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How to plan an Everyday Life with less Noise Pollution

Ingvald Festøy Desserud
Stian Ruud Vaktdal

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Supervisor: Odd Kr. Pettersen, IET

Norwegian University of Science and Technology
Department of Electronics and Telecommunications

Problem Description

Norsonic and Sintef are working with a project where the purpose is to use real measurement data as a basis to calculate noise maps. The goal for the final system is to have a real time update over the noise situation over a larger area from a limited amount of measuring points.

This project will focus on traffic noise. The goal is define microphone positions relative to the road which give accurate source estimation. The task will be to compare simulations based on measurements with actual control measurements and simulations from existing noise computation software.

Assignment given: 01. February 2008
Supervisor: Odd Kr. Pettersen, IET

Preface

This report is a master thesis at the Institute for Electronics and Telecommunications (IET) at the Norwegian University of Science and Technology (NTNU). The thesis is done in co-operation with Sintef and Norsonic as a step in the development of a Nord2000 software implementation.

Thanks to our supervisor Herold Olsen at Sintef IKT and Thorvald Wetlesen at Norsonic for their help and guidance in this thesis. Our subject teacher, Odd Kr. Ø. Pettersen, at Sintef IKT and NTNU also deserves a thanks for the useful input during the course of this thesis.

Abstract

In this master thesis a software, MapMonit, that use real measurement data as a basis to calculate noise maps was studied. The project focus on noise from roads. Simulations in MapMonit based on measurements were compared with control measurements and simulations of existing noise computation software. The software used for comparison was CadnaA.

The project started with measurements of road traffic noise with four microphone heights at four distances that would be used as input to the software called MapMonit. Since this was the first time the software ever got tested with real measurements, the first test site was chosen to be as simple as possible with a long, straight road and surrounding flat fields. The microphone distances from the road edge were 5 m, 10 m, 20 m and 100 m with microphone heights 0.4 m, 1.5 m, 2 m and 4 m at each of the distances. A grid of control microphones were positioned in the vicinity from 10 m to 180 m from the road edge.

At distances 5 m to 20 m for microphone heights 1.5 m to 4 m, the results turned out to be very good. The difference between the A-weighted levels of MapMonit simulations and the control measurements was generally less than 1 dB for all control positions. Compared to CadnaA, the two simulated levels were very similar for propagation paths up to 100 m with differences below 1.4 dB. At control distances over 170 m, the difference was very high, up to 5.3 dB, with MapMonit simulating the highest values. A complicated test site in the vicinity of a noise screen were also studied. The reference microphones for input to MapMonit were placed in front, above and behind the screen, and one behind a garage also on the quiet side. The control measurements were placed around the neighborhood at the quiet side of the noise screen. Due to a flaw with the MapMonit software implementation, the results were presented with flat topography.

The reference microphone in front of and above the noise screen gave satisfying results, with differences less than 2 dB at all control positions except for a position just behind a garage. Obstacles along the propagation path included both a noise screen and buildings. Choosing the microphone mounted just above the noise screen, the difference between the A-weighted levels of CadnaA and MapMonit was less than 1 dB for all positions except the one behind the garage.

Contents

Chapter 1

Introduction

Noise maps shall be made for cities with 100 000 citizens or more throughout the European Union, also for Norway, within the year 2012. This is done by advanced computer programs in order to map how many people are exposed to noise, and how this can be limited by noise restricting actions.

This report will concentrate on noise from roads. In present computer software the source strength of the road is defined by input data such as vehicle frequency and speed. Another approach is to define the source strength with real measurements. This report will test an software implementation of this approach. The software is build on nord2000, the new Nordic Environmental Noise Prediction Method. Noise map simulations based on measurements from this software will be validated with real measurements and the present standard of computer software for noise map calculation. The goal is to define microphone positions relative to the road which give accurate results.

Chapter 2

Theory

2.1 Introduction to Nord2000

The Nordic Environmental Noise prediction Method is a detailed model for calculation of environmental noise. It is divided into two separate parts, a propagation model and a source model. The propagation model is based on modern ray theory and theory of diffraction. It includes topography with surface definition, weather conditions, buildings and man made noise obviations like noise screens. The source model is divided into rail, road and industrial. All calculations are carried out in one-third-octave band levels, which makes the model very powerful [4] [11] [5].

2.1.1 Road Source Model

In Nord2000 a road source is represented by individual moving vehicles. Vehicles are defined in different categories such as passenger cars and heavy vehicles. Each category has its own source model. Each model consists of a set of sub sources. The difference between the vehicle categories is the positions of the sub sources, their strength and frequency distribution. Passenger cars are defined by three point sources of height 0.01 m, 0.15 m and 0.3 m above the road, while heavy vehicles have an extra source at 3.5 m. The sources are located at the nearest wheel relative to the receiver. The vehicle source data are based on measurements of real vehicles and represent source strengths in one-third-octave band levels. The source strength for a given vehicle category varies with speed, asphalt type, driving conditions and road temperature. Complete measurements with all combinations of these parameters are not available. Therefore, the starting point for defining the source strength is vehicle category and speed. Then corrections are made based on road surface, road temperature and driving conditions. [11]

2.1.2 Calculation of Noise Emission from a Road

A road is divided into a number sub segments. Given the composition of vehicles and other input data the sound exposure levels at the receiver for each sub source is calculated for each segment. Each with corresponding propagation path and directivity. The contribution from all the road segments are summed at the receiver.

2.2 Principle behind defining the Source with a Measurement

For a given terrain and weather condition the propagation between two points is linear, so the transfer function represented by the propagation is independent of source strength. This, and the fact that the propagation model and the source model are separated in Nord2000, makes it possible to use the superposition principle to separate the two. The sound level at the receiver L_R, can be written [1]

$$L_R = F(x_{source}, x_{propagation}) = F(x_{source}) + F(x_{propagation}) \quad (2.1)$$

where F is the Nord2000 model, and the source and propagation parameters are x_{source} and $x_{propagation}$, respectively. This is valid for a single point source. In Nord2000, each source is divided into a number of sub sources, n. Introducing this and sound levels for the source and propagation we get

$$L_R = 10 \cdot \log \sum_{i=1}^{n} (10^{\frac{L_{source_i}}{10}} + 10^{\frac{L_{propagation_i}}{10}}) \quad (2.2)$$

If the sub sources had different source power, it would not be possible to distinguish them and connect the right sub source to its corresponding propagation path. However, the Nord2000 model [11] assigns equal strength to each sub source in lack of available reference measurements. This gives

$$L_R = 10 \cdot \log \left(10^{(\log n + \frac{L_{subsource}}{10})} + \sum_{i=1}^{n} 10^{\frac{L_{propagation_i}}{10}} \right) \quad (2.3)$$

Rearranging gives the equation for the sub source sound level

$$L_{subsource} = 10 \cdot \log \left(\frac{10^{\frac{L_R}{10}} - \sum_{i=i}^{n} 10^{\frac{L_{propagation_i}}{10}}}{n} \right) \quad (2.4)$$

L_R can be measured. The $L_{propagation_i}$ levels, while they are constant, can be determined by a simulation. The source strength set in this simulation is not important when we only are interested in the level difference between each sub source and the receiver.

[1] Major simplifications are made. Directivity and scaling of the source strength based on speed, road surface, driving conditions and road temperature are not included. Single sound levels are used when there should be one-third-octave band levels.

To sum up, the backward calculation from a measurement to the source strength includes

- A measurement of the desired source and a defined environment in a Nord2000 implementation.
- A simulation to define the level difference between each sub source and the receiver.
- A comparison of simulated level and measured level. One-third-octave band levels of the source are corrected accordingly, so a simulation with the corrected source strength gives the measured values in the microphone position.

2.2.1 Calculating Source Strength from a Multiple of Vehicles from Different Classes

In theory it is not necessary to know the number of vehicles included in the measurement to calculate the source strength. Given they represent the same vehicle class, a single source calculation as described over is adequate when the sum of two vehicle passings in a given time interval is the same as a single pass by with twice the source power. However, if the vehicles represent different vehicle classes, their source strengths and positions are different. This makes the source calculation a bit more tricky. One calculation for each vehicle class must now be carried out. In addition, to be able to find the contribution from each vehicle class, the relative level difference form each class must be known. Dependent on speed, there is a given level difference for the source data of the different vehicle categories. In addition, the calculations from each class must be scaled according to the vehicle composition. This means that both the speed and the vehicle composition must be known for accurate results.

2.2.2 Measurement Length

Different applications requires different measurement lengths. One goal can be to do a single measurement to define the noise contribution from the road. Another can be to map the noise situation close to real time. In the first application the measurement length must be as long as necessary and in the other as short as possible.

With a single moving vehicle as source, a measurement must include the whole pass by to be able to define the source correctly. This is because the source calculation in Nord2000 includes contributions from every part of the road, including directivity. The pass by time is dependent on vehicle speed and the microphone distance relative to the road. In practice, a pass by in Nord2000 , is restricted to $\pm 79^o$ which gives a error of less than 0,5 dB compared to $\pm 90^o$[11]. With high vehicle frequency, a shorter measurement period can theoretical be used, when there at any time are vehicles at every position of road, so there correspondingly at a receiver position are contributions from every part of the road. However, no road has this high vehicle frequency, so with a limited time interval, an uncomplete pass by will occur and introduce an error. Increasing the measurement time will decrease the error when a single pass by now contributes less to the total sound exposure level. When defining the source strength of a road for a given time interval, it is the total noise situation at the road which is interesting, not a single pass by. To give accurate results, the vehicle composition must be known. A heavy vehicle both have different source strength and source location than a smaller vehicle. The best solution would be to measure the traffic, but then it is not so much of a point in measuring the noise also, since the vehicle information is enough to give a good description of the noise situation with present software. The vehicle composition of most larger roads are known, but these are calculated based on yearly average. A solution would be to use this average vehicle composition for every time interval measured. A shorter time interval will then most likely give larger error when the composition most likely not are representative. The obvious solution is to set the measured time interval long enough to have a good representation of the average vehicle composition.

2.2.3 The Importance of Input Variables

As described in Chapter 2.1.1, the source strength is based on a number of input variables. When the source is defined by measurements, some of these variables does not need to be set, their effects are measured directly. This is true for road temperature, speed, asphalt type and driving conditions. Take the asphalt type for example, this gives some corrections to the frequency levels of the source, but these corrections will automatically be measured by the microphone. The corrections may not even be accurate for that specified situation. Taken this into consideration, and that the source is measured correctly, the source definition based on measurement should be more accurate than the premeasured source definitions with corrections.

The importance of setting the input variables depends on application and situation. If the goal is a local noise map around where the source was measured, and the variables affecting the source are considered to be constant, the variables have no influence. However, the variables are important in more complex situations.

The variables will be important if they change along the source. Local changes around where the microphone is placed are obviously important, as this will give different scaling of the source strength from different parts of the road. For instance, if the microphone is placed at the bottom of an uphill road, the flat part of the road will have different driving condition than the uphill slope, and therefore different source scaling. Even if the variables are constant around the microphone, they may change for other parts of the road, which again will influence the calculation of the total noise map. So if the speed changes some kilometers down the road, and this part also contributes to the noise map, it is important to set the speed both where the source measurement was carried out and for the rest of the road. To summarize, even if the input variables may be unimportant for local situations, they are important for the big picture.

A typical application could be to measure a road, calculate a noise map, and then look at preventive actions to reduce the noise. For example, what happens to the noise level if the speed limit is decreased or another asphalt type is used? Here, the source variables have to be set in order to give accurate results.

2.3 Problems with defining the Source with a Measurement

The most critical part of defining a source with measurements, is background noise. The backward calculation will assume that all the sound at the microphone originate from the road source. With dominating background noise present, a too high source power will be estimated. The signal-to-noise ratio will decrease with increasing distance from the source to the microphone. This means that a microphone position as close to the road as possible should be preferred. However, placed too close to the road, the microphone may be affected by air drought noise from the passing cars. Placing the microphone too close to the road, may also contribute to miscalculate the noise contribution from the different sub sources. In reality, the sub sources of the vehicles are not of equal source power such as the approximation in the Nord2000 model. The main source of smaller vehicles are close to the road, while for heavy vehicles the main source is on the middle. According to [10], this gives an error of 0.6 dB at a distance of 7.5 m.

An error is also introduced by the propagation model. This error will increase with the complexity of the environment between the source and the microphone. When the propagation introduces errors when calculating the source, an corresponding error is introduced at the source strength. If the propagation simulates a level 2 dB higher than actual, the source will be estimated 2 dB to low when the sum of the source strength and the contribution of the propagation has to equal the measured value. To minimize this, the environment should be defined as accurate as possible, and simple environments should be chosen if possible. The propagation error also includes the weather, so this should also be measured and used as input instead of standard weather settings.

Chapter 3

Methods

The purpose of this chapter is to give an overview of the measurement methods, in addition to state the reasons for the choices made with respect to the measurement setup. How the data has been collected, the procedures for data processing, the software used and the different test locations will also be described.

3.1 Scope

The goal is to define a procedure for measurement of a road as a noise source. This mainly includes microphone position relative to the road and measurement time. Measurements with different microphone positions in terrains with different complexity will be carried out. To determine the quality of a measurement setup, the following steps are taken:

1. Measurement of noise from a road.
2. Backward calculation, calculation of source strength based on the measurement.
3. Forward calculation, calculate noise in a number of control positions.
4. Compare calculated values in the control positions with actual measurements in these positions and simulation with other computer software.

Step two and three are done with the MapMonit software described in Chapter 3.3. The software used for comparison in step four was CadnaA described in Chapter 3.4.

3.2 General plan

The first step is to validate the principle with source calculation based on measurement. This will be done by measuring a long straight road with constant vehicle flow placed on a simple flat terrain. This will minimize errors introduced by the propagation model, Nord2000, and the main focus will be on the **source model** and microphone positions relative to the source. Since MapMonit is a prototype software never used before, it will also be easier to find and debug errors this way. The measurements should be done with favorable weather conditions and the terrain should be defined as accurate as possible. On this simple location, measurements with different microphone heights and distances relative to the road will be carried out. The measurement time must be so long that time intervals with favorable weather conditions can be extracted, and short time variations in the traffic flow can be neglected.

When the results from the simple test site have been carried out, a more complicated scenario will be measured. A measurement location with more complicated terrain, noise screens, buildings and non flat terrain will be chosen. This means that microphone positions with increasing complexity of the propagation path from the road will be studied. The chosen location was an urban neighborhood located by a four lane highway, with noise screens on each side on top of a mound. This is a realistic scenario in which the MapMonit software is supposed to be used.

3.3 MapMonit

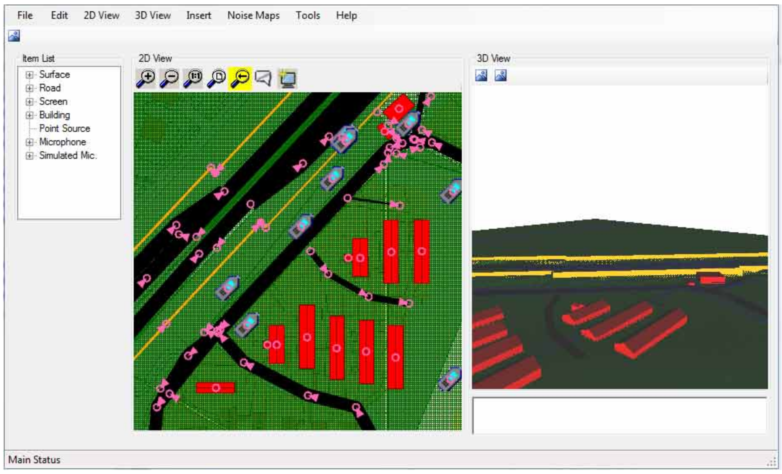

Figure 3.1: MapMonit user interface.

MapMonit is a software for calculation of noise maps based on the Nord2000 [4] model. What makes MapMonit different from present noise simulation software, is that the source strength is calculated based on measurements as described in 2.2. The main window of MapMonit is shown in Figure 3.1. In the 2D view on the left, a bitmap can be imported to serve as a template for placing buildings, roads, noise screens and surfaces, all with varying parameters as defined by Nord2000. A reference microphone with the measured sound levels is placed on the map where the measurements are carried out, and this reference microphone is linked to a noise source.

In this prototype, it is only possible to apply one reference microphone in each scenario. Simulated microphones can be placed in endless numbers though, and make it possible to export noise levels in one-third-octave band resolution. In addition, MapMonit can present the results as a noise map over a selected area. Topography with desired resolution can be included by importing a matrix with the height variations. Weather conditions can be set separately for source definition and for the calculation of the sound levels at the simulated microphones. The vehicle composition is locked and set to only small vehicles with a frequency corresponding to 1000 passings a day. The speed is locked to 80 km/h.

3.4 CadnaA

CadnaA is a Windows based program for noise prediction. The program calculates and predicts noise immission in the neighborhood of trade enterprises, industrial plants, sport and leisure facilities. In addition it predicts noise immission from traffic systems like roads, railways, airports, landing strips or any other noise facilities. In this master thesis, noise emission from roads is the only noise source needed. These source and propagation models follows national and international standards. For roads in Norway, the Nord96 [1] standard was chosen.

In addition to different noise sources, CadnaA also has buildings, surfaces, noise screens, and much more to make the location maps as precise as possible. It is possible to import bitmaps, scanned maps or digital photos. Such bitmaps can be loaded as background in CadnaA, and serve as template for the definition of roads, buildings, noise screens, receiver points, hight curves and other objects. When the map has been drawn correctly with correct ground absorption, building reflection loss etc, the noise source can be estimated. A road noise source has a few vital inputs in order to set the noise level; hourly traffic, average speed, road surface and road gradient.

After this is done, the maximum number of sound reflections in the calculations can be set. The result can be a noise map over the selected area, or tables can be produced with the noise levels at entered receiver points.

An important notice is that CadnaA use the Nord96 [1] standard with a preset favorable weather condition. The sound paths are refracted downwards, for example during downwind. This means that the wind is set to blow from the dominant noise source to the receiver. The wind speed in height 3 m to 11 m above the ground is between 2 m/s and 5 m/s [1].

3.5 What is measured

3.5.1 Reference Measurements

The reference measurement is the input sound level which MapMonit use to estimate the source strength. The noise is recorded in one-third-octave bands with center frequencies from 25 Hz to 10 kHz. The measurements had a time resolution of 1 min on the first measurement site and 1 s for the second. The reference microphone setup specific for the two test sites is described in Chapter 3.7.

3.5.2 Control Measurements

Control measurements were executed in order to evaluate MapMonit simulation levels in one-third-octave bands with center frequency from 25 Hz to 10 kHz. The measurements were 15 minutes of length with one minute resolution at each position (on second for the second measurement site). The sound level meter was mounted on a stand 1.5 meters above ground, see Chapter 3.7 for the control measurement setup specific for the two test sites.

3.5.3 Weather measurements

The weather was measured to ensure favorable weather conditions, and as an input to the Nord2000 implementation for correct sound propagation. It was recorded with a weather station placed along the propagation path between the road and the reference and control microphones. The data recorded includes temperature, wind speed, wind direction and humidity. The time resolution was 10 min. The Nord2000 model also requires the temperature gradient. This data was given by the Norwegian Metrological Institute. Regarding the wind noise, it is assumed that the one-inch free field microphones have similar characteristics as the half-inch that has been used in the measurements. With the windscreen used, they should handle wind speeds up to 10 m/s without getting any noticeable wind induced noise on the measurements [8].

3.5.4 Traffic Measurements

Traffic data are required for input to CadnaA and as reference to the measurements. At the simple test site, see Chapter 3.7.1, traffic data from both a radar and Vegvesenet's counting station was used. The radar can register the time of each vehicle passing in addition to speed and length of each passing vehicle in both lanes [3]. The counting station registers one hour values of total vehicle passings in each lane, average speed and share of heavy vehicles. At the complicated test site, see Chapter 3.7.2, the road had four lanes, and since the radar has a limitation of two lanes it could not be used. Since no counting station was in the area either, the traffic was video recorded for an hour and counted manually.

3.5.5 Ground Impedance Measurements

On the simple test site, the ground impedance was measured to minimize errors in the simulations. The ground was measured and classified according to the one-layer model described in the Nordtest Standard [7].

At the complicated test site, the control measurements was positioned in a quiet neighborhood. Instead of measuring the ground impedance class, it was chosen based upon the impedance class examples listed in Nord2000 Road [11].

3.6 Data Processing

The purpose of this section is to describe how the data are processed before the results are presented in Chapter 4.

3.6.1 The Direct Comparison Approach

The obvious way of comparing MapMonit simulations with control measurements is to use control measurements and reference measurements from the same time interval. This is referred to as the Direct Comparison Approach. This is however difficult to achieve with many control positions. It would lead to many simultaneous measurements, and therefore a lot of measurement equipment. When control measurements in multiple positions are executed with a limited and different time interval in each position, there are two possibilities. The first is to compare simulations from each control time interval corresponding to each control measurement. This requires one simulation and one input interval for each control measurement. With eleven control positions and four reference microphones at four distances this means over 150 simulations in MapMonit. Another possibility is to use the difference approach described in Chapter 3.6.2.

3.6.2 The Difference Approach

Take two noise level measurements, L_{eq1} and L_{eq2}, from the same time interval t_1 at different positions with respect to a sound source. The source in this case is a road. The level difference between position one and two is given by

$$\Delta L_{eq_{t1}} = L_{eq1_{t1}} - L_{eq2_{t1}} \tag{3.1}$$

Given the source position is constant, it is the only source, and that the variables affecting the sound propagation are constant, $\Delta L_{eq_{t1}}$ is a time independent constant. Once ΔL_{eq} is known for one time interval, the sound level of position two can be calculated for any other time interval t

$$L_{eq_t} = L_{eq1_t} - \Delta L_{eq} \tag{3.2}$$

This approach can be used when comparing a control measurement from one limited time period with a simulation based on a measurement from a different time interval. The correction, ΔL_{eq}, will be calculated for each control microphone position and each reference microphone. The corrected control measurement for any time interval can then be written as

$$L_{control_t} = L_{reference_t} - \Delta L_{correction} \tag{3.3}$$

The requirement is that it for the time period of the control measurements also is measured at the position of the reference microphone used as input to the simulations.

This method is not without problems. The source and the variables affecting the sound propagation are most likely not equal for the time intervals of the control measurements and the time interval used as input to the simulation. The source will vary when the passing vehicles have different source positions. Regarding the source position, the difference between light and heavy vehicles is the most critical. Theoretically, the control measurements should therefore be long enough to include the vehicle composition to give accurate results.

The propagation variables are the ground impedance and weather conditions. To minimize the problem with varying propagation constants, the approach can be modified to use the propagation conditions for the input interval for backward calculation and the propagation conditions for the intervals of the control measurements for forward calculation. The MapMonit software makes it possible to use different weather conditions for forward and backward calculation.

Simulating with different weather conditions cause another problem. When calculating backward from a reference microphone to the road, and then forward from the road to the position of the reference microphone with different propagation conditions, the results from the forward calculation will differ from the measured level at the reference microphone. The control measurements must therefore be corrected to the simulated value in the position of the reference microphone in order to take the propagation constants during both the backward and forward calculations into account. The procedure for calculating the corrected control measurement for a given time interval becomes:

- Calculate the difference between the reference microphone and the control microphone for the time interval of the control measurement. This is the correction valid for the propagation conditions for this time interval.

- Calculate the source strength of the road with backward calculation from the reference microphone with the propagation conditions for the time interval of the input measurement.

- Calculate the level at the same position as the reference microphone with the propagation conditions for the time interval of the control measurement.

- Correct the control measurement with this simulated value according to Equation 3.3.

Now the problem is that the weather conditions for each individual control measurement may vary. For exact results, simulations for each control measurement with corresponding weather conditions must be carried out. This makes the difference approach just as little flexible as the direct comparison in Chapter 3.6.1. The solution is to use the mean weather conditions for the time period of all the control measurements. This will introduce some errors since all the control measurements were performed during two to three hours, but it will be the best approximation if not the direct comparison can be used. However, as long as the the control measurements are executed during somewhat constant weather conditions, the error introduced will be small.

3.7 Measurement Setup and Locations

3.7.1 Simple Test Site

The first test site was a long straight, two lane road located on a large and almost flat field. An air photo of the site can be seen in Figure 3.2. The measurements were carried out on the west side of the road. Road information is listed in Table 3.1. The road was elevated 1.3 m above the surrounding fields as can be seen on Figure 3.3. The only other noise source in the vicinity, was a gravel road with none or very little traffic which led to a farm on the west side of the main road.

Location	Road ID	From	To
Norway, Sør-Trøndelag	EV6	Hp 8 - 8300 m	Hp 8 - 9400 m
Traffic, 24 hours	**Age (build)**	**Asphalt class**	**Speed limit [km/h]**
13500	1998-2000	1a Mastic. Asph. 8 - 10 mm	70

Table 3.1: Road information for the simple test site. Asphalt class as defined in [6]. The terminology for defining the stretch of road is from the National Road Database [12].

Figure 3.2: Overview of the simple test site.

Microphone Positions

This site includes four main scenarios with reference microphones placed at 5 m, 10 m, 20 m and 100 m from the road edge. For each distance, measurements with reference microphones at height 0.4 m, 1.5 m, 2 m and 4 m above ground were used, see Table 3.2 and 3.3. These microphones were placed in a mast as seen in Figure 3.3. All four reference microphones recorded simultaneously. The microphones recorded continuously for at least 24 hours at each position.

Control measurements were carried out at eleven different positions in the field on the west side of the road. Each of these recorded 15 minutes with the microphone 1.5 m above ground before the sound level meter was moved to next position. The control microphone positions can be seen in Figure 3.4. The weather station was mounted in the top of the mast 5.5 m above ground, 1.5 m above the highest reference microphone.

Figure 3.3: The mast with mounted reference microphones.

Height above ground [m]			
0.4	1,5	2,0	4,0
Distance from road edge [m]			
5	10	20	100

Table 3.2: List over the different reference microphone heights and distances. All the microphone heights are represented at each distance.

Control microphones						
Microphone ID	1-3	4-7	8	9	10	11
Distance from road edge [m]	10	60	67	110	167	181

Table 3.3: List over the different control microphone distances. All microphones were placed 1.5 m above ground.

Implementation in MapMonit and CadnaA

Since the road was straight, and the surrounding topography was very simple, this was easily implemented in MapMonit. A 2 km long, straight road was first entered, elevated 1.35 m above the surrounding flat fields. As seen in Figure 3.5, the road is positioned

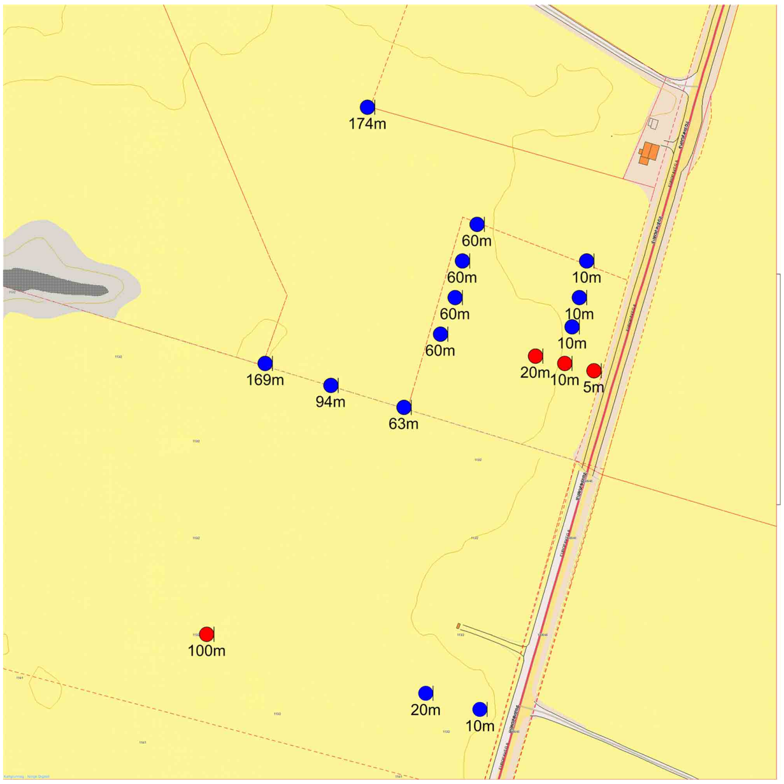

Figure 3.4: Overview over all microphone positions. Reference microphones shown in red, control microphones in blue.

north-south, while the actual road is tilted a little toward north-east. The reason was that it was easier to implement this in MapMonit, and the wind direction could be adjusted so the angle was implemented correctly with respect to the road. A house and a little garage were entered just north of the microphone positions, while a stack of pallets covered with tarpaulin were entered as a small building just to the south. A surface with the measured ground impedance was entered for the entire area.

Instead of having three control measurements at 10 m and four at 60 m, only one control point at each distance was entered in CadnaA. This was done since the control points at the same distances give the same results. Otherwise, the map was made in the exact same way in CadnaA. The input parameters are listed in Appendix E, only the hourly traffic was changing according to each time interval. The implemented maps of both MapMonit and CadnaA are shown in Figure 3.5.

3.7.2 Complicated Test Site

This test site was in an urban neighborhood next to a highway carrying a great deal of traffic. An air photo of the location is seen in Figure 3.6. The road has four lanes, two in each direction, separated by a one meter high concrete wall. Road information

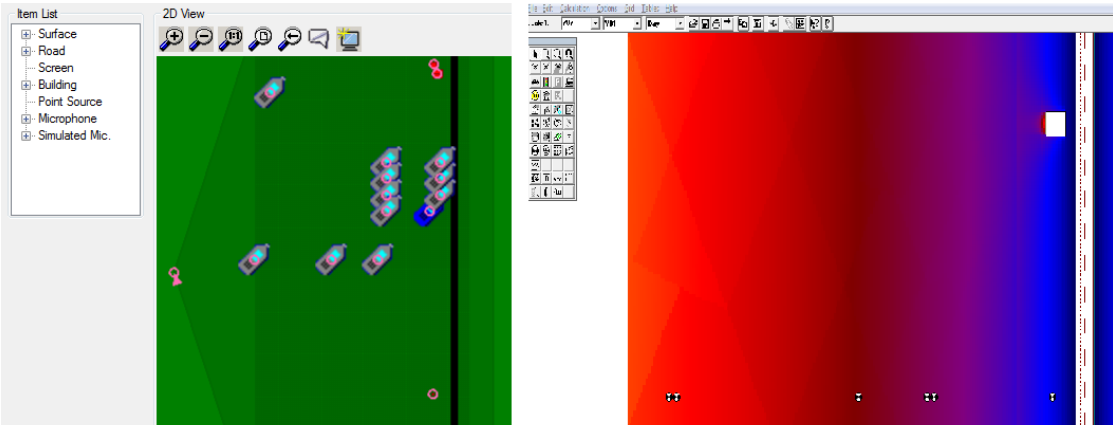

Figure 3.5: Left: Implemented map in MapMonit. Right: Implemented map in CadnaA.

is summarized in Table 3.4. On each side of the road, there were high mounds with an absorbing noise screen on top. On the east side of the road, where the reference and control microphones where placed, there was a neighborhood with mostly one floor houses. A few small roads with very little traffic went through the neighborhood, and the ground was mostly covered with short grassed lawns. On this site, the weather data from a nearby national weather station were used instead of local measurements.

Location	Road number	From	To
Norway, Sør-Trøndelag	EV6	Hp 12 - 3300 m	Hp 8 - 4300 m
Traffic, daily	**Age (build)**	**Asphalt class**	**Speed limit [km/h]**
31800	1998-2000	1a Mastic. Asph. 8 - 10 mm	80

Table 3.4: Road information for the complicated test site. Asphalt class as defined in [6]. The terminology for defining the stretch of road is from the National Road Database [12].

Microphone Positions

Four reference microphone positions were used on this test site. They were placed in the vicinity of the noise screen. One was placed on the road side of the noise screen with height 2 m above ground, and one 0.5 m above the noise screen (5.5 m above road plane). For the last two microphones, one were placed 7 m behind the noise screen on the quiet side, and one behind a garage also on the quiet side. The reference microphones recorded continuously for 2.5 hours, the control microphones for 15 minutes in each position. Due to frequent dominating background noise, some control measurements were repeated several times to ensure good measurements intervals. The four reference microphones were also used as control measurements. Both reference and control measurement positions can be seen in Figure 3.7.

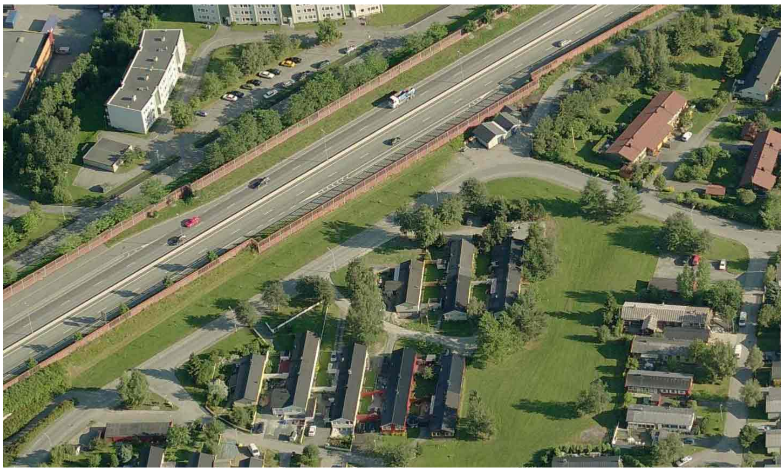

Figure 3.6: Overview of the Angeltrøa test location.

Reference microphones				
Height above ground [m]	2.0	5,5	1.5	1.5
Distance from road edge [m]	6.4	10.0	17.0	22.0
Distance from noise screen [m]	3.0	0.0	7.0	12.0

Table 3.5: List over the different reference microphone heights and distances.

Control microphones										
Microphone ID	1	2	3	4	5	6	7	8	9	10
Height above ground [m]	1.5	1.5	1.5	1.5	1.5	1.5	1.5	2.0	5.5	1.5
Distance to road [m]	16	37	24	60	100	120	6.4	10.0	17.0	22.0

Table 3.6: List over the different control microphone heights and distances.

Implementation in MapMonit and CadnaA

Figure 3.8 shows a snapshot from the complicated measurement site as implemented in MapMonit. A bitmap with a map over the location was imported as background image. The road, buildings and surfaces were placed on top. As seen in the figure, the most important elements between the source and the control microphones were included. The surface classes were selected from a description given in [4].

The implementation of topography in this prototype introduced huge errors when used in combination with a noise screen, so a flat topography had to be used. The two lane road was included as two roads with the same identification. The concrete wall between the lanes was not included, when no standard element for this is implemented in MapMonit. The noise screens were included with absorption on both sides. The absorption coefficient was the standard included in the MapMonit software, and could not be changed. Figure 3.9 shows a snapshot of the 3d map made in MapMonit. The map in CadnaA was made in the exact same way. This means no topography was included

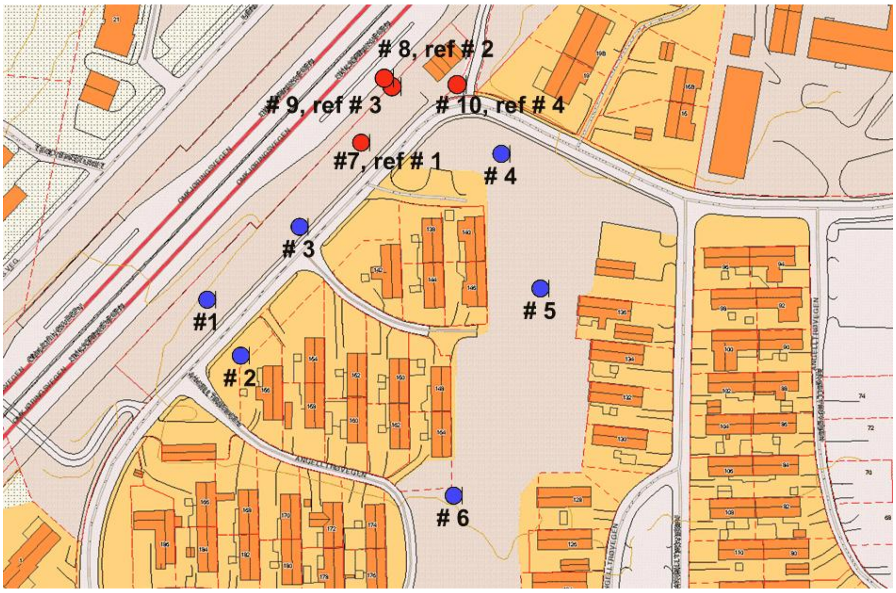

Figure 3.7: Microphone positions on complicated measurement site. Blue are control positions and Red are reference and control positions.

here either. See Appendix E for a summary of the CadnaA input parameters.

Figure 3.8: MapMonit model of complicated measurement site.

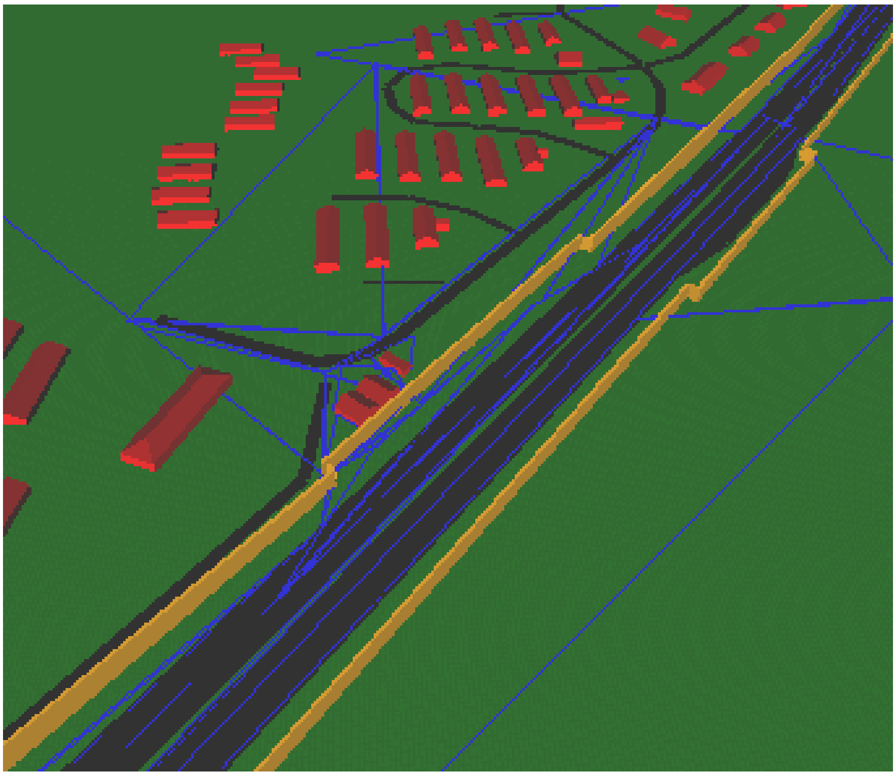

Figure 3.9: 3d model from MapMonit of the complicated measurement site.

Chapter 4

Results

The results are divided into two main sections, the simple test site and the complicated test site. At the simple test site, the first goal was to verify the use of the difference method. Secondly, an evaluation of the importance of measurement time intervals and traffic composition had to be done. Then the evaluation of where the reference microphone should be placed with respect to height above terrain and distance to road edge is presented. To verify the MapMonit simulations, they got compared with control measurements and CandaA simulations, see the measurement setup in Chapter 3.7.

At the complicated test site, MapMonit was tested in a neighborhood by a four lane highway road. Control microphones were placed behind a noise screen and in a neighborhood with mostly one floor houses. This is a good site to see how well the program performs with noise screens and buildings. Due to a flaw in MapMonit concerning noise screens and topography together, the results are only presented without topography. MapMonit simulations will be compared against both control measurements and CadnaA simulations.

4.1 Simple Test Site - Road and Ground Description

The road surface is shown in Figure 4.1 and the road data are listed in Table 3.1. The road surface was wet during the control measurements at 5 m, and dry at 10 m, 20 m and 100 m. As the measurements were executed during the winter, a high share of the vehicles used studded tyres.

The ground was an off season corn field, covered with short straws. It was partly covered with ice and snow, and 2-3 cm down the soil was frozen, see Figure 4.1. The ground was measured according to the Nordtest [7]. This standard suggests a one or multilayer model of the ground impedance. The measured ground did most likely fit the two-layer model best, but since the Nord2000 [4] model only has implemented a one-layer model, the ground was specified accordingly. The results can be found in Table 4.1 and the measurement setup is shown in Figure 4.2.

The Nord2000 model has a rather rough division of seven ground classes from A to G, where A is the softest ground type. This can give some differences between the

Figure 4.1: Left: Road surface. Right: Ground surface of the surrounding fields.

Figure 4.2: Ground impedance measurement setup at the simple test site.

Date	**Mast Distance** $[m]$	**Impedance Class Nordtest** $[kNs/m^4]$	**Ground Class Nord2000**
26.02.2008	10	40	B
27.02.2008	20	160	D
10.03.2008	100	160	D
10.03.2008	100	250	D
12.03.2008	100	630 (400)	E

Table 4.1: Measured ground impedance at the simple test site.

implemented class and the measured impedance. To evaluate actual ground impedance with the values implemented in Nord2000, simulations with all the ground classes were compared with a control measurement. A reference measurement 20 m from the road edge and 2 m above the ground was chosen. Different ground classes are characterized with the dips between 100 - 500 Hz with different widths. As can be seen in Figure 4.3, the best fit between the measurement and the simulations where the dip is located is with ground class D. This is the same as the measured as seen in Table 4.1. Even if the dip is represented good by the simulation with this ground class, there are rather large differences. For the peak around 1 kHz, the simulation with the measured ground impedance gives a few dB higher level than the measurement. Here the harder ground class, E, gives better results. For frequencies below 400 Hz the measured ground class simulates to low values, the measurement lies between the simulations with class D and E. This, and deviations around 1 kHz, indicate that the actual ground impedance lies between class D and E. The errors between the A-weighted measurement and the simulations with different ground classes can be found in Table 4.2. Here ground class E gives a much better result then the measured class D. This is natural when this class fits better to the measured levels around 1 kHz. The errors introduced by the deviation of the implemented measured ground class and the actual ground impedance will be present in all the simulations.

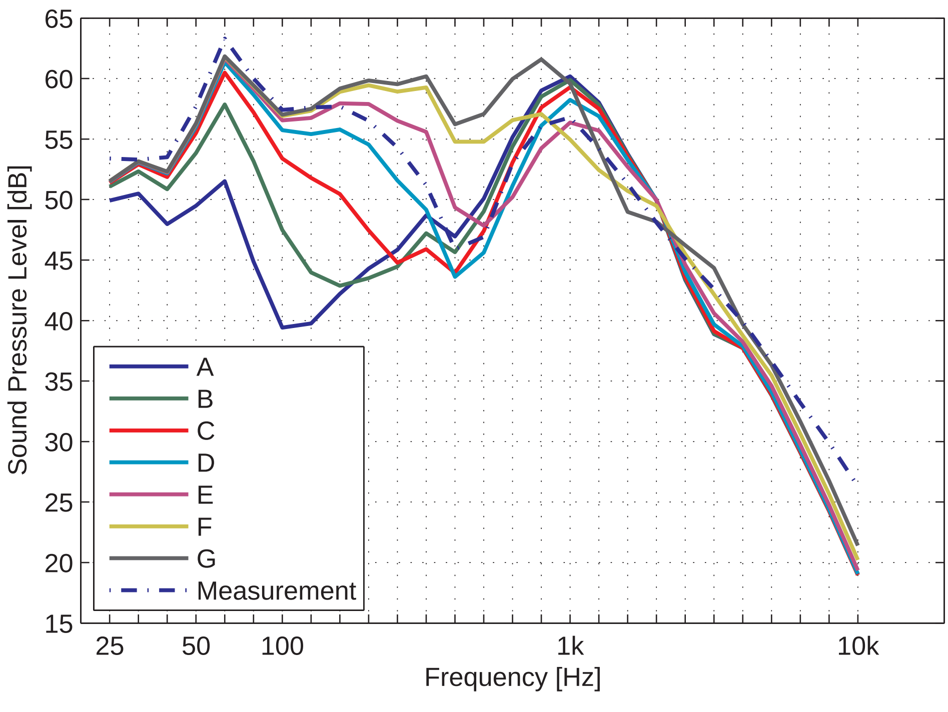

Figure 4.3: Simulation with different ground types compared to control measurement.

Ground class	A	B	C	D	E	F	G
Difference [dB]	2.54	2.21	1.68	0.95	0.21	0.98	3.71

Table 4.2: Difference between A-weighted control measurements and simulations with different ground impedance classes.

4.2 Simple Test Site - Difference Method compared with Direct Comparison

The Difference Approach is evaluated by comparing it to the Direct Comparison Approach, see Chapter 3.6.1 for a description of the two methods. The reference microphone was placed 20 m from the road edge and 2 m above ground. All the eleven control measurements were carried out over a period of three hours. The reference measurement used covers the whole of this period. This means that the Difference Approach use the mean weather from the whole period of the control measurements while the Direct Comparison use the actual weather data for each control measurement. The weather conditions can be seen in Table 4.3. The table shows that specially the wind speed changes for some of the control measurements.

	Wind speed [m/s]	Wind dir [°]	Temp. [°C]	Temp. grad. [°C/100m]	Humidity [%]
Control microphone 1	2.2	168.0	274.5	0.5	75.0
Control microphone 2	1.8	168.0	274.6	0.5	74.0
Control microphone 3	1.9	168.0	275.3	0.5	73.0
Control microphone 4	0.5	190.0	275.1	0.5	73.0
Control microphone 5	1.0	168.0	274.4	0.5	74.0
Control microphone 6	1.3	168.0	274.9	0.5	78.0
Control microphone 7	0.0	145.0	275.3	0.5	78.0
Control microphone 8	0.0	170.0	279.1	0.5	65.0
Control microphone 9	2.3	123.0	277.6	0.5	62.0
Control microphone 10	3.7	168.0	274.8	0.5	73.0
Control microphone 11	5.4	168.0	274.9	0.5	74.0
Difference approach, backward	2.1	167.0	275.3	0.5	72.8
Difference approach, forward	2.2	167.0	275.3	0.5	73.0

Table 4.3: Weather data for measurements used in the comparison of the Direct Comparison and the Difference Approach.

	Mean	Std	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
DC [dB]	-1.3	1.1	-0.2	0.3	0.6	-1.0	-0.9	-2.2	-2.4	-1.9	-2.5	-2.4	-1.9
DA [dB]	-2.1	1.6	-0.3	0.2	0.5	-2.1	-1.4	-2.7	-4.4	-4.1	-2.6	-3.0	-3.0

Table 4.4: Difference between each A-weighted control measurement levels and simulated levels for direct comparison (DC) and the difference approach (DA).

Table 4.4 shows the difference between the A-weighted control measurements and simulated levels for both approaches. It is seen that the direct comparison gives better results. This is because the direct comparison use weather average of 15 minutes specific to each control measurement, while the difference method use a weather average for the entire three hours. This means that the short time variations are better represented with the direct comparison.

The largest differences are represented by the control microphones number 4, 7, 8 and 11, the same as where the wind speed and direction differs the most from the mean value used in the forward calculations, see Table 4.3. The largest differences of the two approaches are 2 dB. Figure 4.4 shows one-third-octave band plots for a few interesting examples. The plots beside each other at the top shows two control positions where the difference approach gives similar results to the direct comparison approach. The two plots below them show positions where the difference approach gives worse results. This is much due to the deviation around 1 kHz. The same behavior can be seen in the two plots at the bottom.

The two plots third from the top have poor results with direct comparison and worse with the difference method. Most likely the weather was changing in the 15 minutes interval the measurements was performed, so the mean value of that interval is misleading.

Table 4.5 shows the standard deviation of the difference between the control measurements and the reference microphone at 5 m from road and 1.5 m above ground for varying measurement lengths. To emphasize, this is the difference that is used to correct the control measurements in the difference method. Each control measurement was 15 minutes long with an one minute resolution. Because of this limitation, the 1 minute interval will have 15 values at each control position, the 2 minutes interval will have 7 and so on. Even so, the tendency is that the error becomes smaller, the longer the time interval is.

Measurement length	**1 min**	**2 min**	**3 min**	**5 min**	**7 min**
Standard deviation	1.10	0.65	0.53	0.36	0.35

Table 4.5: Standard deviation of difference between control measurements and MapMonit simulations for different measurement lengths. Reference microphone was placed 5 m from road edge and 1.5 m above ground.

4.3 Simple Test Site - Measurement Interval and Traffic Composition

As described in Chapter 3.3, the MapMonit software calculates the source as if it consists of only passenger cars and has a vehicle frequency of 1000 passings a day. A question is if the error increases if the reference measurement includes a different composition. Another is if a high vehicle frequency is necessary for accurate results. As described in Chapter 3.6.2, the difference approach also relies on an constant source position when calculating the values for the control measurements. Therefore, a study must be done

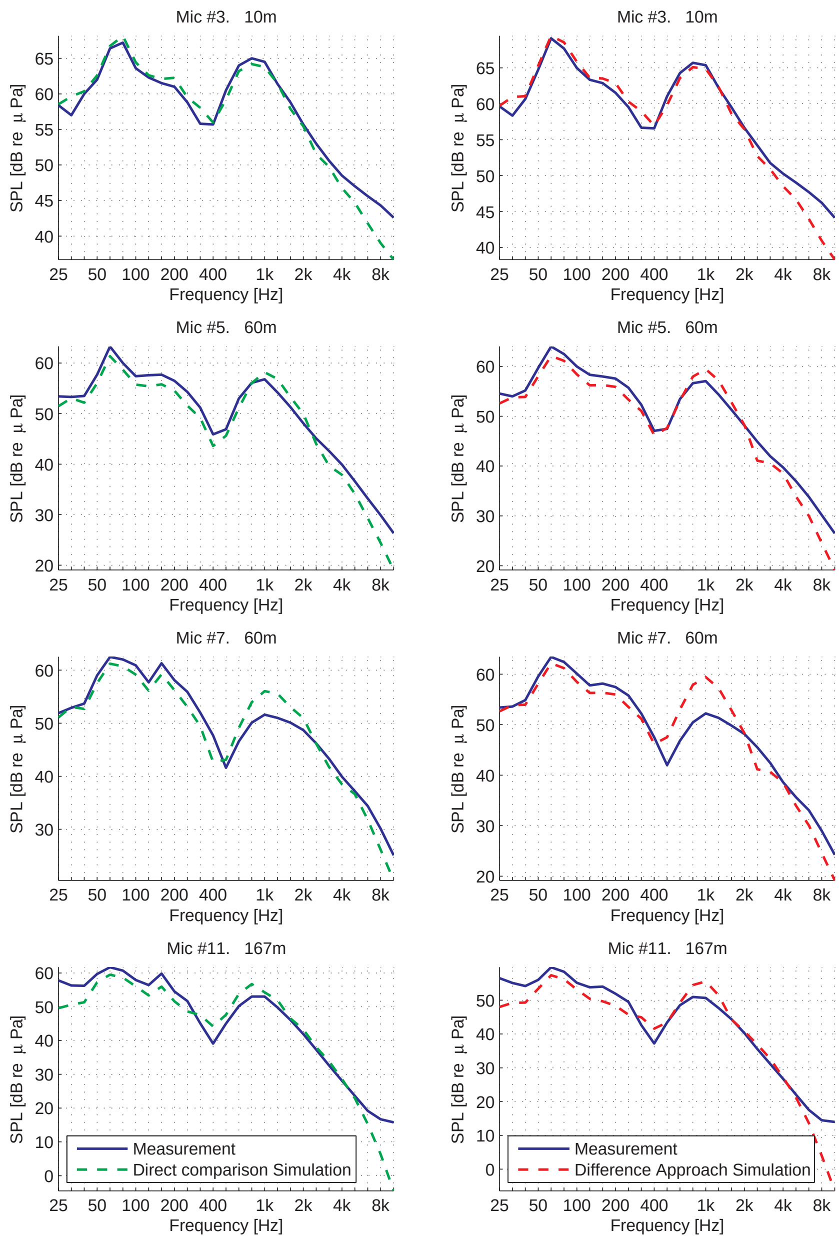

Figure 4.4: Left: Simulations with direct comparison. Right: Simulations with the difference approach.

concerning the validity of the difference between two microphones with different vehicle frequency and composition.

To answer these questions, some different reference measurements were chosen for input, and the simulations were compared with control measurements. A reference microphone 10 m from the road and 2 m above ground was chosen. The control measurements for this distance were carried out between 12.00 and 17.00 o'clock. The traffic statistics for this exact day can be seen in Figure 4.5. The figure shows the control measurements were carried out in a period with high vehicle frequency and domination of light vehicles. The extreme contrast to this is periods with a single vehicle pass by. Table 4.6 shows the intervals chosen for the reference microphone.

MM input interval	Total Vehicles	Speed av [m/s]	Heavy vehicles [%]
Single vehicle, 2min	1	81	100
Single vehicle, 2min	1	77	0
Single vehicle, 2min	1	92	100
Single vehicle, 2min	1	78	100
Single vehicle, 3min	1	97	100
Single vehicle, 2min	1	86	100
Low vehicle freq, 10min	8	84	63
Low vehicle freq, 20min	17	85	65
Low vehicle freq, 60min	55	87	62
High vehicle freq, 2min	49	74	33
High vehicle freq, 60min	1570	75	33

Table 4.6: Traffic statistics for the selected time intervals.

The results can be seen in Table 4.7. It shows the difference between A-weighted simulations and control measurements. The errors for the different input intervals are almost the same. No significant differences can be seen, not even for the single passings of two minutes compared to a one hour input interval with over 1500 vehicles. The error for each control microphone is consistent for the different reference intervals, so the errors seen for the control measurements on 67 m and 110 m are not introduced by the different input intervals. Figure 4.6 shows one-third-octave band plots for a selected control microphone compared with measurements of a single pass by and the one from one hour with high vehicle frequency. The difference approach works well in both cases.

The results indicate that the error introduced by the implementation in MapMonit of only light vehicles with a given frequency is small. Then the error introduced by the difference approach regarding traffic composition of the two different intervals must also be small.

4.4 Simple Test Site - Height and Distance Evaluation

When calculating the control measurements with the difference approach, see Chapter 3.6.2, they are corrected to represent the selected input interval to the reference micro-

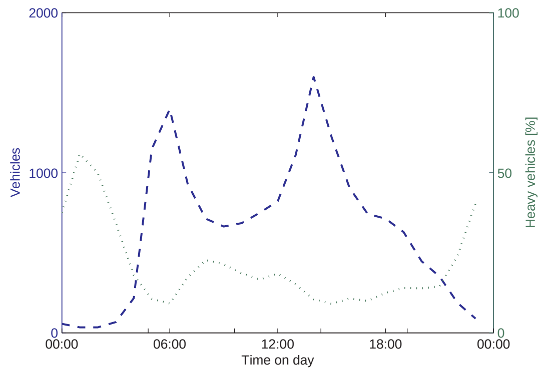

Figure 4.5: Vehicle composition and frequency for the day of the control measurements with the reference microphone placed 10 m from the road.

MM input interval	**10 m**	**60 m**	**67 m**	**110 m**	**181 m**	**167 m**
Single vehicle, 2min [dB]	-0.2	-0.6	-2.5	-1.7	-0.7	-0.4
Single vehicle, 2min [dB]	-0.2	-0.2	-1.8	-1.1	-0.1	0.1
Single vehicle, 2min [dB]	0.1	0.1	-1.5	-0.6	0.4	0.6
Single vehicle, 2min [dB]	-0.2	-0.6	-2.5	-1.7	-0.7	-0.4
Single vehicle, 3min [dB]	0.3	-0.0	-1.7	-0.8	0.2	0.5
Single vehicle, 2min [dB]	-0.2	-0.6	-2.4	-1.7	-0.8	-0.4
Low vehicle freq, 10min [dB]	-0.2	-0.5	-1.8	-0.6	-0.1	-0.2
Low vehicle freq, 20min [dB]	-0.2	-0.5	-2.2	-1.3	-0.3	-0.0
Low vehicle freq, 60min [dB]	-0.2	-0.4	-2.1	-1.2	-0.2	0.1
High vehicle freq, 2min [dB]	-0.2	-0.5	-2.2	-1.4	-0.4	-0.1
High vehicle freq, 60min [dB]	-0.2	-0.6	-2.0	-0.8	-0.3	-0.3

Table 4.7: Difference between A-weighted control measurements and simulated levels. Reference microphone at 10 m from road edge, 2 m above ground. The control measurements had a period of 15 minutes with a one minute resolution.

phones. For a given distance, the input interval is the same when the four microphone heights are recorded simultaneously. In theory, the corrected control measurement should be the same independent of which microphone height it is corrected to, when each height represent an individual correction to the control position.

Figure 4.7 shows the levels of the control measurements corrected to both the input measurement at distance 20 m from the road edge, and corrected to a simulated microphone in the exact same position for all microphone heights. As can be seen, the results are close to identical for the three highest microphones, but with a tiny deviation from the levels calculated from the lowest height. The same behavior also applies to the reference microphones at 5 m, 10 m. As seen in Figure 4.8, the reference position 100 m has a little higher variation. The corrected control measurements from reference microphone height 2 m are used in all the following plots.

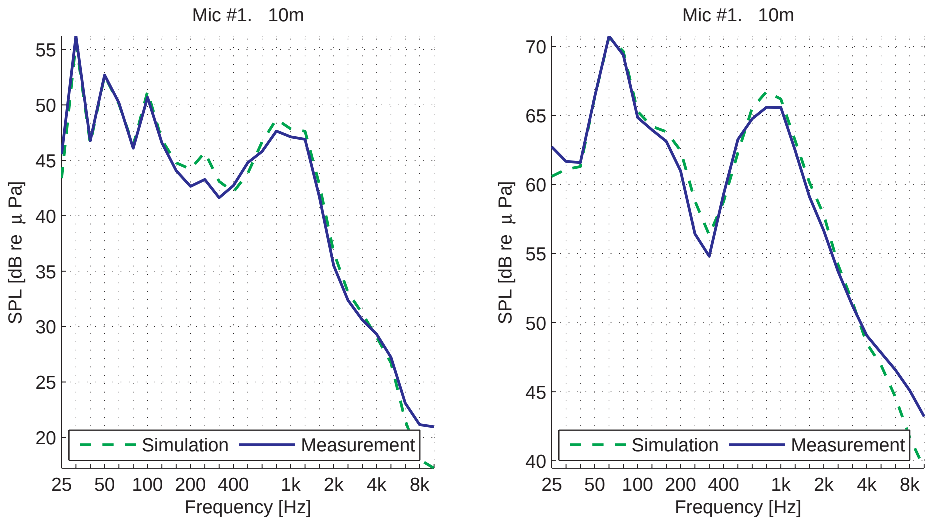

Figure 4.6: Left: Simulation and control measurement with reference input of two minutes with one vehicle passing. Right: Simulation and control measurement with reference input of an hour with high vehicle frequency. The control measurement position was 10 m from the road edge.

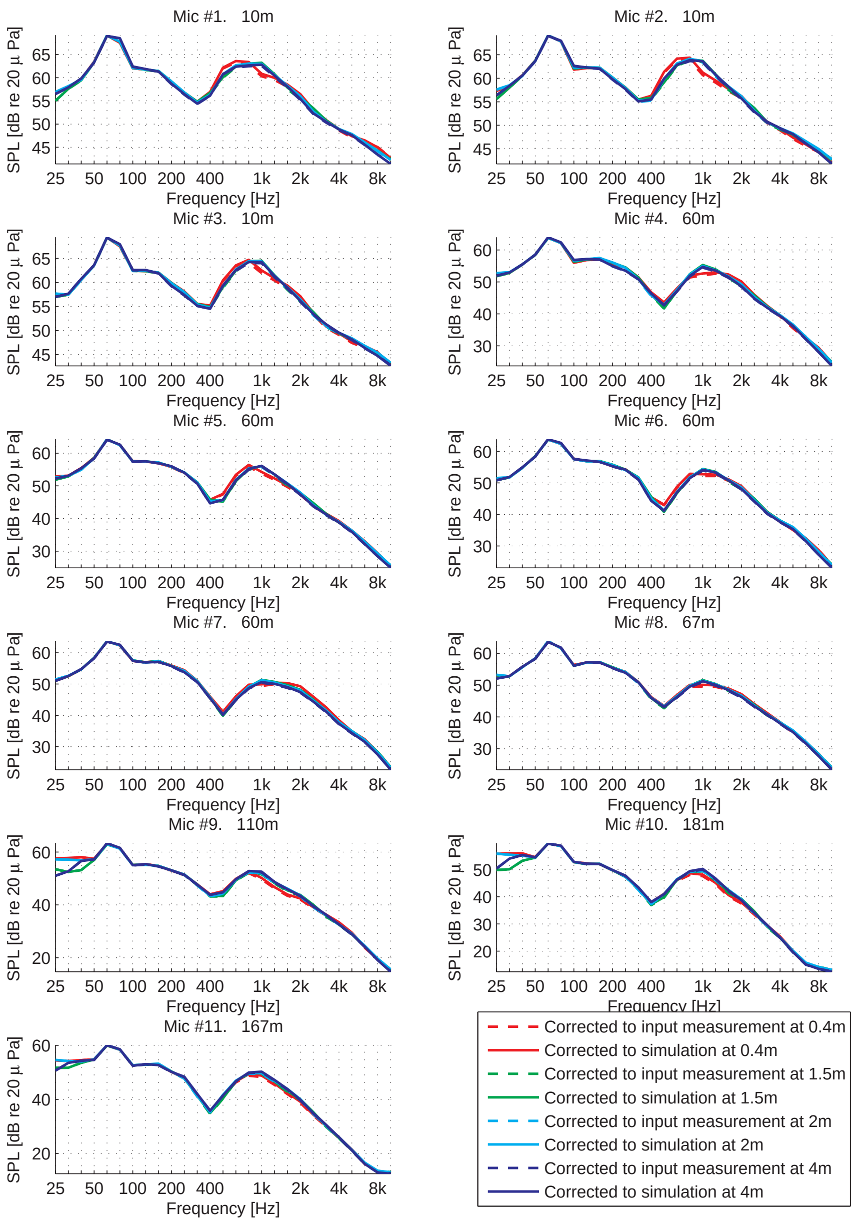

Figure 4.7: Control measurements with reference microphone at all four heights at 20 m from road edge.

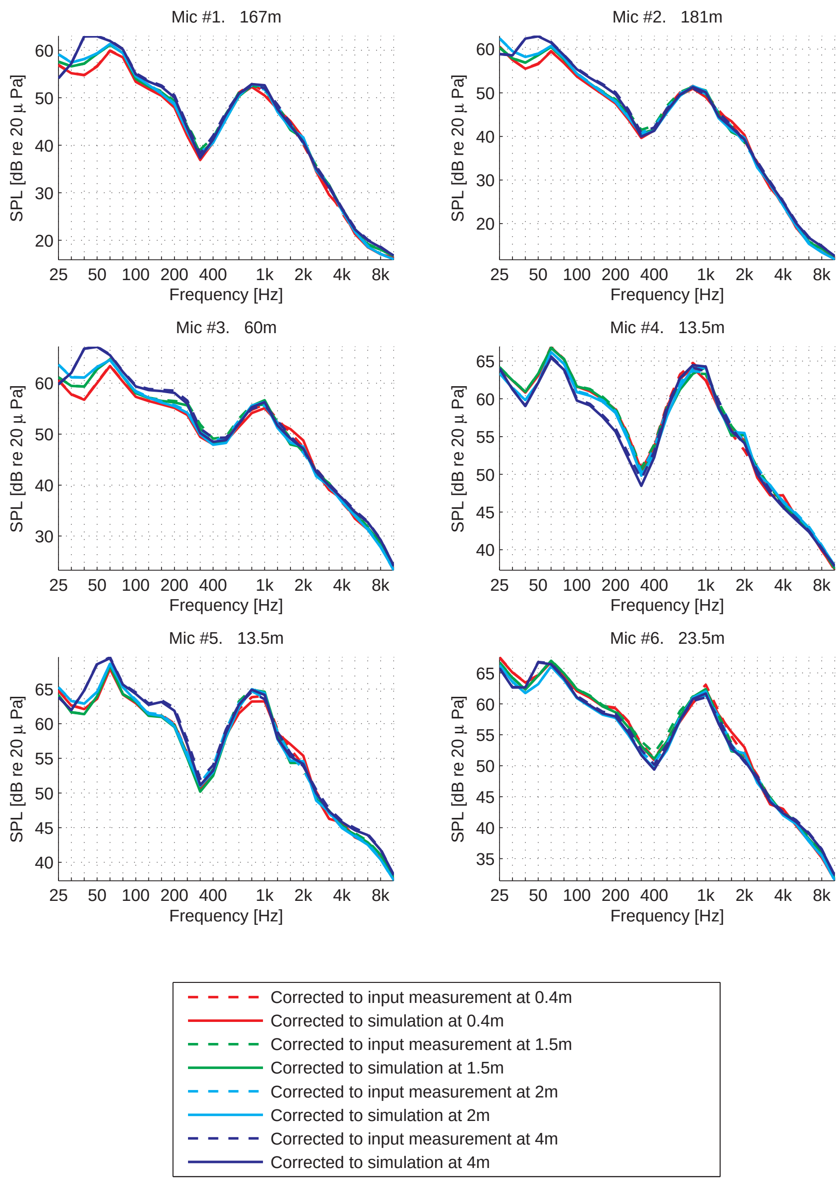

Figure 4.8: Control measurements with reference microphone at all four heights at 100 m from road edge.

4.4.1 Distance 5 m

Total Vehicles	Heavy vehicles [%]	Speed [m/s]
1587	7	71

Table 4.8: One hour car data for input interval used with reference microphone 5 m from road.

	Wind speed [m/s]	Wind direction [°]	Temperature [°C]	Temperature gradient [°C/ 100m]	Humidity [%]
Backward calculation	0.6	327.5	4.2	0.5	70.8
Forward calculation	0.0	145.0	4.0	0.5	75.0

Table 4.9: Weather data for input interval used for microphone 5 m from road.

Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
Distance [m]	10	10	10	60	60	60	60	67	110	181	167
Control - MM, RM at 0.4 m [dB]	1.2	3.2	2.9	2.2	1.5	0.9	0.9	0.6	4.0	4.0	4.2
Control - MM, RM at 1.5 m [dB]	-1.2	-0.1	-0.0	-1.6	-2.1	-2.7	-2.9	-3.1	0.4	0.6	0.8
Control - MM, RM at 2.0 m [dB]	-1.5	-0.2	-0.3	-1.7	-2.2	-2.9	-3.2	-3.4	NaN	NaN	NaN
Control - MM, RM at 4.0 m [dB]	0.3	3.0	1.6	0.2	-0.3	-1.1	-0.9	-1.5	NaN	NaN	NaN

Table 4.10: Difference between A-weighted control measurements and MapMonit (MM) simulations for reference microphones (RM) placed 5 m from the road. One hour input.

Comments

Note that one of the sound level meters had an uncontrolled shutdown before the three last control measurements at height 2 m and 4 m. That means the difference method can not be applied to these, so unfortunately there are no results in these positions.

For the reference microphone at 0.4 m, the simulated values for higher frequencies are heavily underestimated. This can be caused by screening by the road shoulder. For the highest microphone at 4 m the effects are similar. This can be caused by vertical directivity of the source which not is included in Nord2000 [4].

At the two middle heights, the results are good, except for the positions from 60 m to 67 m. This was where the wind variated the most from the mean value, up to 2.6 m/s. The simulations where executed once more with a higher wind speed in order to check if this was the cause. This resulted in small errors at 60 m to 67 m, but higher errors at the other positions. From this, the conlusion is drawn that the errors are caused by the variating wind.

At the highest microphone position, the results are all over very good, with an exception of microphone number 2. With a closer look at the plot at this control position, a peak can be seen in the control measurements at 1.2 kHz that not is at the other two control positions at 10 m. Since height 0.4 m and 4 metre already simulates too low levels, this peak will contribute the most to the error at these heights.

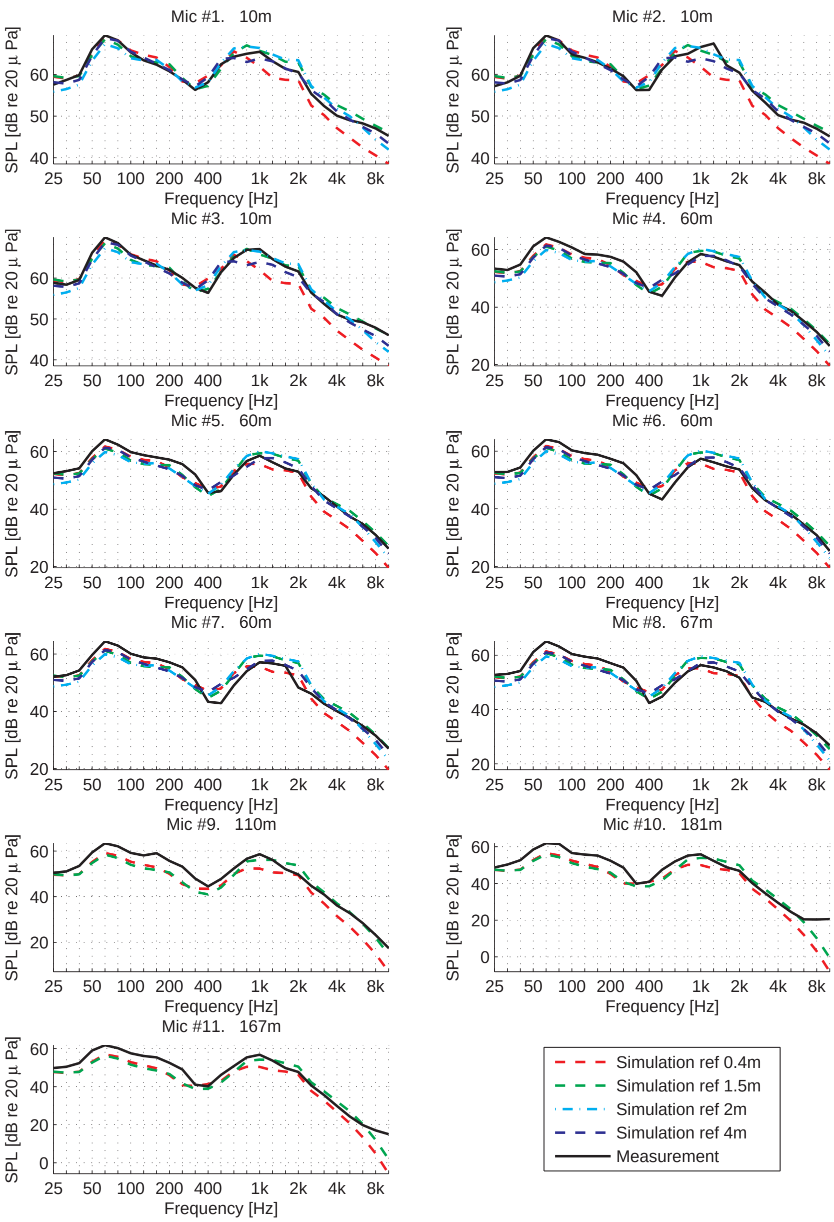

Figure 4.9: Octave band values for control measurements and simulation for all microphone heights at distance 5 m from road edge.

4.4.2 Distance 10 m

Cars	Heavy vehicles [%]	Speed [m/s]
1221	9	74

Table 4.11: One hour car data for input interval used with reference microphones 10 m from the road edge.

	Wind speed [m/s]	Wind direction [°]	Temperature [°C]	Temperature gradient [°C/ 100m]	Humidity [%]
Backward calculation	1.0	122.5	-2.9	0.5	79.0
Forward calculation	1.0	122.5	-2.0	0.5	79.0

Table 4.12: Weather data for input interval used for reference microphones 10 m the from the road edge.

Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
Distance [m]	**10**	**10**	**10**	**60**	**60**	**60**	**60**	**67**	**110**	**181**	**167**
Control - MM, RM at 0.4 m [dB]	1.1	1.7	2.2	2.9	3.5	2.4	1.9	1.4	2.5	3.2	3.7
Control - MM, RM at 1.5 m [dB]	-0.4	0.4	0.7	-0.0	0.7	-0.4	-0.9	-1.5	-0.2	0.1	0.3
Control - MM, RM at 2.0 m [dB]	-0.2	0.3	0.8	0.0	0.9	-0.3	-0.8	-1.5	-0.3	0.2	0.2
Control - MM, RM at 4.0 m [dB]	0.5	0.9	1.6	0.8	1.8	0.6	0.1	-0.6	0.6	1.2	1.1

Table 4.13: Difference between A-weighted control measurements and MapMonit (MM) simulations for reference microphones (RM) placed 10 m from the road edge. One hour input interval.

Comments

Some of the control measurements as seen in Figure 4.10 have far too high levels for frequencies above 4 kHz. Most significant at control microphone 8, 10 and 11. This is probably caused by a high frequency background noise during the control measurements.

At microphone height 0.4 m, MapMonit underestimates the levels from the peak at 1 kHz at all distances. The error is specially large for the closest microphones. In addition, the simulations underestimates frequencies from approximately 3 kHz to 10 kHz. The deviation around 1 kHz results in a rather large difference in the A-weighted levels at most of the control measurement positions, see Table 4.13.

At microphone heights 1.5 m and 2 m, the levels at control positions at 10 m distance are close to identical. This is natural when backward and forward calculation to the same point gives the same result. For distances 60 m and larger, MapMonit underestimates frequencies a little below 400 Hz. This can be addressed to the selected ground class as described in Chapter 4.1. For higher frequencies the simulated values correspond well to the control measurements. As seen in Table 4.13, the difference in A-weighted levels between the control measurements and the simulations are all less than 1 dB at all distances, except for the control microphone at distance 67 m. Here the simulated values around 1 kHz are higher than the control measurement. This can be caused by a bad control measurement, weather variations or local differences of the ground impedance. The field was also not completely flat, and around this positions there were some uneven elevations between the road and the control microphone.

For the microphone at 4 m, the frequencies of the peak around 1 kHz are underestimated for the closest control positions, this can be caused by vertical directicity, but the difference in A-weighted values in Table 4.13 give good results in all positions.

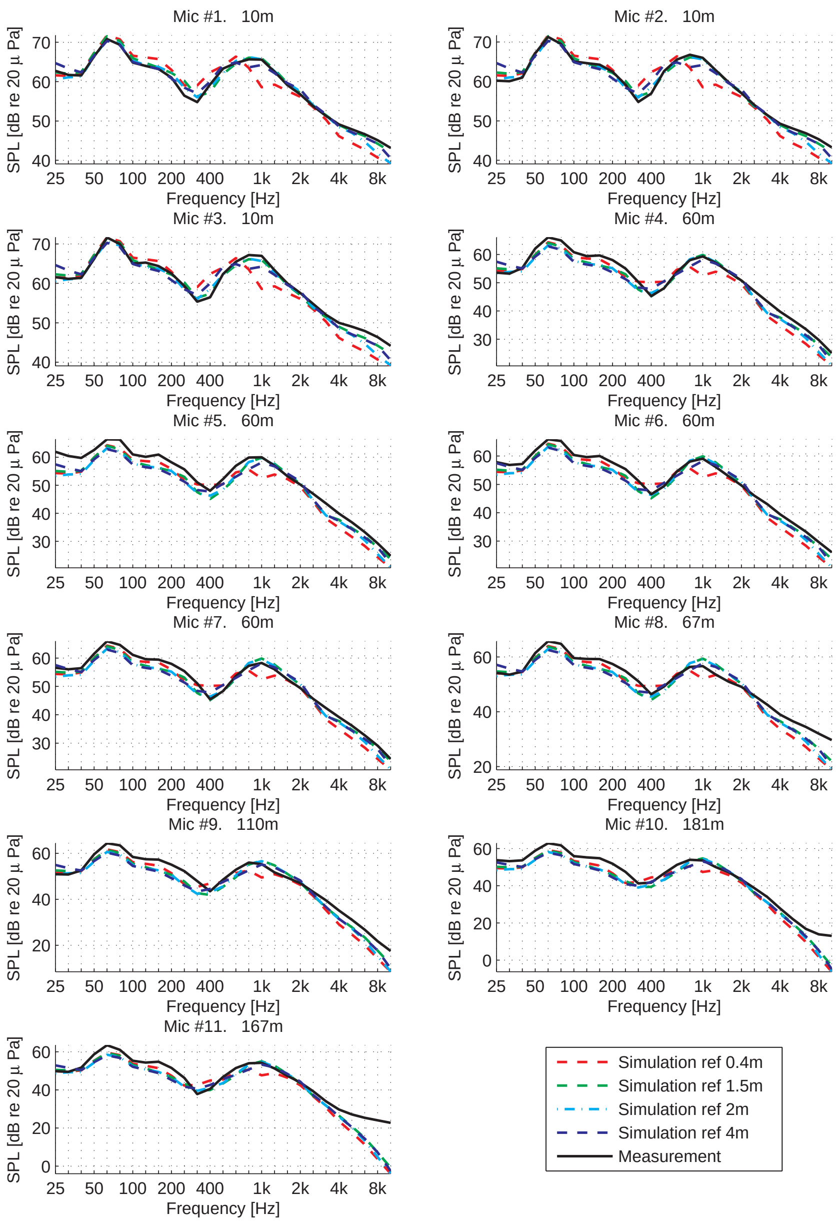

Figure 4.10: Octave band values for control measurements and simulation for all microphone heights at distance 10 m from road edge.

4.4.3 Distance 20 m

Total Vehicles	Heavy vehicles [%]	Speed [m/s]
595	11	74

Table 4.14: One hour car data for input interval used with reference microphones 20 m from the road edge.

	Wind speed [m/s]	Wind direction [°]	Temperature [°C]	Temperature gradient [°C/ 100m]	Humidity [%]
Backward calculation	0.0	325.0	-1.1	0.5	84.8
Forward calculation	0.5	167.0	2.0	0.5	75.0

Table 4.15: Weather data for input interval used for reference microphones 20 m from the road edge.

Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11
Distance [m]	10	10	10	60	60	60	60	67	110	181	167
Control - MM, RM at 0.4 m [dB]	-0.5	-0.3	0.1	0.6	1.4	0.3	-0.9	-0.9	1.0	0.7	0.9
Control - MM, RM at 1.5 m [dB]	0.6	0.9	1.3	-0.6	-0.1	-1.3	-2.8	-2.5	-0.1	0.0	-0.1
Control - MM, RM at 2.0 m [dB]	-0.0	0.4	0.7	-1.1	-0.4	-1.7	-3.3	-3.0	-0.3	-0.3	-0.4
Control - MM, RM at 4.0 m [dB]	0.2	0.8	1.1	-0.7	0.2	-1.2	-3.0	-2.5	0.6	0.6	0.5

Table 4.16: Difference between A-weighted control measurements and MapMonit (MM) simulations for reference microphones (RM) placed 20 m from the road edge. One hour input interval.

Comments

As seen in Figure 4.11 at microphone height 0.4 m there is a rather large deviation at the closest microphones. Frequencies below 1 kHz are overestimated and above 1 kHz are underestimated. Because of this, the difference in A-weighted levels in Table 4.16 actually turns out to be very good. It is seen though, that this is just a coincidence when studying the plots. Note that the dip in the control measurements at 400 Hz is much lower in frequency in the simulations.

At microphone height 1.5 m, the dip in the control measurements at 400 Hz is simulated too high in frequency for the control positions at 10 m distance. The dip fits well at the other distances. It is seen that at microphone number 7 and 8, the simulations have overestimated the peak at 1 kHz. It is not possible to blame the created map used in MapMonit, nor distance errors since the error is not present at the other reference microphone distances. This can be addressed to the selected ground class in the simulations as described in 4.1. The reason may also be varying weather conditions under the control measurements which not are included in the difference approach, as described in Chapter 4.2. The large overestimation results in a rather large difference in the A-weighted levels at these two positions, as seen in Table 4.16, but for the rest of the positions the difference is very small.

At microphone height 2 m, the dip is simulated a little too high in frequency at control positions at 10 m, a little too low at 60 m and fits very well at the three distances furthest away. However, at 1 kHz the same peak simulation overestimation at microphone number 6 and 7 is present. It is also seen that simulations underestimates the highest frequencies for all distances. This could be noise on the control measurements, which cause the mesured levels to be a bit too high. The deviance in the highest frequencies has little effect on the difference in the A-weighted levels, they are very small except for the two control microphones mentioned.

At microphone height 4 m, the frequency dip is simulated too low in frequency for all distances except at 10 m. At microphone number 6 and 7, the same peak simulation overestimation at 1 kHz is seen. These differences may be caused by the selected ground impedance. The difference in A-weighted level difference is very small, and overall for all heights the difference is under 1 dB for all the three highest reference microphones.

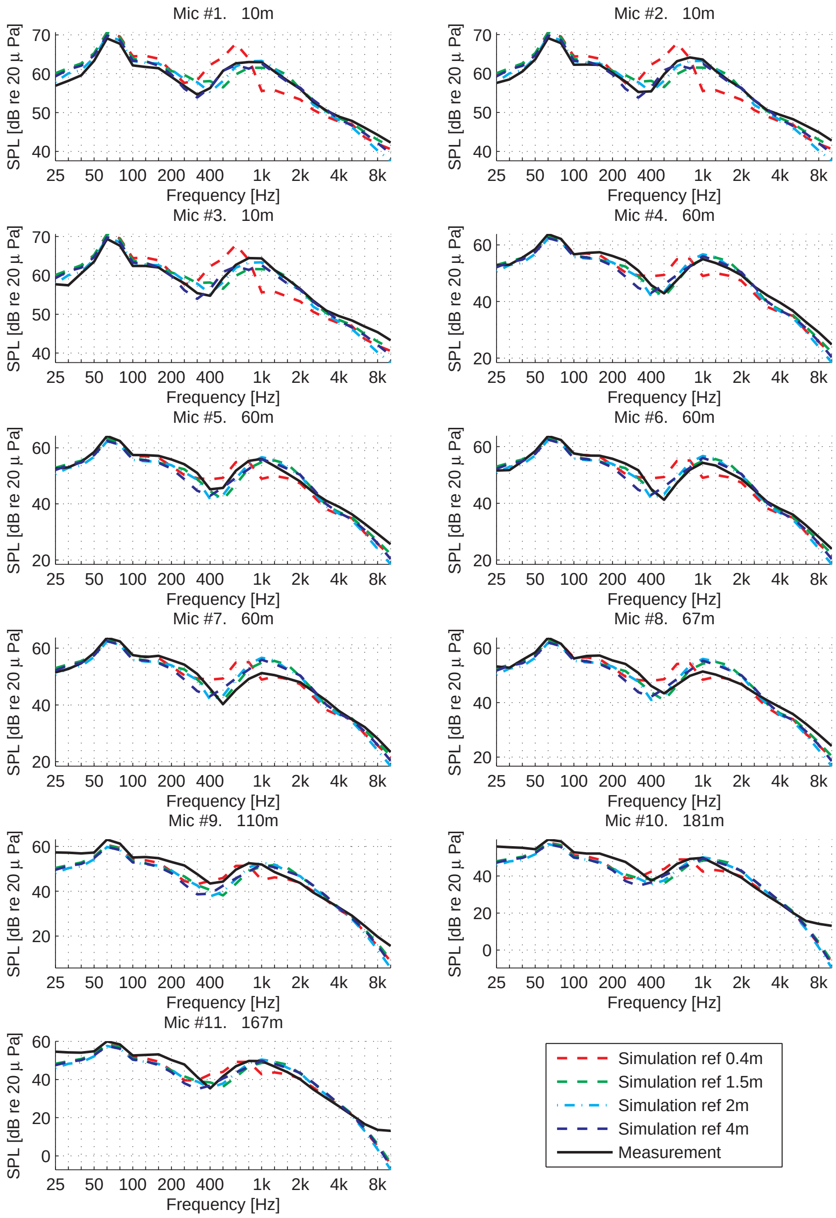

Figure 4.11: Octave band values for control measurements and simulation for all microphone heights at distance 20 m from road edge.

4.4.4 Distance 100 m

Total Vehicles	Heavy vehicles [%]	Speed [m/s]
1587	7	71

Table 4.17: One hour car data for input interval used with reference microphone 100 m from road edge.

	Wind speed [m/s]	Wind direction [°]	Temperature [°C]	Temperature gradient [°C/ 100m]	Humidity [%]
Backward calculation	6.5	154.6	6.4	0.5	49.7
Forward calculation	5.0	167.0	6.0	0.5	50.0

Table 4.18: Weather data for input interval used for microphone 100 m from road edge.

Microphone ID	**#1**	**#2**	**#3**	**#4**	**#5**	**#6**
Distance [m]	**167**	**181**	**60**	**13.5**	**13.5**	**23.5**
Control - MM, RM at 0.4 m [dB]	0.7	-0.4	0.5	1.1	0.9	1.6
Control - MM, RM at 1.5 m [dB]	1.3	0.2	-0.1	0.9	1.4	0.7
Control - MM, RM at 2.0 m [dB]	0.9	-0.3	-0.7	0.9	1.2	0.1
Control - MM, RM at 4.0 m [dB]	1.1	-0.3	-0.5	1.0	1.2	-0.2

Table 4.19: Difference between A-weighted control measurements and MapMonit (MM) simulations for reference microphones (RM) placed 100 m from road edge. One hour input interval.

Comments

Even though the wind speed during the control measurements variated from 4.1 to 9.7 m/s, see Table A.1 wind noise on the measurements is probably out of the question. The windscreens are supposed to handle wind speed up to 10 m/s, see Chapter 3.5.3 for details.

Table 4.19 show that the differences between the A-weighted levels for the simulations and the control measurements for the lowest microphone position, are all less than 1.6 dB. This is actually very good, but Figure 4.12 show that this height is bad for all the control positions, especially for the ones closest to the road. At control position 1, the difference in A-weighted values are over 1 dB for two of the three higest microphones, this is strange when the control position 2 are placed at a further from the road and have very small deviations. For the three highest microphone positions the results are almost the same, this is shown both in Table 4.19 and in Figure 4.12. The difference in A-weighted values are all under 1 dB for all positions except control position 1 and 5. The low difference in the A-weighted values hide the fact that the frequencies under 400 Hz are heavily overestimated. This is best shown for the control positions closest to the road in Figure 4.19. This is most likely caused by background noise. When calculating the source strength, all the measured sound is supposed to come from the source. When the reference microphone is placed a long distance from the road the signal to noise ratio gets smaller, especially for lower frequencies. For the frequencies above 400 Hz the results are good for all the three highest microphones, which gives the good correspondence in dBA values. Over 8 kHz the simulations are overestimated, this is also addressed to background noise. To summarize, the results are actually pretty good for distances at 60 m and greater. However, close to the road, the underestimation of low frequencies is rather pronounced. From this follows that the source is not accurately estimated, even though the results at greater distances turn out to be good.

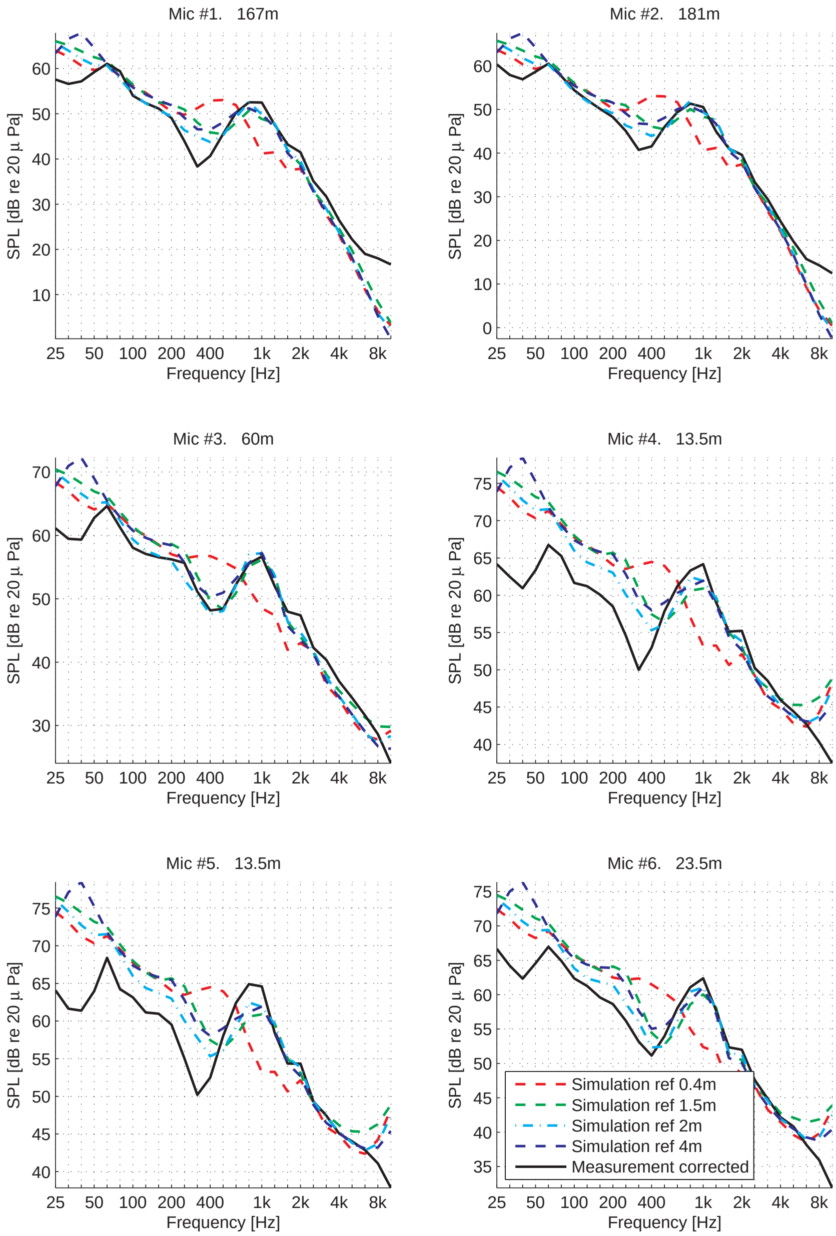

Figure 4.12: Control measurements for all microphone heights at distance 100 m from road edge.

4.5 Simple Test Site - Comparison with CadnaA

In this chapter, MapMonit is evaluated against both control measurements and CadnaA simulations during two different time intervals of one hour length. Since CadnaA presently dominates the market for noise map simulations, it was concluded that this was an important comparison. CadnaA has implemented the Nord96 [1] model, as opposed to MapMonit's Nord2000 model. This means both different source definition and propagation model. The CadnaA input parameters can be seen in Appendix E. One hour traffic statistics specific for each time interval was used to define the road source strength.

4.5.1 Distance 5 m

	Wind speed $[m/s]$	**Wind dir.**$[^o]$	**Temp.** $[C^o]$	**Temp. grad.**$[C^o/m]$	**Humidity [%]**
Period 1	0.2	23	4.5	0.005	77
Period 2	0.6	335	1.4	0.005	71

Table 4.20: One hour average weather statistics for the measurement periods at 5 m.

	Total Vehicles	**Av. speed [m/s]**	**Heavy vehicles [%]**
Period 1	1449	72	11
Period 2	933	72	8

Table 4.21: One hour traffic statistics, heavy vehicles are defined longer than 5.6 m.

	Distance from road [m]	**10**	**60**	**67**	**110**	**167**	**181**
Period 1	**CadnaA - MM [dB]**	-1.4	-1.9	-1.7	-2.1	-5.3	-4.9
	Control - MM [dB]	-0.4	-2.2	-3.0	0.6	0.9	0.7
Period 2	**CadnaA - MM [dB]**	-0.8	-1.1	-0.9	-1.3	-4.5	-4.3
	Control - MM [dB]	-0.3	-2.2	-2.9	0.8	1.1	1.0

Table 4.22: Noise level comparison CadnaA, MapMonit (MM) and control measurements at distance 5 m and height 1.5 m.

Comments

The same tendency is seen here for the control positions at 60 m to 67 m, as was the case in the height and distance evaluation. These positions have a larger error due to the higher wind during these particular control measurements. The differences at the other positions are small because the wind speed during these control measurements are close to the mean wind speed used in the simulations.

The difference between CadnaA and MapMonit simulated levels is small for the distances up to 110 m. At the two positions 167 m and 181 m, the difference is high. CadnaA simulates between 4.3 dB and 5.3 dB less than MapMonit. The reason for this may be that MapMonit use actual weather conditions as opposed to the fixed weather in CadnaA. But the high difference might also be some difference in the two propagation and source models.

4.5.2 Distance 10 m

	Wind speed $[m/s]$	Wind dir.[^{o}]	Temp. [C^o]	Temp. grad.[C^o/m]	Humidity [%]
Period 1	1.2	124	-2.8	0.005	88
Period 2	0.2	168	-2.2	0.005	76

Table 4.23: One hour average weather statistics for the measurement periods at 10 m.

	Total Vehicles	Av. speed [m/s]	Heavy vehicles [%]
Period 1	444	72	15
Period 2	67	85	34

Table 4.24: One hour traffic statistics, heavy vehicles are defined longer than 5.6 m.

	Distance from road [m]	10	60	67	110	167	181
Period 1	**CadnaA - MM [dB]**	-0.4	-0.3	-0.1	-0.7	-3.9	-3.6
	Control - MM [dB]	0.3	0.1	-1.3	-0.1	0.3	0.3
Period 2	**CadnaA - MM [dB]**	1.2	1.3	1.5	1.0	-2.3	-2.1
	Control - MM [dB]	0.3	0.0	-1.4	-0.2	0.3	0.3

Table 4.25: Noise level comparison of CadnaA, MapMonit (MM) and control measurements at distance 10 m and height 2.0 m.

Comments

At this distance, two hours with different vehicle frequency was chosen. The similarity between control measurements and MapMonit simulations is very good at both time intervals for all distances. For the first time interval with higher vehicle frequency, the differences between CadnaA and MapMonit are small for propagation distances up to 110 m. For the two control positions at 167 m and 181 m, MapMonit simulates almost 4 dB higher levels. This can be consistent deviations in the propagation models, or caused by the fact that MapMonit uses actual weather conditions in contrast to the fixed good weather conditions in CadnaA. At the second period the levels close to the road are now simulated higher in CadnaA than MapMonit. This is the only period where this happens, and can indicate that CadnaA handles hevy vehicles worse than MapMonit. At longer distances MapMonit still simulates far higer levels than CadnaA.

4.5.3 Distance 20 m

	Wind speed $[m/s]$	**Wind dir.**$[^o]$	**Temp.** $[C^o]$	**Temp. grad.**$[C^o/m]$	**Humidity [%]**
Period 1	0.0	325	1.4	0.005	93
Period 2	0.0	325	0.0	0.005	94

Table 4.26: One hour average weather statistics for the periods at 20 m.

	Total Vehicles	**Av. speed [m/s]**	**Heavy vehicles [%]**
Period 1	786	72	18
Period 2	1491	72	11

Table 4.27: One hour traffic statistics, heavy vehicles are defined longer than 5.6 m.

	Distance from road [m]	**10**	**60**	**67**	**110**	**167**	**181**
Period 1	**CadnaA - MM [dB]**	-1.1	-0.9	-0.6	-0.7	-3.4	-3.1
	Control - MM [dB]	0.5	-1.3	-2.6	-0.5	-0.5	-0.5
Period 2	**CadnaA - MM [dB]**	-1.3	-1.3	-1.1	-1.2	-3.8	-3.4
	Control - MM [dB]	0.5	-1.2	-2.4	-1.0	-1.0	-1.0

Table 4.28: Noise level comparison of CadnaA, MM and control measurements at distance 20 m and height 2.0 m.

Comments

The difference between the A-weighted control measurements and MapMonit simulations is small at all distances except at distance 67 m. The fact that this measurement has so high error, but not the ones at 60 m and 110 m, indicates that something may be wrong with the control measurement or the model in MapMonit. Since the same map has also been used at reference microphone distance 10 m without this error, it is unlikely that the MapMonit model is the cause. The reason might be variating weather during this particular control measurement, or that some background noise dominates during this time interval.

The errors when MapMonit is compared to CadnaA, are worse for all the control positions for both time intervals. The tendency is that MapMonit simulates higher values at all distances, increasing with distance. For the control position at 67 m, the error seen when compared to the measurement is gone, this supports the fact that something probably is wrong with this control measurement.

For all periods compared to CadnaA the difference seams to be small and constant for distances up to 110 m. Over this distance CadnaA simulates to low levels.

4.6 Complicated Test Site

For the complicated test site, an urban neighborhood next to a four lane highway was chosen. Between the neighborhood and the highway was a mound with a noise screen on top. For the complete location description, see Chapter 3.7.

4.6.1 Road and Area Description

The road surface is shown in Figure 4.13, and the road data are listed in Table 3.4. As mentioned in Chapter 3.5.4, the vehicle frequency and composition had to be video recorded and counted manually. The road and surrounding area was dry during the measurements.


Figure 4.13: Left: Ground surface on the quiet side of the noise screen. Right: Road surface.

The ground on the road side of the noise screen, and the majority of the ground on the quiet side can be described as short grassed lawns, see Figure 4.13 and 3.6. Other smaller areas included gravel, a parking lot, small asphalt roads and houses. Since the measurements were executed in a quiet neighborhood with many different surface types, the ground impedance classes were not measured, but chosen based upon the impedance class description and examples listed in Nord2000 Road [11].

4.6.2 Data Processing

Each control measurement was 15 minutes long. The four reference microphones were also used as control measurements. Because of traffic noise from the local roads in the neighborhood, intervals without dominating background noise were extracted from the control measurements. The length of these varied from two to four minutes. These good intervals were used to calculate the difference used to correct the levels of the control measurements as described in Chapter 3.6.2. When using the difference approach, see Chapter 3.6.2, the control measurements are calculated from a given reference microphone. When using the same time interval for input to each of the four reference microphones, as is the case for the complicated measurement site, the calculated values for the control measurements should theoretically be the same.

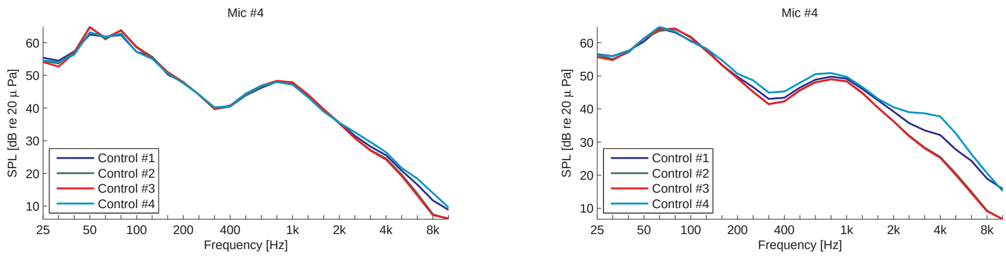

Figure 4.14: Control measurement calculated with the difference approach from each reference microphone. Left: 2 minutes input. Right: 60 minutes input.

Figure 4.14 shows a selected control measurement calculated from one short and one long input interval, for each of the four reference microphones. For the short interval on the left, the control measurements are calculated to have almost the same level except for the highest frequencies. Here, the calculated measurements from the two reference positions behind the noise screen, reference microphone one and four, are higher than the two others. This is because of background noise. For the long interval shown on the right in Figure 4.14, the noise is much more prominent. This is because the one hour interval includes unwanted traffic noise from the local roads in the neighborhood. This makes long input intervals for these two reference positions impossible. Figure 4.14 also shows that the control measurements calculated from reference microphone two and three are exactly the same. To avoid noisy control measurements, the ones calculated from one of these two are used for comparison with the simulations independent of reference microphone.

4.6.3 Results with two Minutes Input

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	**16**	**37**	**24**	**60**	**100**	**120**	**6**	**10.0**	**17**	**22**
RM 1 (behind screen) [dBA]	56.2	59.3	55.5	54.1	52.3	51.7	55.6	79.3	77.4	61.1
RM 2 (in front of screen) [dBA]	54.2	57.1	53.5	52.0	50.4	49.5	53.7	77.6	75.8	59.1
RM 3 (over screen) [dBA]	54.7	57.7	54.1	52.5	51.0	50.0	54.2	78.1	76.3	59.6
RM 4 (behind building) [dBA]	47.9	51.1	47.2	45.9	44.1	43.4	47.3	71.5	69.6	52.7

Table 4.29: A-weighted MapMonit simulated levels in positions of the control microphones.

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	**16**	**37**	**24**	**60**	**100**	**120**	**6**	**10.0**	**17**	**22**
Noise Levels [dBA]	56.4	55.9	55.9	54.3	49.6	48.5	55.6	77.6	76.3	52.7
Standard deviation	0.3	0.5	0.5	1.0	0.8	1.1	0.6	0.3	0.0	0.9

Table 4.30: A-weighted levels of the control measurements. Calculated with the difference method from reference microphone 3 (over screen).

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	**16**	**37**	**24**	**60**	**100**	**120**	**6**	**10.0**	**17**	**22**
Ref.Mic 1 (behind screen) [dB]	0.3	-3.4	0.4	0.2	-2.7	-3.1	0.0	-1.7	-1.1	-8.4
Ref.Mic 2 (in front of screen) [dB]	2.2	-1.3	2.3	2.3	-0.8	-1.0	1.9	0.0	0.5	-6.4
Ref.Mic 3 (over screen) [dB]	1.7	-1.8	1.8	1.7	-1.4	-1.5	1.4	-0.5	-0.0	-6.9
Ref.Mic 4 (behind building) [dB]	8.6	4.8	8.7	8.4	5.5	5.1	8.3	6.2	6.7	0.0

Table 4.31: Difference between A-weighted MapMonit simulations and control measurement levels.

Comments

Table 4.31 shows the difference between the A-weighted MapMonit simulations and the control measurements for a 2 min input to the reference microphones. The interval was selected carefully to minimize background noise. The levels from the simulations and the control measurements can be found in Table 4.29 and 4.30, respectively. The standard deviation of the control measurements in Table 4.30 represents the standard deviation of the difference used in correcting the control measurement values. The standard deviation is calculated with a resolution of 30 seconds from the two minutes intervals of the difference calculation. The values can give an indication of time varying noise and traffic composition in the intervals used for calculating the difference. However, it does not say anything about consistent errors.

Table 4.31 shows that the reference microphone placed behind the building, reference microphone 4, completely fail in defining the source. All the other reference microphones also fails in calculating the noise level in the position of this reference microphone, denoted as control microphone 10 in the table. This means that the Nord2000 propagation model works badly for this position. For the reference microphone placed above the noise screen, the difference between A-weighted levels are all less than 2 dB, except for control microphone 10 behind the building. For the reference microphone placed in front of the noise screen, the results are slightly worse with differences up to 2.3 dB. The reference microphone placed behind the screen gives good accuracy for the control microphones placed in positions corresponding to the reference microphone, but bad results for the rest.

Figure 4.15 shows one-third-octave band plots for simulations based on all four reference microphones compared to the control measurements. Reference microphone 1 behind the screen gives the best values for low frequencies and good values of high frequencies in control position 1, 3 and 4 (and 7 which is the reference microphone itself). As seen in the map of the location, Figure 3.7, these control positions are placed in similar locations as the reference microphone. When back and forward calculation is the same, it is natural that these positions give good results. This is seen for control microphone 8 and 9, in front and above the screen respectively.

Reference microphone 1 overestimates the low frequencies below 400Hz and the high frequencies above 1 kHz. When the propagation includes the noise screen, this error is probably introduced by the screen implementation in the Nord2000 propagation model. The User's Guide to Nord2000 Road [9] mentions the noise screen as one of the elements with the biggest uncertainty. The screen is implemented as a part of the topography, and is not supposed to give accurate results in the shadow zone where reference microphone 1 is placed. Another source of error, is that the absorption coefficient implemented in the MapMonit software not necessary equals the one of the actual screen at the measurement site.

The reference microphones placed in front of and above the screen give similar results. The one placed in front of the screen gives marginal higher levels at lower frequencies and marginal lower at high frequencies. The higher values at low frequencies can be the reflections from the noise screen just behind the microphone. For the control positions close to the screen on the quiet side, they both estimate too low levels at frequencies below 400 Hz. For higher frequencies the accuracy is good in all positions. The lower values at low frequencies can be the implementation of the noise screen, and not necessarily the source estimation.

The control microphones furthest away from the road, number 5 and 6, are estimated well for the reference microphones in front of and above the screen, but the for frequencies between 100 Hz and 1 kHz the simulated values are 5 dB too high in the worst case. This can be caused by a too simple terrain description in the MapMonit model.

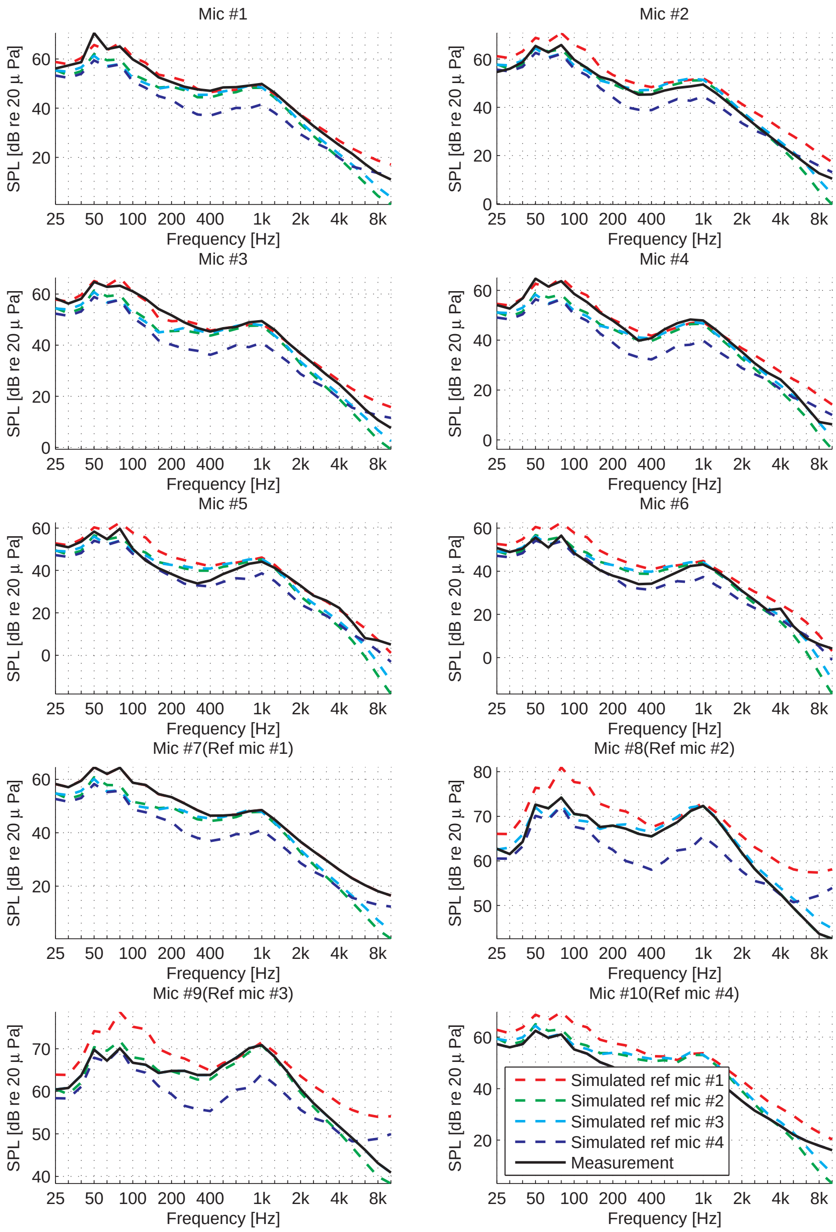

Figure 4.15: Octave band levels for control measurements and simulations based on all four reference microphones with two minutes input interval.

4.6.4 Results with one Hour Input

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	16	37	24	60	100	120	6	10.0	17	22
Ref.Mic 1 (behind screen) [dBA]	58.4	61.6	57.7	56.4	54.6	54.0	57.9	82.1	80.1	63.3
Ref.Mic 2 (in front of screen) [dBA]	55.3	58.3	54.6	53.1	51.5	50.6	54.7	78.6	76.7	60.0
Ref.Mic 3 (over screen) [dBA]	55.6	58.6	55.0	53.4	51.9	50.9	55.1	79.0	77.1	60.4
Ref.Mic 4 (behind building) [dBA]	51.4	54.6	50.7	49.5	47.6	47.0	50.9	76.1	74.1	56.2

Table 4.32: A-weighted MapMonit simulated levels in positions of the control microphones.

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	16	37	24	60	100	120	6	10.0	17	22
Noise Level [dBA]	57.4	56.9	56.9	55.2	50.4	49.3	56.7	78.4	77.1	53.7
Standard deviation	0.3	0.5	0.5	1.0	0.8	1.1	0.6	0.3	0.0	0.9

Table 4.33: A-weighted levels of the control measurements. Calculated with the difference method from reference microphone 3 (over screen).

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	16	37	24	60	100	120	6	10.0	17	22
Ref.Mic. 1 (behind screen) [dB]	-1.0	-4.7	-0.8	-1.1	-4.2	-4.7	-1.2	-3.7	-3.0	-9.6
Ref.Mic. 2 (in front of screen) [dB]	2.1	-1.4	2.3	2.1	-1.2	-1.4	1.9	-0.2	0.3	-6.3
Ref.Mic. 3 (over screen) [dB]	1.8	-1.7	2.0	1.8	-1.5	-1.7	1.6	-0.5	-0.0	-6.7
Ref.Mic. 4 (behind building)[dB]	6.0	2.3	6.2	5.7	2.8	2.3	5.8	2.3	2.9	-2.5

Table 4.34: Difference between A-weighted MapMonit simulations and control measurement levels.

Comments

An hour input to the reference microphones gives similar results as the two minutes input for the two reference microphones on the road side and above the screen. This is natural when the corrections for the control measurements are the same. The only main difference is the smoother frequency spectrum as seen in Figure 4.16, which is natural for a longer input interval. Table 4.34 shows that an hour input gives much worse results for the two reference microphones placed behind the screen. This is because of background noise especially for frequencies over 1 kHz as seen in the simulations for all the control positions. This makes this long input interval not representative for these two reference positions.

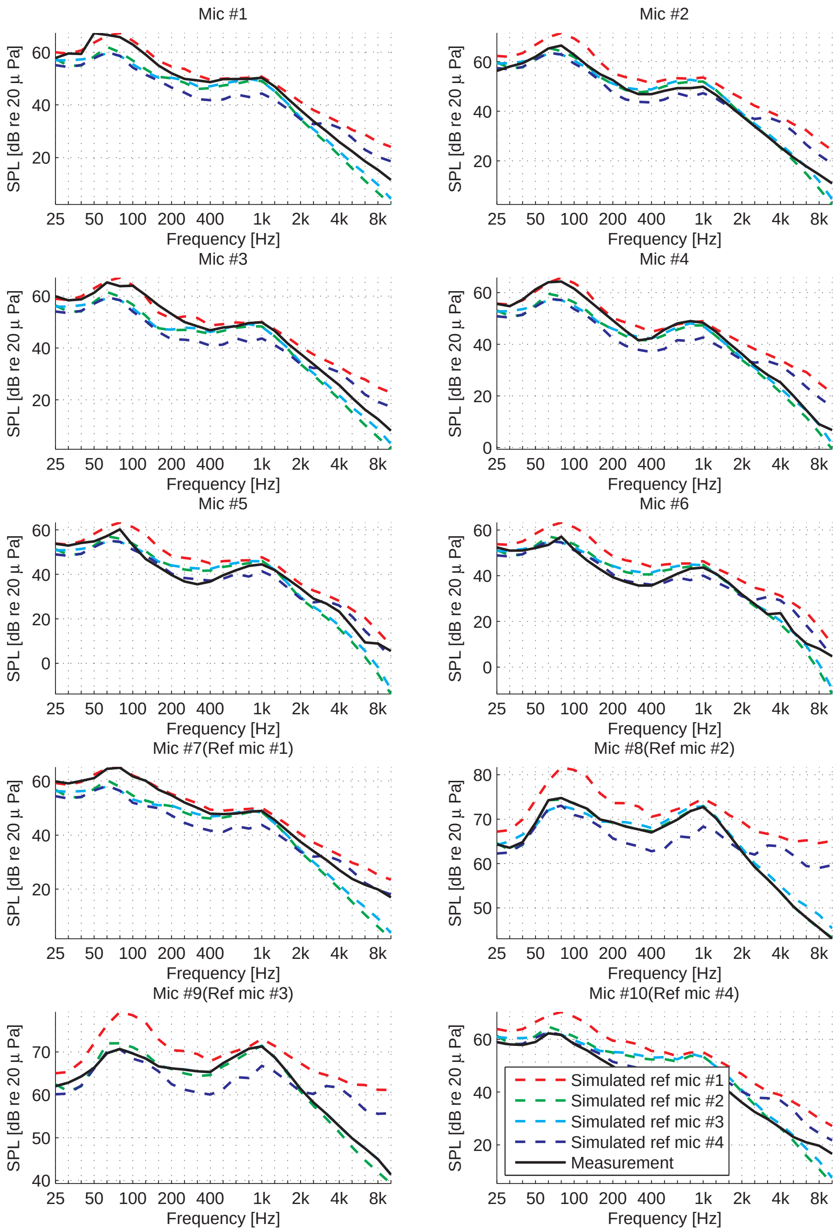

Figure 4.16: Octave band levels for control measurements and simulations based on all four reference microphones with one hour input interval.

4.6.5 Validation with CadnaA

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	**16**	**37**	**24**	**60**	**100**	**120**	**6**	**10.0**	**17**	**22**
Ref.mic 1 (behind screen) [dB]	-0.3	-2.8	-0.1	0.1	0.2	-1.3	-0.5	-1.2	-1.2	-3.8
Ref.Mic 2 (in front of screen) [dB]	1.7	-0.6	1.9	2.2	2.1	0.9	1.4	0.5	0.4	-1.8
Ref.mic 3 (over screen) [dB]	1.2	-1.2	1.3	1.7	1.5	0.4	0.9	-0.0	-0.1	-2.3
Ref.Mic 4 (behind building) [dB]	8.0	5.4	8.2	8.3	8.4	7.0	7.8	6.6	6.6	4.6

Table 4.35: Difference in levels between A-weighted MapMonit and CadnaA simulations, 2 minutes input.

Control Microphone ID	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10
Distance from road edge [m]	**16**	**37**	**24**	**60**	**100**	**120**	**6**	**10.0**	**17**	**22**
Ref.Mic 1 (behind screen) [dB]	-2.5	-5.1	-2.3	-2.2	-2.1	-3.6	-2.8	-4.0	-3.9	-6.0
Ref.Mic 2 (in front of screen)[dB]	0.6	-1.8	0.8	1.1	1.0	-0.3	0.4	-0.5	-0.5	-2.7
Ref.Mic 3 (over screen) [dB]	0.3	-2.1	0.4	0.8	0.6	-0.5	0.0	-0.9	-0.9	-3.1
Ref.Mic 4 (behind building) [dB]	4.5	1.9	4.7	4.7	4.9	3.4	4.3	2.0	2.1	1.1

Table 4.36: Difference in levels between A-weighted MapMonit and CadnaA simulations, 60 minutes input.

Comments

Simulations of both the the two minute and the hour input to MapMonit are here compared with simulations in CadnaA. CadnaA operates with A-weighted levels, so only these can be compared here. The Vehicle statistics used for input to CadnaA represents an one hour average as found in Table B.2 in the Appendix. The CadnaA model was made as equal to the MapMonit model as possible. The two minute interval may not be representative when the vehicle flow for this interval not necessary is representative for the whole hour. The results can be found in Table 4.35 and 4.36. The two reference microphones behind the screen, number 1 and 4 both give bad results when compared to CadnaA. This was also the case when compared to the control measurements.

For the hour interval, the reference microphones in front of and above the screen give good results for all positions, with difference less than 1 dB, except for control position 2 and 10. Position 10 is the position of reference microphone 4, behind the building as seen in the map in Figure 3.7. In control position 2, MapMonit gives around 2 dB higher values than CadnaA. As seen in Table 4.34, MapMonit also simulates almost 2 dB higher than the control measurements. This means that CadnaA and the control measurement are about equal in this position, while MapMonit simulates a too high value. Since this is the case only for this position, it probably addresses to something in the MapMonit model.

The source and propagation model in MapMonit and CadnaA are not the same. Since the implementation of topography in MapMonit didn't work, both the CadnaA and MapMonit simulations were carried out with flat topography. The good agreement with the CadnaA simulations means that the source is similar estimated in MapMonit. The error of MapMonit compared to CadnaA is less then when compared to control measurements. The error may become smaller if the topography could have been implemented correctly.

Chapter 5

Discussion

5.1 Sources of Error

5.1.1 Estimates of Model Accuracy

Nord2000 Road has not been applied to computations by numerous users, and its accuracy is judged based on results of experiments made during the method development.

The source data for free-flowing traffic have been calibrated against measured energy averaged sound exposure levels, and the standard uncertainty for the source level under these conditions has been found to be smaller than 1 dB. For the propagation point-to-point validation for stationary sources has shown small average differences between Nord2000 Road and measured values. The largest difference found are behind screens where Nord2000 Road predicts 1 dB higher noise levels than the reference results. The standard uncertainty of individual differences are in the order of 1 dB for distances up to 400 m unfer favorable weather conditions. In this project, where the source strength is measured the error of the source model is unknown and must be disregarded, but an expected error of 1 dB for the propagation model is used as the error in the Nord2000 model. [9]

5.1.2 Distance Measurement and Positions

At the simple test site, the distances were measured with measuring tape and are considered to be accurate. However, the longer distances where measured with a measuring wheel. This would introduce an error since the wheel follows the bumps of the ground. Since the field was close to flat, this error was not considered to be pronounced. There was also a problem measuring the distance to the microphone perpendicular to the road. With comparison of measurements and landmarks in digital maps however, the distances are considered to be accurate within a 5 meters at the three greatest distances. With point source distance propagation loss, at 110 m this would correspond to ± 0.4 dB, and ± 0.2 dB for a line source. Every distance is defined as distance from the road edge. When estimating the source strength with measurements close to the road, this can give errors when the Nord2000 model assigns equal sound strength to all the sub sources. A truck has its main source at 3.5 m above the road compared to 0.02 m for a light vehicle. According to[10], this will give an error of 0.6 dB for a measurement distance 7.5 m from the road.

5.1.3 Sound Level Measurements

All the measurement equipment used satisfy the Class 1 standard of NEK EN 61672 [2]. The microphones were calibrated before and after the measurements. The error introduced by the equipment can be neglected. To be absolutely sure to avoid wind induced noise on the measurements, the goal was to have wind speed less than 5 ms during the time intervals used for control measurements. This was fulfilled at all distances except for 100 m. Unfortunately the wind variated between $5 - 10$ ms for these measurements. However, if it is presumed that the one-inch free field microphone has the same characteristics as the half-inch used in this project, Brüel & Kjær states that with the windscreen should handle wind speeds up to 10 m/s without getting any noticeable wind induced noise. [8]

Since the reference measurements at the simple test site were recording 24 hours at a time, care could not be taken in order to protect the measurements from dominating background noise and irregularities. For example, birds, planes ambulance sirens and cars on the gravel road next to the measurement site could have disturbed the measurements. During the control measurements, notes were taken when irregularities happened. For the complicated measurement site unwanted noise were excluded by studying the measurements afterwords. This may induce errors if something was overlooked.

5.1.4 The MapMonit Implementation

MapMonit is a software implementation of the Nord2000 source and propagation model. When this project started, MapMonit had some bugs and errors. Errors critical to the simulated noise levels should have all been corrected during this project, but it should be mentioned as a possible error source.

5.1.5 Ground Impedance

The ground impedance was measured following the one-layer model in the Nordtest Project, [7]. The standard also described a multilayer model, but in the Nord2000 model only the one-layer model is implemented. The rough division of seven ground classes showed to introduce an error of 1 dBA compared to the actual ground impedance.

5.1.6 The Use of Difference Method

By using the Difference Approach, see Chapter 3.6.2, another error is introduced to the system. It is shown in Chapter 4.2 that changing weather conditions during the different control measurements causes the Difference Approach to introduce an error compared to the the Direct Comparison approach. This error varied from 0.1 dB to 2 dB for the different control positions. The mean error for all the control positions was 1.2 dB.

5.1.7 Time interval and source definition

As described in Chapter 3.3, the MapMonit software implements the source as only light vehicles with 1000 passings a day at a speed of 80 km/h. In Chapter 4.3 different time intervals of different length and vehicle composition were used as input to the simulations. This resulted in the same error independent of measurement interval and vehicle composition. A single heavy vehicle passing was handled just as good as an hour with 1600 vehicles. This indicates that short time intervals are useful as input to the simulations, and that the source model of a light vehicles used in MapMonit does not introduce significant errors.

5.2 Height and Distance Evaluation

5.2.1 Comparison with Control Measurements

Distance 5 m

At reference microphone distance 5 m, the microphone height 0.4 m above ground underestimated frequencies above 500 Hz. This was probably caused by screening from the road shoulder since the shoulder was positioned between the reference microphone and the lowest source positions of the vehicles. The Nord2000 propagation model should be accurate enough to handle this, but the errors were large. One reason could be how the elevated road was implemented in the MapMonit model. A resolution of 2 m was used for the topography due to a limitation in the number of matrix elements MapMonit could handle. This made the implemented topography differ some from the reality. If the topography was the reason for the bad results it shows that the MapMonit model must be very accurate when the propagation path is complicated. The highest reference microphone at height 4 m underestimated the frequencies between 500 Hz and 2 kHz. This error is most likely caused by vertical directivity of the source which is not implemented in the Nord2000 model.

The results from reference microphones at 1.5 m and 2 m are similar to each other. For the closest control positions 10 m from the road edge, the differences between A-weighted simulations and control measurements were good with variations of 0 dB to 1 dB. For the control positions around 60 m from the road edge the errors were rather large, up to 3 dB. This was mainly caused by an overestimation of the frequencies around 1 kHz. For the control positions further away, the errors were less than 1 dB again. When the control measurements at 60 m were executed, the wind speed and direction during this time interval differed the most from the average for the entire control measurement period. When the actual weather from these control intervals were used, the results for these positions became very good, but worse for the other distances. This shows that the errors at 60 m to 67 m were caused by the varying weather conditions during the control measurements. Since the weather was the cause, there is no reason to believe that the source is estimated wrong.

At the highest microphone position, the underestimation around 1 kHz makes the results at 60 m very good. This is probably because the error as a result of the weather seems to cancel out the error introduced by the calculation of the control measurements. For all the reference microphone heights, the frequencies below 400 Hz were underestimated at all control positions except the closest at 10 m. Since the error increases with distance, it can probably be addressed to the noise propagation parameters. As described in Chapter 4.1, the error is similar to the one introduced by implementing a too soft ground impedance.

Distance 10 m

With the reference microphones placed 10 m from the road edge, the results for the lowest microphone at 0.4 m was still poor. The error between the A-weighted levels was between 1 dB and 4 dB. The problem is the higher frequencies which shows that the ground attenuation introduces errors when the reference microphone is to close to the ground.

For the two reference microphone heights in the middle, the results from this distance are considered to be very good. The error at control microphone position 8 is a little higher than the others with an error of 1.5 dB. This can be caused by the Difference Approach. For the other control positions, the errors were less than 1 dB. The highest reference microphone at 4 m above ground had a little higher errors, but for most control positions the error was small with a deviance less than 1.2 dB.

Distance 20 m

With reference microphone placed 20 m from the road edge, the results from the lowest microphone got worse than when placed at 10 m. This is natural when the ground attenuation will have a bigger effect for the higher frequencies with a longer propagation path. At this distance, the three highest microphones resulted in a source estimation a little bit too low at the area around 1 kHz. Again, this relates to the implemented ground class.

At the closest control positions, the levels for the lowest frequencies were simulated a bit too high. This indicates that the lowest frequencies of the source were overestimated with the reference microphones at 20 m. As described in Chapter 4.1, the measured ground class was probably softer then the actual class. For lower frequencies, this means more attenuation with longer propagation paths. When the reference microphones are placed 20 m from the road edge, and the propagation model attenuates the lower frequencies too much, the source is estimated too high for these lower frequencies. The result is higher levels for the control positions closer to the road. This shows that when the propagation model introduces errors between the source and the reference microphone, the source definition will cancel this error out with wrong estimation of the source.

The same problem occurred for the frequencies between 500 Hz and 2 kHz. Propagation with the measured ground class gave too high levels for this frequency interval. This means that the source will be estimated too low as can be seen for the closest control positions in Figure 4.11. From this follows that when the propagation model introduces errors, the source is defined wrong, but the simulations at the same distance as the reference microphones will give correct results since the errors of the propagation and the source will cancel each other out. The simulations in the control positions further away will to some degree have the same effect.

Rather large consistent errors were introduced at microphone number 7 and 8. The reason can be addressed to the selected ground impedance class or variating weather during the two control measurement periods. Overall though, the differences between the A-weighted simulations and the control measurements for the three highest reference microphones at 20 m were good. Not including control microphone 7 and 8, at all the other control positions, the error was less than 1.3 dB.

Distance 100 m

For all four microphone heights at distance 100 m, the difference in A-weighted levels between simulations and control measurements were good, with 1.6 dB as the biggest difference seen. However, the A-weighted levels hide the large deviations for frequencies below 400 Hz and above 6 kHz seen in the unweighted plots. The worst results are from the lowest reference microphone. The large deviations are probably caused by background noise. The further away the reference microphones are placed from the source, the lower the signal-to-noise ratio becomes. During the source estimation, the MapMonit software believes that all the measured sound at the reference microphone originates from the main source. With background noise present, the source will be estimated too high. For the lowest and the highest frequencies, the source is estimated up to 10 dB too high. When one third-octave-band levels have to be estimated correctly, a distance of 100 m seems to be too large, even though the results for the difference in A-weighted levels were good.

5.2.2 Comparison with CadnaA

Because reference microphone distance 100 m overall gave the poorest results, it was determined that it was enough to compare the simulations from distance 5 m, 10 m and 20 m with the CadnaA simulations. Since the microphone heights at 1.5 m and 2 m resulted in the best and most consistent similarities with the control measurements, it was the same which one of these heights that was used in the CadnaA comparison. CadnaA use an one hour traffic average for source estimation, and the same one hour interval was used for the MapMonit input. This will give the same traffic conditions for both programs.

At the control positions at 10 m, the difference between A-weighted MapMonit and CadnaA simulated levels was good. This indicates that the source was simulated with similar strength. The difference between CadnaA and MapMonit was small out to 110 m, but at the two greatest control distances, the difference became large. When the problem only occurred for long propagation paths this indicates that the great difference was caused by the two different propagation models. Note that the difference between MapMonit and the control measurements were good at these distances. With this said, there are some propagation constants that were implemented differently in the two programs. CadnaA use a fixed weather condition, while MapMonit imports the average of the real weather conditions during the time interval. In addition, while the surface in CadnaA was set to porous, MapMonit implemented the measured ground impedance class. Both these differences might contribute to the large error seen at these control positions.

For all the time intervals used, CadnaA simulates consistently lower levels than MapMonit, except for the second period at reference microphone distance 10 m. The main differences between this interval and the others, were much fewer vehicle passings and a higher share of heavy vehicles. The propagation in the CadnaA simulations seemed to be the same, but since the source was estimated higher than MapMonit this time, the error at the two furthest distances became much better.

5.3 Microphone Positions in vicinity of Noise Screen

The noise screen was placed on top of a mound. Unfortunately, the combination with noise screens and topography still had some issues which could not be fixed in time. These issues resulted in huge errors and it was determined that the results from this site should be presented with flat topography. It is presumed that this will give a higher error than with correctly implemented topography, but nothing can be said for certain until it is fixed and tested. All the following comments are based on simulations with flat topography and the conclusions may not be representative for an implementation with topography.

It is seen in Table 4.31 and Figure 4.15 that the reference microphone placed behind the noise screen gave decent results at control positions behind the screen in similar positions as this reference microphone. This is natural when errors in the propagation to these positions are similar and are corrected by an overestimation of the source. This is seen for the control microphones closer to the road, specially at the position on the road side and over the noise screen. For the reference microphone behind the garage, which have the most complicated propagation path, the source was estimated completely wrong. This makes both the reference microphones on the quiet side of the road useless. The reason is that the Nord2000 propagation model apparently not simulates accurate levels on the quiet side close to the noise screen. When this is said, the actual absorption coefficient of the screen was unknown and did most likely not fit the preset value in MapMonit.

The two reference microphones in front of and above the screen gave almost the same results. The first gave some higher levels for frequencies below 100 Hz and some lower values for frequencies above 2 kHz. The first can be due to reflections from the noise screen and the second can be caused by screening from the center strip. For frequencies above 400 Hz the results from these two reference microphones are good for all positions except for the control position 10 right behind the garage close to the noise screen (the position of reference microphone 4). For the 2 min input and the reference microphone in front of the screen, the highest error in the difference in A-weighted levels between simulations and control measurements was 2.3 dB. For the reference microphone above the screen the largest error was 1.8 dB. For the one hour input the errors were 2.3 dB for the one in front of the screen and 2 dB for the one above the screen. The higher error for the longer input for the reference microphone above the screen is natural when an one hour input gathered more noise from the road and the neighborhood behind the screen.

Compared to CadnaA the largest differences in A-weighted values are 1.8 dB for the reference microphone placed in front of the screen and 2.1 dB for the one placed above, both for control position 2. This may indicate a constant bias for this position. For all the other positions the largest error were 1.1 dB and 0.9 dB for the reference microphones in front of and above the screen, respectively. Since the implementation of topography in MapMonit did not work, both the CadnaA and MapMonit simulations were carried out with flat topography. The good agreement with the CadnaA simulations means that the source was similarly estimated in MapMonit. The error of MapMonit compared to CadnaA was less then when compared to the control measurements. The error when compared to control measurements may become smaller if the topography could have been implemented correctly.

Chapter 6

Conclusion

The criteria stated in this section are based on the limited testing that has been done during this thesis. A more thorough testing is needed to verify these results, with a much larger data selection. However, it is possible to say something about the tendency of these results. The results at the simple test site are mainly based on the difference between the MapMonit simulations and the control measurements, since CadnaA have a great deal of uncertainty due to the fixed weather conditions and implemented ground impedance. Due to a flaw in MapMonit with the combination of both noise screen and topography, the results at the complicated test site was presented with flat topography. MapMonit is evaluated both with CadnaA and control measurements.

6.1 Microphone Positions

At a general basis, it can be said that the more complicated the propagation path becomes, the more inaccurate is the source estimation. This includes both propagation distance from the road to the microphone and possible obstacles that are positioned in between. The propagation variables such as ground impedance and weather conditions had significant influence on the noise propagation. Both ground impedance and weather conditions were measured in order to minimize the error caused by implementing wrong propagation parameters. The rough division of ground classes in Nord2000 introduces some errors. Measurement periods with constant weather were chosen to minimize the problem with varying weather. Unfortunately the measurements at the simple test site were carried out during the winter, and constant weather conditions were hard to achieve. This led to errors in the measurements that would have been avoided during good weather conditions with no wind.

For a simple terrain and a long straight road, microphone positions from 5 m to 20 m give good estimation of the source strength given that the microphone is placed between 1.5 m 4 m above the ground. A lower microphone position suffers too much from high frequency attenuation of the ground. When placed close to the road, the microphone should have free sight to the contact point between the road and the nearest wheels of vehicles in both lanes of the road. Close to the road, the microphone position should not be too high when vertical directivity is not included in the source model. With reference microphone 5 m from the road edge, the microphone height of 4 m underestimated the source strength slightly for frequencies around 1 kHz. The best heights and distances had generally less than 1 dB difference between the A-weighted MapMonit simulations and control measurements for distances up to 181 m. The comparison with CadnaA resulted in similar A-weighted levels at distance 10 m but at distances further away than 160 m the difference could become larger than 5 dB. Part of the reason was probably that MapMonit used the actual weather conditions and measured ground impedance class, while CadnaA used fixed favorable weather conditions and a ground surface set to porous.

When the microphone was placed 100 m from the road, the source was overestimated for frequencies below 400 Hz and above 6 kHz. This was caused by background noise. Since the signal-to-noise ratio decreases with distance, this microphone distance was particularly vulnerable to background noise. When only A-weighted values are important, this distance gave a good source estimation with errors less than 1.4 dB for distances up to 181 m. The difference between the unweighted levels was largest close to the road and became smaller with increasing distance. When both background noise and errors introduced by the propagation increase with longer distances, it is not recommended to place the microphone as far as 100 m from the road for accurate source estimation. It can be used at rural locations such as at the simple test site, but will be impossible in more populated areas with more background noise.

In the vicinity of a noise screen, microphones both in front of and above the screen gave satisfying results. When placed behind the screen, the propagation model is not accurate enough to give satisfying results of the source calculation. In this position, exposure to background noise will also increase and corrupt the source calculation. Since the variation of the terrain in front of a noise screen can be large, the simplest and most universal placement will be to mount the microphone just above the noise screen. At the complicated site, the recommended microphone position was mounted at height about 5.5 m above the road plane and 0.5 m above the top of the noise screen. With flat topography, the difference between A-weighted MapMonit simulations and control measurements was less than 2 dB at all positions except the one just behind a garage. Obstacles along the propagation path included both a noise screen and buildings. For the best microphone position mounted above the noise screen, the difference between CadnaA and MapMonit was below 1 dB at all distances except at a control point placed just behind a garage. At this position the difference between MapMonit and both CadnaA and control measurements was rather large.

6.2 Measurement Time Interval and Traffic Composition

Comparison of different time intervals and traffic compositions, showed that there were virtually no difference between input intervals of 2 min compared to 60 min. This means that MapMonit corrects the noise source level correctly based on the input measurement for intervals at least as short as 2 min independently of vehicle type. The only restriction of the test was that the passings were all complete. This means that there is no basis to state what happens during half passings. This may have an effect during intervals with very few vehicle passings.

6.3 Suggestions for further Work

As said in the introduction to this chapter, the report is based upon limited testing. In order to be certify the assumptions in this report, massive testing with an extended data selection has to be performed. The model should then be applied to computations by numerous unique users.

In urban areas, the placement of the microphone may have to be in the vicinity of reflecting surfaces. The limitations and possible errors around this are important and should be studied. One microphone was placed behind a garage which resulted in a large deviance compared to the control microphones.

During the distance evaluation, it was concluded that a microphone position between 5 m and 20 m was recommended. Further testing should be made regarding how close to the road it is possible to place the microphone without getting directivity or wind drought problems. In certain areas with limited space, it might be necessary to position the microphone much closer than 5 m.

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Appendix A

Weather statistics for control measurements on simple measurement site

	Wind speed [m/s]	**Wind dir [deg]**	**Temp[$^\circ$C]**	**Temp grad[$^\circ$C/ 100m]**	**Humidity[%]**
100m# 1	5.9	145.0	278.6	0.5	52.0
100m# 2	6.9	145.0	278.9	0.5	51.0
100m# 3	5.0	167.5	279.4	0.5	51.0
100m# 4	9.7	145.0	279.4	0.5	50.0
100m# 5	5.4	167.0	279.4	0.5	50.0
100m# 6	4.1	167.0	280.4	0.5	48.0

Table A.1: Weater data for the control measurements at 100m.

Appendix B

Weather and road statistics for complicated measurement site

Temp[$^\circ$C]	**Humidity**[%]	**Wind speed** [m/s]	**Wind direction** [$^\circ$]	**Temp grad**[$^\circ$C/100m]
10.1	53.0	0.0	32.0	0.5

Table B.1: Weather used in simulation MapMonit simulation.

Cars	Heavy vehicles [%]	Speed [km/h]
2904	8.6	83

Table B.2: Vehicle statistics for one hour for complicated measurement site, used in CadnaA simulatoin.

Appendix C

Calculation of Uncertainty

The following are taken from [9]. The standard uncertainty of a predicted equivalent noise level is given by

$$u(L_{Aeq}) = \sqrt{(c_w u_w)^2 + (c_{tf} u_{tf})^2 + (c_v u_v)^2 + (c_N u_N)^2} \tag{C.1}$$

The factors c are sensitivity coefficients, and the uncertainty contributions u are contributions from:

- index W: the source noise emission
- index tf: the sound attenuation during propagation (transfer function)
- index v: the vehicle speed
- index N: the traffic intensity, composition, and diurnal distribution

Index	**c**	**u**
W	1	1 dB
tf	1	1 dB $<$ 400 m 1/3 + d/600 dB d . 400 m
v	10.9/v	3 km/h
N	4.3/N	0.1 $\cdot$ N vehicles (10%)

Table C.1: Guideline values of sensitivity coefficients and uncertainty

Appendix D

Hardware Equipment

Description	Serial number	NTH/SINTEF number
Power supply ZG0199		FC2067
Sound Power Source 4205	844876 A	N2008
Loudspeaker B&K		AN2008 01
Pre-amp. Nor 1201	23823	CB4106
Pre-amp. Nor 1201	19131	CB2087
Pre-amp. Nor 1201	14253	MM202803
Pre-amp. Nor 1201	22038	CB2097
Pre-amp. Nor 1201	23890	CB2101
Pre-amp. Nor 1201	14219	CB2073
Microphone B&K 4165	1867205	BC2105
Microphone B&K 4165	2068936	BC2112
Microphone B&K 4165	2068935	BC2111
Microphone B&K 4165	2068937	BC2113
Microphone B&K 4149	442894	BC2087
Microphone B&K 4149	530499	BC2090
Calibrator B&K 93,6 dB 1kHz	870.749/204	
Nor118	28202	MM4009
Pre-amp Nor 1206	27590	
Mic. Nor1220	27036	MM 4008 01
Radar449	1039	
Nor121	22945	
Nor121	23066	
4*Microphones outdoor protection Nor1212	NB	
Pre amp with heater (modified) Nor336		CB-2105
Pre amp with heater (modified) Nor336		CB-2099
Pacific East LTd - WS-2307-1R	61060535	

Table D.1: Equipment list.

Appendix E

CadnaA Input Parameters

E.1 Simple Test Site

- Number of reflections in the calculations: 4
- Buildings: Reflection loss = 2 dB
- Ground surface: Porous (1.0)
- Main road: Width = 7 m. Surface = 1a Mastic asph. 8-10 mm. Shoulder size = 0.5 m. Height above terrain = 1.35 m. Slope down to the terrain : 2.10 m

E.2 Complicated Test Site

- Number of reflections in the calculations: 4
- Buildings: Reflection loss = 2 dB
- Ground surface: Porous (1.0)
- Main road: Divided into 2 roads, width = 10 m in each direction. Surface = 1a Mastic asph. 8-10 mm.
- Other roads and parkinglots: Totally reflecting ($\alpha = 0$)
- Noise screens: $\alpha = 0.6$ on both sides.