said that the methodology will make the work with ground-borne noise more standardized. One way of expressing this by using Moore's triangle is that the transparency, that is the prerequisite for a more efficient working procedure, will then increase the operational capability. Therefore, the results from the methodology will make it more easy to evaluate how realistic different components are. Moore's strategic triangle can then be observed when an engineering methodology is created and adapted. The last aspect, the authorizing environment is also important and is more connected to the organization. The authorizing environment will become important when the "collaborative perspective" is discussed

The analysis of these sections is that the transparency is the main advantage that is recurring in the interview answers, but other advantages emerge. The methodology will create a new situation where it will be more convenient to compare results for ground-borne noise. With an extensive literature review and a great deal of data, the methodology has all qualities to continue developing. The challenges that remain will become parts that can be discussed in the future. That some of the respondents are already aware of the pros and cons of the methodology means that the methodology has been communicated. The next step is to take the methodology to the next level by understanding the larger context. What differentiates a model from a methodology was how data was processed and integrated. The integration of new data requires cooperation and organization. This organization will now be presented and analyzed in the collaborative perspective.

4.5 Summary of the critical perspective

The critical perspective discussed how the methodology can be improved. Most of the respondents had heard of the methodology, but few people could explain the important points. The advantages with the methodology is that it applies a statistical approach to understand the uncertainty, contains a great deal of new measurement data, is adapted to the rock conditions in Sweden and that it has a detailed literature review. The main advantage is that it is transparent. The challenge is that it cannot capture all aspects. Even if much data was gathered, the results are based on few tunnels which might make it difficult to use the methodology in tunnels that differ from the ones used during the measurements. The results from the interview sessions provides another perspective than what has been presented by previous studies. All stakeholders are willing to communicate and exchange ideas and the structure of the communication strategy does not seem to be important. When introducing an engineering methodology, public value is needed, together with an operational capability and an authorizing environment. The results from this thesis then corresponds to Moore's result. The transparency will make it possible to compare results from different projects, regardless what stakeholder is involved. This is why the new prediction methodology will become such a powerful tool in infrastructure projects.

4.6 Management of a ground-borne noise methodology: The collaborative perspective

Introducing a reference group

The chapter before presented what is needed in order for the methodology to develop. For that to happen, there must exist some kind of structure that can link all parts of the methodology and make it applicable. One theme in the interview answers that relates to this is the use of a reference group. The task of the reference group would be to maintain the methodology. Different respondents have claimed that this reference group should consist of people with different backgrounds. This would include officials from Trafikverket, consultants and other stakeholders. The objective of this group is to discuss and contribute to the development of the methodology. This would mean that the methodology remains as a significant subject. It should be noted that not all respondents have suggestions on how the methodology can be managed. Another theme that arise from the interviews with the respondents is the suggestion to stipulate the methodology in governing documents. Either in a technical report or in a handbook. At the same time, respondents comment that consolidating the methodology in a governing document or in a handbook could make it stagnate. The solution should therefore be to give the reference group the possibility to read through the methodology from time to time. The two options: creating a reference group and documenting the methodology are the primary solutions for managing the methodology. First, the idea with the reference group will be analyzed. Trafikverket will have the responsibility to manage the prediction methodology. The organization will however depend on collaboration with other stakeholders, making collaboration essential.

The idea of having a reference group is for example emphasized by respondent 6 and respondent 7. In the following quote, by respondent 7, this is explained. "In the future, the management of the methodology can be revised by a reference group that reviews the work as the information becomes available." "The Nordic Council of Ministers has has a reference group and a similar reference group can be developed.[...]Another idea is to arrange workshops, where people can meet and discuss results." To use external groups of experts to discuss results is an aspect that respondent 11 also mentions. "We have used the standard committees and the BNAM [The Baltic Nordic Acoustic meeting]." Respondent 6 also introduces the idea of a reference group. "One idea is that a reference group works with the methodology which will keep it relevant."

Previous studies have acknowledged that Trafikverket, as it is a large-scale organization, face several challenges. The study from Stockholm university presented some of these challenges. The authors from a large study recommended the use of planning documents to bridge the gap between the overall strategy and the narrow strategy. The ground-borne noise prediction methodology can be one step towards this goal. By establishing the methodology more thoroughly in documents, Trafikverket's strategy can become even more efficient. The risk still exist that the methodology will be forgotten. Having reliable data will reduce that risk. The next step according to the researchers is to review the strategy. That is the idea with the reference group. The reference group will have the ability to evaluate how effective the methodology is. The reference group can have access to the results from the methodology and can compare those results with conclusions from tunnel projects.

The final report from the same research project, emphasized collaboration between the public client and the private companies. It is not clear from the interview sessions how the reference group could be organized. That is a topic that can be investigated in upcoming projects. Increased collaboration will probably become a reality if this reference group is formed. Even if a public client and a private company can be involved in the same tunnel project, they don't always have the same focus. The complexity can make it difficult to create opportunities where the public client and the private companies can meet. The results from this thesis agree with previous studies that a planning document is useful and that collaboration is a necessity.

Järvenpää, Larsson and Eriksson concluded that output control (using the dynamics of the free market) was more important than process control (bureaucratic processes) [52]. In contrast to what they concluded, information from the respondents instead point towards the bureaucratic process. It was the bureaucratic processes that enabled for the development of the methodology. The free market could play a part in innovation when new discoveries are further developed, but the bureaucratic process appear to be more significant. What is apparent is what Järvenpää et al. define as social control. Many stakeholders had the chance to review the new ground-borne noise prediction methodology which already has enabled for good cooperation.

However, there are risks associated with having a reference group. One risk that is mentioned by the respondents that are familiar with the methodology is that the methodology shouldn't be managed by a person. It is mentioned that this person could suddenly change work place and then the methodology would also change location. This risk is mentioned both by respondent 3 and respondent 4. Related to this risk is the risk that the methodology will cease to be discussed. Respondent 11 describes this risk. "One challenge is that the methodology must be used." Respondent 10 also explains what the risks might be before describing the FTA methodology. "One risk is who will be responsible for managing the methodology." A example that is connected to this risk is that this person monopolizes the methodology. This would lead to a situation where the methodology is hidden and stops evolving. Respondent 3 also mentions this as a major risk. Respondent 6 also continues with this reasoning by adding that the management of a methodology requires commitment. Managing a methodology will not be an easy task, there will always be some risks that occur. Respondent 1 has an idea on what that risk might be. "If the group can manage the model, then it is possible to work with it. If the group would be dissolved, then it would become more challenging to work with these questions." Respondent 3 also sees this risk for the prediction methodology. "One risk is when the person who is responsible for managing the methodology moves[...]." Respondent 12 talks about one risk that can occur due to a lack of financial interest. "One risk occurs when there is a need to save money, the development of the methodology can then cease as the funding is reduced."

When analyzing this risk, it becomes evident that for managing a methodology, it is not enough to have reliable data. The team must also collaborate. A reference group or similar can exist and be efficient, but retaining the methodology requires perseverance from the people involved. Even if a possible reference group will be created, a strategic plan is necessary. That a reference group will stagnate is probably less likely since it is an external group and therefore it is required with a diverse reference group. It is still important to be aware of that all work requires commitment. When this risk has been accounted for, it can be time to follow the next recommendation which is establishing a regulating document.

Establishing a regulating document

That the methodology is explained in a guiding document will enable for better decision making for the project managers. This is highlighted by respondent 13 when asked if more measurements are needed. "What is needed now is a catalogue that explains what tools project managers and decision makers have according to the methodology. The catalogue could also be used for knowing, in greater detail, what levels are generated." Respondent 2 has the same idea. "It would beneficial with a document from Trafikverket, for example a guideline." Another example comes from respondent 16 and here the context is more related to all technical specialists, not only the acousticians. "For a larger audience, good documentation is needed." Respondent 19 gives an example of how a methodology can be managed by planning for the future."The strategy is that we have raised the question and that we want to work more proactive. This has lead to a situation where we have received resources and interest in this question[...]."

There are examples of other engineering methodologies that has been codified. An example that is mentioned by respondent 10 is the guiding documentation that exists for the methodology developed by the FTA (The Federal Transit Administration in the United States). The guiding document is extensive, but this depends on what step or stage the project has entered. In the same way, the new prediction methodology for ground-borne noise has three parts which all require different approaches. A guiding document could be divided into these three steps with extensive information, as the FTA guideline, depending on which phase the project has entered. Respondent 10 comments that FTA is an example of when a methodology has been supplemented with a guiding document. Respondent 8 emphasizes that the methodology must be codified in regulating documents. Technical documents and guidelines are examples of regulating documents that respondent 8 mentions as document types where the methodology could be added. "For example, the FTA methodology has an existing guide attached to it."

From these quotes and summaries of the respondent's answers it becomes possible to see that developing a regulating document actually is an option. It becomes apparent that a regulating document isn't something new, but has been used in engineering contexts in other countries. The guide for the FTA is one example of this. This means that establishing a regulating document isn't an impractical option. That some of the respondents would like to see a regulating document indicates that this is the next step for developing the methodology. To have an explaining document will force the stakeholders to communicate the results from the methodology. It is not only necessary with transparency, communicating the results in an understandable manner is always relevant. Still, the nuanced discussion must remain and parameters must be able to change as was concluded in "The contributing perspective". Establishing a regulating document does not mean that the methodology must be followed at every stage in a project.

Using a guiding document can according to the interview answers, despite the good intent become a risk. This is something that can once again make the methodology stagnate. One risk that has been expressed in the interview answers is how to keep the methodology relevant. Respondent 8 states that the methodology must first be tested, so that the stakeholders know that it is actually useful. "First, it's important to test the methodology to see how accurate it is." Another respondent, respondent 16, mentions that measurements must be performed again. "The model must be validated if it is working as designed. One thing that is really tricky is to see what the difference is between the field measurements and the results from the model." Respondent 14 comments on a risk when having a checklist. "A checklist does not promote thinking and it is especially important to reflect upon the different methodologies that can be used." Respondent 2 has an idea on how a methodology can be used and the risk that comes with it. "That it is used in the wrong context. To use a model that isn't fully adapted to situations with trains in tunnels could be a problem." This risk is also identified by respondent 3. "To think about how the methodology can be continuously developed is a key point. One problem is to use conventional methods for new problems. An example is when solutions for bridges are used for tunnels."

The analysis of this risk concerns the engineering working procedure. A methodology need to have a dialogue with the physics that govern reality. It should be noted that all respondents believe that structure and transparency is important, it is more the idea to strictly follow a document, without questioning it, that can be a problem. The respondents emphasize an important aspect which is when a methodology is implemented without a reflection on what it actually models. For the methodology to work as intended, it must be evaluated with measurement results as was discussed above when specific transfer functions were presented. This issue could create a situation where the results are accepted and never analyzed or reviewed. Introducing a regulating document can create a tendency towards relying on the codified version of the methodology. That is why it is so important to also have the reference group. This reference group could then become a tool for ensuring that results from a prediction methodology are not only accepted without a detailed discussion. What needs to be discussed is not only the current situation, but also how the methodology can be remain in the future.

The use of a reference group and guiding documents could be connected to the instrumental perspective that the prior research emphasizes. The instrumental perspective is focused on the bureaucratic processes and a reference group and the implementation of supporting documents belong to this perspective. The use of a reference group could also be connected to the cultural perspective. The cultural perspective is connected to values, cooperation and change over time. By introducing a reference group, the cooperation would increase and this could lead to a shift over time. As this group establishes new routines, the bureaucracy is completely changed. This changing situation in how ground-borne noise is approached is relevant, but all technical specialists are at the same time observing what happens in the future. Trying to analyze trends and possible outcomes are crucial for being prepared in the future.

The future for ground-borne noise

When asked if a conflict of interest exist between expanding the railway network and protect people from ground-borne noise, the respondents mentions that so can actually be the case. Trains and trams must be able to resist vibrations which respondent 19. "We have strong reasons to believe that the tram itself must be robust in order to be able to resist vibrations." Undeniably, ground-borne noise will not cease to impact people's lives in the future when the railway network expands. As can be read in the interview answers, more people are exposed to traffic noise than to ground-borne noise. There will still be an exposure. In the theory part, exposure was linked to a greater risk of developing cardiovascular diseases.

Respondent 4 explains how to interpret the term exposure. "It is hard to give an exact number, but we usually say that after 10 years of exposure there is a higher risk of developing cardiovascular diseases." Respondent 15 comments how difficult it is to work with ground-borne noise. "Vibrations and ground-borne noise can be harder to shield off and those measures are more expensive." From some of the interview answers it is demonstrated that the researchers have results which indicate that the exposure to ground-borne noise has effects compared to those of airborne noise. This is something that both respondent 4 and respondent 9 mentions. Both respondent 4 and respondent 9 states that more research is needed on how residents are affected by ground-borne noise. Respondent 4 comments that the health risks associated with ground-borne noise possibly are the same as for airborne noise when asked about the health aspects of ground-borne noise. "Yes, that is probably the case. There are no real studies that can prove it, since we need a large sample and not many people live above tunnels." Respondent 9 reasons about this when asked about low-frequency noise. "It has an effect on our sleep and we are more sensitive to that kind of noise. The consequences are probably the same as for other noise[...]." These quotes exemplifies that ground-borne noise probably has the same effect on human health as airborne noise and it is therefore important to continue working with ground-borne noise. As respondent 4 says, there is no data that can be used to verify that ground-borne noise harms people as airborne noise do, but that ground-borne noise has an impact on the quality of sleep is a known fact and the noise criteria exist to protect residents' sleep.

Ground-borne noise affects people's health and knowing that it might be a conflict of interest makes it interesting to analyze if there are specific trends. Some examples of trends that are mentioned are that structures are becoming more complex, which respondent 22 mentions and that the vehicles becomes heavier, which respondent 19 highlights. Respondent 14 claims that there probably isn't a conflict of interest between protecting people from ground-borne noise and expanding the railway network, but the problem must be addressed seriously. Respondent 1 comments on why ground-borne noise must remain as a topic to explore. "We have much more to learn and it takes a long time to gather knowledge about ground-borne noise issues. I would like to have more knowledge about the entire process. The problem is that we are too few who work with these questions and it can be difficult to analyze the outcome of a project."

From these excerpts, ground-borne noise can be viewed as a problem that affects the residents and that are difficult to mitigate. In the future, there might be a challenge with more complex tunnels and heavier trains. Ground-borne noise has a negative impact on the residents and therefore, the question must be in focus. Because of the fact that tunnels are becoming more and more complex and that trains can become heavier, ground-borne noise must be more researched in the future. Together with public health, geology, railway mechanics, construction engineering, environmental engineering and the cultural environment, ground-borne noise is an important aspect. The diversity of fields that the respondents represents indicate that ground-borne noise can be assessed in many ways and that all fields are needed. The methodology is one step towards confronting the ground-borne noise issue. When the methodology was created, many experts were involved and in the future it will be necessary to keep this collaborating environment. Only then can ground-borne noise be assessed. This is almost a requirement for achieving a more practical and reliable infrastructure which is a key part of a sustainable city.

4.7 Summary of the collaborative perspective

The collaborative perspective presented how an engineering methodology, once it has been improved, can be maintained. The results from the interview sessions gives a different perspective than what the previous research had presented. In contrast, the bureaucratic conditions were important for continuously updating the methodology. This thesis confirms that collaboration between Trafikverket and private companies is needed. A reference group was suggested by the respondents. Another similarity from the interview answers is that a planning document is a recommended tool. This document will explain parts of the implemented model, but the risk is that it is strictly followed. At that point, the methodology will no longer represent reality. Therefore, the results must be questioned, even if the methodology has been codified in a document. Another risk is that the methodology stagnates when the reference group is no longer active. By utilizing a reference group, together with a step-by-step user guide, the methodology can be maintained and the risks can be minimized.

This collaboration must continue since ground-borne noise will remain as an issue in the future and more knowledge on the exposure is needed. Still, airborne noise is expected be a greater issue than ground-borne noise. This will however, depend on the traffic capacity and the infrastructure decisions regarding tunnels. When the railway network expands, the focus on ground-borne noise must follow.

4.8 Results from the numerical simulation

This section presents the results from the numerical simulation, i.e. the results from the implemented model. Results from both the location stage and the planning stage will be presented. The focus will however be on the planning stage. The section will introduce the single value results, results in one-third octave bands and the attenuation. Different parameters will be tested and finally a comparison will be made with data from an existing tunnel project.

The implemented model for the location stage

This third part of the results section is the numerical part. Results from the implemented model are compared with results from the EIA and other reports. First, it can be interesting to investigate what the situation will be if standard values for the parameters are chosen. If the track is assumed to be old, the train speed is set to 160 km/h, the loss factor is 0.01, the wave speed is 3000 m/s and the distance from the tunnel to the house is 25 m, then the result becomes as follows for a passenger train:

Table 4.5: Shows the location stage single value results when the distance is 25 m

Old track:LPASmax (uncertainty)	55.7 dB
Old track:LPAFmax (uncertainty)	58.7 dB
Old track:LPASmax	43.3 dB
Old track:LPAFmax	46.3 dB
Old track: Necessary attenuation	26.7 dB
Modern track:LPASmax(uncertainty)	35.7 dB
Modern track: LPAFmax (uncertainty)	38.7 dB
Modern track:LPASmax	25.2 dB
Modern track:LPAFmax	28.2 dB
Modern track: Necessary attenuation	6.7 dB

It can be seen from table 4.5 that the ground-borne noise levels are quite high. It can be questioned if the values really will be as high as approximately 58 dB. The values named as "uncertainty" means that two times the standard deviation has been added to the mean value. These type of values then takes into account the uncertainty by using the confidence interval. For the location stage close to the track, a necessary attenuation of 26.7 dB is needed, which more resembles advanced ground-borne noise measures. In this case, a floating slab track will be needed or similar for ballasted tracks. It is a large difference between the old track and a modern track. The difference is almost 20 dB. By testing another distance, in this case 150 m, it is possible to see how an increased distance will affect the results for the location stage.

Table 4.6: Shows the location stage single value results when the distance is 150 m

Old track:LPASmax (uncertainty)	47.9 dB
Old track: LPAFmax (uncertainty)	50.9 dB
Old track:LPASmax	35.5 dB
Old track:LPAFmax	38.5 dB
Old track: Necessary attenuation	18.9 dB
Modern track:LPASmax (uncertainty)	27.9 dB
Modern track:LPAFmax (uncertainty)	30.9 dB
Modern track:LPASmax	17.5 dB
Modern trackLPAFmax	20.5 dB
Modern track: Necessary attenuation	-1.1 dB

When the distance is increased, different results emerge. From the EIA, the ground-borne noise level was expected to be higher than 30 dBA. This is also demonstrated in table 4.6 for the old track. The most striking result here is that the ground-borne noise levels are about 1 dB below the LAFmax value of 32 dBA when the modern track is chosen. A negative value means that the ground-borne noise level are below the noise criteria by a certain value. From the tables above, it also becomes clear that in this methodology, the relation between the time-weighting SLOW and time-weighting FAST can be expressed as:

$$L_{p,\text{ASmax}} = L_{p,\text{AFmax}} - 3 \tag{29}$$

The location stage is a phase when not much information is available. The calculated required attenuation will be an important tool when an initial description is needed. The planning phase will require more detailed values and this phase must also be studied.

The implemented model for the planning stage

Table 4.7 shows the ground-borne noise level for passenger trains when distance is 25 m. The values are somewhat lower than for the location stage. The required attenuation is then only 5.4 dB, which can be achieved with an under-ballast mat. The values named with "uncertainty" are once again the ground-borne noise level values when two times the standard deviation has been added.

Table 4.7: Shows the planning stage single value results when the distance is 25 m

Old track:LPASmax (uncertainty)	51.2 dB
Old track:LPAFmax (uncertainty)	54.2 dB
Old track:LPASmax	38.8 dB
Old track:LPAFmax	41.8 dB
Old track: Necessary attenuation	22.2 dB
Modern track:LPASmax (uncertainty)	34.4 dB
Modern track:LPAFmax(uncertainty)	37.4 dB
Modern track:LPASmax	23.9 dB
Modern track:LPAFmax	26.9 dB
Modern track: Necessary attenuation	5.4 dB

As for the section above for the location stage, the distance can be increased to 150 m. Table 4.8 shows the ground-borne noise levels for passenger trains. When the old track is in use, the ground-borne noise levels still exceeds the noise criteria. When the modern track is in place, the ground-borne noise levels are 6 dB below the noise criteria. Comparing these two extreme cases: 25 m and 150 m gives information how the tunnel line can be planned. Dwellings close to the track, i.e. 25 m, will experience ground-borne noise levels higher than 32 dBA. If the distance is increased to 150 m, no measures inside the tunnel are needed. In the EIA for the area Lärketorpet, multi-storey buildings will be planned. Varying the distance is not the only parameter that can be changed, the building floor is another.

Table 4.8: Shows the planning stage single value results when the distance is 150 m

Old track:LPASmax(uncertainty)	37.1 dB
Old track:LPAFmax(uncertainty)	40.1 dB
Old track:LPASmax	24.7 dB
Old track:LPAFmax	27.7 dB
Old track: Necessary attenuation	8.1 dB
Modern track:LPASmax(uncertainty)	23.0 dB
Modern track:LPAFmax(uncertainty)	26.0 dB
Modern track:LPASmax	12.6 dB
Modern track:LPAFmax	15.6 dB
Modern track: Necessary attenuation	-6.0 dB

In the implemented model, different building floors can be simulated. As Dashti has stated in her PhD thesis, increasing the building floor results in a reduction of 2 dB. This can be seen in Figure 4.1. This means that a reduction of 2 dB per floor can be added to values for obtaining the ground-borne noise level at other building floors. The worst-case scenario with respect to the ground-borne noise levels is to be found in the basement. In the EIA, building with 2 floors, 4 floors and 6 floors were described. By remembering this change for a building floor and comparing with the results from tables 4.7 and 4.8 it is now time to consider the scenarios. With a distance of 25 m, dwellings with four floors will not exceed the criteria. The lower building floors will also be used as residential rooms, but investigating the effect of building floors is convenient when comparing data with the railway plans. Since tables 4.7 and 4.8 have been based on data from the basement, the results show that the ground-borne noise levels will be even lower for the higher building floors.

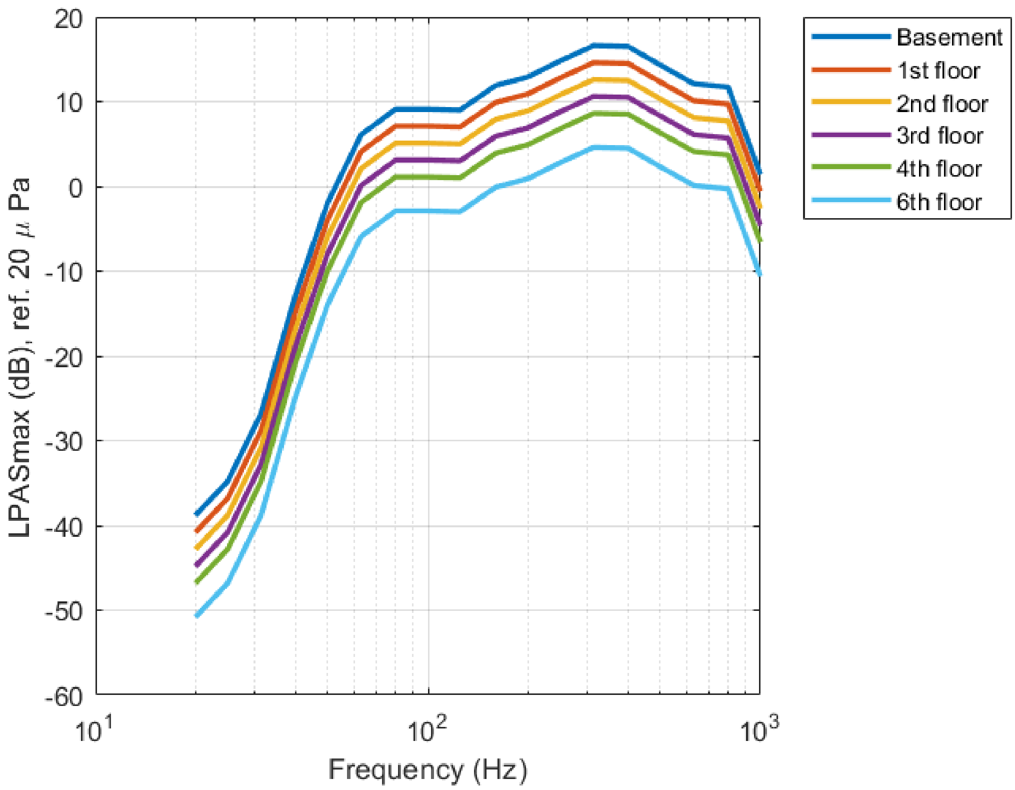

Figure 4.1: Shows the ground-borne noise level for different building floors when the other parameters are kept constant.

Testing different scenarios for the building floors is not the only parameter that can be tested. The parameters related to the rock, such as the damping and the wave speed can also be tested. Figure 4.2 shows how the ground-borne noise level varies for a passenger train, but with different damping and wave speed. It can be seen from the figure that increasing the wave speed from 3000 m/s to 6000 m/s actually gives quite a small contribution. Instead, it is the damping that gives greatest effect. The standard value suggested in the implemented model is 0.01. This is the preferred value, but the value of 0.1 was also tested in this section. For a project manager or similar it is therefore most interesting to chose the damping and the wave speed can remain unchanged. It is probably seldom to have such detailed information on wave speeds. What then becomes relevant is compare the parameters damping, track type and train speed to see what is most important to change.

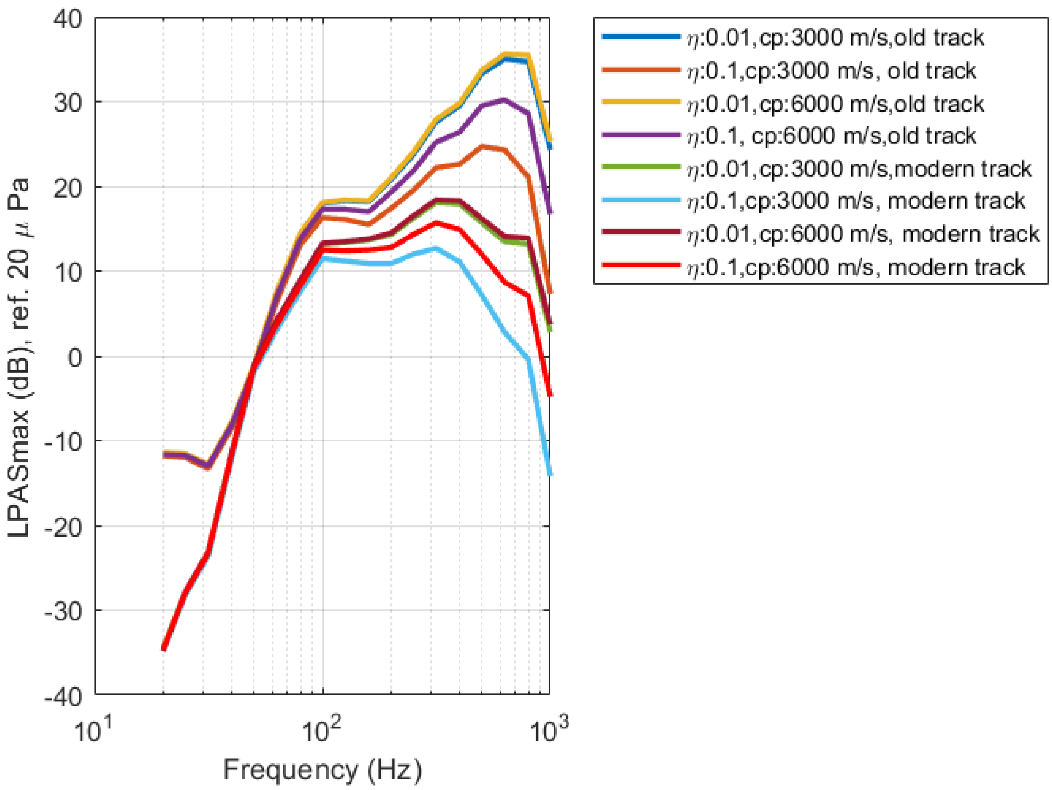

Figure 4.2: Shows the ground-borne noise levels inside a dwelling located at ground level for passenger trains when different parameters are changed.

The variation can be explored in the implemented model and since it is possible to test several options, numerous scenarios can be tested. Figure 4.3 shows the ground-borne noise level for a passenger train with different damping, track types and train speeds. The results show that a damping coefficient of 0.01, an old track and a velocity of 200 km/h gives the highest ground-borne noise levels. Choosing a damping coefficient of 0.1, a modern track and a velocity of 160 km/h gives the lowest ground-borne noise levels. As in Figure 4.2 above, the velocity of the train give quite a minor contribution. It seems that choosing the track is more important than choosing the damping as the ground-borne noise levels seem to be more affected by the track type. The great difference between the track types should be assessed carefully, since the difference might not be that high in reality. At the same time, having knowledge of the track type is perhaps the most important information for a user of the implemented methodology in the future. Table 4.9 shows the numerical values when the parameters related to Figure 4.3 are changed.

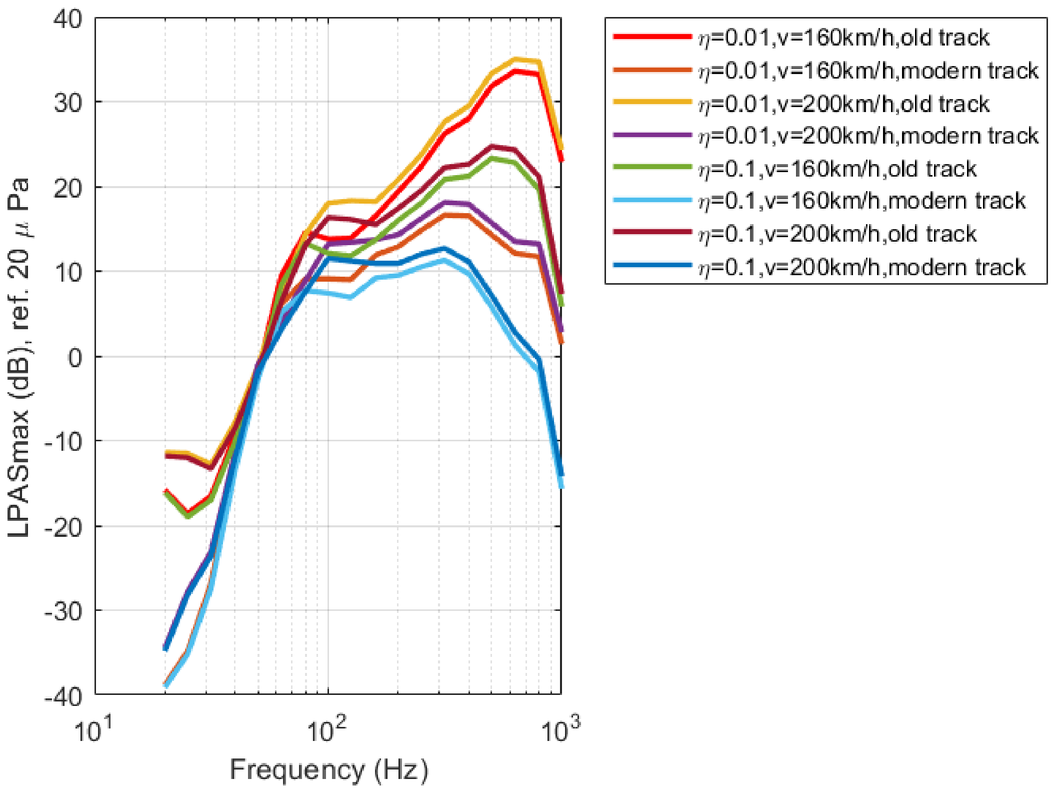

Figure 4.3: Shows the ground-borne noise levels inside a dwelling located at ground level for passenger trains when different parameters are changed.

The table shows the total ground-borne noise level values for passenger trains when several parameters are changed. The distance is 25 m from the dwelling. The uncertainty, the values with two times the standard deviation, is also presented. The value in the parenthesis in this column shows the required attenuation related to the LAFmax value of 32 dBA. Choosing a modern track gives a reduction of about 15 dBA, but again, this difference can be questioned. Increasing the train speed from 160 km/h to 200 km/h gives an increase of about 2 dBA for the LAFmax values and an increase of about 2.5 dBA when the uncertainty is included. However, one last parameter that can be explored is the train type and how the situation is across the frequency range.

Table 4.9: Shows the single max values for the different scenarios. The number in the parenthesis is the required attenuation

Description	LAFmax (dBA)	LAFmax, uncertainty (dBA)
η:0.01,v:160km/h,track:modern	26.9	37.4 (5.4)
η:0.1,v:160km/h,track:modern	21.9	32.4 (0.4)
η : 0.01,v:200km/h,track:modern	28.5	39.8 (7.0)
η:0.1,v:200km/h,track:modern	23.7	34.1 (2.1)
η:0.01,v:160km/h,track:old	41.8	54.2 (22.2)
η:0.1,v:160km/h,track:old	32.7	45.2 (13.2)
η:0.01,v:200km/h, track:old	43.2	52.7 (23.7)
η:0.1,v:200km/h,track:old	34.3	46.7 (14.7)

In the EIA, the track was assumed to be of sufficient quality. This could mean that the track is more modern and a modern track is therefore chosen. Figure 4.4 shows the ground-borne noise levels for a passenger train. The A-weighted levels are once again shown with the time-weighting setting SLOW. The frequency range is 20 Hz–1000 Hz. Including the uncertainty and comparing this to the noise criteria valid at the time when the EIA was published, 30 dBA in SLOW gives an interesting result. The ground-borne noise levels are below the noise criteria, except for the 315 Hz band. That the frequency distribution can be examined creates valid data on what frequencies new measures should target. If a specific measure can be focus on a certain frequency range, then this data can be advantageous for knowing how to combine different measures. It is also relevant to investigate how the situation will be for freight trains.

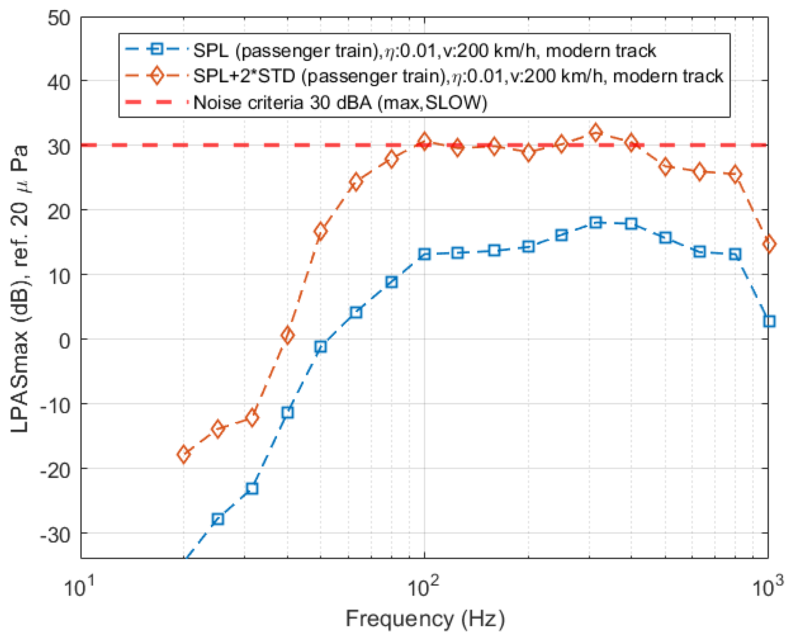

Figure 4.4: Shows the ground-borne noise levels for passenger trains, 25 meters from the track. The values are compared with the noise criteria, valid when the planning document was published.

Figure 4.5 shows the same type of graph, but for freight trains. The train speed is 100 km/h. The uncertainty values are included and can be compared with the noise criteria. Here, the situation is quite different and the ground-borne noise levels for a freight train is considerably higher compared to a passenger train. At approximately 125 Hz, ground-borne noise level values starts to exceed the noise criteria. Utilizing the one-third octave bands gives a great deal of information about what frequencies are important to consider. The contribution from freight trains are considerably higher than for passenger trains and in the planning phase it is necessary to explore the situation for the two train types. The opportunity to use the information from the one-third octave bands means that it is not enough to only include frequencies up to 200 Hz, as it often is in an international context.

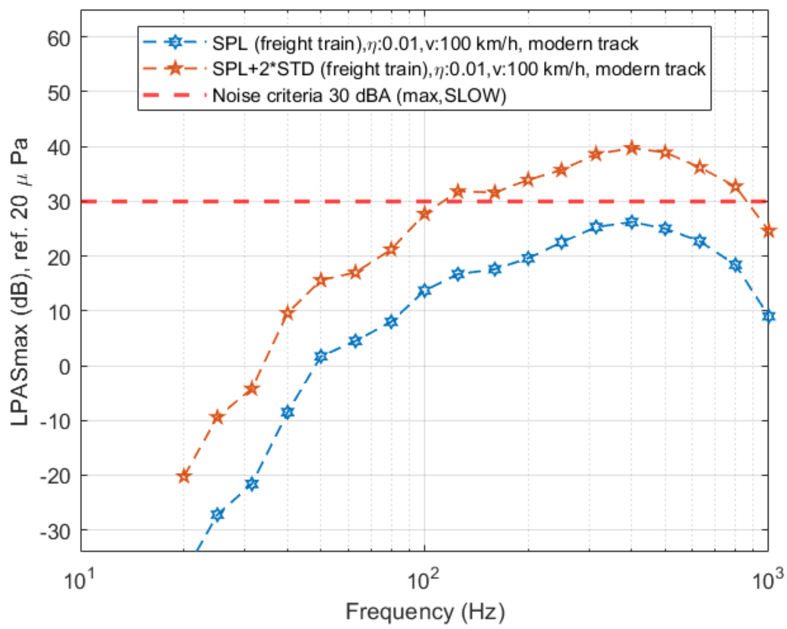

Figure 4.5: Shows the ground-borne noise levels for passenger trains, 25 meters from the track. The values are compared with the noise criteria, valid when the planning document was published.

The passenger trains has only been tested in the tables above. Freight trains must also be considered and in the implemented model it is possible to differentiate between passenger trains and freight trains also for the single values. How the ground-borne noise values varies with distance can be seen in table 4.10. Previous tables presented values based on a distance of 25 m and 150 m. It is of course necessary to include more distances. From the table, it can be seen that for passenger trains, it is enough with a distance of 100 m from the track. Traffic with freight trains require a distance of at least 200 m. It should be noted that this is the worst-case scenario and residents living on higher floors might not experience the same ground-borne noise level values. As an example for freight trains with a damping of 0.01, residents living 50 m from the track will experience 31.5 dBA. In a multi-storey house the residents will experience ground-borne noise values of 27.5 dBA and 23.5 dBA for the second respectively. Buildings with six floors will also be planned which will result in even lower ground-borne noise level values.

The damping will also have an effect which can be seen in the table. The damping parameter will probably not be changed. For a use of the new implemented prediction model, the track type, the train type and the distance is enough for achieving accurate values. The information on the attenuation is beneficial since it is related to the noise criteria in FAST. What sometimes can be confusing is the negative attenuation values, but compared to the LAFmax values, they are comprehensive.

Table 4.10: Shows the single max values for the two train types as the distance from the tunnel increases. The number in the parenthesis is the required attenuation in dBA, related to the noise criteria of 32 dBA

Description	LAFmax (dBA)	LAFmax,uncertainty (dBA)
η : 0.01,passenger, 25 m	28.5	39.0 (7.0)
η : 0.01,passenger, 50 m	24.7	35.2 (3.2)
η : 0.01,passenger, 100 m	20.3	30.8 (-1.2)
η : 0.01,passenger, 200 m	14.9	25.4 (-6.6)
η : 0.1,passenger, 25 m	23.7	34.1 (2.1)
η : 0.1,passenger, 50 m	16.1	26.6 (-5.4)
η : 0.1,passenger, 100 m	6.8	17.3 (-14.7)
η : 0.1,passenger, 200 m	-5.3	5.1 (-26.9)
η : 0.01,freight, 25 m	35.4	49.0 (17.0)
η : 0.01,freight, 50 m	31.5	45.1(13.1)
η : 0.01,freight,100 m	26.8	40.4 (8.4)
η : 0.01,freight, 200 m	20.7	34.4 (2.4)
η : 0.1,freight, 25 m	29.4	43.1 (11.1)
η : 0.1,freight, 50 m	20.4	34.0(2.0)
η : 0.1,freight, 100 m	9.2	22.8 (-9.2)
η : 0.1,freight, 200 m	-4.2	9.4 (-22.6)

In the EIA, the total value of 27 dBA with tine-weighting FAST was introduced. The overall values from the implemented model are in general higher, especially when the uncertainty is considered. The sources of error for the numerical part must however be considered. These were presented in the method section and an important source of error was that the frequency ranges weren't equal. The results can be compared with the table 3.23. The values from table 3.23, found in the EIA are compared directly in table 4.11. Note that only the velocities of 200 km/h have been included because this represents the maximum velocity of a passenger train. Because of the fact that the values from the EIA were presented in SLOW, they had first to be converted to corresponding values in FAST, by using equation 29 above.

Table 4.11: Shows the compared values from the EIA and the values from the implemented methodology. Note that 3 dB were added to the values from the EIA to obtain values with time-weighting setting FAST. The values from the methodology are the values related to the uncertainty

Distance to the house	Value from the EIA	Value from the model
25 m	44.0 dB (LAFmax)	39.0 dB (LAFmax)
50 m	42.0 dB (LAFmax)	35.2 dB (LAFmax)
100 m	36.0 dB (LAFmax)	30.8 dB (LAFmax)
200 m	30.0 dB (LAFmax)	25.4 dB (LAFmax)

When comparing the values, it can be seen that the difference is almost 5 dBA. Despite this difference, the values are comparable which demonstrates that the implemented model can be used as an effective tool. The most important parameters: the train speed, the track type and the train type can be found in an EIA or in a railway plan. Even with this lack of information, retrieving the data is possible and gives values that are only deviating with a difference of 5 dBA.

4.9 Summary of the numerical results

The results from the numerical analysis shows that the track has the biggest impact on the reduction of the ground-borne noise levels. For passenger trains with a velocity of 200 km/h, the dwelling must be located 100 m from the track, otherwise measures are needed. For freight trains with a velocity of 100 km/h, the dwelling must be located approximately 200 m from the track. Freight trains are generally a greater issue than passenger trains. The insertion loss varied from 2 dBA–25 dBA. The ground-borne noise level will however vary with the building floor. A decrease with 2 dBA per building floor is expected which means that the experienced ground-borne noise levels can be lower.

The results in one-third octave bands provided insight into the frequency distribution. For passenger trains with a speed of 200 km/h, the corresponding noise criteria is exceeded at 315 Hz. For freight trains with a speed of 100 km/h, the corresponding noise criteria is exceeded at approximately 125 Hz. When comparing results from the EIA with results from the implemented model, the conclusion is that the values from the EIA are about 5 dBA higher. What makes it difficult to compare the data is that different frequency ranges were used, it is unclear what the assumptions were in the EIA and that measures were already present in the project. For a future user of the implemented model, the information on the track, train speed and train type are the most important aspects. That the difference is merely 5 dBA means that it is possible to use the implemented model with good accuracy.

5 Discussion

This final chapter summarizes and problematizes all perspectives. The results are put in a larger context in a discussion part.

The results in a larger context

To establish and integrate a new prediction methodology requires some important steps as could be understood by reading the transcribed interview answers. The methodology is today an efficient tool for estimating the ground-borne noise levels in three stages. The stages are the localization phase, the planning phase and the construction phase. The respondents state that the methodology is transparent, incorporates the uncertainties, contains a detailed literature review and relies on a detailed processing of the available data. A transparent methodology determines how accurately stakeholders can use the results to put pressure on the planning process and shift focus towards parts that need to be reworked. An example is that transparency makes it possible to compare measures, products and different railway corridors. The challenge is to include data from more tunnels and to investigate what occurs at the coupling between the building and the rock. This gives perspectives on what data should be added. The result section presented guidance on how the methodology can be managed and what risks there are. The most clear explanation as to why a certain methodology is successful is that it is reviewed. Discussing assumptions and new data within a reference group will become an important step towards establishing the methodology. Conferences can support the ongoing discussion and in that way, results from the methodology can be widely recognized. Previous studies have concluded that collaboration is essential. It is only by cooperating that large infrastructure projects can be maintained and yield correct results. The reference group is a part of this perspective, since a reference group that includes experts from different fields can include ideas from the public agencies, the consulting firms and the product developers. A reference group can discuss results, compare results and assist in the development. The use of a reference group is more connected to a cultural perspective.

An opposing perspective is that the work will stagnate, an aspect that previous research projects link to a lack of organizational overview. The interviewed respondents state that it becomes problematic if only one person is responsible for managing the methodology. This expert would then have all the data and be the only one who actually could interpret the methodology. When that specific expert suddenly changes work place, the methodology would also change location, to another company or stakeholder. The advantage mentioned above, with the transparency and the sharing of collective data, would be diminished. For the methodology to remain, the core parts of the methodology cannot be managed by an individual. Even if the data is still processed, measurement results are not discussed. This signifies a short-term risk where data is not connected efficiently in larger infrastructure projects. Reliable data is needed to capture the rock conditions, the train type and the train speed. It is in this case necessary with a plan for how knowledge transfer can be improved. The risk with stagnation is probably less realistic in a reference group because this external group can remain over time. Having a reference group can still have this risk and that is why it must be mentioned. The risk related to the stagnation can only be reduced by introducing a document where the methodology is described. This document does not depend on the participants and will not be affected if one member moves.

Trafikverket's governing documents (TDOK) are regulating the infrastructure procedure. The regulating documents can also have a guiding function and this is now that it is correct to speak of a guide. Interview answers from the respondents contain information which shows that a guiding document often is a reliable tool. This includes, as was analyzed in the result section, both a descriptive and a governing part. The implemented model can be both explained and at the same time enforced. If the methodology would be assimilated in a TDOK or similar, the methodology would be described and enforced. By having a written version of the methodology, it survives between all infrastructure projects. In that way, the interpretation of the methodology is not dependent on a single expert or project manager. A TDOK can make it possible to directly compare the demands with the project results. Apart from utilizing this type of documents, the implemented model can also be explained in a step-by-step user guide. The use of a step-by-step guide is connected to the instrumental perspective. This guide can explain how to use the model, what data is necessary and what the parameters mean. Since most engineers aren't familiar with the new methodology it is helpful with an explaining document. However, another risk becomes visible here. Following a regulating document can create false precautions in a project.

It has also been mentioned in the interview answers that following a guiding document can reduce the efficiency. Simply following a documented procedure has the consequence that the methodology isn't questioned. The methodology must therefore be compared with the reality, which in this case is the measurement results or results from simulations. A methodology that no longer describes reality is not useful. Related to this is an issue that the respondents also emphasize: a methodology must be flexible enough so that it can be changed in every stage. The respondents argued that all parts of a methodology should be open for change. In that way, no parts should be locked or hidden for editing. That the methodology must be depicting the reality and that it must remain flexible can be a contrast to the regulating document because the results are then strictly accepted. This leads to a situation where there are long-term risks that are connected to the development of the methodology, in the form of a too heavy focus on following a predetermined guide. The long-term risk is that there are too large differences between the local measurement results and the results from the methodology. This can in turn make it hard to work with new railway lines when there are differences related to the results. To encourage critical thinking and to continue with the development, local measurements are essential.

From the interview answers, there is no substantial support for developing other noise criteria. Some of the experts point out that it can be appropriate with criteria for other buildings, such as offices. Utilizing a variety of noise criteria are also a tool for building in new areas which are more exposed to ground-borne noise. These areas might not be suitable as sites for residential buildings, but can be a preferable spot for other building types. Introducing objective-specific noise criteria will in that case create better flexibility. On the other hand, having different noise criteria means that buildings can't be upgraded. Since the planning phase in infrastructure projects is characterized by a changing process, it can be an advantage to have the same demands so that the quality is the same regardless of what happens in the process. Other respondents mentioned that developing objective-specific noise criteria is not relevant for ground-borne noise. This type of noise is possible to handle with the current criteria of 32 dBA (max, with time-weighting setting FAST). Developing an objective-specific noise criteria requires time and effort. More research on the exposure in other building types than primarily residential buildings would then be needed. Since tunnel projects involve many phases, where ground-borne noise is just one part, developing objective-specific noise criteria should not have high priority for the moment.

A similar thought process can be seen when studying how the respondents valued the current criteria. Everyone agrees on the fact that the noise criteria is important for protecting people from the harmful effects that ground-borne noise cause. Some respondents mean that the criteria can be too strict and make it difficult to build in new areas. Others say that the value is an acceptable value. From the case studies it became apparent that the same value had been used in infrastructure projects before it became a recommended value. This is interesting because it indicates that after all, infrastructure projects have had the same demands which makes it possible to compare data from tunnel projects in the future. One aspect to discuss further and develop is a noise criteria during the day. This exists for airborne noise and since there is a great deal of train traffic during the day, it would be beneficial with a value for the daytime. The ground-borne noise assessment is dependent both on what the situation is today and what it will be in the future. The traffic capacity vary greatly between the day and the night and so does the type of train. A daytime criteria makes it possible to adjust the loads, the train type and the traffic flow. Because of the fact that the capacity likely will increase in the future, it will be important to investigate how much the ground-borne noise level can be exceeded during the night. However, when the capacity increases, there can be a shift in the traffic flow between different regions and this will affect the ground-borne noise situation. As with objective-specific noise criteria, developing a criteria for the day requires commitment and it can be better to use that planning for other questions. This discussion of criteria is interesting to follow and affects the choice of measures in tunnels, but the scope is more diverted to the management of this new prediction methodology.

The numerical simulation was the final part of the results. The results in this thesis should be reviewed critically since limited information from the project reports were available. More information from the projects are needed in order to fully understand exactly how the information from a tunnel project can be translated into meaningful input for the implemented model. The structure of the track provided the most significant difference. For passenger trains, a distance of 100 m was required in order to not exceed the noise criteria of 32 dBA (max, with time-weighting FAST). For freight trains, a distance of more than 200 m was required. The implemented model gives a hint on when measures are required. That one of the parameters is the train type makes it possible to test scenarios with both passenger trains and freight trains. Information on the ground-borne noise levels and data on the required information are powerful tools that will be necessary when the model is in use. Already in this thesis, data from the model could directly be used and compared with information from an EIA. This demonstrates that the model is ready to be used in a project.

The difference between the values from the project and values from the implemented model were 5 dBA. The difference is still not significant and an interpretation of this is that it is possible to use the methodology despite the fact that the information is limited. The implemented model provides realistic values that are possible to interpret. A project manager with the task of interpreting the values from the implemented model has several tools to choose from. For example, the track type, the train type and the building floor can directly be tested in the implemented version. As was stated in the PhD thesis, data from measurements on site are preferred to adjust the results. With more information, new options can be tested when the project enters new phases.

Ensuring a successful management

The solution to further enhance the methodology can be said to consist of four different parts. The first step is to verify the methodology by using the implemented model in a tunnel project. The second step is to appoint a reference group and the purpose of that reference group is to oversee the development of the methodology. It is vital that the group consists of members with different backgrounds as input is needed from many fields. The members will also have the opportunity to question and compare results. The contribution from that reference group can be presented at a conference, for example BNAM. The third step is to write a guiding document that will be used by project managers to evaluate the ground-borne noise levels in tunnel projects. This will make it more easy to choose the right measures for new tunnel sections. Utilizing an explaining document for the implemented model will make it more clear to understand what input data to enter in a correct manner. The objective is also to increase the understanding and to keep the methodology relevant. The fourth and last step is perhaps the most important one. It includes developing the methodology by adding more data. However, these steps cannot just be followed. The discussion must remain. It is important to continue with measurements and to encourage other approaches. By conducting more measurements, especially measurements for understanding the transmission properties, it will be possible to improve the methodology. Specific transfer functions can be an option here that can provide more information on the transmission. The methodology builds on transfer functions, but the correction factors found in the description might be too general.

The analyzed result that is based on the interview answers together with results from the numerical part gives a holistic view on the research questions. There is a need for more information on the transmission from the rock and into the building. For the implemented model, additional data can be added. The results from the numerical simulation demonstrated that it was possible to use the implemented model despite the fact that little information is available. The implemented model provides results with both time-weighting settings and this makes it possible to compare the result with data from an EIA. Other details can be added to the implemented model and an example of this new data is the contribution from switches.

The theoretical approach in the form of the new prediction methodology can be combined with results from FEM. The FEM analysis is suitable for understanding transmission properties. Measurement data can be added in a FEM model and compared with the simulations. FEM simulations were carried out within the PhD project that led to the new prediction methodology. As was presented in the theory section, the FEM simulations gave more insight into the tunnel shielding effect and the effect of rock formations, but it is not evident how to model this. Unlike steel or wood, rock is a material that is hard to model and the geometries plays a part. Even if the methodology includes the uncertainty, it will be difficult to model rock sections as detailed as other materials. The uncertainty is something that will always remain. Continuing with more measurement campaigns is an everlasting task. Combining the prediction methodology with simulations is required for bridging the gap between the theoretical assumptions and the practical implementation.

A topic in a future study could be to compare results from the implemented model with a recent project, where more data is available. This would decrease the gap between the methodology and the reality. What has become apparent is that the geological conditions play a part. It could be interesting to explore how the methodology works in other geological conditions and how geological conditions can be approached. This would lead to an improved understanding on what parts differ the implemented model from the ones used today. The construction phase could also be studied. This phase has not been described in this thesis, but it contributes to ground-borne noise in a key phase. Conclusions on how to model ground-borne noise that occurs during drilling and blasting are always aspects to consider.

6 Conclusion

This thesis has focused on a new predicion methodology for ground-borne noise. The purpose of this thesis has been to understand how a methodology can be maintained and continuously updated. In order to answer the purpose, several research questions were formulated: What new data should be added to the methodology? What are the risks when managing the methodology? What strategy should be used to ensure a successful management? The method consisted of both a qualitative analysis and a numerical analysis. A literature review was also performed. The qualitative analysis included case studies of railway tunnel projects and interviews with respondents in the field. The results from the case studies demonstrated that under-ballast mats are common options and that assumptions related to the ground foundation differ between projects. In Sweden, the same noise criteria had been used in many projects, verifying the statement that in practice, the criteria were similar.

The interview session demonstrated that information on the coupling is to be added. For the implemented version of the model, rail components, for example switches, can be added. The challenge with the methodology is that it cannot capture all aspects and that more data is needed to understand the transmission. The great deal of data, the detailed literature review, the uncertainty and the transparency are main advantages. The risk is that the officials responsible for managing the methodology changes workplace which makes it stagnate. To ensure a successful management, a reference group must be formed that can discuss the results. Explaining the implemented model in a document is needed and this will assist the project managers in a tunnel project during the decision making process. Still, comparisons between other methods, such as specific transfer functions can be utilized.

The numerical analysis included applying the implemented model on a real-world project. The numerical simulation provided results for both passenger trains and freight trains. Ground-borne noise levels were compared with the noise criteria of 32 dBA (max, with time-weighting setting FAST). The implemented model gave information on when measures are needed depending on the distance. For passenger trains, a distance of 100 m is needed and for freight trains, the same number is more than 200 m. For measures situated closer to the tunnel, measures will be needed as to not exceed the noise criteria. The difference between the EIA and the implemented model was approximately 5 dBA. There are sources of error when comparing results, however the implemented model is a practical and accurate tool.

Future studies could examine how the ground-borne noise methodology is applied in a real-world project. This would give greater insight into what possibilities exist when implementing a methodology. Hopefully, this could give engineers and project managers an even more effective tool for assessing the ground-borne noise situation. The construction stage can be studied. It generates noise levels due to the influence of the blasting procedure or due to the TBM. This thesis has mainly focused on the planning phase and more information on the construction phase would create a better picture of the ground-borne noise levels. Understanding ground-borne noise will become even more important in the future when the railway network will expand, with possibly new tunnels. That is however something that will be revealed in the future.

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Appendix

Interview with respondent 1

Q: What other experts do you need to cooperate with?

A: At the moment, I work with a group that has its main focus on analysis. The unit works with both airborne noise, vibrations and air quality. It's me and a colleague of mine that has his office in Borläne who work with noise related issues. Other colleagues here in Gothenburg can also help with the work related to noise. I also work internationally, together with the organization UIC [The international Union of Railways]. In that work, ground-borne noise is treated as vibrations. Another important task is to oversee standards. The Swedish standard doesn't include ground-borne noise, however the international standards actually include ground-borne noise. In the European standard, the focus is on the building and not on the source.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: I have worked both with the tunnel in Varberg and with The West Link [Västlänken]. I have worked with the overbuild of the central station in Stockholm.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes, absolutely. I have been involved since the start of the project.

Q: What other ground-borne noise prediction methodologies exist and what is the difference between them?

A: The advantage that the model from Chalmers has is that it is adjusted for the Swedish soil conditions. In Norway, they have started to develop a model, but in Finland, they're not quite there yet. There is a cooperation between the Nordic countries and the model is well known in Norway and Finland. Sweden has a lot of data compared to the other countries. In Finland, it is more common to focus on the measures. In Norway, the approach is more similar to the one we have here in Sweden. Many consulting firms have their own models and it can sometimes be hard to know what input data they have used.

Q: What information would be interesting to know more about?

A: It can be how the model functions and also what is happening along the way.

Q: How did you work with ground-borne noise in a typical project?

A: It depends on what type of project I work with, but first an overview is given and this initial analysis is then fine-tuned. When the construction part starts, it is common to compromise between different fields of interest. It can for example be what type of ballast mat that should be used. I have worked a great deal with target values and I rarely become involved during the construction phase. It can be costly to implement measures afterwards and for many projects, it is unsure how effective the measures were.

Q: What information do you hand over to other experts that work with ground-borne noise?

A: We want to know what the results were for a project and not just the result for a single measurement point. I have emphasized that measurements should become a more substantial part of the procedure. This has been implemented in some cases. The problem is that other noise can mask the ground-borne noise.

Q: What is needed in order to work with ground-borne noise related issues?

A: That is more measurements, we are good at implementing measures in the tunnels, but it's unsure exactly how good we are. Why is it important to work with ground-borne noise from a long term perspective?

A: We have much more to learn and it takes a long time to gather knowledge about ground-borne noise issues. I would like to have more knowledge about the entire process. The problem is that we are few who work with these questions and it can be difficult to analyze the outcome of a project.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: It is mostly when we hear about complaints.

Q: What makes it hard to work with ground-borne noise in tunnels?

A: It is always difficult to work with questions that are somewhat unknown. It is only when we work with tunnels that ground-borne noise can become a problem, but it can be hard to grasp what ground-borne noise means. The energies that create ground-borne noise are quite small, but the effect can still be noticed.

Q: How should a new prediction methodology be managed?

A: We [Trafikverket] have much experience in this question, but it can still be a challenge to have an overview. Questions such as who will have access to the software for example or how more input data is used are also things that need to be discussed. It has not been decided what division will have responsibility for this new prediction methodology.

Q: What risks exist when a methodology is managed?

A: One challenge is how a model can be connected with the investment part. For example we have had the possibility to guard a database for ground-borne vibrations. The unit responsible for that database was our planning and health unit and that succeeded because one person and one group were responsible. So, it can depend on the specific person or group. If the group can manage the model, then it is possible to work with it. If the group would be dissolved, then it would become more challenging to work with these questions.

Q: What approach should be used for making it possible to continuously update the new methodology?

A: We have discussed this together with representatives from Norway and Finland. I review the Norwegian standard at the moment and we hope to exchange experience regarding how to work with ground-borne noise more effectively. The management process itself can continue as long as more data is used and then the model will be based on more data. The target value 32 dB [A-weighted with the time-weighting FAST] can be a tough value which many are aware of. However, if a higher target value is used, it can be a problem when measures must be implemented. In the industry, that value was already commonly used even before it became a recommended value. It is important to discuss what the standard contains and what frequency range is used during measurements.

Interview with respondent 2

Q: What other experts do you cooperate with?

A: Geotechnics or people that work with soil and ground reinforcement. I also cooperate with railway experts, especially when ballast is discussed. It is common to work with vibrations even when the task is coming from the geotechnical domain.

Q: What infrastructure projects have you been a part of during the last five years?

A: I have been a part of The Harbour Track [Hamnbanan] in Gothenburg and the new metro line in Stockholm [the yellow line] and there I worked with all kinds of noise. Often, we have to both do measurements and calculations for a scenario in the future. As soon as it is possible to make measurements, that should be prioritized. I have also worked with many detailed development plans. Other projects are the central station in Stockholm and the central station in Gothenburg. It's fun to work with complex projects.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes, I am familiar with it and I have reviewed the PhD thesis in some stages.

Q: What other prediction methodologies exist?

A: It depends on what stage the project has entered. The model that we have at my workplace is semi-empiric that is more used to get an overview of how many dwellings will be affected by ground-borne noise. The model HS2 comes from England. Another model is FRA [Federal railroad association] which comes from a public institution in the US. Findwave is a model that is a detailed numerical software. A calculation model or software is really reliable first when verified to measurements.

Q: What additional data is required in order to work with ground-borne noise?

A: During the localization phase of a tunnel, information on the ground type, train type, train speed and distances and type of building are most important. As the project enters the next phase, more details are needed such as information on railway sleepers. The train type, train speed and railway type also play a part together with more details like track type (eg. railway sleepers etc) and building layout. Most important is also perhaps the geometry and distance to the track. What we need to calculate and what we need to protect is important.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: There is no exact procedure. In some projects, it is more important to evaluate the results. It is always interesting to come back to the project and this is also something that the suppliers would like to know more about. It can for example be how effective some ballast mats are. All projects are unique, however if a project is evaluated, that will put more pressure on the team to perform better.

Q: What risks exist when a methodology is managed?

A: That it is used in the wrong context. To use a model that isn't fully adapted to situations with trains in tunnels could be a problem.

Q: How should a new prediction methodology be managed?

A: It is important to know what limitations the model has if the conditions change. Local adaptations, such as switches can have an impact on the noise propagation. It would be beneficial with a document from Trafikverket, for example a guideline. Everything doesn't have to be included in the guideline, but a guideline can be good as a tool. The goal is maybe to have more clear target values, almost like the ones that exist for airborne noise. It also depends who will interpret the documents and if that might require extra knowledge.

Q: What do you think about the target value of 32 dBA with time-weighting setting FAST?

A: It is a reasonable value for dwellings considering sleep annoyance. They conducted sleep experiments at Sahlgrenska and then 35 dB with time weighting setting fast became the absolute threshold. It can be different for offices and in that case Boverkets's Building Regulations can be helpful. On the other hand, it can be hard to know what values are valid for specific scenarios. An example can be that offices are being planned where there will be a railway. Then, the target value can be an obstacle. The risk is that measures can be needed after the building has been constructed and then it becomes difficult. One solution could be to use a margin of let's say 5 dB. The source strength is best to know and also the variations of the track, but you never have all the information. The reason as to why 32 dB is used is partly because the ground-borne is of a low frequency character and the inability for the residents to localize the source increases the annoyance.

Interview with respondent 3

Q: What other experts do you need to cooperate with?

A: During the past year, I have been working with the project at Lindholmen. There, I work with many different experts, from geotechnics, environmental questions to almost every other technical field. The construction part in a project is the biggest challenge for an urban area. I also need to gather information from the contractors. We must ensure that there is space for the measures and that consider the future apartments and houses above the tunnel.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: I have worked with Västlänken [The West Link], the railway line between Göteborg-Borås, the railway line in Linköping and I have supervised the project at Ostlänken [The East Link]. I have been an administrator for the city tunnel and I have been little involved in the Stockholm City Line.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes, I have studied that methodology.

Q: Does the methodology have any pros or cons?

A: The model is transparent and I hope that this will lead to a more uniform working process. It is unclear how source data is processed. Something that needs to be developed is how measures are incorporated into the model. For example, for airborne noise the measures can be adjusted and implemented directly into the model. Today, we either work with demands that a specific company has or demands that are suggested for certain spaces. We are not always certain what properties a measure has and this can be investigated further. The measures in Sweden are more effective since the geological landscape is characterized by crystalline rocks compared to for example Denmark which is characterized by weaker rock types.

Q: What other prediction methodologies exist and what is the difference between them?

A: HS2 is one of those methodologies, which we have adapted to loose soils, but we haven't used it since it more useful for weaker rock such as sandstone.

Q: What is needed in order to work with ground-borne noise related issues?

A: The source strength is the most important one. However, local differences will always be present when constructing a railway line. For Sweden, I don't believe that the differences will vary that much as we have almost the same geology everywhere. Still, the geology will have an impact and it is important to know the geological conditions. When we work with Environmental impact assessments, we follow a standard that tells us what measures are appropriate. For a new methodology to be introduced, it can be beneficial to explain how measures can be included and what limits there are. The mass of the vehicle and the source strength can differ depending on the context, so it is important to see if the methodology is complete. The local variations are then important? Yes! For example, different train types are used for the metro in Stockholm compared to here in Göteborg. The conditions for the rail is widely different which effect the sound radiation.

Q: Does conflict of interests exist?

A: The decision to use a specific measure is based on the result from a prediction methodology. In the context of railway lines, many consultants have taken the initiative to develop methodologies and to make comparisons with international methodologies. The problem is when measurements are made at a local spot which differs from the results from the methodologies. The results from the measurements might even be lower than the target value. Then, there is no safety margin and the result is based on a few measurements. Another problem is when information from measurements and projects are archived and not really used.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: If the railway line is already in operation, it can be hard to implement measures. Measures can also be expensive. If we reach precisely below the target value, it's good. If we are too good at mitigating ground-borne noise, then we have a project that is overdimensional. It can be beneficial to have a project that is overdimensioned if the background noise level is problematic. Some more sensitive environments, for example laboratories, require that we have an overdimensioned project. A new project needs a great deal of information. In Findwave, we have a source model where the mass of the train, the rail type and the source strength is added. The source strength can radiate from the tunnel wall or it can be modeled by observing what happens at the rail. It is difficult to have all the details about the train. For this new methodology, we must understand where the model ends. So, is it necessary to adjust the methodology according to local differences? Yes, that is how I view it. An example is that we have many rail types and this is also a question of transparency, depending on what data is enabled.

Q: What risks exist when a methodology is managed?

A: To think about how the methodology can be continuously developed is a key point. One problem is to use conventional methods for new problems. An example is when solutions for bridges are used for tunnels. It is an advantage with a responsible stakeholder that can guarantee quality. Should it be a person or a group that is responsible for managing the methodology?

A: One risk is when the person who is responsible for managing the methodology moves. I think that the environmental aspects must be emphasized because the environmental demands will become integrated in the methodology. One risk is if we have a situation with monopoly. It must be possible to add new measures. For road traffic noise, we have a list that can be used to add a measure.

Q: How should a new prediction methodology be managed?

A: It requires that someone, for example Trafikverket, manages the methodology. It also needs to be transparent and easy to understand. A more advanced methodology will provide more detailed results, but can be difficult to understand. More precise measurements can be conducted at the project site if needed. So, the methodology will give a first hint of the result?

A: Yes, it is possible to decide what safety margin that should be used. It will be vital to know if more measurements are needed or if the result that the methodology gives is enough information.

Q: What is your opinion on the target value 32 dBA, maximum value with time-weighting FAST?

A: It can maybe sometimes be a bit too hard. High demands lead to good quality, but we must discuss when the health aspects become relevant. The health aspects are relevant when we have reached a decent level that can be tolerated. Measures are always compared with the costs. A high target value is good for ensuring that as few people as possible will experience annoyance. It can be a difficult task to find out how many people are annoyed by ground-borne noise because of the character of the noise. More people are normally annoyed by airborne noise.

Interview with respondent 4

Q: What other experts do you need to cooperate with?

A: It is mostly statisticians and medical doctors. In the clinical work I cooperate with health staff, for example people who work with radiation or with contaminated soil.

Q: What projects have you been a part of recently?

A: I have been involved in the project called "Soundscape for improved health" [Ljudlandskap för bättre hälsa] and now I am a part of a project called Scapis where we follow 30.000 participants.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I know it very well. I was not involved when the project started, but I have revised and I was an opponent when the thesis was presented. Earlier, I have worked together with Trafikverket in a project about ground vibrations, so I know what challenges exist when calculating pressure waves in soils.

Q: What pros and cons does the methodology have?

A: It is transparent and completely developed. It is also transparent with the uncertainties.

The challenge is that the reality is always more complex and it can be a difficult task to capture all the aspects in one methodology.

Q: What is the most important finding in your study on ground-borne noise and sleep disturbances?

A: The most important result is that the low frequency components aren't vital for the quality of our sleep. We know that the low frequency components are causing more annoyance than what can be expected by only looking at the A-weighted levels. Even if our result demonstrated the opposite, the low frequency components can still contribute to the sleep initiation process.

Q: What is your opinion on the target value 32 dBA (max, with time-weighting FAST)?

A: It protects from too dangerous effects on human health. Sometimes it can be exceeded without people noticing, but it provides good sleep conditions if it is followed.

Q: Should ground-borne noise be more researched?

A: Of course, more research is always needed. However, ground-borne noise doesn't affect that many residents. From a public health perspective, it will not have a huge impact. It is interesting to understand exactly how ground-borne noise effects our health. There is still much to learn.

Q: Is the health perspective a substantial aspect when investigating ground-borne noise related issues?

A: The agencies want to limit the exposure in living environments, but the amount of people that are really affected by ground-borne noise is probably quite small.

Q:Are ground-borne noise and airborne noise having the same consequences on human health?

A: Yes, that is probably the case. There are no real studies that can prove it, since we need a large sample and not many people live above tunnels. More people are effected by airborne noise, so that is easy to test. In the end, I think that it is the same mechanisms behind ground-borne noise and airborne noise.

Q: How can it be interpreted that the value can be exceeded 5 times per night?

A: In the lab we make sure that all trains generate the same level and we want the environment in the lab to resemble reality. In the real world differences exist between every train passage. The challenge is to interpret what the exposure means outside the lab environment.

Q: What do you look for in the Scapis project?

A: We want to examine effects on human well being, sleep and recovery. If a larger population sample is used, then we can actually notice effects on the cardiovascular system. Noise results in cardiovascular diseases, for example high blood pressure and heart attacks. Living in a noisy environment with much traffic noise is harmful. We expect that approximately 1000 heart attacks every year are because of this exposure. We have reasons to believe that the same number is valid for strokes. There are of course many other factors that create this situation and not only the exposure itself. This exposure probably results in a higher risk of developing diabetes and depression. All participants on the Scapis project have been interviewed and they have been tested in many ways. We also include their living environment and the noise situation close to where they live. From other studies we know that exposure to noise has a negative impact on human health, but we do not know exactly how this works. We hope to discover some early warning signs of this exposure.

Q: What is a long term exposure?

A: It is hard to give an exact number, but we usually say that after 10 years of exposure there is a higher risk of developing cardiovascular diseases.

Q: Why is it hard to introduce measures and measures can be used?

A: Measures are often expensive and examples are under-sleeper pads [UPS] or elastic rail pads. There is a discussion on the cost and this must be compared with the consequences on public health. We that study the health aspects of ground-borne noise and noise in general, are not involved when measures are discussed.

Q: Is it possible to distinguish between ground-borne noise and vibrations?

A: Ground-borne noise has been more researched than ground vibrations. In the lab, the participants can tell the difference between ground-borne noise and vibrations. Sometimes people who are exposed to low-frequency noise can misinterpret that as vibrations and they can describe that their chest is "vibrating", but what they actually mean is that the floor is vibrating.

Q: Is it clear in the lab that people are sensitive in different ways?

A: That is very clear because some participants sleep well and others don't. Some people sleep badly even if there is no exposure. This makes everything more complex and we always let people sleep at home to have something to compare with. The individual differences can be large and that is why we compare individuals. In the greater Scapis study, we use a larger sample, so those results will be more representative.

Q: How many people can visit the lab at the same time?

A: We have three beds in the lab and in a typical study we have 50 participants and they sleep maybe 4–5 nights in our lab. Have similar studies been conducted in other countries? Yes, in almost all countries they have the same type of lab, but it is most common in the Western world. Some countries create a test situation at the participant's home. What is unique in our case is that apart from ground-borne noise can simulate vibrations.

Q: Is it possible to adjust to a noisy living environment that is characterized by ground-borne noise?

A: To some extent, yes it is possible. The health effect will not disappear, but people can compensate for bad sleep. It is when the sleep becomes fragmented that the risk starts to increase. How often the sleep disturbance occurs is of as much importance as the level of the noise.

Q:Does this effect the possibility of falling asleep? Either that or that we don't get enough deep sleep. These mechanisms are not fullt understood and it is possible that the compensation for a bad night's sleep can reduce the negative effect.

Q: How well-known is the new methodology for ground-borne noise?

A: I don't have that many contacts outside of my field related to this methodology, but

I think that it isn't that well-known. Among consultants it might be more widespread. Trafikverket has an important role here to inform other stakeholders on the new methodology. Many consultants would probably like to know how the methodology works and then the uncertainties that it has is an aspect to consider.

Q: What other data is needed?

A: More things could surely be added, but for now I think that the methodology contains the important aspects.

Q: How should the new prediction methodology be managed?

A: That is not really within my main field of expertise, but one way would be to include it in an international standard. If that would happen, then the methodology would be more easily integrated into the environmental impact assessments. This will of course take time. In that case a committée will handle the development, but the members still need to finance everything. A public stakeholder is probably the best choice and the issue is who to contact if there are questions on how it works.

Q: What risks exist when a new methodology is managed?

A: That is if it's unclear who is responsible because then the methodology will be forgotten. Should a group, a division or a person be responsible? It should not be a person. Usually it is a division or a group that is responsible. A key point here is trust, a methodology that is sold will directly lose credibility.

Q: Are people in Sweden more exposed to ground-borne noise compared to populations in the other Nordic countries?

A: I'm unsure, but Norway has many tunnels, so ground-borne noise is a problem there. A tunnel in a city will lead to more ground-borne noise and the soil properties play a part in this context.

Q: Is there a conflict between expanding the railway network and protecting residents from ground-borne noise exposure?

A: It is a complex question, but initially we want the city planners to be able to foresee the consequences of new decisions. Every option requires a risk assessment and here the target value is very useful. In other cases, for example when building a vibration sensitive building, then the conditions are different.

Q:In Finland the target value of 35 dBA (max, with time-weighting SLOW) is used.

A: Yes and there are differences between the standards and between the soil conditions. Many approaches exist at the same time.

Q: How good are the health staff at interpreting acoustical definitions?

A: Generally speaking, health staff have a great deal of knowledge in our field despite the fact that they aren't engineers. They know that the human body is complex and this is a perspective that they have in mind when discussing noise exposure. However, the dB concept can create confusion from time to time.

Q: How does psychoacoustics impact your field of research?

A: Frequency modulation impacts the study, but at the same time we don't know how modulation and sleep disturbances correlate. Another similar question is that we can adapt and learn to handle ground-borne noise in our living environment. How does masking impact your study? Masking can definitely have an impact, but people will be affected by ground-borne noise even if they can't perceive a train passage.

Q: In the lab do you consider the urban environment, for example that people are used to noise since they live in large cities?

A: We assume that after some nights in the lab, all participants will have the same conditions. Differences depending on where the participants live and how much traffic there is will hopefully not effect the results. In the ideal case, we don't want people to be too exposed to ground-borne noise before they enter the lab.

Q: Will problems related to ground-borne noise be a greater problem in the future?

A: It can lead to increased costs in construction projects, but I don't think that there will be a huge issue with ground-borne noise.

Interview with respondent 5

Q: What kind of infrastructure projects have you worked with during the last five years?

A: I have worked with the central station in Halmstad and there my responsibility was airborne and structure-borne sound. I have worked with detailed development plans and with The West Link [Västlänken], but at that time more with noise during the construction.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes and I was a part of the reference group.

Q: What pros and cons does the methodology have?

A: Well, the initiative to create such a methodology was good because we all get the same overview with a consistent methodology. There are some differences between how the calculations are done where I work, but in the end we get near and close to same result. An advantage is that we use the same source strength, but now we need the same approach with respect to the calculation part. The details become different when we don't have the same calculation procedure. The source strength and the distance correction term are more clear to interpret, but the interesting thing is what happens along the way, from the rock to the building. The source strength and the distance correction can be calculated using known formulas. In reality, it is of course much more complicated depending on the rock formations on other properties. Here we can have many cases, depending on if we have sand, stone, or more loose rock formations. The geology can attenuate or increase the results. It is therefore not always conservative to assume 0 dB. In order to work more effectively with detailed development plans, we must use one-third octave bands. Only then is it possible to adapt to the situation and plan measures at an early stage. The coupling at the foundation is important.

Q: So, the aspects to consider are the coupling between the rock, the foundation, the floor and the room?

A: Yes, we need more research here. The new methodology is appropriate in the initial phase when the railway is planned and it is good that the methodology differentiates between passenger trains and freight trains.

Q: What other data is needed?

A: That is more information on the coupling between the rock and the building as I see it.

Q: What other methodologies exist and what is the difference between them?

A: In our case, we don't use Findwave. We have our own methodology that is similar to the new one and we are very transparent with how we work and what data we use. International standards are very helpful and we use them in our working process.

Q: Do you have a special organization in your division?

A:We are not so many that work with ground-borne noise. We consider the circumstances, for example if we have different building types. We make judgments based on the source strength and what the distance to the houses are. At my work place we have technical areas of expertise that we have further divided. Every technical area of expertise has its own agenda, data and procedure so that all knowledge is preserved. The group that works with building acoustics can have a different procedure since their division is larger. The fact that we are a small group of people can be an advantage, but is not uncommon that people switch positions. Knowledge can disappear when people move, but information can always be recorded. Trafikverket could have a knowledge base.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: If we don't get any feedback, then the project is not followed up. In projects, it is common to have a conservative approach because it is so hard to change things afterwards. That the noise criteria can be exceeded 5 times per night for single passages means that the approach doesn't need to be too conservative.

Q: What risks exist when a new methodology is managed?

A: You must analyze both what happens at the source and along the track. I see no actual risks, but all calculations must be reviewed. One challenge is that changes in the methodology from an earlier project remains and influences another project. To change one parameter and suddenly the methodology shows a 20 dB difference without anyone noticing could be a risk.

Q: How can that be avoided?

A: Data on the source and information on common measures could Trafikverket provide so that all stakeholders have the same choices and possibilities. More measurements can be carried out by the consultancy firms. Trafikverket can also be responsible for updating the methodology, so that we can work more with the measures. It is hard to initiate measurements once the project has finished and measurements give a hint on where to start. New tunnel projects enable us to measure more.

Q: What strategy should be used in order to be able to continuously update the methodology?

A: Focus should be on how we work with one-third octave bands. The problem is that every location is unique and that is extra important for ground vibrations. For ground-borne noise, it is the foundation that matters the most. In a long-term perspective measures on the track are better since measures are expensive. One idea is that it is possible to customize the track in the methodology or to choose measures. More source data might also be needed. Every infrastructure project is complex and all problems must be simplified. For a single building which is constructed when the track is already in place, details are more important. When planning a new track it is not possible to look for the details.

Q: Should site-specific target values be developed?

A: In some projects, we work with site-specific target values, but not in all projects. As soon as we are below 50Hz–100 Hz, then it becomes difficult to measure and then target values can be hard to implement.

Q:For airborne noise we have more regulations, should we be as precise for ground-borne noise?

A: We don't differentiate between different rooms, the target value is based on the room used for sleep. For schools it can be worth reflecting on if another value is needed. Another aspect is if new target values are needed for different building types. For pure vibrations a target value can also be discussed. The target value that we have nowadays is a good target value and we now have technical reports to use as references. There is no target value during daytime which can be discussed.

Q:Should ground-borne noise get more attention?

A:Much is already done, especially for pure vibrations. There are studies on how many people are annoyed. They recently changed some standards which creates a problem when it comes to how we assess if people will be annoyed by vibrations. A target value enables us to put pressure on the builders to do everything correct.

Q: What is your opinion on the target value of 32 dBA (max value, with time-weighting FAST)?

A: We have had 32 dBA for a long time. A challenge is that we use A-weighting for a low-frequency problem. In the end, the public health perspective must be deciding what decisions we make.

Q: How do you interpret that the target value can be exceeded 5 times per night?

A: The target value is based on sleep disturbances. To have 32 dBA is not a too strict value and other building types are not included. An example is to review the TDOK [Trafikverket's governing documents].

Interview with respondent 6

Q: What other experts do you need to cooperate with?

A: It is the tunnel workers, the construction companies and the suppliers of products related to ground-borne noise.

Q: What kind of infrastructure projects have you been working with during the past five years?

A: The tunnel in Varberg, The West Link [Västlänken] and Getingmidjan.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes, I initiated the project. I was responsible for the measurements that the methodology has used.

Q: What pros and cons does the methodology have?

A: It's good that the methodology is transparent and has a more clear structure. The idea with the source strength and the correction factors. It's an advantage that real data from different tunnel projects has been implemented in the methodology. However, I haven't applied the methodology in a project that I have been a part of.

Q: What other methodologies exist?

A: For one project that I was involved in, we used data that we gathered in Excel. That methodology doesn't really give much information on the correction factors. Therefore, there is a risk that the solution becomes under-engineered or over-engineered. I have used methodologies that have been developed by other consultants. The result [in dB] is almost the same. The problem is that every location is unique and that creates local conditions for every project.

Q: What is needed in order to work with ground-borne noise related issues?

A: How the building is connected to the bedrock and the coupling through the foundation are the most important aspects.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: Usually, it is only when a problem occurs that measures are evaluated. There are some exceptions where extra measurements have been arranged without there being an initial problem.

Q: What actions are important when working with ground-borne noise?

A: First, the source strength must be measured together with the coupling factors and the effect of the damping. When working as a consultant, we administer the knowledge from projects and that can explain why safety margins have such a big impact. One thing that makes the process more efficient is if the contractor has an experienced project manager.

Q: What makes it hard to work with ground-borne noise in tunnels?

A: Ground-borne noise has been more discussed recently and it is good that measurements are continuously made so that the level of knowledge can increase.

Q: Do conflicts of interest exist, for example between ground-borne noise and geotechnics?

A: No, I would not say that it is a problem.

Q: How should a new prediction methodology be managed?

A: From the consultant, it requires commitment, perseverance and a willingness to be prepared to change opinion. It's all about communicating and to look at the costs in a project. It is also important to have knowledge about the measurement procedures. One problem is that there are so many different methodologies for ground-borne noise,and that was partly why I initiated a project to develop a new methodology. What is needed is a consistent procedure. This can be compared with airborne noise, where many guidelines exist. For airborne noise, the level of knowledge is greater. One reason why more regulations exist for airborne noise is because we have more problems with airborne noise. I think that Trafikverket should manage the methodology. One idea is that a reference group works with the methodology which will keep it relevant. A tunnel project has a big impact on the local infrastructure and the same noise criteria should be used nationally. In Norway, a new standard is being developed and they want to take part of transfer functions. Q: Should object specific noise criteria be developed?

A: Yes, it is always necessary to see if the noise criteria can be evaluated.

Q: What is your opinion on the noise criteria of 32 dBA (max value, with time-weighting FAST)?

A: I think that it doesn't matter so much if the time weighting slow or fast is used, eg. 32 Smax or 35 Fmax. The character of the ground-borne noise makes the choice of time weighting not so important. In Sweden, I believe that there are reasons to keep the noise criteria at 32 dBA or to lower it. For sleep disturbances, ground-borne noise becomes an issue. Keeping the noise criteria at 32 dBA or lower is to protect residents even if the situation can be different for schools.

Q: How do you interpret that the noise criteria can be exceeded 5 times per night?

A: Researchers have concluded that sleep disturbances begin already at the noise criteria. It is accepted that the value can be exceeded 5 times per night. However, this is more a question for a public health expert.

Q: What order of priority should exist when managing a new methodology?

A: The group needs to create a structure on how the tasks are handled and who is responsible. It is best if the people involved remain as the strategy is formed. An external stakeholder, such as a person from a consultancy firm or from academia might not be suitable to manage the methodology.

Q: Will problems related to ground-borne noise become a greater issue in the future and how should the prediction methodology be managed in the future?

A: Yes, if more railway tunnels are planned next to new dwellings, it will be a problem. In the future, the management of the methodology can be revised by a reference group that reviews the work as the information becomes available. For example, a consultant can review the relevant data in a report. For the methodology to be managed as efficiently as possible, each consultant can summarize details from their current project in a document. For this to function, there should exist a uniform template for reporting project details on ground-borne noise.

Interview with respondent 7

Q: What other experts do you need to work with?

A: In tunnel projects, I work with rail managers, project managers, geotechnicians and with the Swedish Environmental Protection Agency. Sometimes I need to inform other stakeholders, such as the County Administrative Board, on what ground-borne noise actually is and what it means. Collaboration is important and for example when I work with rail managers because the measures for ground-borne noise are fastened under the rail.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: During the past five years I have been involved in The East Link [Ostlänken] and in The Bergslagen Line [Bergslagsbanan. The sections that I have been involved in, didn't have a tunnel. When we speak of tunnel projects, then I have been a part of The City Tunnel [Citytunneln], the tunnel in Varberg and in The Southern Main Line [Södra stambanan]. I have also worked with minor tunnel projects.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I was involved at an early phase and I was asked to contribute with my findings from measurements. Before this model was developed, every consultancy firm had their own model.

Q: What pros and cons does the methodology have?

A: I have not studied the methodology that much, so it is hard for me to say something about the pros and cons.

Q: What other ground-borne noise prediction methodologies exist?

A: HS2 and Findwave are two examples. Handbooks can also be helpful.

Q: What is needed in order to work with ground-borne noise related issues?

A: The geological information is vital at an early stage together with detailed digital information on the rock types. From that information it is possible to determine the next step. In one project, we could actually take advantage of the density of the rock in order to understand the propagation properties of the vibrations.

Q: Why is ground-borne noise important to investigate?

A: Ground-borne noise has not been researched as much as airborne noise. It is only when we have a tunnel project that ground-borne noise is investigated. For surface lines, the ground-borne noise is often masked by the airborne noise. It is also only the tunnel projects that are associated with a noise criteria.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: The product is often in focus, for example that we want to know how good a certain measure actually was. I have worked a lot with LVT [Low Vibration Track] products that can be replaced quite quickly. This means that it is possible to repair a part of the track during the night and the whole line doesn't have to be closed for too long. Before the tunnel opened we measured the vibrations in basements and then from that data we calculated the ground-borne noise in the apartment. There will never be a construction project where you can't measure the effect. The maintenance of the track is very important. It is good to start with a methodology and then try to measure the coupling effects. Perhaps measures can be incorporated in the new methodology that Chalmers has developed.

Q: What risks exist when a new prediction methodology is managed?

A: I think a critical point is to not have an ambassador or someone who is responsible. For airborne noise there is a center of competence and that we do not have for ground-borne noise. A reference group can also be a good idea.

Q:You mean a reference group where people have different backgrounds?

A:I think a group with consultants, academics and other backgrounds is essential.

Q: How should a new prediction methodology be managed?

A: Most important with a new methodology is that we get the same results when we repeat the measurement. To maintain a new methodology is to understand what works, but at the same time continue to address the challenges that every methodology has. This is not only true for new methodologies, but applies to all kinds of methodologies. I can only see benefits if consultants use the same methodology, then the variation of the results will decrease. Where I work we have technical areas of expertise and we cooperate together and that is required when we work with both the construction phase and the post-construction phase. The Nordic Council of Ministers has a reference group and a similar reference group can be developed. I know that they previously have had a focus on acoustics and vibrations. Consultants should be a part of this group because they have experience from numerous tunnel projects where they have been involved. Another idea is to arrange workshops, where people can meet and discuss results.

Q: What is your opinion on the noise criteria of 32 dBA (max value with time-weighting FAST)

A: I think it is a safe and secure value, but as always, target values tend to be revised at some point.

Interview with respondent 8

Q: What other experts do you need to cooperate with?

A: We cooperate with other experts within the field of environmental health. We have an environmental management system and we work together as we develop a new document.

Q: What larger projects have you been part of?

A: I have been involved in The West Link [Västlänken] at one stage, but not so much. When the noise criteria was discussed, then I was involved and one task I had was to investigate customs.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes, I have heard of it. However, I'm not so familiar with the details.

Q: What is needed in order to work with ground-borne noise related issues?

A: Documentation on expected sleep disturbances are important and the next step is to compare the health aspect with the economic cost.

Q: When will ground-borne noise become a problem?

A: We have defined a noise criteria and it is permitted to exceed this value five times per night. One thing to keep in mind is that this criteria only is used for new construction. It is when a new building is constructed that the noise criteria becomes relevant.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: It is not common to do measurements to confirm what the ground-borne noise level actually is, but for some projects we could follow up the results. These projects were The Stockholm City Line [The Stockholm City Line] and The City Tunnel [The tunnel in Malmö].

Q: What risks exist when a new methodology is managed?

A: It's a bit hard for me to answer that, but I think that it is important that the engineers that will use it can accept the methodology. That's why it must be tested, even if that process takes time.

Q: So, is it important that the methodology has legitimacy?

A: Yes, that is how I view it.

Q: How should a new prediction methodology be managed?

A: First, it's important to test the methodology to see how accurate it is. It could be included in guidelines and technical documents. It must also be present in the investment documents. Another possibility is to include it in the procurement documentation or to implement it in other agencies. Apart from The Swedish Environmental Code there are other documents that regulate the planning and building of new railways. Managing a methodology is not easy. We have an obligation to protect people and this is the most important aspect. The legal process is very important and an example is the use of consultations which makes the process democratic.

Q: Should object specific noise criteria be developed?

A: Object specific noise criteria has not been investigated further. There exists no comprehensive guideline for other building types. Sometimes it can be too difficult to work with specific noise criterias. The noise criteria for ground-borne noise is only used in dwellings where residents sleep. It is possible to investigate if this criteria should be in use during daytime, especially when there is increased traffic. It could be important to investigate if object specific noise criteria is needed.

Q: What is your opinion on the noise criteria 32 dBA (max, time-weighting FAST)?

A: It is value where we have applied the precautionary principle. This value ensures that people's health is protected.

Q: What other information or data is needed in general?

A: More data on how people are affected by ground-borne noise would be beneficial. For airborne noise, more studies exist and there are more data on disturbances. Ground-borne noise is a small issue, not that many are exposed to ground-borne noise. Measurements require much time and we often have insufficient data to make larger health estimates. I think that this noise criteria we have for ground-borne noise is a safe value, it is perhaps the airborne noise criterias that are to be investigated further, they might need to be more strict.

Q: Is there a conflict between expanding the railway network and to protect people's health?

A: We will know more about that when we actually can compare the consequences, but dwellings above railway lines should be avoided.

Q: Other noise criteria is used in the Nordic countries, why was 32 dBA (max, time-weighting FAST) chosen?

A: When the noise criteria was developed, we conducted measurements and used surveys. We also had discussions with many authorities. The reason why 32 dBA (max, time weighting fast) was finally used was because it was a value that was already in use. This value might be too strict, but since it's hard to make adjustments and introduce measures afterwards, it is better to have a safe value. The setting fast was chosen because it represents how people respond and react to sound. The noise criteria is something that we strive to fulfill, but it doesn't mean that a railway line is stopped if the ground-borne noise level exceeds this value.

Q: How is a disturbance due to ground-borne noise defined?

A: We follow a scientific guideline and in that document, it is defined what can be counted as a disturbance. What is an actual risk can of course vary and depends on the context.

Interview with respondent 9

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I have heard of this methodology, but I'm not that familiar with it.

Q: Is low-frequency noise a problem to public health?

A: It has an effect on our sleep and we are more sensitive to that kind of noise. The consequences are probably the same as for other noise. There are not so much research on this issue. We investigate the noise situation and we have recommendations for many different kinds of noise.

Q: Should more projects focus on ground-borne noise?

A: More knowledge would be beneficial. When a new noise criteria is developed, we investigate how the situation is in other countries. We use The Swedish Environmental Code [Miljöbalken] and the noise criteria mainly target existing dwellings.

Q: Are you a part of a special project?

A: It depends on what you mean. Central authorities like us are rarely involved in local projects. However, within the National Noise Coordination [Bullernätverket], we have discussed the need for new guidance on structure-borne noise. The National Noise coordination is composed of the Swedish Environmental Protection Agency, the Public Health Agency of Sweden, the National Board of Housing, the Swedish Transport Administration and the Swedish Transport Agency.

Q: How easy is it to communicate and discuss topics related to ground-borne noise?

A: The World Health Organization [WHO] has published several reports on noise, where ground-borne noise is one part. The Swedish Public Health Agency sends out surveys every 4th year that asks questions on traffic noise in general.

Q: Does a conflict of interest exist between expanding the railway network and protecting people from ground-borne noise?

A: Speaking of noise in general, then I would say yes. We have seen some reliefs regarding the building regulations which have enabled for construction of buildings in vibrant, noisy areas. Ground-borne noise can be hard to mitigate. As traffic is planned closer and closer to existing housing, the sound can spread into the dwellings. Our recommendations are connected to the legal documents and we have a responsibility for the environment inside dwellings, however we do not discuss measures.

Q: Is there a certain building type that must be protected?

A: We have recommendations for, among others, residential buildings, care homes and schools. Most of the complaints we receive are related to noise disturbances. However, complaints about structure-borne noise are not as common. But locally, it can be a problem. The most important part is to protect people's health.

Q: Will problems related to ground-borne noise become a greater issue in the future?

A: That is difficult to say. Noise from road traffic is a complex issue. The noise criteria that we have are neither adapted to a specific building type, nor to a specific source. The National Noise Coordination has discussed developing general guidance that would apply to the whole country, not just specific projects.

Interview with respondent 10

Q: What other experts do you need to cooperate with?

A: That is geotechnicians and they have for the most part already solved some of the problems with vibrations, for example by piling the soil. Other groups are the people who work with environmental impact assessments or officials that work with the cultural heritage. Rail experts are also important because we need information on the foundation.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: I have worked with the metro in Stockholm, The East Link [Ostlänken], The Transverse Line [Tvärbanan] and The Sluice [Slussen].

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I'm not that familiar with the methodology, but I have understood the objective of the new methodology. I haven't used it.

Q: What information do you need in order to work with ground-borne noise?

A: Two processes are dominating; the construction phase and the post-construction phase. During the construction phase, we cooperate with those who construct parts of the tunnel. It is important to know where they will drill and where they will pile. Working with ground-borne noise includes many fields. The construction phase often generates more ground-borne noise when the pile driving machine is in use. The post-construction phase continues for a very long time and generates more ground-borne noise in the long term. The urban environment is sensitive and it can be difficult to work during the day since that would disturb for example office workers or schools. The foundation has a great impact on the ground-borne noise levels.

Q: What aspects make it difficult to work with ground-borne noise?

A: The precision in many calculations is not that developed which is a problem. The effects of the terrain and the soil are parameters that are challenging to control. These parameters can differ from case to case. In Sweden, we have other soil conditions compared to what they have in Central Europe.

Q: How should a new prediction methodology be managed?

A: I don't know exactly how Trafikverket is organized, but a reference group can be useful. If consultants are to be involved, the financial support can be an issue. A designated budget for managing the methodology will probably be best, but I'm unsure. The most convenient approach is to publish a pdf that contains information on the methodology. Trafikverket must review the pdf and this could be done by a reference group. Otherwise, the methodology will stop developing. For example, in our work we have technical areas of expertise. Within our technical areas of expertise, we have files and folders that describe the data, the methodologies and source terms that we have used.

Q: What risks exist when a new prediction methodology is managed?

A: One risk is who will be responsible for managing the methodology. Another question is what resources are available. It's best if a group is responsible and that a guiding document is ready to be used. This guiding document could be created with the help of conference papers. For example, the FTA methodology has an existing guide attached to it. It is the US authorities that are responsible for the guiding document.

Q: So, the document related to the FTA methodology is a good example?

A: Yes, it is very detailed and comprehensive. It consists of several steps with one more brief and another more detailed. The more detailed a calculation step is explained, the more steps are described for the specific part of the methodology. It is better to work with recognized methods and not with "black boxes". This is important because it will make everyone more aware of the relevant methodology and the client can review the methodology. We have used other methodologies apart from FTA, for example HS2 which we have complemented with measurements.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: Feedback only reaches us if we have residents that complain. It is difficult to know what a specific measure will give, but a slab track is an effective measure. It is costly to implement measures after the project has finished. In the end however, not that many buildings will be affected by ground-borne noise. It can be difficult to find ground-borne noise measures that can be combined with demands for the rail. The track must be stable, but some ground-borne noise measurements utilize elastic components that enable the mechanical parts to move. Railway lines are often situated far from dwellings, often approximately 30 m, which makes ground-borne noise a minor problem compared to metro lines.

Q: What measure is most effective?

A: For trains, we want a big mass on a soft element and this will result in a lower resonance frequency. An example of this approach are floating slab tracks.

Q: Is a slab track a better solution than a ballast mat?

A: Yes, it is possible to have better reduction of the ground-borne noise levels, even if ballast mats also can be effective. The ballast is not always entirely equally distributed which can be a problem. Another type of measure is rail pads. This type of measure is used when there is a lack of space. One issue is that all measures must be able to be repaired which increases the demand of spare parts. Measures are combined in many cases to form a more robust solution.

Q: Should more measurements be conducted?

A: Yes, I think one method would be to only make measurements for critical buildings that will experience much ground-borne noise. Buildings that have the same foundation with respect to the soil, will experience the same type of ground-borne noise levels. If the soil conditions aren't the same, then more measurements are needed.

Q: Should ground-borne noise be introduced earlier in a project?

A: The planning of the track geometry must be decided before the ground-borne noise can be investigated. I don't think that it is a problem that ground-borne noise isn't introduced earlier.

Q: More information and data exist for airborne noise, does ground-borne noise require more research?

A: Yes, because the methodologies are more reliable for airborne noise. The calculation procedure for ground-borne noise can be more thoroughly investigated. Ground-borne noise is not that common as airborne noise, but it can cause more annoyance since it is harder to block.

Q: What is your opinion on the noise criteria 32 dBA (max, with time-weighting FAST)?

A: It is an appropriate noise criteria and it corresponds to when we had 30 dBA with time weighting slow.

Q: Should objective specific noise criteria be further developed?

A: Often, we want more demands than what is actually necessary. Dwellings and hospitals usually require more specific demands. I know that Region Stockholm has introduced criteria for hotels. To find information on sensitive equipment is rare, so formulating criteria for sensitive purposes is not always included. Sometimes, however, product information for sensitive medical machines are registered, such as product information for MRI [Magnetic Resonance Imaging] scanners.

Q: Is there a need to make local adjustments when using the methodology?

A: Yes, that is necessary. Many methodologies are composed of several parts in the form of a source term and correction terms for the transmission. Another term is the sound radiation in a room. Adjustments could be made in one or more of the terms. It is possible to take parts from several methodologies depending on the local circumstances.

Q: Does a conflict of interest exist between expanding the railway network and protecting people from ground-borne noise?

A: Sometimes, the environmental code can make it hard to build. Therefore, we need to optimize. Both vibrations and ground-borne noise are not easy to work with. We don't know what the rock looks like at every given point. That is why we must conduct measurements and complement that with data from the methodologies. Measurement results are crucial for understanding the situation.

Interview with respondent 11

Q: What other experts do you need to cooperate with?

A: I cooperate with geologists, geotechnicians and structural engineers.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: I have been involved in the project at Drammen and at Moss.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes, I have received data used for creating the methodology. However, I haven't been involved in the discussion on the methodology.

Q: What advantages and disadvantages does the methodology have?

A: As the methodology was developed, new measurements were conducted. This data is excellent and will be of very good use. There is a risk that the conservative results remain and that the methodology becomes too general. Data from more tunnels is needed. The geological information can be very different from place to place. The geological aspect is very important as it has an impact on the material damping. It would be good to plot the results for several sites and compare.

Q: What other data is needed?

A: More information on the loss factor could be beneficial, for example how the geological parameters impact the loss factor.

Q: What other methodologies exist?

A: The tunnel in Gårda provides data that we [standard Norway] have used together with our own data. We have not considered a FEM model or similar.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: It is uncommon to get feedback from projects. One time, we actually got feedback which was positive.

Q: What measures are effective?

A: There are not that many measures that can be used since we often have a ballasted track.

Q: Should measures be included in the methodology, for example as a new parameter?

A: It is difficult to have that as an input parameter since there are numerous products and it must work to change products in the methodology. Measures can be included afterwards.

Q: Are there aspects that make it difficult to work with ground-borne noise?

A: It can be difficult if the builder has specific requirements that differ from the overall requirements.

Q: How should a new prediction methodology be managed?

A: Before a methodology is integrated, it must be reviewed. As an example, for the Norwegian standard, a methodology will be described along with geological information. This standard will be established together with the builders. Many different stakeholders will be involved such as builders, the research institute NGI [Norwegian Geotechnical Institute] and those who will use the methodology. Different roles are needed and Trafikverket could be an advisor in this case. The new prediction methodology that Chalmers developed could be used as in benchmarking. One opportunity would be to include consultants because they will most likely use it in the future.

Q: What risks exist when a prediction methodology is managed?

A: One challenge is that the methodology must be used. A solution would be to demand that it is followed. In standards on the other hand, everything is clearly defined and a standard can in that case be more neutral.

Q: What is your opinion on the noise criteria of 32 dBA (max, with time-weighting FAST)?

A: I don't know exactly what the regulations say in Sweden, but in Norway, the noise criteria can't be exceeded as in Sweden. The noise criteria has become more strict. We have the same noise criteria in Norway and it is based on when residents feel annoyed.

Q: Is there a conflict of interest between expanding the railway network and protect people?

A: Yes, I think so. Increased speeds and loads for the trains creates this conflict of interest.

Q: Should objective specific criteria be further developed?

A: In Norway, we mostly have demands on the dwellings. In some cases, we also have specific demands, such as for the opera house in Oslo. The demands in Norway are more strict and not only a recommendation. The noise criteria in Norway is based on the statistical maximum level, so it is possible to exceed the noise criteria.

Q: What should be fixed in the methodology?

A: All parameters should be flexible so that they can be changed as long as it can be explained in the methodology. The correction factor between the foundation and the house is especially important to change.

Q: Shall new measurements be planned?

A: Yes, especially when the circumstances are controlled. It is more interesting with measurements for many locations, rather than many measurements for a single area.

Q: What channels have you been using for informing about the new standard in Norway?

A: We have used the standard committees and the BNAM [The Baltic Nordic Acoustic Meeting].

Q: What frequency range is valid for ground-borne noise?

A: In the standard project, we have chosen 20 Hz-250 Hz. We have also included the 500 Hz band.

Q: Will problems related to ground-borne noise become a greater issue in the future?

A: Airborne noise is a bigger problem than ground-borne noise and ground-borne noise will probably not become a greater issue.

Interview with respondent 12

Q: What other experts do you need to cooperate with?

A: I mostly work with acousticians because my work is directed towards solutions, which in the extension become the products.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I have read about it.

Q: What advantages and disadvantages do the methodology have?

A: The advantage is that the methodology provides a broadband result on structure-borne noise. It is good that the methodology connects results and data from other projects. The results from the methodology can be used as a guidance. This is especially important since it must be easy to compare different calculation results during procurement. For the suppliers, it will become clearer when prediction results can be compared from different sources. The development of a new standard in Norway will also be beneficial as will be an upcoming EN-standard. A disadvantage is that the foundation of the track does not seem to be included in enough detail. This could lead to overestimation of the performance of the chosen solution; calculations do not always show reality. Also, it must be possible to compare different products.

Q: So, it must be clearer how products can be compared?

A: It must be defined how it can be verified that two products actually are equal. In measurements where products have been determined to be "equal" a deviation of much as 12 dB between the two products. Standards can help with that, so that it becomes easier to compare products [for example the standard EN 17282]. The specific acoustic parameters that are needed must be well defined in each case and then can we compare products.

Q: What other data is needed?

A: Parameters that should be incorporated are the stiffness of the foundation, the loss factor and the properties of the elastic layer under the actual load in track.

Q: How should a new prediction methodology be managed? A: It is important that the responsibility lies with the public agency and that the agency is neutral.

Q: What risks exist when a methodology is managed?

A: One risk occurs when there is a need to save money, the development of the methodology can then cease as the funding is reduced.

Q: What is your opinion on the noise criteria 32 dBA (max, with time-weighting fast)?

A: It is probably not strict enough. It can be worth to have some margins, of maybe 5 dB. How correct the noise criteria is depends on the building standard. For instance, when the target is Sound Class B in Sweden the background noise masking of 32 dB will not be enough to create a disturbance free environment.

Q: What measure is most effective?

A: This is actually described fairly well in a standard, ISO14837-1. Generally, a sleeper pad for vibration isolation can give up to 10 dB reduction and if a greater reduction is needed, a ballast mat is typically used. For a reduction greater than 25 dB, a mass spring system is usually required. This standard gives a reasonable description of how the different solutions compare. It is important to remember that all parts of a system will interact and therefore the subgrade must be considered to make sure that the correct solution is chosen. But it is easy to say that a well-maintained system will usually be better than a poorly upkept system. A maintained track of good quality is the best predictor of a good ground-borne noise situation. If elastic materials are then used in the right way, you will meet the requirements but often also postpone the deterioration of the track. Using USP for vibration isolation can for instance reduce the maintenance of a ballasted track as well as increase the typical service life of the system at the same time. Another way to view it can be that these elastic systems can be used to make other cost saving measures such as reducing ballast depth to save ballast and through this add value to a system designed for vibration isolation. As an example, by using the correct combination of elastic system with USP and ballast mats, a ballast depth of 300 mm could potentially be reduced to 150 mm without loss of function and without a quicker deterioration of the tracks system, which is something that is being investigated in other jurisdictions.

Interview with respondent 13

Q: What other experts do you need to cooperate with?

A: I work with almost all of the fields. When a new railway is planned, many specialists are involved. Apart from experts that work with the railway itself, I also cooperate with environmental specialists and city planners. There is often a balance between different fields, such as between noise, health and railway planning.

Q: What kind of infrastructure projects have you been working with during the past five years?

A: The railway project in Göteborg-Borås and The West Link [Västlänken] are two prominent examples where ground-borne noise has been an aspect to consider.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: Yes, I was given the opportunity to see results from the methodology for a section of a railway line. I think that it can be further developed. What can be more clear is what happens along the way, from the equations to the actual result. How the methodology is presented is one key part. As a project manager for railway lines, I want to know what ground-borne noise levels I get without measures being installed. We must understand how big the IL [insertion loss, the level difference between a case with a measure and a case without a measure] is and where the measures will be placed. This will enable us to choose the correct track and rail system. It can also be important before negotiations with landowners take place.

Q: What is needed in order to work with ground-borne noise related issues?

A: A good methodology is one thing that is needed, so that calculations can be performed. The methodology that Chalmers has developed is one solution to this problem. The next step is to take the methodology from Chalmers and into the practical world. An example is how the methodology can be expanded and include a presentational perspective. We need to see what measures we have available. Another important point is to see what rail systems I can choose depending on the noise criteria. The methodology is essential for understanding uncertainties. Then, we know what measures are relevant. At some point, the project manager needs to decide, together with others, if a ballast-free track or ballast track is preferred. The cost can be very different for these two alternatives and the methodology can help us understand what track system is best.

Q: How is the ground-borne noise issue approached during the construction phase and the post-construction phase?

A: That is a bit hard for me to answer, since I don't really work with the construction phase.

Q: What measure is most effective?

A: We don't want to make measures that are too costly. The most convenient solution is a ballasted track system without any measure. To install additional ballast mats isn't that expensive. On the other hand, it will be complicated if new measures must be installed afterwards. New mats need to be installed when the lifespan of the old ballast mat is over. Continuous maintenance of existing ballast mats or the decision to buy new products are always something that must be considered. One solution is to have a more expensive system, but it can be reinstalled and maintained over time. I don't think that measures should be integrated in the methodology, but it can of course be an idea to do so. From my point of view, the methodology has its focus on the transmission from track to building. One type of measure for ground-borne noise is to buy properties, but that is mainly done during the post-construction phase.

Q: What makes it difficult to work with ground-borne noise related issues?

A: Increasing costs is one such thing. The ground-borne noise levels must be within a limit value, so that we can protect people from the harmful effects that ground-borne noise has. At the same time, every project has a budget. We have an uncertainty related to when we build. We need to build as cost-effective as possible, but the houses need to be of good quality. The methodology can help us reduce the uncertainty.

Q: What is your opinion on the noise criteria 32 dBA (max, with time-weighting FAST)?

A: I find it difficult to say something about that criteria other than that I use it as a project manager. For many projects, we want to be below the noise criteria and that is why there must be sufficient data which can be used to decide what rail system will be optimal. In some cases, there is only one remaining estate that will have high ground-borne noise levels, then one solution is to buy out that specific property.

Q: How easy is it to install ballast mats inside a railway tunnel?

A: The ballast mats are transported in parts and are installed almost like a puzzle. The ballast-free track requires more precision and the track must be correctly planned from the beginning. It is, however, not impossible to create the conditions for the ballast-free track.

Q: Are more measurements needed?

A: If the ground-borne noise levels are very close to the noise criteria, then more measurements are needed for understanding what measures are relevant. As always, we want to reduce the uncertainties and connected to this is what type of capacity different track systems have. Projects can also require additional measurements, specifically for knowing more about the transmission. More measurements could be conducted before the rail system is installed. As a project manager, I want to know how I can calibrate the system when we start the planning and building process. This would enable for better decision making regarding the IL that is adapted to a certain traffic volume. What is needed now is a catalogue that explains what tools project managers and decision makers have according to the methodology. The catalogue could also be used for knowing, in greater detail, what levels are generated.

Q: So, a catalogue that is connected to the methodology?

A: Yes, we can investigate how we can continue with this. The methodology is one part and now a manual or guide would be preferred.

Q: Is it possible to see a trend in the future, what track system will be more used?

A: The trend that we see in Sweden is that we continue to build ballasted track systems. For tunnels, the same trend can be observed. The ballasted track is less expensive than the ballastless track. We have a rock quality that is suitable for building tunnels. It is only when ground-borne noise becomes a problem that the ballastless track system will be an option.

Interview with respondent 14

Q: What other experts do you need to cooperate with?

A: I collaborate with experts from many fields and I can be involved in all phases of a railway project.

Q: What kind of infrastructure projects have you been part of during the past five years? A: Many. One interesting project is the Mälaren Line [Mälarbanan] in Stockholm.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: No, I would not say so.

Q: What is needed in order to work with ground-borne noise related issues?

A: It is difficult to answer that question because it depends on the circumstances. However, noise and vibrations are often introduced late in a project. There is an annoyance dimension that needs to be addressed and in order to minimise annoyance a proper vibration isolation is required. The latter includes the supporting structure.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: Tests by the contractor. The ultimate test, however, is carried out by third parties, if the design is robust enough, no complaints will occur.

Q: Are there aspects that make it difficult to work with ground-borne noise? A: No not really. As a builder we need to be in control of the source because without a proper source definition contractor cannot submit a bid to a tender. We also need to have a structured working process to coordinate relevant engineering disciplines. If a comparison is made to structural engineering, transparency is required throughout the verification process, starting with a design basis. For noise and vibration problems, it not uncommon to work with black boxes. This create problems, without transparency it is virtually impossible to review a design solution. There are many ways to deal with vibrations and ground-borne noise but normally a statistical approach is not favoured. There is also a gap between functional requirements of supporting structures and how annoyance is analysed. There is also a gap between structures and how vibration isolation measures, for example of a track structure is implemented. If we cannot estimate train capacity in the future, ground-borne noise predictions may not be accurate. Use of standardised methodologies in general have a negative impact on innovation. Then there is a focus on how something should be done rather than the underlaying physics to deliver a balanced engineering solution.

Q: What conditions are important when measures are installed?

A: We must view e.g. a railway tunnel as a system. Before the tunnel is built, it is important to understand the requirements as it is not always possible to change things afterwards. A concrete tunnel with supporting piles requires a different approach than a tunnel in bedrock. The foundation need to be correct from the beginning so that it has the suitable dynamic properties.

Q: So, the foundation is a significant factor?

A: Yes, in most cases . In order to succeed, inter-discipline coordination is required, specifically between the structural engineer and the environmental specialist as the responsibilities differ, i.e. source and receiver. A poor foundation may lead to insufficient vibration isolation. If things go wrong it may be difficult to handle later.

Q: How should a new prediction methodology be managed?

A: I have no idea or suggestion on how this could be done.

Q: What should be able to change in a methodology?

A: It must be possible to change everything. There is a risk with too simple methods using e.g. correction factors, such methods may not be ideal in a design phase.

Q: What other approach can be used instead of correction factors?

A: One example could be transfer functions. They can be measured as well as simulated, but correction factors can be good to get a first estimate.

Q: Should objective-specific noise criteria be further developed?

A: That is more a question that is related to perception and annoyance. At certain levels, there will be specific requirements, but I have no real opinion.

Q: Does a conflict of interest exist between developing the railway network and protecting people?

A: I cannot see an actual conflict here, but it is important to take the problem seriously and work close to the source. From an engineering point of view, the problem is solvable.

Q: Should ground-borne noise be even more investigated?

A: No, not in that way. We know what ground-borne noise is and what the general mechanisms are. We know how waves propagate in solids, how they enter buildings and lead to noise. It could be beneficial to know more about soil wave propagation properties. It can for example be wave propagation in a two-phase materials or wave propagation in random media. With more knowledge, correction factors would not become as interesting.

Q: Can the source in the form of a train passing through a tunnel be characterized as a point source or as a line source?

A: For the calculation procedure, it is more interesting to look at the load characterization in general. If you consider a bridge it would be impossible to design for a specific bearing capacity without knowledge of the expected load. The same applies for ground-borne noise. Different load models can be used, but both the builder and the contractor need to know how the load is be defined whether in the time domain or in the frequency domain. The load model should however represent the traffic flow today and what can be expected for the future.

Q: Should the source be examined in greater detail?

A: The more knowledge about the source, the better tender documents can be produced, and ultimately better chances of good solutions to reduce annoyance. One problem within the field of noise and vibration is that measurements are carried out inside a building with the transfer function of the foundation rarely observed. In addition, the building has its own dynamic properties that also must be taken into account. Q: What is a relevant working procedure in this case, is it for example to use a check list?

A: I would avoid using the word checklist. A checklist does not promote thinking and it is especially important to reflect upon the different methodologies that can be used. It would be better with collaboration between disciplines and data sharing through the design process, but I wouldn't use a checklist.

Q: What type of knowledge from a related field could those who work with ground-borne noise learn from?

A: We have a tendency to only follow standard procedures and it is not always appropriate to do so if it means that we lose our ability to understand the physics behind. To use an example from structural engineering; a bridge engineer needs to have a sense of stresses and strains. The same applies for the noise and vibration engineer, stresses, strains and relevant acoustic measures. Only relying on computer generated result will not help.

Q: What ground-borne noise measure is most effective or most common in Sweden?

A: In Sweden, ballasted tracks are favoured, thus ballast mats are common in ordinary tunnels. More complex solutions, such as freely suspended structures on e.g. rubber isolators are not that common. The choice of solution is also related to what maintenance strategy each project has. Regardless of what system is preferred, each system has its limitations. When it comes to vibration isolation properties the railway track system in general must be taken into account. A simple solution does not have to be a bad solution, but it is important to understand its limitations.

Q: Should acousticians be better at understanding the working process connected to the structural engineers?

A: The world of noise and vibration need to become more transparent and encouraged to more collaboration. Without a design basis and proper design documentation a design review is difficult.

Q: Is there something you would like to emphasize?

A: Available knowledge within the field should be used in a broader extent. Much more can be done and it is necessary to start from where we are today. A review of recent accomplishments and start from there to move forward. That is why the strategy of using black boxes never will work in this context.

Q: Where can an engineer start, what is the first step?

A: I do not really know, but the builder needs to know what is important to fulfil functional requirements. The contractor, on the other hand, must know how to address and to solve the problem. As there are many ways to solve an engineering problem, regulations do not have to be directly connected to method used.

Q: Does it matter if the time weighting SLOW or FAST is used?

A: From an engineering perspective, it can be different depending on the frequency spectrum. However, it is a question that is more related to perception and annoyance.

Q: How will it be in the future, will simulations or measurements be more important or is a combination required?

A: It would be valuable with more site specific seismic investigations. Understanding the soil dispersion characteristics would help. A combination of simulations and experiments would certainly be a way forward.

Interview with respondent 15

Q: What other experts do you need to cooperate with?

A: The planning of new roads or railways require cooperation between many different fields. We that work with land acquisition often cooperate with environmental experts and construction managers.

Q: What kind of infrastructure projects have you been involved in during the past five years?

A: If you mean tunnel projects, then the Harbor track in Gothenburg [Hamnbanan] is one example. I have also been somewhat involved in The West Link [Västlänken] and the tunnel in Varberg. As a land acquisition specialist, I work with 10–30 projects and there are not so many tunnel projects. We are sometimes involved when the tunnel is repaired or reconstructed.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I am aware of it.

Q: What does the land acquisition process look like?

A: We spend a great deal of time with the planning phase. Later, we enter the core part of the land acquisition process. Here we can either be proactive and this is for example when questions related to the area acquisition are discussed. In other cases, for example when emissions such as noise are discussed, it is more common that residents reach out to us with liability claims. We also have a responsibility to reach out to the residents if the noise levels are considered to become an issue. Then, we address the issue and communicate clearly. To inform about measures and how they will impact on the resident's daily life is another task that we are involved in.

Q: How common is it that properties are purchased within a project?

A: It is not unusual, but here we need to differentiate between two things; purchasing and acquiring a property. The property owner can decide that we will need to purchase a property. We also have the ability to acquire a property by applying the right of acquisition. That is more common than expropriation. What motivates a property acquisition is the health aspect. How disturbed the residents perceive that they are is also an important factor. Acquiring a property is in some cases less expensive because we might have the possibility to ignore some construction procedures. It can for example be the case that there is a property where it is too costly to implement measures. All this is regulated in the Swedish Environmental Code. The expropriation is regulated by Trafikverket within special guidelines and the noise levels are only governed by the noise criteria.

Q: Is the economic aspect or the health aspect most important?

A: They are independent from each other, but they also affect each other. For example, the economic situation can affect how effectively we can protect a resident. The laws and regulations say that we should protect, acquire or decide not to take action. According to the Swedish Environmental Code it is possible to be compensated if the property is expected to drop in value. The noise levels can be below the criteria, but the residents can still be compensated. It is however unusual that the levels are below the criteria. Liability claims are more common for airborne noise than for ground-borne noise. Residents can contact us and express that they experience annoyance and then it is important that the claim is equitable. Depending on the type of project and what type of annoyance that the residents experience, it can be easier or harder to be granted compensation.

Q: What aspects are important to consider when investigating issues related to noise?

A: Since my role is more about investigating the economic aspect, I'm not directly in contact with the decibel values. One factor that increases the annoyance is if the noise source can be seen by the residents. An example is if the residents can see the train passages and this will make them feel more annoyed. That's why it's not only important to have the data, but also spend time on making an analysis. The terrain can be remodeled with soil masses which acts as a visual barrier that shields the residents from the train line. If sections of the line can be constructed so that the exposure is minimized, then that is good. However, for railway lines, individual interests must be compared with the economic cost, which can be very high. We usually don't make more than what is necessary. Often it can be difficult to implement measures against ground-borne noise. At the countryside, it can be even more challenging to create a good environment. Since this environment is undisturbed, the introduction of a train line or a tunnel creates an imminent change in the landscape. This can increase the annoyance. So, even if the noise criteria is fulfilled, the residents can still feel annoyed. This means that the noise criteria becomes more strict in an undisturbed environment. Also, if measures have been implemented the residents might not have the right to be compensated.

Q: What is your opinion on the noise criteria 32 dBA (max value, with time-weighting FAST)?

A: I have no actual opinion, but we can discuss how this noise criteria was developed. At the moment, there is an ongoing research project on the combined effect of both vibrations and noise in general. If the study shows that the combined effect is severe, the noise criteria can be changed. I believe the noise criteria to be a reasonable value. More research is needed in order to understand how noise affects our health. Many say that they neither feel vibrations nor hear ground-borne noise. That is why the research must continue, to understand the factors behind our exposure. Evaluation of the noise criteria is performed, but this is also an economic cost.

Q: How are you collaborating with acousticians?

A: We investigate what measures we must implement and a part of that is to read reports from acousticians. They conduct extra measures inside the dwellings and we are involved as the measures are discussed. We order measurements from the acousticians and later look at the samples. Our responsibility is to have contact with the other stakeholders and to inspect the dwellings. The noise criteria is one tool and that criteria is used to make decisions in the planning phase on what measures are necessary. Measures can either be installed close to the source or in a dwelling. Measures that are installed before the construction phase begins can reduce the noise levels during the construction. One aspect that is discussed is who has the right to be protected and how this is done most effectively. Vibrations and ground-borne noise can be harder to shield off and those measures are more expensive.

Q: What noise data would be beneficial to know more about?

A: To only have data from the train passages during the night can be problematic. We would like to know what the situation is for the day. Disturbances occur during the day as well. That information is available, but data on the train passages must often be retrieved. The noise levels during the night are advantageous to know more about for understanding the noise disturbance, but for the buyer of the property the daytime values are better. The number of passages and how the annoyance can be described are two examples of what I would like to know more about, especially for the daytime.

Q: How often do you study the source?

A: I read the documents and decisions. At the moment I'm involved in a process where the foundation is constructed. Our work is based on several protocols and according to the regulations, we shall make the slightest encroachment. My role is to protect the residents by using the regulations. As mentioned, the economic cost is one part, but the most important aspect is to protect people. We consider the damage each alternative will give and many fields cooperate.

Q: Does a conflict of interest exist between expanding the railway network and protecting people?

A: For small projects, it can be a problem because the cost of implementing measures is greater, but normally it's not a problem. We must plan if the environmental impact is substantial. The planning can be very costly and for a small project it is a main part of the budget. If we have made an error, the residents can have the right to compensation.

Interview with respondent 16

Q: What infrastructure projects have you been involved in during the past five years?

A: I'm involved in many projects. We use many consultants and I advise on many of the projects. I assist in many different projects.

Q: What tunnel projects in Finland are new?

A: The Helsinki project is one, which is going through a densely populated area. Another one is the line from Helsinki to Esbo.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I have seen a short presentation about it, I'm aware of it.

Q: What other fields do you cooperate with?

A: It can be ground water issues and other environmental fields.

Q: What input or data is needed in order to work with ground-borne noise?

A: First it's the overall assessment, we need to look at the railway plans. Then, if we see that there is a risk of ground-borne noise, we investigate the soil conditions. We should look at what the track is. The transmission is the geology part. The receiving part is connected to the house. The foundation is not always clear. Information on the source and the transmission can be found, but it can be hard to find information on the receiver.

Q: What is the noise criteria for ground-borne noise in Finland?

A: We have different values for tunnels and for surface lines, 30 dB for tunnels and 35 dB for surface lines. We don't make a distinction between day and night and it's just one value.

Q: Is there a specific calculation procedure in Finland? A: The government research center (VTT) has published a report on the procedure. The method is similar to FTA. It is a bit rough on some parts, but it is a good preliminary estimation. If we do measurements for existing houses, they don't measure the sound inside the building. They instead measure the vibrations from the building foundation. In most cases, it is a bit conservative. We have had a research project on the FTA method (line transfer mobility), but using the FTA requires more labour. Typically, the information on the soil type and traffic is used too. There is no guideline on what measure to use. We need to know how we can choose the correct mitigation measure.

Q: What measure is most effective or most common?

A: Under ballast mats are common or UPS [under- sleeper pads], but they are not so good at low frequencies. For under ballast mats, we are a bit unsure on the installation. If we want to install it on a section, we can have stiffer soil. Putting it directly on the soil can create problems related to the track maintenance. At the moment, we have an ongoing research project on the usability of under ballast mats. The primary source is the traffic, which creates energy and this energy enters the soil. Discontinuities create vibrations. In Finland and in Sweden, we have mixed railway lines. Sometimes, the wheel or rail can be repaired or serviced so that it becomes more smooth. This would probably also be better for ground-borne noise.

Q: How about water filled cracks?

A: Seismic method (refraction seismic) can be used to estimate the bedrock seismic wave velocity. This might be helpful when assessing ground-borne noise issues. Typically, the seismic velocity is lower in crushed rock and higher in intact rock.

Q: Do you have a specific methodology that you use?

A: The methodology we have tends to become a standard, but it is not required to be used. For ground-borne noise, it tends to be different for different consultancy. It can be good to have a standardized methodology and it can be easier to compare.

Q: Do you have different objective criteria?

A: We have different criteria for houses, commercial buildings and offices. We can use the values as guideline values. At the end, if there was a complaint, then the guideline values would consider these values. It can be problematic that we don't have separate values for the day and for the night.

Q: What should we measure?

A: For vibrations and ground-borne noise measurements, we must capture what the traffic is on the line. The statistical representative is always a question mark. If we only have passenger traffic or freight trains, that is something to consider. Having proper equipment and following the standard is of course always important. When they install the sensors.

Q: What trend can you observe?

A: We will stick with the ballasted tracks. I think the non-ballasted tracks are expensive and the ballast can also mitigate the vibrations.

Q: How should a methodology be managed?

A: For a larger audience, good documentation is needed. If you don't know how it can be used, then it's a problem. The user interface is one component. The model must be validated if it is working as designed. One thing that is really tricky is to see what the difference is between the field measurements and the results from the model. That is a problem that you often run into. Often, we trust the measurement more, but we need both.

Interview with respondent 17

Q: What other experts do you need to cooperate with?

A: If we mean vibrations, then I cooperate with geotechnicians. I also cooperate with colleagues from the transportation field, they simulate the traffic flow. Architects are another group and when studying ground-borne noise, the building is important. Experts that work with FEM or with time difference modeling are other examples.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: I was involved in the measurement session in the Åsa tunnel. I have been part of environmental impact assessments where sound and vibration is one factor. I have also worked with tunnels.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I was involved in the discussions and I answered questions. I have read the PhD thesis where the prediction methodology is described.

Q: What pros and cons does the methodology have?

A: An advantage with the methodology is that the literature review is substantial and very well written. One challenge is that few tunnels are studied and that more aspects should be added, for example the contribution from switches. Transfer functions could be more in focus, so that we know how the tunnel is excited by the vibrations. We must know the nearest point from the tunnel to the house and that isn't always the point of excitation.

Q: What other methodologies exist?

A: There are methodologies described in the standard on vibrations, which contain different coefficients. The results from that methodology give an indication on how large the vibrations will be. For houses, risk assessments are made and vibrations are affected by the soil type.

Q: What measure is most effective or most common in Sweden?

A: When ballasted tracks are discussed, ballast mats or UPS [under sleeper pads] are used. Both these solutions are based on viscoelastic materials. There are other mats, but they are not based on the viscoelastic property. It is possible to make changes during the construction phase, but in most cases we come in too late in a project. There are other aspects, such as safety, which has a higher priority. It can be an advantage to look at the transfer function from the tunnel to the foundation. There is often a gap between the planning phase and the construction phase. If a building has already been constructed, then measures are diverted towards the track. Different municipalities can have different demands and the demands can also differ between the suppliers of the measures. During the planning phase, FEM tools are used and if there is a risk, measures are recommended. The suppliers can have different calculation procedures and supply different parts. If there are no complaints, there is no feedback, which means that we don't return and measure. Measuring ground-borne noise is difficult. Using a more detailed methodology could lead to a better estimate than only following a standard.

Q: What should be measured?

A: When measuring ground-borne noise, microphones are placed inside the room. Measuring vibrations in a tunnel is made by installing geophones. One issue is that we use A-weighting and therefore, we do not know what is happening. When transfer functions are used, A-weighting shouldn't be used. When vibrations are measured inside the house, it's important to know where the measurement tools are placed. Knowledge and good tools are essential.

Q: What aspects make it difficult to work with ground-borne noise?

A: Having representative material data is one aspect. Using FEM tools and especially time difference models is one solution.

Q: How should a new prediction methodology be managed?

A: It's good that there is an Excel sheet, but this implemented methodology must be adapted to new scenarios. Trains will excite the tunnel differently. If new measurements can be analyzed, then that is beneficial. However there can be multiple combinations of the point of excitation, the soil and the building. Therefore, AI can be used to create a database with these combinations. This is something that could be done for ground-borne noise. However, the measurements can have different purposes, so it can be hard to compare data from numerous measurement sessions. Using AI also requires more from the measurements.

Q: Should objective-specific noise criteria be further developed?

A: It is now clear that ground-borne noise has an effect on human health. Noise also has an effect on children and their development, so it's strange that there are no criteria for schools. Recommendations are not the same thing as requirements. Existing guidelines can sometimes refer to older documents and there can be contraindications with respect to the requirements. These documents need to be updated, but many agencies must cooperate for this to happen, it's not only one agency that is responsible for updating the documents.

Q: What is your opinion on the noise criteria of 32 dBA (max, with time-weighting FAST)?

A: In the documents, nothing is mentioned about how the criteria can be exceeded. Instead, the traffic flow has been in focus and the traffic in the future gives insight into the disturbance. Ground-borne noise will affect people even if they can't feel the vibrations. That the value can be exceeded five times per night can be too much. In Sweden, we are good at formulating requirements.

Q: Is the construction phase or the planning phase most important?

A: Both are important. In projects, we now see that residents are affected by ground-borne noise. More research is needed on how humans react to ground-borne noise.

Interview with respondent 18

Q: What other experts do you need to cooperate with?

A: I cooperate with several stakeholders within The City of Stockholm. Another stakeholder is of course Trafikverket.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: I have been part of all projects related to the metro in Stockholm. I have been involved in The Mälaren Line [Mälarbanan] and in The Roslagen Line [Roslagsbanan]. Another example is The Stockholm Bypass project [Förbifart Stockholm].

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: No, but I know that it exists.

Q: What is needed in order to work with ground-borne noise?

A: We review the reports that consultants produce and they investigate what houses are exposed to ground-borne noise. This includes both existing properties and planned buildings. Our task is to evaluate the results. The distance from the tunnel to the house is important. The geology and train type are also important aspects. It is not always that we know what the foundation looks like.

Q: When does ground-borne noise become a problem in a project?

A: It's already in the detailed development plan that we address ground-borne noise issues. In the railway plan, we must know where to place certain measures. Either the project engineers can calculate every section very carefully or we can place measures along the whole line. Later, the details of the line are studied.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: Usually, we don't get any feedback. It's more common to get feedback if people complain. For houses situated above a tunnel, it is sometimes necessary to measure the ground-borne noise levels.

Q: What aspects make it difficult to work with issues related to ground-borne noise?

A: For ground-borne noise especially, it's necessary that everything is correctly done from the beginning. Problems should be solved directly at the source and compared to airborne noise, we can't install measures in a tunnel after some time has passed.

Q: Should objective-specific noise criteria be further developed?

A: Yes, I think so! It would be beneficial to have these objective-specific noise criteria. This of course still means that there must be the same quality despite the type of building. Different demands can make it more convenient for the developer as it can be a challenge to have the same demands that we have for residential buildings on all building types. On the other hand, having objective-specific noise criteria means that an office can't be upgraded to a residential building. Within The City of Stockholm, we have a policy that we follow, which states that buildings shouldn't be changed, so that the cultural environment is protected. We might need to demolish a house that does not fulfill the ground-borne noise demands and having the same criteria for all buildings creates flexibility on how the building can be used.

Q: What is your opinion on the noise criteria of 32 dBA (max, with time-weighting FAST)?

A: I understand that the value exceeded, but it also means that people can be disturbed five times per night. This can be a problem for the planners, for example when houses are planned along a line. Freight trains can generate higher noise levels which can be problematic if the traffic flow cannot be changed. The freight trains must also fulfill the demands and this can become an issue.

Q: Does a conflict of interest exist between expanding the railway network and protecting people from ground-borne noise?

A: That depends on what the situation was like from the beginning. It is the maximum levels that create problems and not the equivalent level. The train capacity cannot increase if the value only can be exceeded five times per night.

Q: How are problems related to ground-borne noise investigated after the project has finished?

A: Measures are discussed as soon as the line has been localized. Measures are included from the start, because it is difficult to implement measures after the line has been completed. The rail must be isolated and the sections of the line must be analyzed. The measure must be reviewed and it must also be sustainable. For the yellow line, measures are implemented across the whole section and it's only the section under water that doesn't have measures installed. Many parts of the line are characterized by urban areas. I assume that The Roslagen Line also will have measures installed across the whole line.

Q: Is it common to make measurements?

A: It is uncommon to measure as the line is constructed. The FUT model that the consultants have access to in Stockholm can be used to simulate different scenarios and it can also be a tool when investigating complaints.

Q: How are consultants presenting the data?

A: Consultants present the results in a clear way, but there is no uniform way of presenting the results. It can for example be that the maps which give an overview of the ground-borne noise levels in an area can be presented in many different ways. We would like all consultants to present the results in the same way.

Q: How should a new prediction methodology be managed?

A: There must be a clear vision and purpose with the methodology. It must also be remembered so that the methodology isn't forgotten.

Q: What parameters were changed in the FUT model?

A: I know that the train type was changed. If the budget for the project changes, then it can be useful to test different train types depending on what the new decisions are.

Q: Is it possible to see a trend, will ballasted tracks remain as the most optimal choice?

A: I'm not really the best one to answer that question, it's best to ask the rail expert that question.

Interview with respondent 19

Q: What other experts do you need to cooperate with?

A: I work with all aspects of trams in cities and I work with city planning, acoustics and construction. However, trams and rail systems are not only about construction.

Q: What kind of infrastructure projects have you been part of during the last five years?

A: I support projects in the cities of Uppsala and Lund and I also support The City of Stockholm. Other projects are The West Link [Västlänken] and the project at Lindholmen.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: No, I haven't been informed about it.

Q: What is needed in order to work with issues related to ground-borne noise?

A: I'm involved in most stages and my task is to be responsible for the overview. Security issues are another responsibility. It's important to acquire support from the Swedish Transport Agency. It's also important to conduct measurements.

Q: Is ground-borne noise important to investigate in a project? Why or why not?

A: I think that we in general are bad at preparing for ground-borne noise issues. We receive complaints, but the analysis of the problem can be improved. Recently, we have started a project to gather information in order to understand the soundscape. We look into different products, typical railway sections and the construction phase. In Sweden, we don't have that many tunnels that are relatively new and the regulations can vary a lot depending on when the tunnel was constructed. The purpose with this new project is that we want to work more proactive. It can for example be that we want to be more proactive during the procurement process of new trams. It is hard to consider all aspects and there is always an economic cost. There are different demands both from the Swedish Environmental Code [Miljöbalken] and there can also be a difference in who defines these claims. Sometimes, we might not have demands that are adapted to a specific city or to trams. There are differences between trains and trams and the hope is that the project can give information that is adapted to our case.

Q: How will you work with ground-borne noise in the near future?

A: This project that we have initiated, includes analysis of the soundscape and that we want to continue working with. The project builds on smaller projects and we want to be able to make different analyses, depending on the foundation. It can for example be macadam tracks.

Q: What aspects make it difficult to work with ground-borne noise related issues?

A: Noise can be more prioritized and we often have too little data. We use general values, but I would like to know more about the details. We could become better at working with the combined soundscape. I want to know what causes certain vibrations or sounds and in the documentation, the term screech [gnissel] occurs, but it is seldom defined. By understanding what boogie creates a certain sound, the sounds can be described in a better way.

Q: What risks exist when a methodology is managed?

A: The challenge is to coordinate a large team and to extract the data. It has been a challenge to decide what case studies to use and the lack of measurements in tunnels make it difficult. In most cases, the measurement results from one tunnel cannot be transferred to another. Tunnels can have been constructed in many different ways and this means that we must use a cluster analysis. We must be open to unexpected results and the perspective must be widened.

Q: How should a new methodology be managed?

A: The strategy is that we have raised the question and that we want to work more proactive. This has led to a situation where we have received resources and interest in this question. The noise question is relevant in cities.

Q: Is there a trend for rail types?

A: We have slab tracks and rubber materials. Using materials that can mitigate vibrations is a relatively new thing, but it is not always clear what measures can be used in different cases.

Q: Has it been common with complaints from projects?

A: We have not received that many complaints.

Q: Are you including the construction phase in the project?

A: No, we will not include the construction phase. Rather, we want to see what demands we can have during the implementation phase. We want to use the project in many phases and the project will result in a description of the soundscape. The project will not primarily result in a calculation methodology. The idea is that we want to go from a description to a data focused part. An important idea is that we want to be able to test different tram speeds and it would also be interesting to see how the result varies with wear on the rail.

Q: What stakeholder will be responsible for the project?

A: The Transport Administration in Göteborg will have responsibility for the project. The project will be defined in several documents and we need to make sure that the demands are connected to the project.

Q: What general trends do you see?

A: We now see that the trams will become heavier and longer. We have strong reasons to believe that the tram itself must be robust in order to be able to resist vibrations. At the same time, the comfort must be good. New trams generate a rolling noise even if they don't vibrate that much compared to older trams, so new complaints will appear.

Interview with respondent 20

Q: What other experts do you need to cooperate with?

A: So, where I work, acoustics is now a part of track engineering. We have a section called track engineering. Part of my work is improving the technical r and I also work towards the decision makers. I cooperate with property work, maintenance work and all of these fields are related to acoustics. The people from track dynamics are the people that I work most with.

Q: What kind of infrastructure projects have you worked with during the past five years?

A: The Follo Line is one example and projects in Bergen are two examples where we had to look at structure-borne noise. In the Follo Line, we had to use a mass-spring system.

We had different track systems to mitigate structure-borne noise such as the vanguard system.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I'm familiar with it, but I haven't used it. We collaborate with Sweden. We are discussing the frequency range as we are developing our own standard, so we have had presentations on the methodology and discussions with experts from Chalmers and Trafikverket. We have a standardization committee, and they investigate what we need to research. I think it would be good if the methodologies from Sweden, Norway and Finland are harmonized. Then, the consultants could share the information across borders.

Q: How do you work with ground-borne noise in a typical project?

A: We are currently developing a new standard. So far, there has not been a standardized method. Every consultant has to some degree chosen their own methodology and parameters. It's always difficult to evaluate and validate the work even if it is of good quality because of this. The work now will aim to develop a national standardized method. We aim to finish this in 2028 and we currently work on the source terms. One possibility recently discussed is if we can use measurements during the blasting to will give us updated information on the rock porosity and chances to revise parameters before implementing the mitigation measures. We don't know fully how the vibrations are propagating and if we don't have that information, then the assumptions become too conservative and in turn can lead to unwanted introduction of very soft ballast mats. We are comfortable with the 32 dBA as a value for structure-borne noise. We have discussed whether slow or fast time-weighting is best. In Europe, I think that we see a greater focus on ground-borne noise than before. We see this trend from a policy perspective, for example in France.

Q: What is needed in order to work with ground-borne noise related issues? What measures do you use in tunnel projects in Norway?

A: Ballast mats are a common option. For most tunnels, ballast mats are a choice. The challenge is to mitigate enough at the receiver and at the same try to not introduce too much elasticity in the track. We don't want more than 2 mm deflection of the rails. We have the LAFmax value of 32 dBA in Norway, and technical rules that are quite stringent on what static stiffness we allow for ballast mats. This means we often have to deviate from the rules to resolve matters, with the challenge being that we don't know what adverse effect and maintenance schemes this will result in. Currently the requirements are for static stiffness, but there's an ongoing discussion about introducing requirements for dynamic stiffness. The mass springs systems allow for much more freedom. It's much easier to work on that level. We know that we can introduce 10 dB from a mass spring system without concerns. We don't know how a ballast mat will be impacted by for example switches, so we often have more stricter requirements. For a tunnel, the cost is higher than for a normal track. More research could lead to a situation where we could have less strict demands if we know how the transmission actually works and how we can implement different measures.

Q:What would you like to know more about?

A: I would like to know the considerations done when they [the consultants] define the parameters. If we have a standardized method, then we could compare more easily. I lack information on what they have done. The fundamental assumptions are sometimes missing. Sometimes, the dB values are provided, but not the detailed assumptions. It extends the work load to ask and review the reports at several stages. Another aspect is that one method is to blast the rock, so that we get more ballast. Introducing more ballast is a mitigation measure, but it's unsure how to review that mitigation measure. This is called deep blasting, this claims to give a reduction of 3 dB, but we cannot maintain this added depth through regular maintenance, which in turn can lead to adverse effects in the track. For ballast mats, there can also be uncertainty, but we know the values for the ballast mats. We will need more research on this. It can be difficult to implement measures afterwards. More in-depth knowledge is desirable.

Q: What should we measure?

A: I'm interested if accelerometers on trains could be used in order to better understand the source characteristics. The properties of the source are important and properties such as the deflection could perhaps be captured. Short distances could have a great impact on the ground-borne noise levels due to the porosity of the rock. I think that we could have much to gain from knowing more about how sound propagates through a site-specific mediums like porous rocks. I hope that measurements conducted during the blasting can be a feasible option to provide us with relevant information.

Interview with respondent 21

Q: What other fields do you need to cooperate with?

A: At the moment, I'm involved in a project concerning "blast loading" and we want to understand what structures that need to be able withstand vibrations from explosions. It can be about water pipes, so it's not only about the buildings. In this project, we cooperate with other faculties. As a researcher within structural dynamics, we must understand the research results that are produced by other faculties and this is important because then we can ask new research questions. For the individual researcher, cooperation between faculties is not always common, but it is beneficial for the whole faculty.

Q: What infrastructure projects have you been involved in during the last five years?

A: My research is more diverted towards understanding the physics behind vibrations, so I'm rarely involved in more applied projects. I was involved in the project with the central station in Gothenburg. Another example is the Max IV research station in Lund [a research facility that generates X-rays, used for research purposes]. In the Max IV project, they were concerned with the vibrations and not with the ground-borne noise.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I have heard about it, I know that it was a PhD project.

Q: How important are measurements?

A: I work more with numerical simulations, but when conducting measurements, it is difficult to measure correctly. It is not evident that a measurement is correct even if it yields results. For a wooden floor, the eigenfrequency cannot be measured, but the response of the floor is something that we can measure. Then, with a frequency response function, the eigenfrequency can be presented. A homogenous wooden floor can we conduct measurements on, but it is much more difficult to measure ground-borne noise.

Measurements are very important. We can always construct models, but they must represent reality. In our projects, we always use measurement data, except for when we develop an algorithm.

Q: How do you model vibrations?

A: The finite element method [FEM] is useful, but it has its limitations at higher frequencies. At higher frequencies, details are important to capture and at that point, FEM can no longer be used. If the air volume is to be included, then FEM is also insufficient. A combination of FEM and SEA can be used. For capturing the actual noise, then SEA is more suitable than FEM.

Q: How often do you use a combination of programs or approaches in your research?

A: In most projects we have used FEM. For ground vibrations, we have used semi-analytical methods. FEM becomes difficult for ground vibrations. For modelling ground vibrations, a large geometry is needed, otherwise reflections from the boundaries will occur. With semi-analytical methods, a stiffness matrix is created and results from this matrix are combined with results from FEM. FEM is used to model the building, while semi-analytical methods are used to model the ground. The different methods do not imply limits, instead it is the scope of the specific research question that defines the limits. For ground-borne noise, I can imagine that a FEM model is not enough and one part must perhaps be replaced with a machine learning program. For ground-borne noise, the difficult part is to model the transmission between the tunnel wall and the structure. There is a great deal of uncertainty, especially regarding the soil properties.

Q: How are you working with the uncertainty?

A: Both for vibrations on a wooden floor and for vibrations that are induced by trains, we have investigated how different parameters affect the uncertainty. We have used Monte Carlo simulations where normally distributed data is processed. Within the field of dynamics, we use pre-defined methodologies, but at the same time, we want to know more about the uncertainty. The goal is to understand the material parameters, but also to understand the models. Researchers used many assumptions and one way to understand more on the assumptions is to compare them. For example, the dynamic properties have been measured for CLT [Cross-Laminated Timber] panels and this gives a variation. There are larger organizations that also work with uncertainties and there are data on reasonable values for the standard deviation for common properties. Correction factors are used to describe what parameters affect each other.

Q: How do you work with the risk that project results can be overestimated, that you have too large margins?

A: In my projects we investigate research questions related to the basic research. Eurocode has made it easier to construct buildings, but for optimizing a detail, Eurocode can sometimes not be the best solution. For modelling details, FEM is better. Margins are deliberately chosen in projects because buildings must be safe. Another aspect is the cost. No building is identical and optimizing a building takes time which in turn increases the cost. Optimization requires more advanced numerical methods and this takes time. Over-optimization is a problem for the construction sector and it does not become more easy when there are multiple stakeholders involved in the building process.

Q: What is a valid frequency range for ground-borne noise?

A: I'm unsure how it is for ground-borne noise, but for vibrations we use frequencies up to about 80 Hz. Most of the energy for vibrations are found in the range 10 Hz–60 Hz. The ISO standards generally mention that the limit is up to 80 Hz. It becomes a bit more complicated because the higher frequencies are damped by the soil layers. Humans can be sensitive in different ways. If residents can see the source, it becomes less disturbing.

Interview with respondent 22

Q: What other fields do you need to cooperate with?

A: I work with all environmental issues, so there are many environmental fields that I work with. Used to work more with soil and water questions.

Q: What other infrastructure projects have you been involved in during the last five years?

A: For now, it has been The West Link, but before that I worked with the project at Olskroken.

Q: Are you familiar with the new prediction methodology that has been developed by Chalmers together with Trafikverket?

A: I have heard about it, but I can't explain it or the details.

Q: What is needed in order to work with ground-borne noise related issues?

A: A complete calculation procedure is needed. When we don't have enough information on the property that we are working with, then that is a problem. Sometimes, we have information on a property from an archive that doesn't seem to be correct when we actually start working with the building. The consultants that are responsible for the measurements often want to have information on the foundation.

Q: What makes it difficult to work with ground-borne noise?

A: It is hard to attenuate the ground-borne noise. If we reduce the ground-borne noise, then the vibrations will start to be more dominant and vice versa. We build for a long period of time and the ground-borne noise is often perceived as more disturbing than the airborne noise.

Q: What does the construction phase look like?

A: A project starts with a planning phase where we design the structure and investigate if there will be ground-borne noise problems. Large projects include an environmental assessment and for ground-borne noise, the disturbance is analyzed. Ground-borne noise always occurs in big cities and is hard to mitigate. For the construction phase, we have specific demands and we also inform the residents on the disturbance. An initial calculation is performed and more detailed calculations are performed as the project proceeds. The problem with the first calculations is that they aren't precise. First, we need to know what the foundation looks like. We are provided with more ground-borne noise reports from the consultants during the construction and we also review the reports if we have questions. We also conduct measurements so that we can compare the results from the consultants. Complaints are another important part. Complaints can give an indication on how accurate the calculations are because if the calculated levels were actually too high, we will receive more complaints.

Q: Is it common that you receive complaints?

A: Some residents complain and others do not. We offer accommodation during the day when we are drilling, but few actually take the offer.

Q: What measures can be used for the construction phase?

A: For the construction phase, there is not so much that we can do. When we drill in the rock, ground-borne noise is generated and when we drill directly below the house, the ground-borne noise level is particularly high.

Q: Are the ground-borne noise reports clear and easy to interpret?

A: We have demands and the reports are clear, but there is no standard. The demand that we have is that we verify calculation results by conducting measurements. It is special to work with rock because we don't know what the conditions are. It can for example be that the rock is characterized by formations that we suddenly discover. For the construction phase we have different demands that we evaluate and we follow the demands from the Swedish Environmental Protection Agency.

Q: Have you had any cooperation with other countries, for example Norway or Finland?

A: We don't have a cooperation with other countries, but we have looked at similar cases in Sweden.

Q: How is the drilling process performed?

A: Drilling is the main source of the ground-borne noise. Some residents think that the ground-borne noise from the blasting is worse, but after all it is limited to a certain period of time. Fracturing is the method used and this method involves drilling. The working environment is improved when fracturing is used compared to blasting. Another method is to use a rock saw and this is done to reduce the vibrations. Reducing vibrations that can damage buildings has a higher priority than reducing ground-borne noise. The vibration levels cannot be exceeded, while the ground-borne noise levels can be exceeded. When blasting, we drill holes in the rock that we fill with liquid explosives.

Q: What problems exist regarding the organization of the work?

A: Sometimes, it can be that tasks, such as drilling, are performed simultaneously, but at different locations. The ground-borne noise levels can sometimes be underestimated.

Q: Do you have a certain working procedure?

A: We have developed a specific working procedure, but there is also a practice in the building sector. It can be a problem related to how demands are to be interpreted and there are few acousticians who work with the construction phase. Time is an important factor and we often have a need for quick assessment reports and the conditions can change fast.

Q: Is it possible to identify a trend?

A: We see that the demands increase and another trend is that the structures become more and more complex. Building more complex structures requires new building methods that haven't been used in Sweden that much before, which in turn makes it uncertain what the consequences and effects will be.

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