Analysis and Improvement of the Acoustic Conditions During Ambulance Transports

– Master Thesis –

Section of Acoustics
Department of Electronic Systems
Aalborg University 2009
4$^{\text{th}}$ Master Semester
Project Group 09gr1064

AALBORG UNIVERSITY

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Title:

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Project period:

E10, spring semester 2009

Project group:

09gr1064

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Copies: 6

Number of pages: 93

Enclosures: CD

Date of completion:
June 3rd, 2009

Abstract:

This report describes and documents the measurements, analysis and improvement of the acoustic conditions during emergency response in the danish ambulance, model 2008.
A series of measurements were carried out, and an analysis of the results led to parameters describing the acoustic properties of the ambulance.
The highest SPL measured during emergency response was 68.2 dB(A) $L_{\mathrm{Aeq,1s}}$, where the most prominent exterior and interior noise sources were wheels and vibrating equipment respectively.
The noise from exterior sources can be reduced significantly by increasing the window thickness and insulating the doors and body with 25 mm glasswool.
Interior noise resulting from vibrating equipment can be reduced by improving the suspension system, the equipment mountings or both.
Additional improvements such as door closing mechanisms and attenuation of the siren were proposed. Furthermore, a number of possible future studies were suggested.

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Preface

This report is the master thesis written by project group 09gr1064 at the Section of Acoustics, Department of Electronic Systems at Aalborg University during the 4^{th} semester of the master programme in the period spanning from February 2^{nd}, 2009 to June 3^{rd}, 2009. This project concerns the analysis and improvement of the acoustic conditions during ambulance transports.
The report is aimed at people with knowledge equivalent to the 4^{th} semester master programme in acoustics. The project was proposed by Per Rubak and Per Thorgaard.
The reader should pay attention to the following when reading of this report:

- The report is divided into two major parts:
  - The main report which is divided into numbered chapters.
  - The appendices which are arranged alphabetically.
- Figures, tables and equations are numerated consecutively according to the chapter number. Hence, the first figure in chapter one is named figure 1.1, the second figure is named figure 1.2 and so on.
- The Harvard method is used for citation. The bibliography can be found after the main report.
- The CD contains additional literature, MATLAB scripts, measurement data, pictures, project proposal and a copy of the report.

Aalborg University, June 3^{rd} 2009.

Table of Contents

Chapter 1

Introduction

There are more than 150.000 emergency responses in Denmark each year, where the patient is transported to the hospital in an ambulance. In the critical cases, where the patient is in a life threatening condition, factors such as stress and anxiety influence the patients survivability. It is therefore important that the transport to the hospital where the patient can be treated, occurs without stressing the patient unnecessarily. The paramedics should therefore do what they can to keep the patient's stress and anxiety levels low.

The ambulances are designed for the purpose of getting the patient to the hospital as quickly as possible first, and to make it a comfortable drive second.
The ambulance stretcher table is constructed with a vibration reduction system so that the patient is spared the worst potholes and the roughness of the road. It is however less certain what effort has been put into obtaining a comfortable sound environment inside the ambulance. As stated in the project proposal, found on the enclosed CD, patients are stressed by the noise present during ambulance transport, however no studies have been performed determining the actual noise exposure in the ambulances currently in use. From a survey made in 2006 on the former ambulance model [Carius, 2006], 16 patients suffering from a heart attack participated in a survey. After their treatment, these patients were requested to rate the effect of the noise sources present during the ambulance transport to the hospital. It was concluded that patients found themselves affected by noise from engine, wheels, siren, equipment and closing doors.

Imagine being loaded into an ambulance, the door behind you is slammed shut, the ambulance accelerates fast and you hear the roaring engine, the ambulance siren, electronic voices fill the cabin with warnings and electronic equipment is beeping.
All this noise has a negative influence on the patients anxiety and stress levels. In addition, these transports can be anything from minutes to hours in duration.

Thus the following questions arise:

- What noise levels are patients exposed to during ambulance transport in the currently used ambulances?
- What can be done to improve the sound environment in these ambulances?

Over the last years, an effort has been put into improving the sound environment on hospitals for several groups of patients both during surgery and after. Here, soothing music is introduced to the patient in order to give a more positive experience and to block the negative noises [Falck, 2008]. Little is however done in the ambulances, where the sound pressure level, SPL, the patient is exposed to is considerably higher than at the hospital.

An interesting study would therefore be, to analyze the noise sources present during an ambulance transport and determine what can be done to attenuate these. Furthermore a study could be made on the possibility of introducing the concept of soothing music playback to the patient during ambulance transport.

This project will focus on measuring the noise sources present during an ambulance emergency response in order to determine the actual noise exposure inside the ambulance. Through an analysis of these noise sources and the ambulance's acoustic properties, suggestions for improvement of the sound environment will be given.
In essence, the goal of this project is to:

> *Measure and analyze the acoustic conditions of the patient cabin in the danish ambulance in order to ascertain the degree of noise the patient is exposed to during emergency response, and to give suggestions for improvement of the conditions based on this analysis.*

Chapter 2

Ambulance Specifications

This chapter describes the danish standard ambulance model 2008 in terms of technical specifications, physical dimensions, interior and siren details.

Type

The ambulance is a rebuilt Mercedes Sprinter 315 CDI, with a 2.1 l diesel engine with 150 HP. The model is a standard Sprinter with high roof. The vehicles are rebuilt at AMZ-Kutno in Poland.

Physical Dimensions

The dimensions of the ambulance were measured during a visit at Falck Aalborg. Only the dimensions relevant to this project were obtained. Figure 2.1a shows the front of the ambulance, figure 2.1b shows the rear and figure 2.2 shows the ambulance from the right side.

(a) Front of the ambulance

(b) Rear of the Ambulance.

Figure 2.1: Front and rear view of the ambulance. The red box on (a) shows the location of the siren.

The part of the ambulance that is of interest is the patient cabin in the rear of the ambulance, referred to as the "ambulance cabin" or simply "cabin" throughout this report.

Figure 2.2: Right side view of the ambulance.

The walls of the ambulance are double leaf constructions with a leaf of metal on the outside and metal+plastic on the inside separated by approximately 10 cm air space. There is a strong structural coupling between the two leaves, which is necessary for vehicle construction.
It was not possible to obtain more detailed data on the materials and exact construction and dimensions of the body, doors and windows. The data listed in table 2.1 is therefore obtained through manual measurements as best possible without disassembling the ambulance. It was determined that the windows were all single glass windows of approximately 6 mm thickness. Car windows are however constructed differently from ordinary glass, to prevent splintering and shattering if an object hits it. This can have an effect on the insulation quality of the windows, however it was not possible to determine to what degree since no information was available. The doors are double leaf constructions with a varying thickness and the dimension given is therefore an assessed average thickness. There is also a strong structural coupling between the two leaves in all doors.

Body dimensions			
	Height [m]	Width [m]	Length [m]
Outside	2.60	1.90	5.70
Inside cabin	1.90	1.70	3.30

Door (window) dimensions			
Door:	Height [m]	Width [m]	Thickness [cm]
Right side door	2.3 (0.7)	1.5 (1.4)	10 (0.6)
Left rear door	2.1 (0.7)	0.9 (0.6)	10 (0.6)
Right rear door	2.1 (0.7)	0.9 (0.6)	10 (0.6)

Table 2.1: Ambulance dimensions. The door (window) dimensions give the dimensions of the door+window, and in parenthesis the window dimensions alone. The doors are double leaf constructions and the thickness thus includes the air space.

The volume of the ambulance is $1.9 \cdot 1.7 \cdot 3.3 \approx 10.7$ m^3.

Interior

The interior of the cabin is shown on figure 2.3 with the stretcher positioned on the vibration reduction system to the right. The defibrillator and other equipment is placed in holders on the right side wall, while cabinets occupy the left side wall. Two chairs are available for paramedics, one against the partition to the driver's cabin, another next to the patient. Additional cabinets and shelves used for equipment are positioned against the partition to the driver's cabin.

Figure 2.3: Interior view of the ambulance.

Siren

On the former models the siren was placed on top of the ambulance however it resulted in SPLs inside the ambulance so high that it caused hearing damage to the paramedics, and was a very displeasing factor for the patients. It was therefore moved to the front of the ambulance on the newer model, as marked by the red box on figure 2.1a.
It has not been possible to find any data on the noise level of the siren inside the new ambulance models. This will therefore be determined through measurements in this project.

The siren has three different modes, however from speaking with paramedics at Falck, Aalborg it was ascertained that only two of these are used. The sound level of the siren is preset and can not be adjusted by the paramedics. The characteristics of the two used siren modes will be determined through measurements in this project.

Chapter 3

Noise Analysis

The purpose of this project is to determine the noise level and sources contributing to the sound environment inside the danish ambulance model, described in chapter 2, during an emergency response.
No information about the acoustic properties was available from AMZ-KUTNO's side. Previous work in the field of ambulance noise study was also found insufficient in terms of acoustic details and the desired acoustic information must therefore be obtained through own measurements. This chapter describes the measurements that must be carried out, the post-processing and analysis of the results.

3.1 Acoustic Behavior of the Cabin

The acoustic behavior of the cabin depends of several factors. The relevant factors will be determined through physical and acoustical measurements and observations. These include reverberation time, absorption and reflections. These measurements will provide the possibility to determine in which frequency bands extra absorption is needed. When the reverberation time is measured, the absorption coefficient for the cabin can be calculated from the reverberation time. Further details regarding the reverberation time measurement are given in the measurement report in appendix A.

3.1.1 Post-processing

If a sound source produces a stationary SPL, and is then turned off, the reverberation time is defined as the decay time it takes the SPL to decrease 60 dB (one millionth) from -5 dB to -65 dB, also shortened as T_{60}. If the absorption area and volume of the room is known T_{60} can be calculated from

$$T_{60} = 6 \cdot \ln(10) \cdot \frac{4 \cdot V}{c \cdot A}, \qquad [\mathrm{s}] \tag{3.1}$$

where V is the volume of the room [m^3], c is the speed of sound in air [m/s] and A is the total absorption area [m^{2}sab].[Rindel, 2001, p. 11]
Equation (3.1) is used for calculating T_{60} of a room where all data is given, and is normally shortened

$$T_{60} = 0.16 \cdot V/A. \qquad [\mathrm{s}] \tag{3.2}$$

The reverberation time measurement results are depicted on figure 3.1, where T_{60} for both microphone positions is shown as a mean for the two loudspeaker positions.

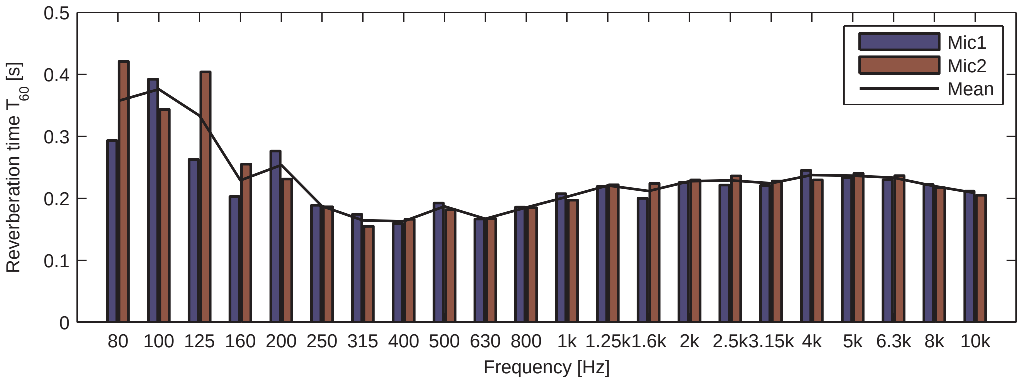

Figure 3.1: Results of the reverberation time measurement for the two microphones and the mean reverberation time measured in one-third octave bands.

The reverberation time measurement makes it possible to determine the absorption coefficient of the room. The absorption coefficient is used to describe the surface's ability to reduce reflections.
In order to get a relation between T_{60} and the absorption coefficient, an expression for the absorption area of a room is given by

$$A = \alpha \cdot S, \qquad [\mathrm{m}^2\mathrm{sab}] \tag{3.3}$$

where α is the absorption coefficient of the surface [-] and S is the surface area [m^2].[Kinsler et al., 2002, p. 337] This equation can also be extended, so other materials, objects or persons can be included in the equation, and is given by

$$A = \sum_{\mathrm{i}} \alpha_{\mathrm{i}} \cdot S_{\mathrm{i}}, \qquad [\mathrm{m}^2\mathrm{sab}] \tag{3.4}$$

so that the total absorption area of the room can be calculated. [Kinsler et al., 2002, p. 337]
In order to determine the mean absorption coefficient of a room, α_{mean} is calculated by

$$\alpha_{\mathrm{mean}} = \frac{A}{S_{\mathrm{tot}}}, \qquad [-] \tag{3.5}$$

where S_{tot} is the total surface [m^2]

The absorption coefficient for each frequency band, α_{m} is calculated by rewriting Sabine's equation as

$$\alpha_{\mathrm{m}} = \frac{0.16 \cdot V}{T_{60} \cdot S}. \qquad [-] \tag{3.6}$$

As seen, the absorption coefficient is directly dependent of T_{60}, since the surface area and volume of the room are constants. The highest absorption coefficient is thereby in the bands where the reverberation time is lowest. The absorption coefficients for all one-third octave bands is seen in figure 3.2.

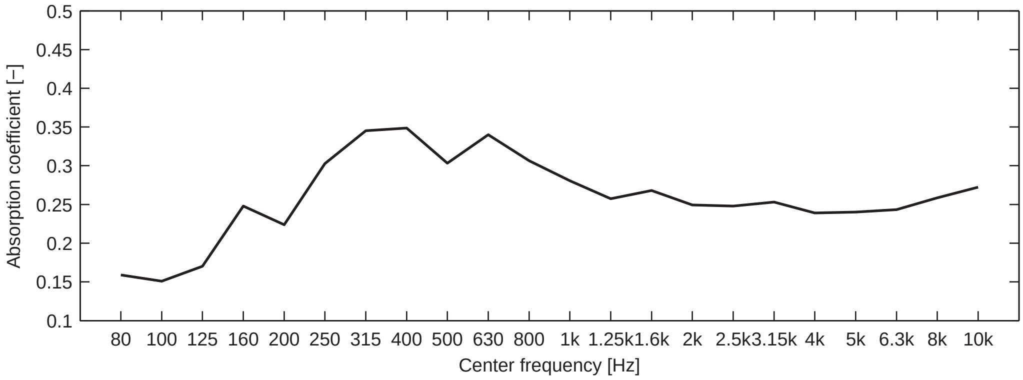

Figure 3.2: Absorption coefficient for the mean reverberation time in one-third octave bands.

Another important measure in room acoustics is to determine at which frequencies standing waves occur. In a rectangular room with the dimensions L_{x}, L_{y} and L_{z}, standing waves occur at frequencies related to the dimensions. For each dimension, the lowest frequency at which a standing wave occurs, is called the axial mode. The room modes can be calculated from

$$f_{\mathrm{n}} = \frac{c}{2}\sqrt{\left(\frac{n_{\mathrm{x}}}{L_{\mathrm{x}}}\right)^2 + \left(\frac{n_{\mathrm{y}}}{L_{\mathrm{y}}}\right)^2 + \left(\frac{n_{\mathrm{z}}}{L_{\mathrm{z}}}\right)^2}, \qquad \text{[Hz]} \tag{3.7}$$

where f_{n} is the frequency of the room mode [Hz] and $n_{\mathrm{x,y,z}}$ is the number of nodes in the room mode [-].[Rindel, 2001, p. 4]

The definition of a large room in frequency, is when the frequency is above the Schroeder frequency. This frequency approximates when the density of room modes increases substantially and the modes overlap and makes a more uniform response. The frequency can be calculated as

$$F_{\mathrm{L}} = 2000 \cdot \sqrt{\frac{T_{60}}{V}}, \qquad \text{[Hz]} \tag{3.8}$$

where F_{L} is the Schroeder frequency [Hz], T_{60} is the reverberation time [s] and V is the volume [m^3]. The Schroeder frequency is not an exact definition, because it is more a measure that defines the transition between single room modes to overlapping room modes.[Davis and Davis, 1994, p. 209]
The Schroeder frequency in equation (3.8) indicates that for frequencies below F_{L}, the room is considered a small room.

The reverberation time is not always possible to measure, since it is not always possible to place the microphone further away than the reverberation distance (see equation (A.1)), and thereby make a diffuse field measurement. This means that the results of all measurements, should be examined to determine if the times seems reasonable. The primary difference between small and large rooms is that the sound field in a large room is dominated by the reverberant field whereas the sound field in a small room is dominated by room modes. [Davis and Davis, 1994, Chp. 8–9]
A reverberant sound field does not exist in a small room because the sound energy is not able to develop a diffuse distribution. Since there is no reverberant field in a small room, a random placement of absorbing material will not improve the sound environment of the room as much as if placed coinciding with the room modes.

3.1.2 Result Analysis

As seen on figure 3.1, the reverberation time is low at all frequency bands relative to a small room e.g a recording studio, where the reverberation time is between 0.2 and 0.6 s. Normally the reverberation time of a room is given by the mean of the 500 Hz and the 1000 Hz reverberation times, which in this case for the cabin is 0.19 s. The reverberation time was measured with no people present inside the ambulance as a worst case measurement. Normally two people are present inside and therefore the reverberation time calculation is adjusted with the addition of two persons. The reverberation time with 2 people present inside the ambulance was calculated to be 0.17 s. The reverberation time at the bands lower than 200 Hz varies substantially, which indicates that room modes are present and that one of the microphones is placed in a node. Figure 3.3 depicts the room modes and the Schroeder frequency. The Schroeder frequency is calculated with use of equation (3.8) to be 266 Hz, which is also in agreement with figure 3.1.

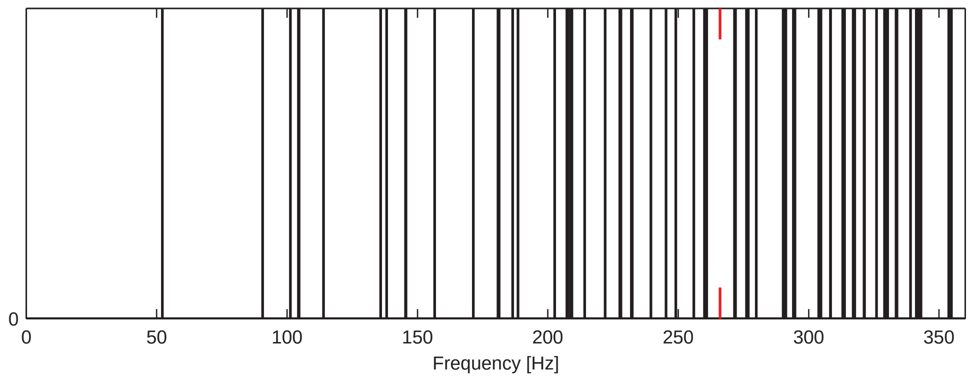

Figure 3.3: Room modes in the cabin below 360 Hz, where the calculated Schroeder frequency is marked by the red lines at 266 Hz.

Since the reverberation time is low compared to the recommended for a recording studio, there is no need to lower the reverberation time for any frequency bands.

The speech intelligibility for these reverberation times is sufficient, because the paramedic should be able to speak clearly with the patient.

As seen, the absorption coefficient is relatively low for all frequencies, which indicates that it must be possible to lower the reverberation time. If the reverberation time at a frequency band needs to be lowered by a factor of two, the absorption coefficient must be doubled at the given frequency band. This gives a 6 dB reduction of the diffuse field SPL inside the cabin.
Since the reverberation time is as low as it is, no more work is done to shorten the reverberation time inside the ambulance. Overall the reverberation time is low, but the volume of the room is also low, and thereby many reflections occur in short time and the sound dies out by the reflections. If a calculation is made of the Mean Free Path [Davis and Davis, 1994, p.209] it is possible to calculate how many reflections occurs in 0.1 s, and thereby determine why a low absorption coefficient results in a low reverberation time. First the MFP is calculated

$$\begin{aligned} \mathrm{MFP} &= \frac{4 \cdot V}{S} \qquad [\mathrm{m}] \\ &= \frac{4 \cdot 10.7}{30.2}\ \mathrm{m} \\ &= 1.4\ \mathrm{m} \end{aligned} \tag{3.9}$$

and together with the distance sound travels in 0.1 s equals

$$343 \cdot 0.1 = 34.3\ \mathrm{m}. \tag{3.10}$$

This gives $\frac{34.3}{1.4} = 24$ reflections within the first 0.1 s. This shows that even if the absorption coefficient is low, the amount of reflections is so high it makes the reverberation time low.
A conclusion on the reverberation time measurement is that it is sufficiently low for speech, even though the absorption coefficient is low. This is due to the short MFP, and thereby many reflections occur in a very short time and the sound dies out quickly.

3.2 Airborne Sound Insulation

The airborne sound insulation of the ambulance must be measured to determine how big an influence a noise source outside the ambulance has on the sound environment inside. Two measurements are performed to determine this. The first measurement is an airborne sound insulation measurement where a noise source is placed outside the ambulance. Then, the attenuation provided by the facade can be obtained by measuring and comparing the resulting SPLs outside and inside the ambulance. This is done in the measurement report in appendix B.

The second measurement to determine the airborne sound insulation of the ambulance is a facade leakage measurement. Here, an omni-directional noise source is placed inside the ambulance and a mapping of critical points is obtained by measuring the SPL on the outside of the ambulance close to the surface. This will show where noise from outside the ambulance will get into the ambulance with the least attenuation and thus point out where additional insulation should be considered. This measurement is described in the measurement report in appendix C.

3.2.1 Post-processing

A number of calculations and plots are made based on the raw results from the two measurements. Two single number quantities are used to describe the results of the airborne sound insulation measurement, along with frequency spectrum plots. Interpolation plots are used to represent the results from the facade leakage measurement. Note that all references to left and right ambulance facades are based on seeing the ambulance from the rear.

Airborne Sound Insulation Measurement Post-processing

For the first measurement, the post-processing consists of calculating the standardized level difference D_{nT} and the apparent sound reduction index R' in one-third octave bands for each of the facades. This is done using the calculated level difference D presented in appendix B, page 69.

The level difference results are shown on figure 3.4.

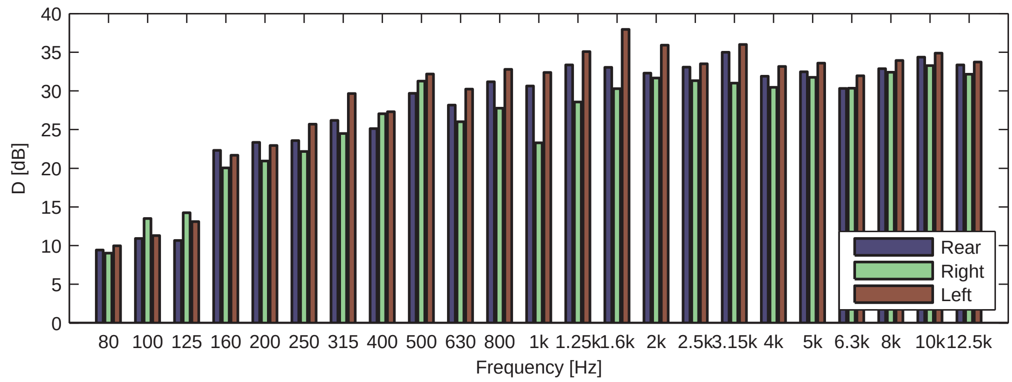

Figure 3.4: Calculated level difference D for the three cabin facades represented in one-third octave bands.

The level difference D however does not take the sound absorption area of the receiving room into account. Several corrections can be applied to do that. One is based on a reference absorption area of 10 m^2 and is called the normalized level difference as given by

$$D_{\mathrm{n}} = D - 10 \cdot \log_{10}\left(\frac{A}{A_0}\right), \qquad [\mathrm{dB}] \tag{3.11}$$

where A is the absorption area of the receiving room [m^2] and $A_0 = 10$ m^2 is the reference absorption area. [ISO 1405, 1998]

Another way to correct this is by including the effect of the reverberation time inside the receiving room. This is called the standardized level difference and is given by

$$D_{\mathrm{nT}} = D + 10 \cdot \log_{10}\left(\frac{T}{T_0}\right), \qquad [\mathrm{dB}] \tag{3.12}$$

where T is the reverberation time measured inside the ambulance [s] and $T_0 = 0.5$ s is the reverberation time reference value. [ISO 1405, 1998]
D_{nT} was calculated for the measured data and is shown on figure 3.5 for the three facades, using the mean T_{60} from the reverberation time measurement.

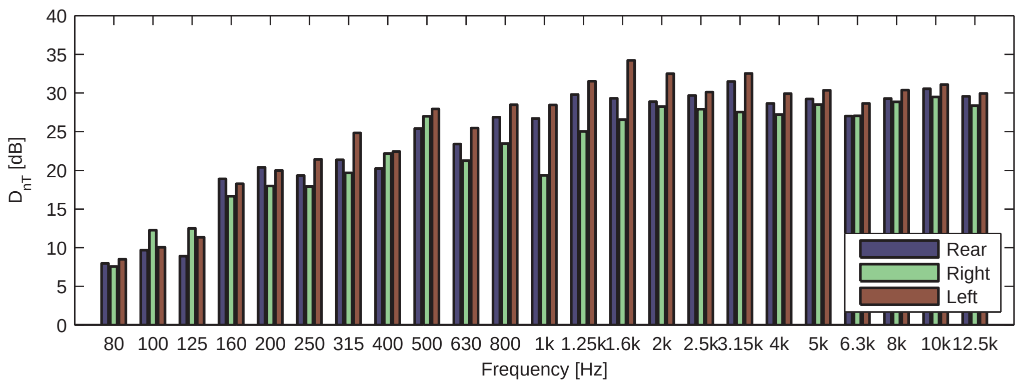

Figure 3.5: Calculated standardized level difference D_{nT} for the three cabin facades represented in one-third octave bands.

The two measures D_{n} and D_{nT} however lack the effect of the facade and receiver room dimensions. These factors are included in the apparent sound reduction index R' given by

$$R' = D - 10 \cdot \log_{10}\left(\frac{A_2}{S}\right), \qquad [\mathrm{dB}] \tag{3.13}$$

where A_2 is the total absorption area of the receiving room [m^2] and S is the wall surface area in [m^2].[Maekawa and Lord, 1994, p. 164]
The apparent sound reduction index measure is useful when it is desired to compare facades of different dimensions. R' was calculated for the measured data and is shown on figure 3.6.

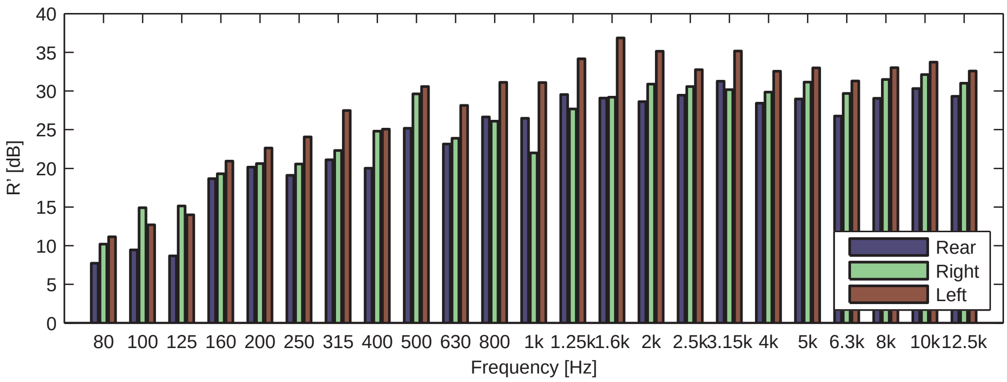

Figure 3.6: Calculated apparent sound reduction index R' for the three cabin facades represented in one-third octave bands.

For evaluation of the effect of the window in the right facade, R'_{window} should be obtained as well. Since it was not possible to measure it directly, it must be calculated from the composite transmission coefficient. Further theory on sound reduction index and transmission coefficient is given in section 4.1.1. In this case, the composite transmission loss is given by

$$\overline{\tau} = \frac{S_{\text{wall}} \cdot \tau_{\text{wall}} + S_{\text{door}} \cdot \tau_{\text{door}} + S_{\text{window}} \cdot \tau_{\text{window}}}{S_{\text{total}}} \Leftrightarrow \tag{3.14}$$

$$\tau_{\text{window}} = \frac{\overline{\tau} \cdot S_{\text{total}} - S_{\text{wall}} \cdot \tau_{\text{wall}} - S_{\text{door}} \cdot \tau_{\text{door}}}{S_{\text{window}}}, \tag{3.15}$$

where S is the surface area [m^2] and τ is the transmission coefficient given by

$$\tau = 10 \cdot \log_{10}\left(\frac{1}{R'}\right). \qquad [-] \tag{3.16}$$

[Maekawa and Lord, 1994] In order to calculate R'_{window}, the two quantities τ_{door} and τ_{wall} must be known. τ_{wall} is obtained from equation (3.13) which is calculated based on measurements, and equation (3.16). τ_{door} was not measured and not available from the manufacturer and an assessment was therefore that $R'_{\text{door}} = R'_{\text{wall}}$. This assumption is based on the assumed construction of the door, and the dimension observations made during measurements.

Note that this is an assumption and a simplification as the influence from several other uncertainties such as flanking transmissions and gaps between door and body are not considered. Further measurements should be performed to precisely specify the door and window R'.

To allow for a simpler evaluation of the results, a single-number is introduced from the ISO 717-1 standard:

> *The purpose of this part of ISO 717 is to standardize a method whereby the frequency-dependent values of airborne sound insulation can be converted into a single number characterizing the acoustical performance.* [ISO 7171, 1997]

The procedure for calculating the single number is as follows:

1. Given the results from an ISO 140-5 measurement, the calculated one-third octave band values of R' from 100 Hz to 3.15 kHz are plotted together with a reference curve given in the ISO 717-1 standard.
2. The reference curve is moved in 1 dB steps towards the calculated R' curve until the sum of unfavorable deviations are as close to 32 dB without exceeding this limit. (An unfavorable deviation is the difference in dB when a reference curve band value is larger than that for the corresponding band's R' curve value.)
3. The value at 500 Hz after this shifting is the single number value R'_{W}. (The same goes for D_{n} and D_{nT})

A MATLAB function was created to perform this fitting and the results can be seen in table 3.1

	$D_{\mathrm{nT,W}}$ [dB]	R'_{W} [dB]	R'_{W} unfavorable deviation sum [dB]
Rear	27	27	31.6
Right	25	27	23.4
Left	29	32	29.6
Door (assumption)	29	32	29.6
Window	-	21	26.3

Table 3.1: Weighted standardized level difference $D_{\mathrm{nT,W}}$, weighted apparent sound reduction index R'_{W} and unfavorable deviation sum for R'_{W}.

Facade Leakage Measurement Post-processing

For the facade leakage measurement, the post-processing consists of representing the measured SPL's in a graphical manner.

This is done by means of interpolating the data for the three facades into maps representing the level of insulation for the different surface areas. The results are given in appendix A, and are used to create three leakage mappings, one for each facade. These are shown on figure 3.7 to figure 3.9, where the "+" indicates a measurement point, while the values in between points are created using the interpolation function in MATLAB called interp2 with a cubic interpolation level of 2.

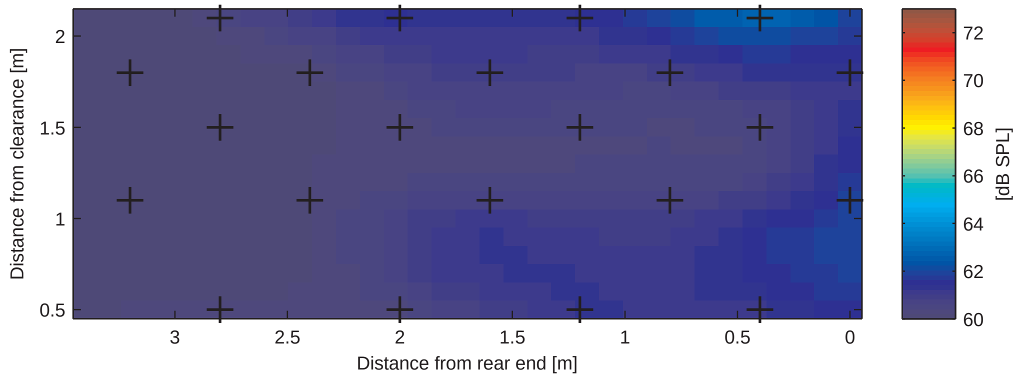

Figure 3.7: Left facade leakage, where + indicates a measurement point. Higher dB values means higher leakage and thus worse insulation at that point.

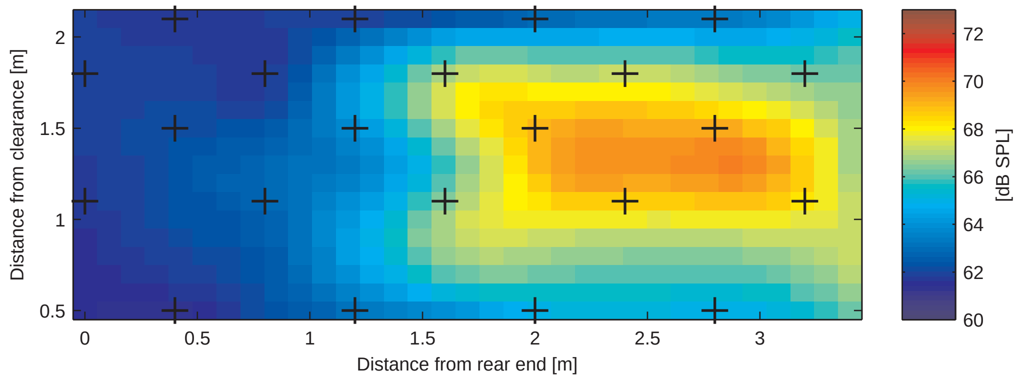

Figure 3.8: Right facade leakage, where + indicates a measurement point. Higher dB values means higher leakage and thus worse insulation at that point.

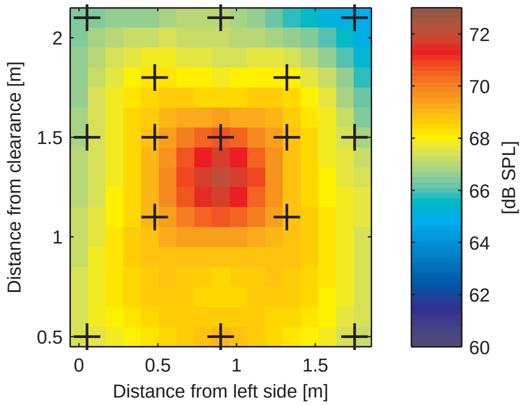

Figure 3.9: Rear facade leakage, where + indicates a measurement point. Higher dB values means higher leakage and thus worse insulation at that point.

3.2.2 Result Analysis

The data obtained in the two measurements has now been processed into plots and measures that can be used for analysis. The airborne sound insulation quality of the different facades will be examined.

Comparison of Left and Right Facade

Common for the results of the airborne sound insulation and facade leakage measurements, is a great difference between the left and right facade. The left facade has no doors and windows and thus having the same construction throughout the facade results in a very uniform insulation which is also seen on figure 3.7. It is therefore implied that $R'_{\mathrm{W}} = 32$ dB is the maximum obtainable attenuation with the current body-construction. There are ways to improve this level, however they will not be described in this chapter.

On figure 3.6 it is seen that for nearly all frequency bands, the value of R' is greater for the left facade than for the right and rear. The difference between the left and right facade stems from the sliding door and the window in the right facade. This is noticed by comparing figure 3.7 and figure 3.8 where the lowest insulation is visible on and around the door and window. By examining the construction of the door it is noticed that when closed there is a small gap between the door and body where rubber strips are attached to make the ambulance cabin airtight. These strips do not insulate as well as the double leaf construction used for the rest of the facade and thus results in a degraded insulation around the edges of the door.

The window in the door is by inspection assessed to be a 6 mm thick single glass and as figure 3.8 shows it is the least insulating part of the right facade. R'_{W} was calculated for the window to be 21 dB, using equation (3.15) and equation (3.16).

This is considerably less than for the body and door, and therefore results in a considerable reduction in the right facade total R'_W.

Comparison of All Facades

Examining figure 3.7 to figure 3.9, the rear facade is the worst in terms of airborne sound insulation quality. The rear facade consists of 2 doors with a window in each. This means that there are the same factors as for the right facade that degrade the insulation.

Rubber strips between the two doors and between the doors and body reduce the insulation quality. The construction of the doors was again not possible to obtain any information on, however was by observation assumed similar to the car body. Figure 3.9 indicated that the doors provided less insulation than the car body however this may also be due to the gaps and windows, as well as a poor resolution in measurement points. Lastly, the windows are of the same type as used on the right facade and therefore also degrading the overall insulation of the facade.

In conclusion, the facade leakage measurement shows the left facade as the one with the best insulation, while the right facade is second best and the rear facade is the one providing the least insulation. This however is not a fair conclusion in itself, as the ambulance cabin in this measurement was the source room, and the outside environment was the receiving room. From building acoustics, it is known that the dimensions of the two rooms has an effect on the result and can not be interchanged without seeing a difference in results. Therefore the results of the airborne sound insulation measurement are now examined to see what happens when the ambulance cabin is the receiving room as is the case in any real situation. Examining figure 3.4, which gives the raw level difference, it is clear that the left facade provides the best level difference, however the rear facade is the second best over the right. This contradicts with the conclusion from the analysis of the results of the facade leakage measurement. The explanation to this contradiction lies within the difference in the dimensions of the right and rear facades.

When sound from the outside hits the facade to the receiving room, the resulting sound pressure inside the receiving room depends on the dimensions of the facade. The loudspeaker will radiate sound in its directional pattern and wherever sound from it hits the facade the result is a reflected and a transmitted sound pressure. Since the right facade is larger than the rear, it will be hit by sound in more points and thus a higher total sound pressure is transmitted to the inside of the ambulance than through the rear facade. Therefore, even though the average insulation of the right facade is better than that of the rear, the difference in facade dimensions causes the rear facade to have a better insulation in terms of raw level difference.

As previously calculated in the post-processing R' gives a measure that takes facade dimensions into account and thus allows for a fair comparison of right and rear facade insulation quality. Figure 3.6 shows R' for the different facades, and here it is clear that the right facade provides better insulation in almost every frequency band and especially for the low frequencies.

Standardized Acoustical Performance Comparison

To get a standardized single number quantity for the acoustical performance of the facades the ISO 717-1 standard was used in section 3.2.1. The results given in table 3.1 for R'_{W} shows that both right and rear facades has an $R'_{\mathrm{W}} = 27$ dB while the left facade has an $R'_{\mathrm{W}} = 32$ dB.
It was clearly seen on figure 3.6 that the right facade provided better insulation over the rear facade, however they have the same R'_{W}. The reason for this lies within the method of calculating R'_{W}. Using this method, two almost equally insulating facades can result in the same R'_{W} value even though one of them is clearly the better. This can be seen by examining the undesired deviation sum resulting from the calculations. The higher the unfavorable deviation sum of a facade, the closer it will be to the R'_{W} value. That means, for lower unfavorable deviation sums, they are closer to $R'_{\mathrm{W}} + 1$ dB, however not close enough. Since the method always rounds down even $R'_{\mathrm{W}} = 27.99$ dB results in $R'_{\mathrm{W}} = 27$ dB. The unfavorable deviation sum was given in table 3.1 and it is noticed that the rear facade has a sum 6.2 dB higher than the right facade. This means that the right facade is much closer to $R'_{\mathrm{W}} = 28$ dB than the rear facade, and is therefore a better insulating facade.

This also gives a good numeric evaluation of the insulation loss caused by the window in the right facade. The difference is $R'_{\mathrm{W}} = 5$ dB, and thus a considerable reduction of the insulation quality. As also calculated the window had an $R'_{\mathrm{W}} = 21$ dB and therefore clearly a big part of the reason for the lower insulation performance of the right facade compared to the left.

3.3 Noise from Closing Doors

From the survey [Carius, 2006], one of the noise sources the test subjects noted as stressing was when the doors were closed. It was not possible to obtain any information regarding the force applied when closing the doors in this survey, and therefore it is decided to make a worst-case measurement. The doors are not constructed to slide in silently, and in addition when the paramedics are in a hurry the doors might be closed very quickly and thereby loudly.

Two of the important factors when determining the effect of a noise is whether the patient is aware of the type of noise and the time it occurs or not.

It is a well known fact that impulsive sounds occurring unnaturally and unexpectedly will cause the human stress response to activate and have the patient alert. If the patient therefore is not warned that the doors are being closed, the noise can be surprising and even shocking to the patient, thereby increasing anxiety and stress levels. Therefore a measurement will be made using a microphone placed at the patients head and the doors are then closed with force, in order to obtain a worst-case measure. This measurement is further described in the measurement report in appendix D.

3.3.1 Post-processing

The measure used to determine the noise level of doors closing is the equivalent continuous sound pressure level $L_{\mathrm{eq,T}}$:

> *The value of the sound pressure level of a continuous, steady sound that, within a specified time period, has the same mean square sound pressure as a sound whose level varies with time.* [Nordtest, 2002]

Since it is the annoyance effect of the sound that is desired, the measure takes the A-weighted input and is given by

$$L_{\mathrm{Aeq,T}} = 10 \cdot \log_{10}\left(\frac{1}{t_2 - t_1}\int_{t_1}^{t_2} \frac{p_A(t)^2}{p_0^2} dt\right), \qquad \text{[dB]} \tag{3.17}$$

where T gives the integration time [s], that is t_1 and t_2 are the start and end time respectively of the specified time interval in [s], $p_A(t)$ is the A-weighted sound pressure [Pa] and p_0 is the reference sound pressure (20 μPa) [Nordtest, 2002]
$L_{\mathrm{Aeq,1s}}$ was calculated for the loudest door slam for each side and with a time interval $T = t_2 - t_1 = 1$ s, the results in table 3.2 were obtained.

	$L_{\mathrm{Aeq,1s}}$ [dB(A)]
Rear Right	78.4
Rear Left	84.8
Side	80.6

Table 3.2: Calculated $L_{\mathrm{Aeq,1s}}$ for the three cabin doors.

3.3.2 Result Analysis

The effect of the door slams on the patient is evaluated based on the calculated $L_{\mathrm{Aeq,1s}}$ and how the patient is affected psychophysically. First, a few observations from the measurement are considered.

The rear doors are constructed such that when they are opened approximately 90° they are held open by a fastener. When released from this fastener, the door will "fall" in by itself if the ambulance is parked on a plain surface. Therefore, even if the paramedic does not apply any force and allows the door to fall in, it results in a loud noise. If, on the other hand, the paramedic closes the door by pushing it in, it results in an even louder noise. The door can as well be closed more silently if the paramedic holds the door back and carefully closes it.
The side door is a sliding door that, when fully opened, is held open by a fastener that is released when the door handle is pulled. When the door is out of the fastener, a considerable amount of force had to be applied to slide the door in. This resulted in a loud noise when the door slid in.
It was also noticed that there were thin rubber strips between all doors and the car body for the purpose of making the cabin airtight. The strips however seem to have little to no noise reducing effect since the sound of metal against metal was heard clearly when closing the doors. This will be further elaborated on in a later chapter.

Psychophysical Evaluation

The comfort of the patient is of vital importance, especially when the patient is in a life-threatening condition, such as when having a heart attack. It was earlier noted in the survey [Carius, 2006] that the door slams are a stressing factor to the patient, and as a result of that, having a negative influence on the patients condition. As mentioned earlier in this section, the human stress response to unexpected noises puts the brain in alert, and raises the stress level. This is an undesired effect and should be avoided.

In order to get a more tangible impression of the effect of noise on the human being, the article [Griefahn et al., 1992] is examined. This article investigates the effect of noise on a number of test subjects in terms of displeasure, heart rate increase and vasoconstriction, which means the muscular wall of the blood vessels contract and thus restrict the flow of blood.
Here, three types of noise: pink, traffic and gunshot (2 shots pr. second), each lasting for 19 s, were presented to a number of test subjects and their heart rate and vasoconstriction were monitored. After measurements, the test subjects were requested to rank the displeasure felt as a result of the different noises on a scale from 1 to 6 where 1 is the least displeasing. It should be noted that this test was run with healthy patients under no stress in controlled conditions and thus the results should only be taken as guidelines as they are not directly comparable to actual patients in a life-threatening situation. It does however provide a relation between noise and its effect on the human psychophysical conditions. The noise type that is most comparable to the door slams is the gunshot noise as it is also of impulsive nature, however closing the doors in an ambulance will not occur twice every second for 19 s like the gunshot noise used in the test. Therefore, the comparison of the article's results with the measurement results and calculated $L_{\mathrm{Aeq,1s}}$ is only a guiding evaluation and is subjective due to interpretation of the results.

This test showed that whenever a noise was presented to the test subject it resulted in an elevated heart rate for the duration of the noise and a steady decrease back to the normal level when the noise stopped. Also the blood flow decreased whenever a noise was presented however increased again halfway through the noise duration until it reached normal level again.

Figure 3.10 shows the average reaction to noise exposure using the three types of noise. Since the noise duration in the test is 19 s, the response caused by a single gunshot, which would be more comparable to a single door slam, will cause a different response in heart rate and blood flow. The effect of a single gunshot can not be directly concluded from the test, and is therefore assessed by examining the top plot of figure 3.10. It is estimated that the heart rate will have a peak shortly after the shot occurs and then a steady decrease when the noise has ceased. The effect on the blood flow is estimated to be a small decrease, as it is noted on the bottom plot in figure 3.10 that the decrease begins 3 s after exposure.
Further study into this should be made in order to draw better conclusions on the effect of a single impulsive noise on a human subject, however this is not the focus of this project and the estimated effects will therefore be used for further analysis.

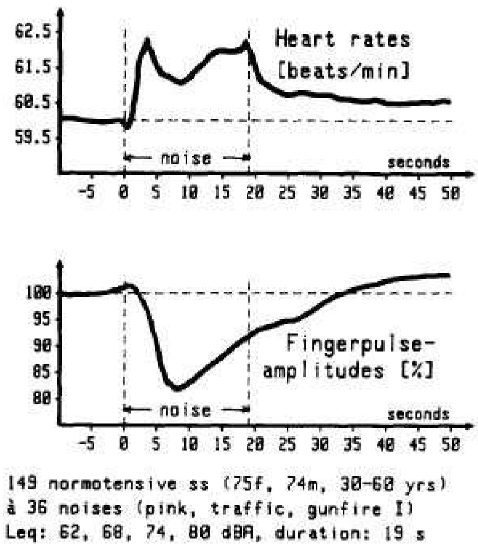

Figure 3.10: Heart rate and vasoconstriction increase as a result of noise exposure. Average response for three types of noise for 149 test subjects. (Normotensive means that the subjects all have normal blood pressure level.)[Griefahn et al., 1992]

The test results presented in [Griefahn et al., 1992] are compared to the calculated $L_{\text{Aeq,1s}}$ values in the door slam measurement. In experiment I, the displeasure, heart rate and vasoconstriction were measured for gunshot noise with $L_{\text{Aeq}} = 62, 68, 74, 80$ dB, the results of which are shown on figure 3.11. No specifications are given of how L_{Aeq} was calculated in [Griefahn et al., 1992], however it is assumed to be $L_{\text{Aeq,1s}}$.

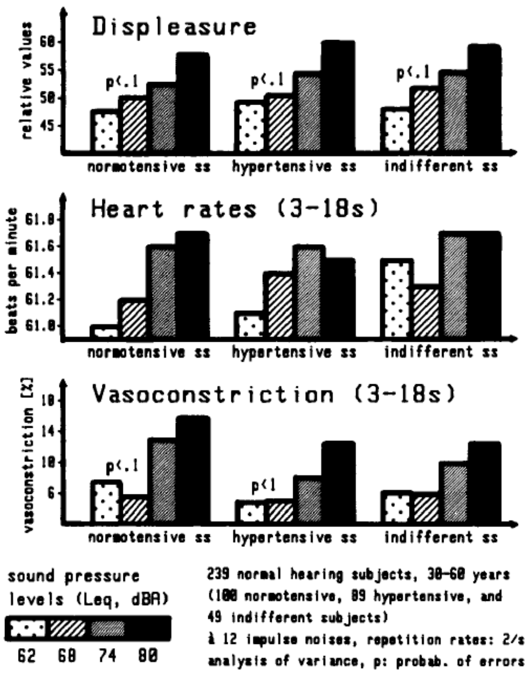

Figure 3.11: Displeasure, heart rate and vasoconstriction increase as a result of gunshot noise exposure at $L_{\mathrm{Aeq,1s}} = 62, 68, 74, 80$ dB. [Griefahn et al., 1992].

From the post-processing results of the door slam measurement, both the side door at $L_{\mathrm{Aeq,1s}} = 80.6$ dB and the rear right door at $L_{\mathrm{Aeq,1s}} = 78.4$ dB can reasonably be compared to the article results for $L_{\mathrm{Aeq,1s}} = 80$ dB. As earlier explained there is a difference in duration of stimuli and thus in the degree and duration of heart rate and vasoconstriction increase. Here, a significant increase in all three parameters is observed, and what can be noted, is that the parameter levels in general increase for increasing levels of $L_{\mathrm{Aeq,1s}}$. Therefore, the rear left door with $L_{\mathrm{Aeq,1s}} = 84.8$ will presumably result in even higher levels of displeasure, heart rate and vasoconstriction. This indicates that if the doors are shut with the applied force used during the measurements, the patient will be greatly affected by it. In the article, it is clear that if the noise $L_{\mathrm{Aeq,1s}}$ is lowered, the psychophysical effects on the test subject will also be less significant. A significant reduction in the displeasure, heart rate increase and vasoconstriction increase can therefore be achieved by reducing the noise level, thus reducing the psychophysical effect of the door slam on the patient.

A simple solution to this problem is for the paramedics to be aware of this effect on the patient and therefore always close the doors as quietly as possible. Other possible solutions are presented in a later chapter.

3.4 Noise Exposure during Emergency Response

To measure the noise exposure during emergency response, several scenarios are considered. The siren on the ambulance was pointed out by the patients in [Carius, 2006] as one of the most annoying noise sources during ambulance transport and the raw siren must therefore be measured. The complete noise exposure will be measured in four scenarios, when the ambulance is stationary, when the ambulance drives in the city, on the freeway and on the highway respectively. These measurements are described further in the measurement report in appendix E.

3.4.1 Post-processing

The noise measured in the cabin is depicted in several scenarios in the following. All the data in this section is A-weighted, to get a better indication of how the noise is perceived. The figures all have a color bar to the right of the figure, to be used as a reference, so a frequency at a given time has a SPL at e.g. -40 dB, where another frequency is -80 dB and thereby -40 dB compared to the first frequency. The values on the color bar should only be used as reference and not as SPLs. The spectrograms are calculated with a window length of 512 samples, 256 samples overlap and an FFT length of 1024 samples.

The first scenario is when the ambulance is stationary, and the two siren types are recorded. A spectrogram of both types are presented in figure 3.12 and figure 3.13, where the frequency content of both sirens is shown. Figure 3.14 is a spectrogram depicting the frequency content of the noise measured inside the ambulance when it is stationary with the siren turned off.

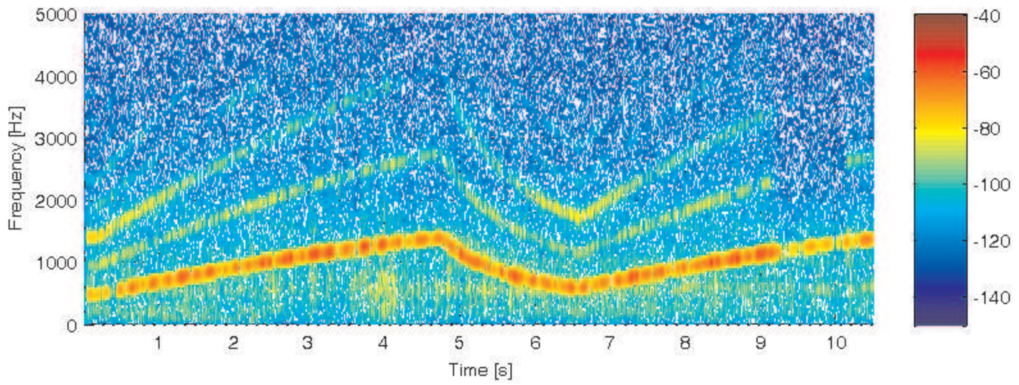

Figure 3.12: Spectrogram of the noise measured in the cabin when the ambulance is stationary and siren 1 is turned on. Note the duty cycle of siren 1 is seen.

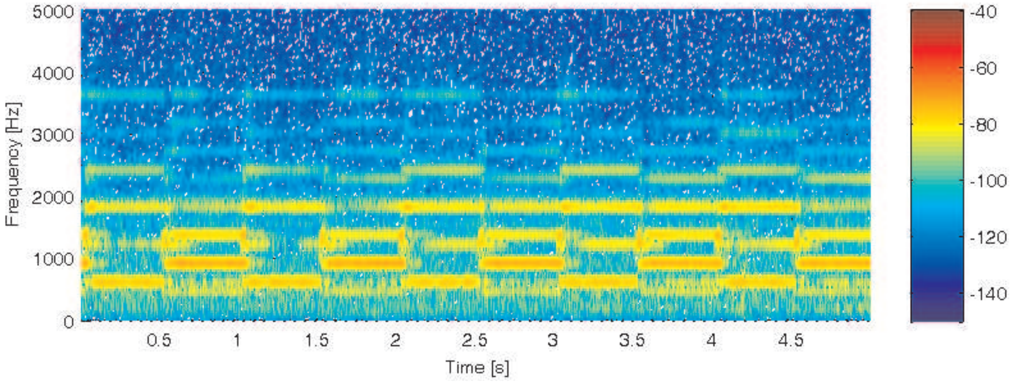

Figure 3.13: Spectrogram of the noise measured in the cabin when the ambulance is stationary and siren 2 is turned on. Note the duty cycle of siren 2 is seen.

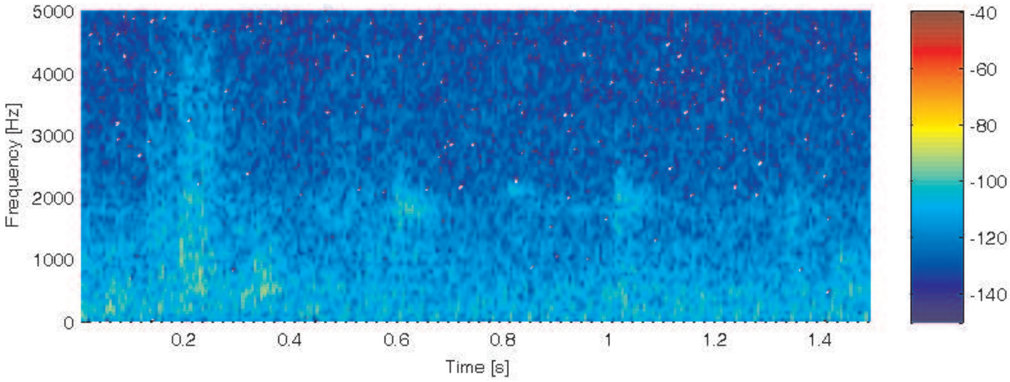

Figure 3.14: Spectrogram of the noise measured in the cabin when the ambulance is stationary and siren is turned off.

The second scenario was when the ambulance was driving in the city with use of both siren types. Figure 3.15 and figure 3.16 shows the two siren types, where the recording with no siren is not presented. Since siren 2 was not heard at all, the session with no siren was excluded.

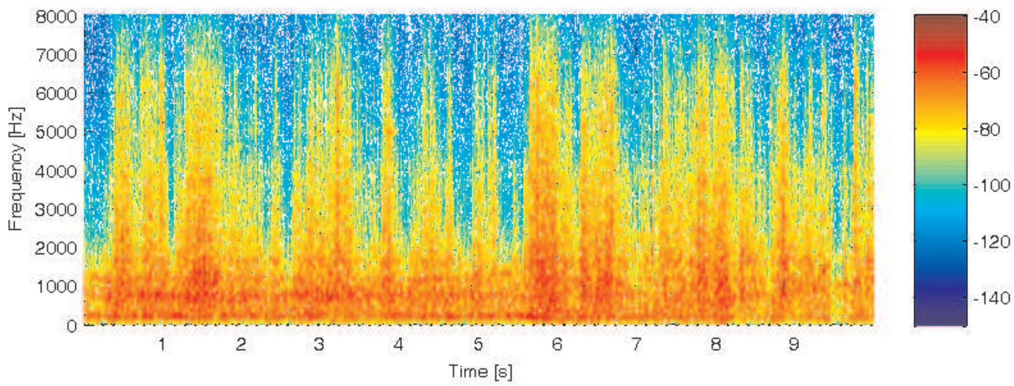

Figure 3.15: Spectrogram of the noise measured in the cabin when the ambulance is driving in the city with siren 1 turned on.

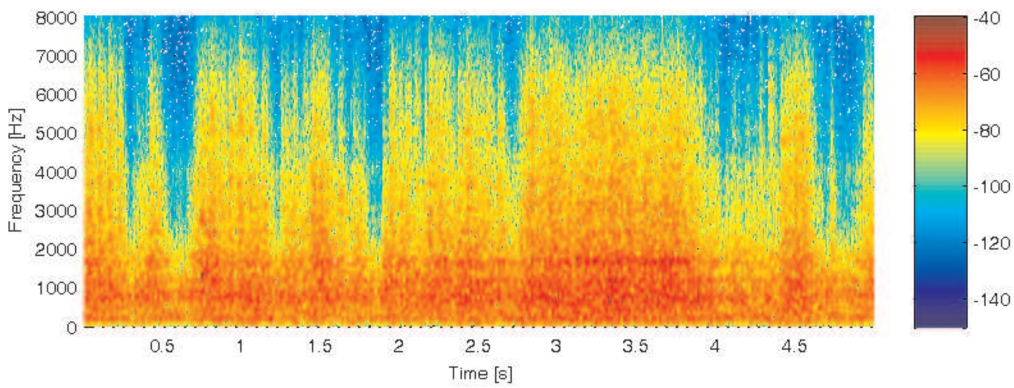

Figure 3.16: Spectrogram of the noise measured in the cabin when the ambulance is driving in the city with siren 2 turned on.

The third scenario was when the ambulance was driving on the freeway with use of both siren types, and with the siren turned off. Figure 3.17 and figure 3.18 shows the two siren types, where the recording with no siren is presented in figure 3.19.

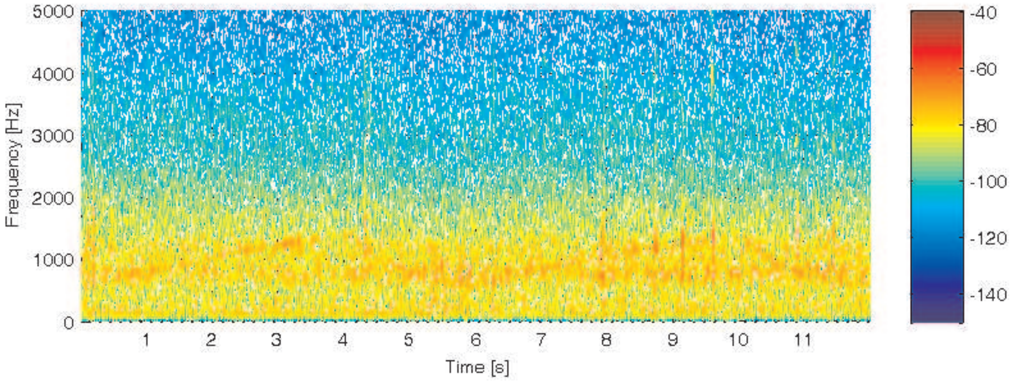

Figure 3.17: Spectrogram of the noise measured in the cabin when the ambulance is driving on the freeway with siren 1 turned on.

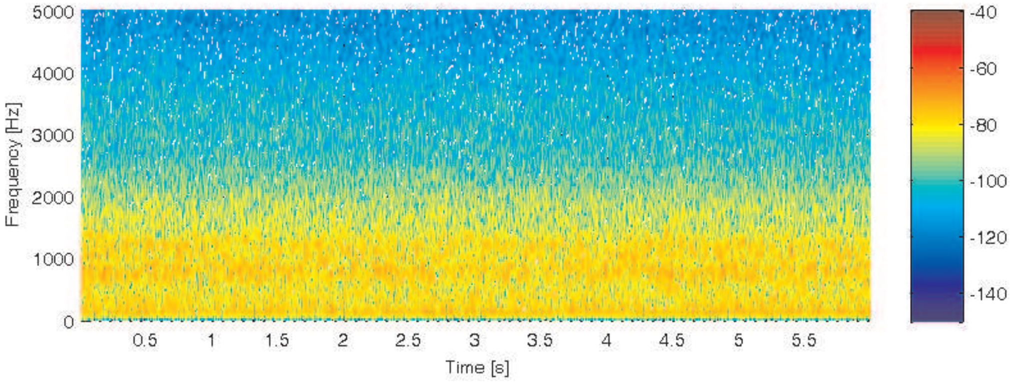

Figure 3.18: Spectrogram of the noise measured in the cabin when the ambulance is driving on the freeway with siren 2 turned on.

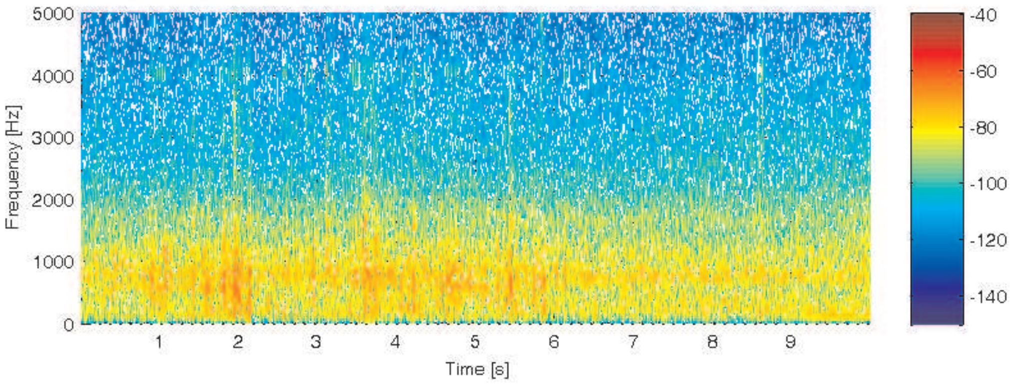

Figure 3.19: Spectrogram of the noise measured in the cabin when the ambulance is driving on the freeway with the siren turned off.

The fourth scenario was when the ambulance was driving on the highway with use of both siren types, and with the siren turned off. Figure 3.20 and figure 3.21 shows the two siren types, where the recording with no siren is presented in figure 3.22.

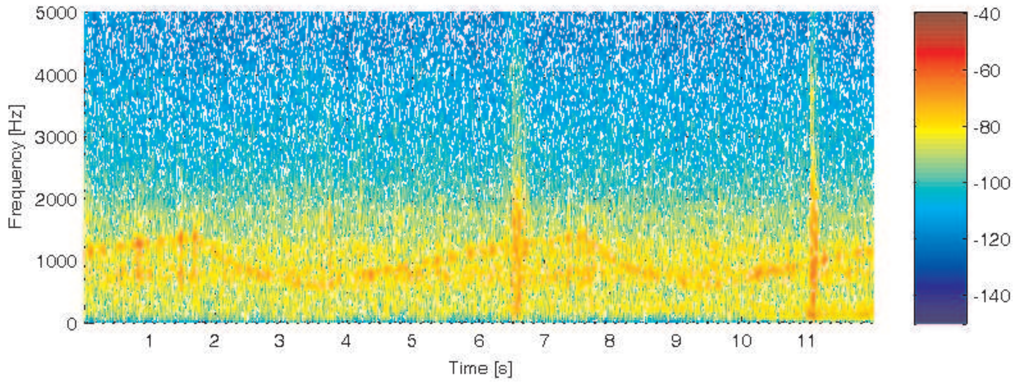

Figure 3.20: Spectrogram of the noise measured in the cabin when the ambulance is driving on the highway with siren 1 turned on.

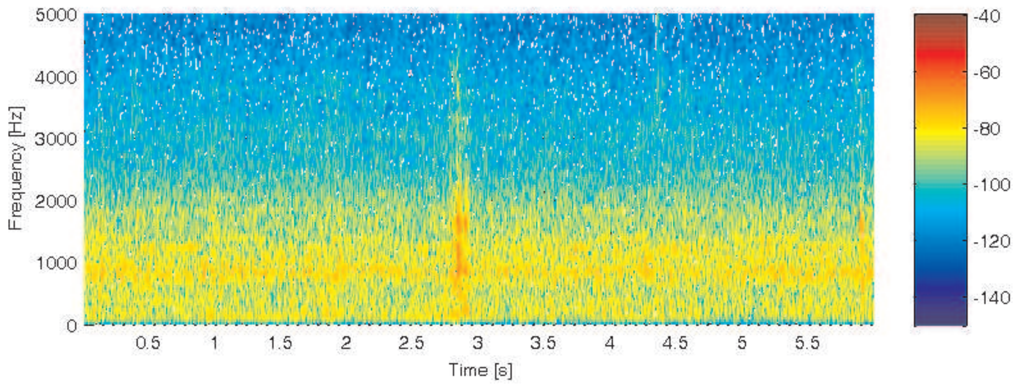

Figure 3.21: Spectrogram of the noise measured in the cabin when the ambulance is driving on the highway with siren 2 turned on.

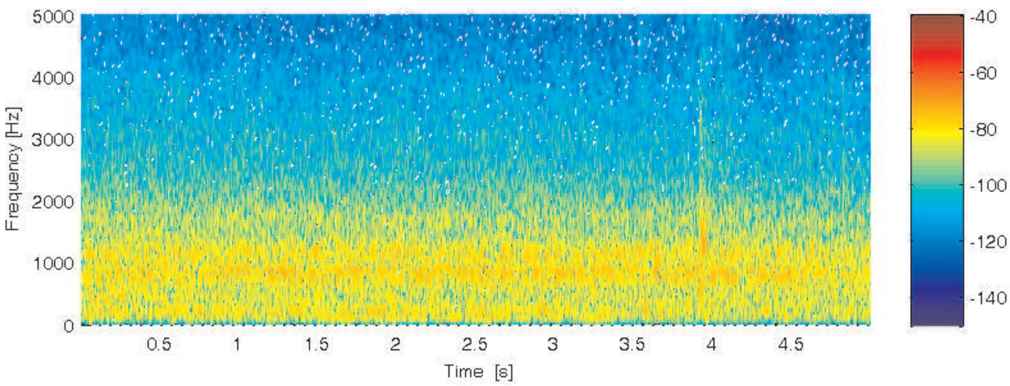

Figure 3.22: Spectrogram of the noise measured in the cabin when the ambulance is driving on the highway with the siren turned off.

$L_{\text{Aeq,1s}}$ is calculated using equation (3.17) for each of the previous shown scenarios and is listed in table 3.3. It is used to determine the equivalent continuous sound pressure level of the noise in the cabin, at the ears of the patient.

Scenario		$L_{\text{Aeq,1s}}$ [dB(A)]
Stationary	Siren 1	48.5
Stationary	Siren 2	41.6
Stationary	No siren	19.5
City	Siren 1	66.2
City	Siren 2	68.2
Freeway	Siren 1	48.4
Freeway	Siren 2	47.4
Freeway	No siren	49.9
Highway	Siren 1	49.3
Highway	Siren 2	47.4
Highway	No siren	44.1

Table 3.3: Calculated $L_{\text{Aeq,1s}}$ for the noise measured in the cabin in the different scenarios during emergency response.

3.4.2 Result Analysis

Two approaches to the analysis of the results are made, namely an objective analysis and a subjective analysis. Last an annoyance impression is given based on the experience of the ambulance transportation during measurements.

Objective Result Analysis

In the first scenario the duty cycle and characteristics of the sirens are seen, see figure 3.12 and figure 3.13. These characteristics should be located in the other figures in the post-processing where the siren type is present.

Siren 1 Characteristics Figure 3.12 presents the frequency characteristics of siren 1. As seen, this siren type is a frequency sweep between 500 Hz and 1500 Hz and has a duty cycle of approximately 6 s. As seen there are also overtones, which are not as intense as the main sweep, but should be noticeable when the other scenarios are inspected to determine if the sound of siren 1 is audible inside the cabin. $L_{\mathrm{Aeq,1s}}$ inside the cabin is calculated to 48.5 dB(A) when the ambulance is stationary, the engine is idle and siren 1 is used.

Siren 2 Characteristics Figure 3.13 presents the frequency characteristics of siren 2. As seen the siren is more complex than siren 1. Siren 2 has a duty cycle of 1 s, and the first half of the duty cycle consists of a 600 Hz tone, while the second half is a dual tone consisting of a 900 Hz and a 1300 Hz tone. There are also overtones as for siren 1, but it should be noticed that the overtones of siren 2 are more intense. $L_{\mathrm{Aeq,1s}}$ of the noise inside the ambulance is calculated to 41.6 dB(A) when the ambulance is stationary, the engine is idle and siren 2 is used.

City Figure 3.15 and figure 3.16 shows the frequency content of the noise within the cabin during transport in the city with the sirens turned on. The increased noise levels in this scenario compared to the stationary, are due to the movement of the ambulance. The engine is running, the air turbulence is increased, friction from the wheels and vibrations from potholes in the road are sources for the increased noise levels. As seen, the frequency content below 2 kHz has increased and many peaks are present compared to the stationary scenario. These peaks are represented with frequency content up to 8 kHz, and have impulse characteristics. The presence of these impulses are in the city scenario the most dominant noise sources, and compared to the stationary scenario the $L_{\mathrm{Aeq,1s}}$ levels are increased by approximately 20 dB to a maximum of 68.2 dB(A). These impulses originate from potholes in the road that makes the equipment inside the ambulance vibrate, and thereby increasing the noise. An impulse is seen in figure 3.15 at 3.9 s. This scenario is a worst case scenario, since the road is paved with cobblestones, and therefore quite bumpy.

Freeway Figure 3.17 to figure 3.19 depicts the noise characteristics within the ambulance during transport on the freeway. The frequency characteristics of siren 1 is seen in figure 3.17, where $L_{\mathrm{Aeq,1s}}$ is calculated to 48.4 dB(A).

The main frequency content is located between 500 Hz and 1500 Hz, which is the same as for siren 1, when the ambulance is stationary. The characteristics of siren 2 are not seen in figure 3.18, which could indicate that the sound from siren 2 is masked by other noise sources. $L_{\text{Aeq,1s}}$ within the cabin is calculated to 47.4 dB(A), which is only 1 dB less than with siren 1. The main frequency content is between 200 Hz and 1500 Hz, which includes the frequency content of siren 2, but still the characteristics of siren 2 are not clearly visible. The last session on the freeway is when traveling with the siren turned off. This session has the highest $L_{Aeq,1s}$ within the scenario, which is 49.9 dB(A). This $L_{\text{Aeq,1s}}$ at the no siren session is due to potholes in the road, and would therefore be decreased if no potholes were present. The spectrogram depicted in figure 3.19 shows that several impulses are present and can thus be the reason for this increase.

In all three freeway scenarios, a narrow band of noise centered at 800 Hz is present. This noise is generated by the wheels, engine and air turbulence during transport.

Highway The last scenario is when the ambulance is traveling on the highway. Figure 3.20 depicts noise in the cabin on the highway with siren 1 on, where again the characteristics of the wheels, engine, air turbulence and siren 1 is noticed. $L_{\text{Aeq,1s}}$ is calculated to 49.3 dB(A), which is approximately the same as for the freeway scenario. Figure 3.21 depicts the same scenario, but with siren 2 instead. Again the characteristics of the wheels, engine and air turbulence are dominant, and the characteristics of siren 2 are not observed. $L_{\text{Aeq,1s}}$ is calculated to 47.4 dB(A), which is also approximately the same as for the freeway scenario. The last session on the highway is when no siren is present and is depicted on figure 3.22, where the frequency peak around 800 Hz is seen.

The contribution from the siren types is calculated for the stationary, freeway and the highway scenario, from

$$P_{\text{total}}^2 = P_{\text{siren}}^2 + P_{\text{no siren}}^2 \qquad [\text{Pa}] \tag{3.18}$$

$$P_{\text{siren}} = \sqrt{P_{\text{total}}^2 - P_{\text{no siren}}^2}, \qquad [\text{Pa}] \tag{3.19}$$

where P_{total} is the $L_{\text{Aeq,1s}}$ for Siren X in [Pa], and $P_{\text{no siren}}$ is the $L_{\text{Aeq,1s}}$ for the No siren session also in [Pa]. These are then calculated back to dB again, and shown in table 3.4. The levels are calculated to determine the contribution of the siren in the cabin compared to other noise sources. As seen, the contribution of the siren on the freeway and highway scenario is approximately 3 dB lower.

Subjective Result Analysis

During the measurements, siren 1 was the most distinctive, since siren 2 could not be heard clearly in the scenarios where the ambulance was moving. One of the reasons for not hearing siren 2 is that it consists of constant frequencies and not a sweep like siren 1.

Scenario		$L_{\text{Aeq,1s}}$ [dB(A)]
Stationary	Siren 1	48.5
Stationary	Siren 2	41.6
Freeway	Siren 1	43.8
Freeway	Siren 2	45.4
Highway	Siren 1	47.7
Highway	Siren 2	44.7

Table 3.4: Calculated contribution of the siren noise (P_{siren}) in the cabin in the different scenarios during emergency response.

City In the scenario where the ambulance was driving in the city, none of the siren types could be heard clearly, since both of them to some degree were masked by other noise sources. The noise sources were identified as vibrations from the equipment inside the cabin, due to the bumpy road, and noise from the wheels, engine and air turbulence. Siren 1 was only heard in fragments in this scenario.

Freeway In the freeway scenario, siren 1 was heard, and siren 2 was masked. When listening to the recording, the equipment does not vibrate to the same degree as in the city scenario. This is again due to the road conditions, where the road in the city is not optimized for high speed. In the freeway scenario it is again the sound from the wheels, engine and air turbulence that is dominant inside the cabin. In the last session of the freeway recording where no siren is present, the SPL was increased compared to the session where siren 2 is present. This is due to potholes in the road, that made the equipment in the cabin vibrate.

Highway The highway scenario is the only scenario where siren 2 is heard inside the cabin during transport. If all three sessions are compared, the sound from the wheels, engine and air turbulence are still significant, but not as strong as in the freeway scenario.

Overall Noise Sources The noises represented inside the cabin originates from the wheels, engine and air turbulence. An overall conclusion is that when the speed increases, the noise from the wheels, engine and air turbulence increases and thereby masks siren 2 to a higher degree. Potholes in the road makes the equipment inside the cabin vibrate and thereby generate noise.

Subjective Annoyance Impression

During measurements, the person exposed to the highest degree of discomfort was the one acting as patient lying on the stretcher. The vibrations during city transportation were so intense at times, that the stretcher jumped on the stretcher table.

The equipment inside the ambulance was noisy due to vibrations, which is directly dependent on the condition of the road and the speed of the ambulance. None of the sirens had a high SPL inside the cabin, and were in all scenarios below speech level. A comment from the paramedics, was that the noise level from the siren is low in the 2008 ambulance models, compared to the older models. As the paramedics said, it is possible to have a conversation with the patient in a normal speech level in the ambulance model. This is supported by [Arbejdstilsynet, 2007, p. 10] where speech has a SPL between 55 dB(A) and 60 dB(A), and to clearly hear the speech the noise has to be 10 dB lower than the speech level. Table 3.3 shows that only when driving in the city, the noise level is higher than the speech level.

3.5 Summary of Analysis

To determine the acoustical behavior of the cabin, a reverberation measurement was carried out. The mean absorption coefficient inside the ambulance was calculated from the reverberation time measurement results to $\alpha_{\mathrm{m}} = 0.3$ which is considered low, however due to the presence of a significant number of reflections within the first 0.1 s, the average reverberation time was 0.19 s which is suitable for an ambulance cabin. This gives a high speech intelligibility, and thereby makes it easy for the paramedics to communicate with the patient.

It was desired to measure the airborne sound insulation provided by the left, right and rear ambulance facade to determine how well the ambulance attenuates exterior noise. The weighted apparent sound reduction index R'_{W} was calculated for each of the facades and used as a measure for their acoustical performance. The left ambulance facade had the highest $R'_{\mathrm{W}} = 32$ dB, while the right and rear facade both had $R'_{\mathrm{W}} = 27$ dB, a reduction caused by the windows and doors in those two facades. It was also noticed that no insulating material was present between the inner and outer leaves of the car body.

One of the stressing noise sources pointed out by patients, was when the ambulance doors were closed. The SPL at the patient position when closing the ambulance doors was therefore measured, and $L_{\mathrm{Aeq,1s}}$ was afterwards calculated for each door, to be used as a measure to evaluate the door slams. The following $L_{\mathrm{Aeq,1s}}$ were measured for the three doors: 80.6 dB for the side door, 78.4 dB and 84.8 dB for the right and left rear door respectively. The article [Griefahn et al., 1992] was examined and used for evaluation of the psychophysical effects of noise on the human being based on noise type and $L_{\mathrm{Aeq,1s}}$. It was assessed that a door being shut with the applied force would result in an elevated heart rate, a decreased blood flow and an increased level of displeasure for the patient.

It was also desired to determine the noise level the patient is exposed to during ambulance transport. Therefore, the SPL at the patient's head was measured during city, highway and freeway transport. Siren 1 was the most dominant of the two siren types, and could be heard in all scenarios. Siren 2 was masked by other noise sources in all scenarios except during highway transport. The masking noise sources were air turbulence, wheel noise and engine noise. In average the noise level inside the ambulance was below speech level (55-60 dB(A)) and considered very reasonable.

Chapter 4

Acoustic Improvements

An analysis of the acoustic conditions in the danish ambulance model 2008 was performed in chapter 3. Measurements were made to determine the reverberation time, airborne sound insulation, noise during emergency response and noise from closing doors. The measurement results were used to calculate a number of parameters that could be used to evaluate on the acoustic performance of the ambulance. This chapter will elaborate on the conclusions made in the analysis, presenting suggestions for possible improvements of the acoustic conditions.

4.1 Airborne Sound Insulation Improvements

Two of the measurements were concerned with determining the airborne sound insulation provided by the cabin facades. The facade quality determines the amount of exterior airborne noise transmitted to the inside of the ambulance. Exterior noise sources include tires, engine, siren, air-turbulence and other traffic noise. This section will present suggestions for improvement of the airborne sound insulation.

In section 3.2 it was determined that the left facade provided an attenuation of $R'_{\mathrm{W}} = 32$ dB, while the rear and right facades only provided $R'_{\mathrm{W}} = 27$ dB, due to the presence of windows and gaps between doors and car body.

As described in chapter 2, observations showed that the ambulance body is a double leaf construction with a strong structural coupling and an air space separating the two leaves of metal and metal+plastic respectively. Observations indicated that the doors were double leaf constructions with a strong structural coupling as well. The windows were by observation assessed to be 6 mm thick single glass windows.

Since the windows are single glass constructions while body and doors are double wall constructions, both single and double leaf wall theory is described in the following to make a more qualified assessment of possible improvements.
The theory in this section is based on [Maekawa and Lord, 1994, Chp. 5] and all non-cited equations and statements are from this source.

4.1.1 Single Wall Theory

For normal incidence, $\theta = 0°$, the transmission loss of a single wall is given by

$$R_0 = 10 \cdot \log_{10} \frac{1}{\tau} = 20 \cdot \log_{10}(f \cdot m) - 43, \qquad \text{[dB]} \tag{4.1}$$

where R_0 is the transmission loss at $\theta = 0°$, and m is the wall mass in [kg] and τ is the transmission coefficient [-] defined by the sound power of the transmitted wave relative to the incident wave and is given by

$$\tau = \frac{\Pi_t}{\Pi_i}, \qquad [-] \tag{4.2}$$

where Π_t is the sound power of the transmitted wave [W] and Π_i is the sound power of the incident wave [W] on a partition as illustrated on figure 4.1 where Π_r is the reflected sound power [W] and Π_a is the sound power absorbed in the wall [W].

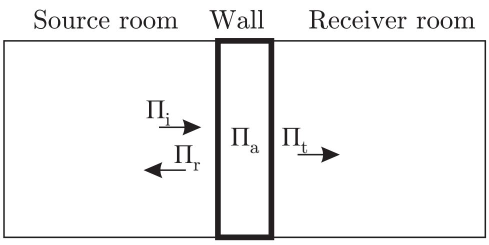

Figure 4.1: Illustration of sound transmission through a wall.

This is however based on the assumption that the wall acts like a piston when a sound wave hits, whereas in reality it does not. When a sound wave is incident on the wall it will excite the wall into a bending vibration reducing the transmission loss considerably. This bending vibration will at some frequency have an amplitude comparable to that of the incident sound and therefore result in a decrease in transmission loss. This is known as the coincidence frequency and will appear as a dip in the transmission loss at that frequency. The coincidence frequency is given by

$$f_\theta = \frac{c^2}{2\pi \cdot h \cdot \sin^2(\theta)} \sqrt{\frac{12\rho(1-\sigma^2)}{E}}, \qquad \text{[Hz]} \tag{4.3}$$

where c is the speed of sound in air [m/s], ρ is the density of the wall material [kg/m^3], E is Young's Modulus of the wall material [Pa] and σ is Poisson's ratio [-].

When a sound wave is incident on a partition that consists of more than one material, the total (composite) transmission coefficient is given by

$$\overline{\tau} = \frac{\sum S_{\mathrm{i}}\tau_{\mathrm{i}}}{\sum S_{\mathrm{i}}} = \frac{\sum S_{\mathrm{i}}\tau_{\mathrm{i}}}{S_{\mathrm{total}}}, \qquad [-] \tag{4.4}$$

where τ_{i} is the transmission coefficient of material i [-] with surface area S_{i} [m^2].

As seen in equation (4.1), to double the transmission loss at a given frequency, twice the mass is required. This is known as the mass law. For a constant mass equation (4.1) also implies that a 6 dB/oct increase in R_0 is obtained. For random incidence, that is for sound waves with incident angle $\theta = 0° \rightarrow 90°$, the transmission loss is given by

$$R_{\mathrm{random}} = \int_0^{\pi/2} R(\theta)d\theta = R_0 - 10 \cdot \log_{10}(0.23 \cdot R_0). \qquad \text{[dB]} \tag{4.5}$$

For actual sound fields however, incident angles $\theta = 0° \rightarrow 78°$ is considered more realistic. The transmission loss in this case is the field incidence R_{field} given by

$$R_{\mathrm{field}} \approx R_0 - 5. \qquad \text{[dB]} \tag{4.6}$$

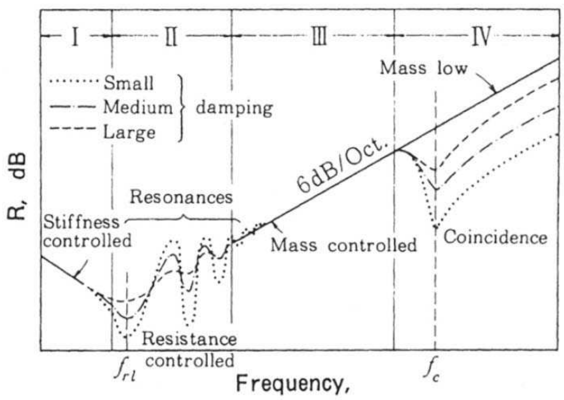

Figure 4.2: Frequency characteristics of single wall transmission loss. [Maekawa and Lord, 1994, p. 173]

Figure 4.2 shows the transmission loss of a single wall where the mass law is noticed in region III by the 6 dB/oct increase in R. The coincidence frequency is noticed by the dip in region IV. In the lower frequencies, the wall's internal properties and fastening to other walls, ceiling and floor has a great influence on R. In region I the stiffness of the wall and the fastening determines R, whereas in region II R is dominated by resonances controlled by mass, internal energy loss and boundary loss of the wall.

4.1.2 Double Leaf Wall Theory

A single wall has its practical limitations as indicated by the mass law where only a 6 dB increase in R is obtained by doubling the wall thickness. As seen in equation (4.3) an increase in h also leads to a lower coincidence frequency. Also, increasing the thickness increases the weight, and might therefore not always be a suitable solution.
Another method to increase R is to have the wall consist of two leaves separated by an air space, thereby in theory obtaining a transmission loss that is the sum of the individual transmission loss for the two leaves. To obtain the maximum effect of a wall with two leaves however would require the two leaves to be completely acoustically and structurally detached from one another, which in practice is not possible. Several methods however exist to obtain a high degree of decoupling of the two leaves. One is to have a resilient connection between leaf and stud, thus reducing structure-borne vibrations. Another is to fill the air space between the leaves with an absorbing material to reduce the SPL.

The transmission loss of a double leaf wall is illustrated on figure 4.3.

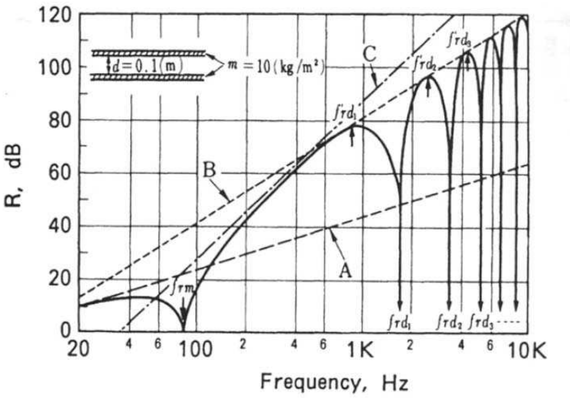

Figure 4.3: Frequency characteristics of double leaf wall transmission loss. [Maekawa and Lord, 1994, p. 179]

The dips in the transmission loss curve at f_{rm} and $f_{\mathrm{rd(n)}}$ are due to the internal properties of the leaves and therefore material dependent. A method for reducing the severity of these peaks is to use two different types of leaves in the wall thereby getting different resonance frequencies. If chosen so that a resonance frequency for one leaf is an anti-resonance in the other leaf, the resulting dip in transmission loss at that frequency would be less severe. Another option is to add absorbing material in the air space between the leaves. An example of this is examined later in the section.

As mentioned, no exact information on the construction and materials of doors, windows and body was available and it is therefore not possible to directly compare the measurement results with theory. Using the theory as a guideline however gives certain hints on how to improve the current conditions.

The following subsections will elaborate on the possible improvements based on theoretic knowledge of single and double wall efficiency and improvement techniques.

4.1.3 Left Facade Improvements

The left facade of the ambulance is body only, meaning there are no doors or windows.

The ambulance body construction is a double leaf construction with a strong structural coupling and has an air space of approximately 10 cm. The strong structural coupling can be the reason for many structure-borne vibrations and noises as a result thereof. It is however not easy to avoid this due to safety and structural integrity of the ambulance. This topic is not considered within the focus of this project and will not be further elaborated on.

A possible improvement however is, as also mentioned in section 4.1.1, to add an absorbing material in the air space between the leaves. An example is given in [Maekawa and Lord, 1994, p. 180] of a double leaf plywood wall with a 75 mm air space. Here, a 25 mm glasswool layer is placed in between the leaves resulting in an increase in transmission loss throughout the frequency range 100 Hz to 4 kHz of up to 8 dB in several frequency bands. Besides providing additional airborne sound insulation it also provides an increased thermal insulation. Having an estimated 10 cm air space throughout the ambulance body construction, it is possible to add at least 25 mm glasswool to the construction.

To calculate the theoretical improvement by applying a layer of 25 mm glasswool, the example from [Maekawa and Lord, 1994, p. 180] is examined. The transmission loss increase from the glasswool was read from the graph and added to the calculated R'_{wall}, after which the method for determining R'_{W} was applied. This was done in MATLAB and resulted in a new R'_{W} for the left facade of 37 dB, which is a 5 dB increase. This corresponds to almost a doubling of the insulation efficiency and is therefore a considerable improvement over the current construction.

4.1.4 Right Facade Improvements

The right facade consists of three parts, the car body (55% of the total surface area), the sliding door (29% of the total surface area) and the window (16% of the total surface area).

As explained in section 3.2, the doors are assumed to have the same R'_{W} as the car body, that is $R'_{\text{W}} = 32$ dB and the window has a calculated $R'_{\text{W}} = 21$ dB, resulting in a facade total $R'_{\text{W}} = 27$ dB.

The improvement of the car body is the same as suggested for the left facade; a 25 mm layer of glasswool in between the two leaves. However since this facade has more parts, it will not result in a 5 dB increase.
The actual increase is calculated from the composite transmission loss given in equation (3.15) and the transmission coefficient in equation (3.16), page 14, and the result is given in table 4.1. The overall increase in R'_{W} for improving the body was 1 dB. The same increase was seen when improving the door. Even when improving both door and body at the same time, only a 1 dB increase in R'_{W} was obtained. This is considered to be due to the window which has an R'_{W} that is 11 dB lower than for body and door and therefore has a significant influence on the total R'_{W}.

The least insulating part of the right facade is the window which has an estimated thickness of 6 mm, and is a combination of glass and plastic to avoid splintering and shattering of the glass as is typical for all car windows. No detailed information was available, and therefore all improvement suggestions are based on the measurements and observations.

As described in section 4.1.1, the mass law for a single leaf window states that a doubling of the mass leads to a doubling of the transmission loss. Therefore, it is suggested to double the car window thickness. Equation (3.15) and equation (3.16) were used to calculate the resulting transmission loss which is then used to determine R'_{W}. The result is an overall increase in R'_{W} of 4 dB as listed in table 4.1.

Even though the window surface area is only 16% of the entire facade, it has a big influence on the overall R'_{W} since it has a very low R'_{W} compared to that of the body and door. From the calculation of the improved windows, the right facade R'_{W} increased by 4 dB, which is high compared to the glasswool insulation improvement that only provided an overall 1 dB increase. The reason for this is that if part of the facade has a very low R'_{W} compared to the rest of the facade, then it degrades the overall R'_{W} considerably, like a hole in a wall degrades the overall R'_{W} of the wall.

4.1.5 Rear Facade Improvements

The rear facade consists of two parts, namely two doors (78% of the total surface area) and two windows (22% of the total surface area).

The doors and windows are considered to be the same construction as the door and window in the right facade. Therefore, the same improvements are suggested for the rear facade as for the right facade, that is a 25 mm glasswool insulation in the doors and a doubling of the window thickness. The resulting R'_{W} of such improvements are listed in table 4.1.

Facade + improvement	R'_W [dB]	R'_W unfavorable deviation sum [dB]
Rear (without improvements)	27	31.6
+ 25 mm glasswool doors	27	24.2
+ double window thickness	30	24.2
+ both improvements	32	26.1

Right (without improvements)	27	23.4
+ 25 mm glasswool body	28	27.2
+ 25 mm glasswool door	28	30.5
+ 25 mm glasswool body & door	28	24.2
+ double window thickness	31	31.6
+ all improvements	33	28.3

Left (without improvements)	32	29.6
+ 25 mm glasswool body	37	31.4

Table 4.1: Weighted apparent sound reduction index R'_W and unfavorable deviation sum for R'_W for the suggested improvements.

4.2 Door Improvements

One of the investigated noise sources was the noise occurring when closing the ambulance doors. There are two types of doors; the two rear swing doors, and the right side sliding door. This section will propose improvements in terms of noise reduction for the two door types, based on the conclusions presented in section 3.3.

As described in section 3.3, when the ambulance is parked on a plain surface, the rear door closing mechanism makes the doors fall in when released from the fastener. Whenever one of the rear doors is being closed, the amount of noise it will produce depends on how the paramedic closes it.

As mentioned in section 3.3, the side door is constructed such that it requires a considerable force to close it, and as a result it produces a loud noise. This door is located next to the patients head and it is therefore important that this door is closed silently.

4.2.1 Rear Door Improvements

The paramedic is the key factor deciding how much noise will result from closing one of the rear doors. A simple and straightforward solution to reduce the noise would be to ensure that every paramedic is aware of the effect the noise has on the patient and therefore be mindful of this whenever closing the doors.

This solution however is solely dependent on the paramedic to close the door silently every time and an alternative, that does not include the paramedic as a factor, should be considered.

A possible alternative is to modify the door closing mechanism. Currently, an arm attached to the door slides on a track providing no resistance thus enabling the door to "fall in" quickly.

An interesting principle used for doors in buildings is "silent-close" hydraulic door mechanisms, that catch the door when it is near its closing point by increasing the resistance thus slowing the door the last few cm before it closes. An example of this type of product is shown in [Svalk, 2009, p. 10]. If this principle is adapted to the danish ambulance model, the noise could be reduced significantly and be independent of how much force the paramedic applies when closing the door.

4.2.2 Side Door Improvements

The side door is a sliding door and contrary to the rear doors it can not close by itself when released from the fastener. It is necessary to apply force to close the door. This produces noise when the door closes, up to the worst-case which was calculated in section 3.3. Like with the rear doors, the noise level therefore depends on the force applied by the paramedic. Again, a possible solution to reduce the noise is to inform the paramedics about the effect on the patient and recommend that the door is closed silently every time.

Alternatively, a simple solution that already exists, is an electric door closer, available as an accessory to the Mercedes Sprinter model currently in use. This accessory is an electric closing mechanism that activates when the door is near the point of closing, ensuring that it occurs silently and without any force required by the paramedic [Mercedes-Benz, 2006, p. 22].

4.2.3 Rubber Strips

Between each door and the car body there are rubber strips placed in order to make the ambulance airtight. As they are placed between the metal surfaces of the door and body another usage for the rubber lists could be to reduce the noise when closing the doors. This usage is not utilized in the current construction since the sound of metal against metal was heard very clearly when the doors were closed during measurements.

The rubber strips were not examined in detail during the measurements so a further analysis of the rubber strips, their placement and thickness should be performed in order to determine whether they can be used for noise reduction.

4.3 Wheel, Engine and Air Turbulence Improvements

The noise exposure from the wheels, engine and air turbulence are the most dominant noise sources inside the ambulance when driving on the freeway. The noise from these sources has a contribution of 49.9 dB(A) without siren, which is more than the approximately 44 dB(A) the sirens contributes to the total SPL according to table 3.3 and 3.4. The SPLs of the wheels, engine and air turbulence when driving on the freeway masks siren 1 partly and siren 2 completely. Since no recordings of only the engine, wheels or air turbulence was obtained, it is unknown which of the three noise sources contribute the most. Therefore each of them will be considered as equally contributing in the following. Overall the earlier mentioned facade improvements would reduce the airborne noise from the wheels, engine and air turbulence.

4.3.1 Wheels

The noise generated from the wheels are due to the tire type and tread pattern. The tires are all-season tires, which are used instead of changing from winter tires to summer tires throughout the year. According to [Michelin, 2009], the tire noise is caused by three different factors.

- The tire hitting the ground.
- The vibrations passing through the tire.
- The vibration of the air through the tread pattern.

The winter tire has the most aggressive tread pattern, since most rain and snow occur in the wintertime, and the structure of the tread pattern must therefore remove snow and rain to get the best grip. Summer tires are optimized for dry roads, and the structure of the tread pattern is therefore less aggressive than on winter tires. This reduces the air flow through the tread pattern, and thereby also the noise from the tire.

The all-season tire is a compromise between winter and summer tires with a tread pattern that is a combination of both, and thereby the air flow through the tread pattern is in between the summer and winter tires. The reason for choosing all-season tires, is that the ambulance is not only expected to drive on dry road, but also off-road if the situation requires it. Therefore the tire choice should still be all-season tires, but it should be investigated if a more silent all-season tire could be used. This is usually not specified by the manufacturer, and therefore a measurement of the tire types should be made to determine what brand of all-season tires are least noisy. The tire type is not the only thing that could be changed, as the material on the road has a large influence of the noise as well. According to [Grontmij Carl Bro, 2009], the noise can vary up to 8 dB with the same tire on different roads.

4.3.2 Engine

The noise from the engine is heard when the ambulance accelerates, and especially right before changing up a gear. Here the engine is running at the highest rpm, and thereby generates the most noise. The noise from the engine is dominant during acceleration when the speed is below approximately 40 km/t [Michelin, 2009], whereas when the speed is above approximately 40 km/t, the other noise sources are more dominant. The noise from the engine is both structure- and airborne, and both noise sources should be considered. Since the mounting of the engine would requires a construction modification, it should be done in the design stage by Mercedes, with focus on the structure-borne noise. The airborne noise could be reduced by insulating the engine room, and the wall between the driver's cabin and the cabin. Structure-borne engine noise is not considered a part of the project focus, and further study into this topic is omitted.

4.3.3 Air Turbulence

The air turbulence increases when the speed increases. The air turbulence is due to the non aerodynamic parts of the ambulance. This includes the front, flashing blue lights, gaps between doors and other parts outside the ambulance that are not streamlined. The flashing blue lights could be integrated in the roof of the ambulance as the normal headlights are, instead of being placed on a roof bar, as seen on figure 2.2. If these were integrated in the roof, less air turbulence over the cabin would occur, and thereby result in a reduction of the noise.

4.4 Equipment Improvements

The equipment inside the cabin is the most dominant noise source when driving in the city. The noise has the origin from the suspension, and thereby structure-borne vibrations that make the equipment vibrate and thus generate noise. In the following, the apparent equipment noise sources are examined.

4.4.1 Equipment Noise Origin

All noise sources with origin in the vibration problem could be decreased by improving the ambulance suspension. It is a standard suspension, that could be changed to an adjustable pneumatic suspension. Falck already has an ambulance with this kind of suspension, called a baby ambulance, where the focus on the vibrations has been high.

> *It is of crucial importance that vibrations are minimized during transport as these may prove harmful to the baby. The ambulance is supplied with an adjustable pneumatic suspension. Continuous monitoring of the vibrations is being developed in order to adjust the pneumatic suspension of the ambulance and speed to minimal vibration level.* [Baby Ambulance, 2000]

Thus vibrations can be minimized if a pneumatic suspension is implemented in the ambulance.

4.4.2 Stretcher

The stretcher is, when placed in the cabin, located on a stretcher table, that has a built in vibration reduction system. The stretcher is locked to the table so the stretcher can not be moved unless the paramedic unlocks it. However the mounting of the stretcher to the stretcher table is insufficient regarding noise. The top of the stretcher table is made of aluminum that the wheels of the stretcher rests on. When vibrations occur, the stretcher jumps on the stretcher table, thereby causing impulse noises to occur. It is not only the noises that are considered in this case, but also the vibrations since they are not pleasant for the patients. If the wheels were resting on vibration damping materials, the impulse noises and vibrations could be decreased. The stretcher should also be fastened to the stretcher table so no jumping of the stretcher occur.

4.4.3 Helmets

On the left rear door, two helmets are fastened to an aluminum bracket, see figure 4.4. This implementation results in noise when the door is shut, and when vibrations occur during transport. The noise occurs when the hard plastic helmets hits the aluminum brackets. These vibrations can be decreased by optimizing the mounting with a strap, that fastens the helmets, limiting their ability to vibrate.

4.4.4 Stretcher Chair

On the right rear door a stretcher chair is hanging on two brackets and fastened with two straps, see figure 4.4. The chair is collapsible, and has a frame made of aluminum. When the stretcher chair is hanging on the door, folded up, it rattles when vibrations occur. The rattling from the chair itself could be reduced by coating the aluminum frame with a kind of vibration damping materials, so it is not metal hitting metal when vibrations occur. The mounting of the chair on the door is sufficient if the aluminum frame is coated with vibration damping materials, but the strap should always be fastened as tight as possible, limiting the ability to vibrate.

Figure 4.4: Picture of the helmets and the stretcher chair mounted inside the ambulance.

Figure 4.5: Picture of the defibrillator mounting.

4.4.5 Defibrillator

The right wall is equipped with a defibrillator that is held in a hard metal mounting with a lock on top, see figure 4.5. The lock on the top is equipped with a piece of carpet, which is assumed to be an attempt to decrease the noise occurring as a result of vibrations. However the bottom mounting is still bare metal. This should also be covered with carpet or another vibration damping material to obtain the best effect.

4.4.6 Plastic Bin

The right wall is also equipped with a small bin made of thin hard plastic. The bin mounting rattles when vibrations occur. This mounting should be made more stable, and equipped with a piece of vibration damping material in order to decrease the noise from vibrations.

4.5 Siren Improvements

As mentioned in section 3.4, the noise from the siren is not dominant compared to other noise sources. But since the siren on the ambulance was pointed out by the patients in [Carius, 2006] as one of the most annoying noise sources during ambulance transport, principles of removing the noise from the siren is investigated in this section.

4.5.1 Masking

The siren could be masked by using a sound signal covering the frequency range of both siren types. Siren 1 is a frequency sweep between 500 Hz and 1500 Hz and siren 2 contain three sinus tones of 600 Hz, 900 Hz and 1300 Hz.

There are two types of masking, simultaneous and non simultaneous masking. These two types will be described in the following. Non simultaneous masking denotes masking of brief signals where the masker is presented right before or after the signal, respectively called postmasking and premasking.
The effect of premasking has through several studies been found dependent on the amount of training the listener has in listening to premasking, where more training results in less masking effect [Moore, 2003, p. 107]. The application of premasking is therefore very inefficient for repeated scenarios.
The effect of postmasking depends on how close in time the masker is to the signal, and is limited to maximum 200 ms prior to the signal [Moore, 2003, p. 107]. Common for pre- and postmasking is that their effect is limited to masking of signals of brief duration, and is therefore not considered viable for the ambulance noise scenario.

Simultaneous masking is used to define when the signal and masker are present simultaneously. A simultaneous masking is often made with a narrow band masker around the signal. Figure 4.6 shows how a narrow band noise masker centered around 410 Hz mask tones between 100 Hz and 4 kHz. This narrow band masker can mask a 62 dB 410 Hz tone, however its masking capability an octave below and above is reduced to 10 dB at 205 Hz and 40 dB at 820 Hz. As illustrated, the masker amplitude must be greater than that of the signal.

The slope of the masking curve is at the low frequency side between 55 dB/octave and 190 dB/octave for narrow band masking. The slope for the high frequency side is less steep than for the low frequency side, and is to a certain degree dependent on the level of the masker. When the level increases, the slope steepness decreases.

Since siren 1 covers the frequency range of siren 2, and was determined more audible than siren 2 in all scenarios, a masking of siren 1 would therefore also mask siren 2.

As seen in the beginning of this section, a narrow band noise masker, can mask a single sinusoid that has a frequency close to the narrow band masker to a certain degree. It would in this case be obvious to use a broadband noise signal as masker. This means that a noise signal in the range of 600 Hz to approximately 1200 Hz should be used.

The maximum contribution inside the ambulance is according to table 3.4, 48.5 dB(A) calculated as $L_{\mathrm{Aeq,1s}}$. In the freeway scenario, siren 1 was heard inside the ambulance, and the contribution of the siren noise was within 2 dB of the total exposure, see table 3.4, which indicates that the siren is more dominant than other noise sources.

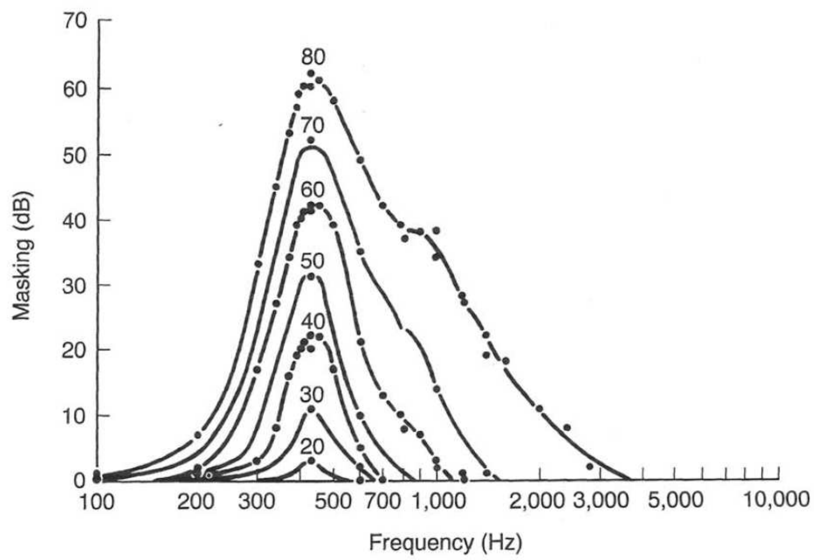

Figure 4.6: Masking patterns (masked audiograms) for a narrow band of noise centered at 410 Hz. Each curve shows the elevation in threshold of a pure tone signal as a function of signal frequency. The overall noise level for each curve is indicated in the figure.[Moore, 2003, p. 88]

In the city scenario, none of the sirens were heard clearly, so a masking signal should have an SPL below approximately 68 dB(A), since the siren is not heard when other noises are present at this SPL. A broad band white noise signal with a frequency range of 600 Hz to approx 1200 Hz, and maximum SPL of 55 dB(A), could be used. This masking might not be sufficient, but it is also important to keep the overall noise SPL below speech level (55-60 dB(A)). An adaptive masking could also be used, so that at increased noise levels the SPL of the masker increases as well.

Another masker could be music or natural sounds instead of using white noise. In the hospitals, music and natural sounds are used to mask the electronic sounds from the equipment, to make the patient less traumatized. [Falck, 2008, p. 16] Here the loudspeakers are placed near the patients ears, and with the option for the patient to adjust the volume. There are two possible places to position the loudspeakers either on the stretcher or in the ceiling. These are the only places the loudspeakers could be mounted without being an inconvenience for the paramedic. If music or other natural sounds should be used as a masker inside the ambulance, it would not have a constant masking effect at the desired frequency range and thereby the siren, since music is built of rhythms organized in time. The effect of such masking must be determined e.g. through listening tests. This however is not considered the focus of this project and therefore not considered further.

4.5.2 Active Noise Control

Another way of removing the noise from the siren is by using Active Noise Control. An ANC system is an anti-noise system, that cancels out the primary noise. It works by a superposition of the acoustic waves by creating anti-noise, which has the same amplitude as the primary noise, but with opposite phase. This principle is illustrated in figure 4.7 where a feedforward ANC system is shown.

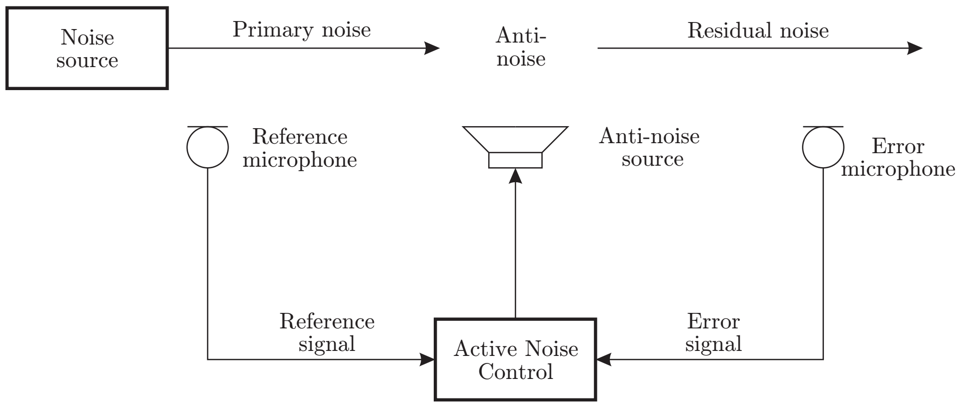

Figure 4.7: Principle of a feedforward active noise control system.

The noise source produces a primary noise which is recorded by the reference microphone and fed to the active noise control system. The adaptive filter in the system is then adjusted to this input noise to create anti-noise. This anti-noise is emitted by the connected loudspeaker and cancels out the primary noise. The residual noise is the product of this cancellation and recorded by the error microphone. The active noise control system then adjust the adaptive filter used to create the anti-noise based on the error signal. The ANC system is effective in the low frequency regions, where passive insulation methods are ineffective.[Kuo and Morgan, 1996]

The article [Campos et al., 2007], describes a study of how the siren noise can be attenuated inside an ambulance by using ANC. An attenuation of 10.5 $\mathrm{dB_{mean}}$ of the siren inside the ambulance was achieved. If this attenuation could be applied inside the danish ambulance, the SPL of the siren would be below 38 dB(A), which would cause the other noise sources such as engine and air turbulence inside the ambulance to be completely dominant. These noise sources are dealt with in other sections of this chapter.

4.6 Summary of Improvements

Possible improvements for the ambulance facades were proposed based on the analysis and theory of airborne sound insulation. For the left facade, a 5 dB increase in R'_{W} can be achieved by inserting a 25 mm layer of glasswool between the inner and outer leaf.

For the right facade, the same solution was suggested for the body and door, along with a doubling of the window thickness, which in total gives an increase in R'_W of 6 dB. For the rear, by inserting a 25 mm layer of glasswool in the doors and doubling the glass thickness, an increase in R'_W of 5 dB can be achieved. It was also determined that the windows are the most important parts of the facade to improve, since they currently degrade the overall performance of the right and rear facade significantly.

Three suggestions for reducing the noise occurring when closing the doors were proposed. The first solution was to inform the paramedics of how noise affects the patients and make them mindful of how they close the doors. The second proposed solution was to install a device that controls the closing of the doors, either by mechanically or electrically reducing the speed of the door near its closing point, so that it is independent of the paramedics. The third solution is to make a deeper analysis of the rubber strips in order to determine whether they also can be used to reduce the metal-metal sound heard when closing the doors.

The noise exposure during emergency response includes several noise sources. The first group of noise sources is the noise originating from wheels, engine and air turbulence. It was assessed that the current all-season tires generate a lot of noise inside the cabin, and a measurement of noise generated by other brands of all-season tires should be performed in order to find the ones generating the least noise inside the cabin. It was also determined that the noise exposure from the wheels, engine and air turbulence masks the siren, so if a tire type with less noise exposure is chosen, the siren may be heard more clearly when traveling at high speed. The noise from engine and air turbulence would also be decreased by improving the facade insulation.

Other noise sources during transport are vibrating equipment, the most noisy of which is the stretcher. A global improvement to reduce noise from vibrating equipment is to implement a better suspension system in the ambulance. This would decrease the vibrations inside the ambulance and thereby also the noise from the equipment. Other improvements of the equipment noise can be made by adding vibration damping material at the equipment mountings.

The siren was also pointed out by patients as an annoying noise source, and possible improvements to reduce it inside the cabin was therefore suggested. By use of masking techniques, the siren noise could be replaced by a more pleasant sound such as music, however it would increase the total SPL inside the ambulance. If an ANC system is implemented, it would attenuate the siren so the patient would hardly notice it when the ambulance is moving.

Chapter 5

Conclusion

The survey [Carius, 2006] concluded that the noise inside the cabin in the danish ambulance during emergency response was a big stress and annoyance factor to the patients. Since then, Falck has taken a new ambulance model in use for which no survey or interior sound environment details are available. An interesting study was therefore to:

> *Measure and analyze the acoustic conditions of the patient cabin in the danish ambulance in order to ascertain the degree of noise the patient is exposed to during emergency response, and to give suggestions for improvement of the conditions based on this analysis.*

A series of measurements was therefore carried out, and an in depth analysis of the results was performed.

It was desired to determine the acoustic behavior of the ambulance cabin, specifically regarding the reverberation time and the speech intelligibility. The average measured reverberation time was 0.19 s which is suitable for an ambulance cabin, and gives a high speech intelligibility and it was therefore deemed unnecessary to improve the sound absorption in the cabin.

In order to determine how well exterior noise is attenuated, an airborne sound insulation measurement and a facade leakage measurement was carried out for the left, right and rear facade of the cabin. It was assessed that the contribution from the front was negligible due to the partition between the driver's cabin and the ambulance cabin. The R'_{W} values for the facades were 32 dB for the left, while the right and rear facade only provided 27 dB each, due to the presence of windows in those two facades. Improvement of the facades and especially the right and rear facade should be considered.

In the survey [Carius, 2006], the noise from closing doors were pointed out as an annoying noise source. A worst case measurement of closing the doors was therefore performed by measuring the SPL at the patients head. From this, an $L_{\mathrm{Aeq,1s}}$ of 80.6 dB, 78.4 dB and 84.8 dB was calculated for the side door, left rear door and right rear door respectively. The article [Griefahn et al., 1992], describing the psychophysical effect of a gunshot noise on human test subjects, was examined for comparison with the measurement results. Based on this article, it was concluded that further study into the psychophysical effect is needed, however it was assessed that an increase in heart rate and vasoconstriction would occur as a result of a door being closed. Improvements hindering loud noise when closing the doors should be considered.

A measurement of the total noise exposure during emergency response was also performed while driving on freeway, highway and in the city. The SPL was measured at the patient's head, and by listening to the recordings, the different noise sources were identified. Siren type 1 was audible in all scenarios while siren type 2 was inaudible in all scenarios, except for the highway. Air turbulence, wheel noise and engine noise were the most prominent exterior noise sources, while vibrating equipment and stretcher were the most prominent interior noise sources. In average, the noise SPL inside the cabin was below speech level (55-60 dB(A)), with the exception of the city scenario. Improvement of equipment mountings, as well as attenuation of airborne noise sources should be considered.

Based on this analysis, suggestions for possible improvements of the acoustic conditions of the ambulance were proposed.

In order to reduce the influence of exterior noise sources, it is important to improve the airborne sound insulation provided by the windows, since they degrade the overall noise reduction significantly. If the window thickness is doubled and 25 mm glasswool is inserted in doors and walls, an increase in R'_{W} of 5 dB for the left and rear facades and a 6 dB increase for the right facade can be achieved.

Suggested improvements for a reduction of the noise occurring when closing the doors were also proposed. One improvement was to inform the paramedics to always close the doors silently. Another suggestion was to install devices that add resistance when the door is near its closing point so that it will always close silently.

The noise exposure during emergency response includes several noise sources. The noise the wheels generate was heard inside the ambulance, and therefore, the ambulance should be equipped with tires that are less noisy if possible. An improvement of the facades would also reduce the airborne noise from the wheels.

During emergency response, potholes causes equipment to vibrate and thereby generate noise to the discomfort of the patient. One way to reduce the vibrations would be to implement a better suspension system to the ambulance. Another option is to add vibration damping material to the equipment mounting.

The noise from the siren could, with use of masking, be replaced by a more pleasant sound such as music, however this would increase the total SPL inside the ambulance. If an ANC system was implemented, it should be possible to attenuate the siren approximately 10.5 $\mathrm{dB}_{\mathrm{mean}}$, so the patient hardly would notice it during emergency response.

The most important suggested improvements are those regarding the windows and the suspension of the ambulance. Both suggestions would improve the acoustic conditions inside the ambulance significantly. Improving the windows would lead to an overall reduction of noise from exterior noise sources, while improving the suspension of the ambulance would reduce all interior noise sources resulting from vibrations.

Future Work/Perspective

Based on the conclusions, this section presents suggestions for future work for improvement of the acoustic conditions in ambulances during emergency response.

In the analysis of the noise from closing doors, the article [Griefahn et al., 1992] was used for evaluation of the psychophysical effects of noise on the patient. The noise that was used in the article was however only partially comparable to the noise in the measurement, and the concluded effect of the closing doors was therefore an assessment at best. A proposal for a future project is therefore to monitor the heart rate, blood flow and displeasure of patients when exposed to noise from the actual doors closing. Also this study could include monitoring the same parameters during transport to the hospital, and to determine the relation between the psychophysical parameters and the noise they are exposed to. Recordings made during this project could be used if a field testing is not possible.

Another interesting study would be to measure and analyze the structure-borne vibrations and noise occurring during transportation, and from a structural point of view, determine how to reduce these. It was pointed out in section 4.4 that one of the possible solutions to reduce the structure-borne vibrations would be to implement a better suspension system in the regular ambulances. The possibility of doing this should be further investigated.

The ambulance sirens purpose is to alert nearby vehicles of its presence. In order to do so, the SPL has to be high to ensure that it is audible inside other vehicles, even if the driver listens to loud music. This is a problem due to the resulting SPL inside the ambulance.
A future project proposal is to develop a system so that e.g. the car radio plays an alert in vehicles within a certain range of any ambulance. Such systems exist for traffic informations such as accidents and traffic jams. A similar system should be developed either as a stand alone system or added to an existing traffic messaging system, such that drivers who have the radio turned on receives an in-car alert, when in the vicinity of an ambulance. This could reduce the need for the high siren SPL and thereby also reduce the audibility of the siren inside the ambulance.

One of the proposed improvements of the ambulance was to use music to mask the noise. This proposal is two-fold and includes an acoustic part and a psychological part. First off, a study is needed in how to design and implement a music playback system in the ambulance. Second, an analysis of what music to play must be carried out. Different types of music have different effects on the human being dependent on mood, situation etc.. A study in the psychological effect should therefore be carried out to determine what music to play to which patients. Also, the study should consider what noise is desired to be masked, that is the frequency content should be able to mask the undesired noise.

One of the noise sources addressed in section 4.3 was the wheels. The tires used for the wheels are all-season tires, in order for the ambulance to be able to reach its destination no matter the road condition and time of year. As was pointed out, in order to reduce the noise from the tires, an analysis of all-season tire noise is required. A comparison of different all-season tires should be performed measuring the resulting noise inside the ambulance cabin, and the ones producing the least noise should be used instead of the currently used ones.

In addition to the future studies, a number of topics treated in this report should be further processed and studied to get more precise details on the acoustic environment of the ambulance.

Only three of the four facades were measured in the airborne sound insulation measurement. It was prior to the measurement deemed irrelevant to measure the airborne sound insulation from the front of the ambulance. This assessment was based on that the driver's cabin is in the front of the ambulance and the focus of this project is the patient cabin which is separated from the driver's cabin. It was therefore assessed that any exterior noise source from in front of the ambulance would have little to no effect inside the patient cabin.
To determine the validity of this assessment, an airborne sound insulation measurement from the front should be performed.

Had more information about the materials and construction of the ambulance been available, it would have been possible to more accurately determine how to effectively improve the acoustic conditions. This was one of the reasons why the transmission loss of the doors had to be estimated. Obtaining the correct transmission loss of doors and windows would require a laboratory measurement where the transmission loss of each part was measured individually. Had the exact construction and materials been known, it would have been possible to ascertain the validity of the assumptions.

Had a higher measurement resolution been used in the facade leakage measurement for the rear and right facade, it would have been easier to evaluate on the individual performance of the doors, windows and gaps.

All the improvements suggested in chapter 4 should be further analyzed to determine the effect of such improvements more precisely. If found useful, these improvements should be further developed so an implementation in current or future ambulance models will be possible.

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Appendices

Appendix A

Measurement Report: Reverberation Time

The purpose of this measurement is to determine the reverberation time inside the ambulance cabin. The reverberation time is used to obtain knowledge about the room, and can be used to determine at which frequency ranges most damping is needed inside the ambulance.

Measurement Theory

This section describes the theory behind the reverberation time measurement.
The reverberation time is the time expressed in seconds it takes the SPL to decrease 60 dB from -5 dB to -65 dB, also shortened as T_{60}. It is very important that the source is able to reproduce a SPL high enough, so the SNR is larger than 65 dB, so the decrease can be measured. If the background noise is too high, T_{30} or T_{20} can be measured instead, and thereby T_{60} can be calculated. The reverberation time should be measured in one third octave bands from 80 Hz to 10 kHz.
The measuring system uses an MLS signal as stimulus, and calculates the reverberation time automatically.

The distance between the loudspeaker and the microphone have to be determined with calculation of the reverberation distance. The reverberation distance is the length from the source where the SPL of the direct field and diffuse field are equal. The microphone should be placed further away from the source than the reverberation distance in order to approximate diffuse field conditions. The reverberation distance is calculated as

$$r_{\text{rev}} = \sqrt{\frac{A}{16\pi}}. \qquad [\text{m}] \tag{A.1}$$

The equation is normally shortened $r_{\text{rev}} = 0.14 \cdot \sqrt{A}$. [Rindel, 2001, p. 12]

Measurement Considerations

The reverberation time should be calculated based on an average of the reverberation time in different positions. Therefore, in this measurement, both the loudspeaker and microphone will be placed in two positions and an average will be taken of the results.

Source and Measurement Positions

The source and measurement positions are depicted on figure A.1, and listed in table A.1.

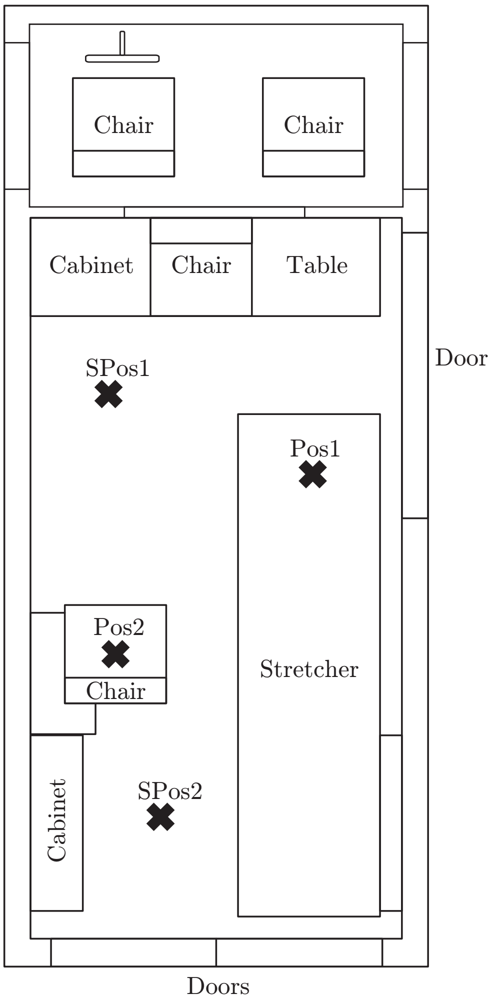

Figure A.1: Top view of the ambulance, with source and measurement positions marked by **X**.

	Distance from floor [m]	Distance from left wall [m]	Distance from rear wall [m]
SPos1	0.40	0.40	2.00
SPos2	1.15	0.65	0.55
Pos1	1.00	1.20	1.90
Pos2	1.30	0.30	1.30

Table A.1: Positions of the loudspeaker(SPos) and microphones(Pos).

Measurement Setup

For the reverberation time measurements, the setup on figure A.2 will be used. Input 1 and 2 on the Harmony system are connected to the two microphones, and output 1 is connected to the loudspeaker.

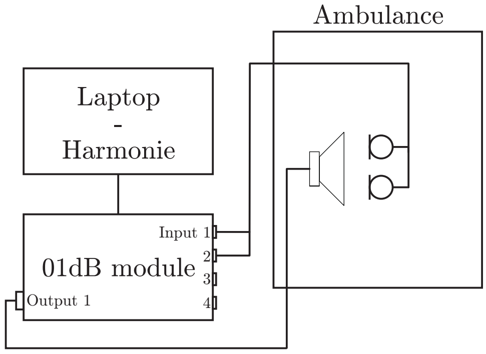

Figure A.2: Measurement setup for the reverberation time measurement.

Calibration

The calibration procedure for the microphones is as follows: First, the microphones are placed at the measurement positions shown on figure A.1 and connected to the Harmonie system. The calibrator is then mounted on the microphone positioned at Pos1 and the calibration function in Harmonie is activated for that microphone. When the calibration is complete, reaching 94 dB SPL for that microphone, the calibrator is removed from the microphone. This procedure is carried out for all microphones in the setup.

Equipment

Measurement Procedure

1. Make the setup as shown in figure A.2, and place the microphones in the two positions marked on figure A.1.
2. Place the loudspeaker at SPos1.
3. Record the reverberation time for the two microphones.
4. Move the loudspeaker to SPos2.
5. Record the reverberation time for the two microphones.

Description:	Type:	AAU number:
Harmonie	4 channel measurement system	56524
Measurement laptop for Harmonie	HP OmniBook6000	47200
Microphone Pos1	B&K 4164	08712
Microphone Pos2	B&K 4164	07954
Microphone preamp Pos1	G.R.A.S. 26AK	32810
Microphone preamp Pos2	G.R.A.S. 26AK	32811
Calibrator	B&K 4231	33691
Speaker	B&K 4296	33949

Table A.2: Equipment used for the reverberation time measurement.

Results

The results for the reverberation measurement are presented in table A.3 as an average of all the measurements. However there was an error in the 100 Hz band, where 2 of the eight measurements were "NaN". This is considered as an error in the measurement system, and will not be investigated further.

Center frequency [Hz]	Reverberation time T_{60} [s]
80	0.36
100	0.38
125	0.33
160	0.23
200	0.25
250	0.19
315	0.16
400	0.16
500	0.19
630	0.17
800	0.19

Center frequency [Hz]	Reverberation time T_{60} [s]
1000	0.20
1250	0.22
1600	0.21
2000	0.23
2500	0.23
3150	0.22
4000	0.24
5000	0.24
6300	0.23
8000	0.22
10000	0.21

Table A.3: Average reverberation time calculated from the measurement results.

Appendix B

Measurement Report: Airborne Sound Insulation

The purpose of this measurement is to determine the airborne sound insulation of the ambulance cabin.

Measurement Theory

The global loudspeaker method described in the ISO 140-5 standard [ISO 1405, 1998] will be adopted to obtain a measure of the airborne sound insulation of the ambulance. As this standard is designed for measurement of sound insulation of buildings and building elements, several deviations from the standard will be made to fit the measurement method to sound insulation measurement of an ambulance. These deviations will be mentioned.

The level difference gives a measure for the sound insulation provided by the ambulance without any adjustments and is given by

$$D = L_1 - L_2, \qquad [dB] \tag{B.1}$$

where L_1 is the SPL 2 m in front of the facade [dB] and L_2 is the average SPL measured inside the ambulance, given by

$$L_2 = 20 \cdot \log_{10}\left(\frac{p_1 + p_2 + ... + p_{\mathrm{n}}}{\mathrm{n} * p_0}\right), \qquad [\mathrm{dB}] \tag{B.2}$$

where p_{x} is the sound pressure measured at microphone x [Pa], n is the number of microphones and $p_0 = 20\ \mu\mathrm{Pa}$ is the reference sound pressure.[ISO 1405, 1998]

It is desired to obtain the level difference D in one-third-octave bands to show the attenuation provided by the ambulance for the different frequency bands within the range 80 Hz to 12.5 kHz.

Stimulus

For the global loudspeaker method, the stimulus is played through a loudspeaker. The stimulus is a white noise signal covering the frequency range from 80 Hz to 12.5 kHz and is created by the Harmonie system. The Harmonie system afterwards applies one-third-octave band analysis.

Measurement Positions

The global loudspeaker method specifies loudspeaker and microphone positioning. However, since the method is designed for buildings, the positions and number of microphones used in this measurement as well as the loudspeaker positioning will deviate from the specified due to the dimensions of the ambulance cabin compared to that of a room inside a building. The ISO 5128 standard [ISO 5128, 1980], gives specifications for microphone placement inside motor vehicles and is therefore adopted.

Three measurements will be carried out, one for each side of the ambulance and one for the rear of the ambulance. All measurements are performed using the same procedure, only the outside microphone and loudspeaker are moved.

Loudspeaker Position

ISO 140-5 specifies the loudspeaker position to be 7 m from the facade and to be placed so that an angle of 45° to the center normal to the surface is obtained. This however was not possible due to the dimensions and measurement location conditions, so a smaller distance of 3.5 m was chosen. Also the specified 45° angle was impossible to obtain due to the height of the ambulance. Therefore it was chosen to have normal incidence thus placing the loudspeaker in the same height as the center of the facade.

Microphone Positions

ISO 140-5 specifications for the microphone positions are not possible to use for this measurement since the dimensions of the inside of the ambulance are very small. The specifications are to have at least 5 microphones spaced with 0.7 m between each microphone, with 0.5 m to any surface or object and 1 m between any microphone and the sound source.

The specified 0.7 m distance between each microphone allows 5 microphones inside the cabin, however due to the dimensions and interior of the ambulance the 0.5 m distance is impossible to obtain for any of the microphones. A compromise was therefore chosen with 3 microphones placed inside the ambulance in the three positions marked by "**X**" on figure B.1. Since ISO 140-5 does not specify any specific positions inside vehicles, ISO 5128 [ISO 5128, 1980] was used for the specific positioning of the microphones given in table B.1.

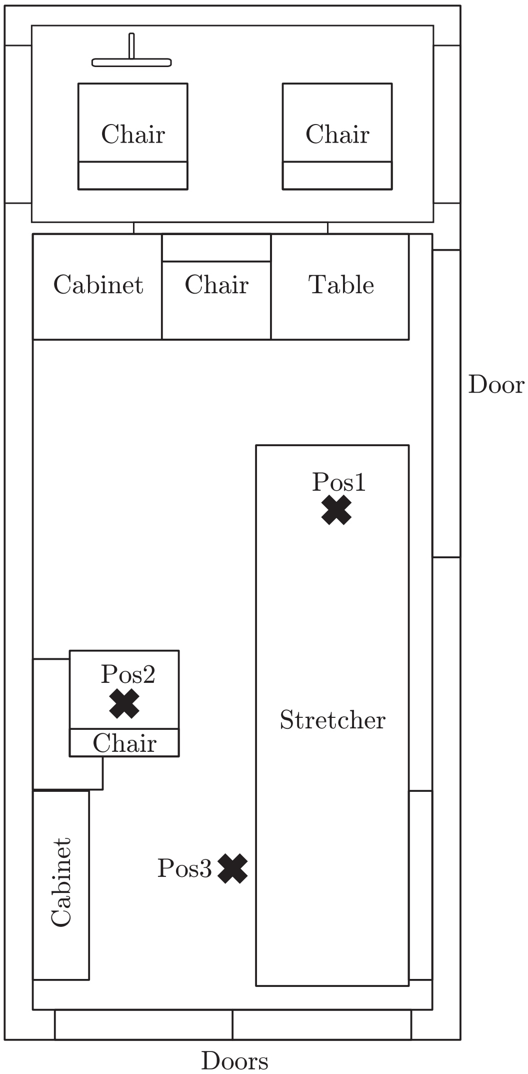

Figure B.1: Top view of the ambulance, with source and measurement positions marked by **X**.

	Distance from floor [m]	Distance from left wall [m]	Distance from rear wall [m]
Pos1	1.00	1.20	1.90
Pos2	1.30	0.30	1.30
Pos3	1.60	0.85	0.50

Table B.1: Positions of the microphones(Pos).

The microphone outside the ambulance is specified to be placed in a 2 m distance from the facade facing the loudspeaker. However it was assessed that due to the adjustment of the loudspeaker position, it would be best to move the microphone closer to the facade by the same percentage as the loudspeaker, thus placing the outside microphone at a 1 m distance and in level with the center of the facade. Due to this adjustment, the calculated quantities will have the index "1m" instead of "2m" as specified in the standard.

Measurement Considerations

For this measurement, there are several conditions that must be taken into account.

Engine and Siren

Both the ambulance engine and siren must be turned off during this measurement as it is not of interest to determine the effects of these.

Measurement Location Conditions

The measurement location is of importance with regards to the presence of undesired noise sources. Since it was required that the ambulance was available to Falck at all times for emergency response, this measurement was made at the Falck parking lot. This resulted in additional car noise from the nearby roads. Every time measurements were performed, it was strived to be when no vehicles were passing by so as to get the least influence. Due to the circumstances at the available measurement location, a 10 m distance to closest wall was possible.

Background Noise

The background noise must be measured to have a reference for the sound insulation measurement. The background noise should be at least 6 dB lower than the signal+noise level during the measurement and preferably at least 10 dB according to ISO 140-5 specifications. The background noise measurement is also made to ensure that there are no extraneous sound interfering with the measurements. The background noise measurement uses the same setup and equipment as the sound insulation measurement specified in the following section.

Measurement Setup

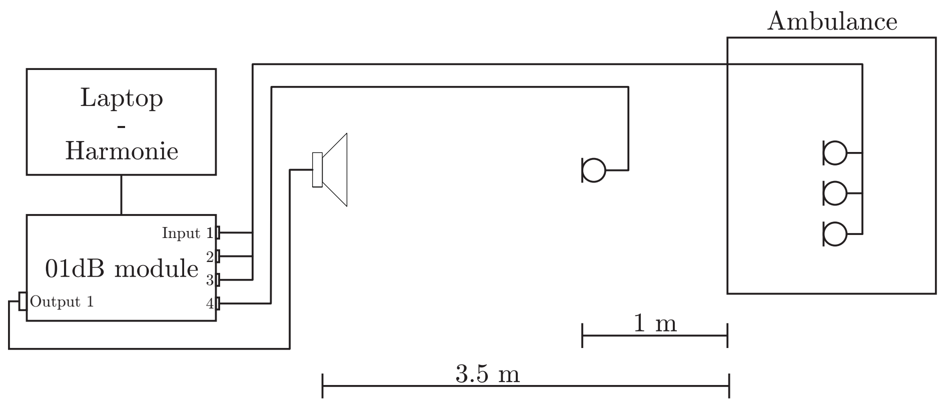

Figure B.2: Measurement setup for the airborne sound insulation measurement.

Calibration

The calibration procedure for the microphones is as follows: First, the microphones are placed at the measurement positions shown on figure B.1 and connected to the Harmonie system. The calibrator is then mounted on the microphone positioned outside the ambulance and the calibration function in Harmonie is activated for that microphone. When the calibration is complete, reaching 94 dB SPL for that microphone, the calibrator is removed from the microphone. This procedure is carried out for all microphones in the setup.

Equipment

Description:	Type:	AAU number:
Harmonie	4 channel measurement system	56524
Measurement laptop for Harmonie	HP OmniBook6000	47200
Calibrator	B&K 4231	33691
Amplifier	Pioneer a656	8699
Loudspeaker	EV	8722
Microphone Pos1	B&K 4165	08712
Microphone Pos2	B&K 4165	07954
Microphone Pos3	B&K 4165	07955
Microphone Pos4	B&K 4165	08133
Microphone preamp Pos1	G.R.A.S. 26AK	32810
Microphone preamp Pos2	G.R.A.S. 26AK	32811
Microphone preamp Pos3	G.R.A.S. 26AK	52664
Microphone preamp Pos4	G.R.A.S. 26AK	52665

Table B.2: Equipment used for the airborne sound insulation measurement.

Measurement Procedure

A background noise measurement is first performed:

1. Make the setup shown on figure B.1.
2. Ensure that ambulance engine and siren are turned off.
3. Fit a wind screen on the microphone positioned outside the ambulance.
4. Calibrate all microphones.
5. With the loudspeaker turned off, measure the sound pressure at the four microphone positions.
6. Check the measured SPLs to ensure that no large spikes or undesired noise sources are present.
7. Store the recorded data.

Then the sound insulation is measured:

1. Keep the setup from the background noise measurement.
2. Turn on the loudspeaker.
3. Play the stimulus through the loudspeaker using Harmonie.
4. If the measured SPL inside the ambulance is at least 6 dB above the background noise, store the data.
5. If the measured SPL does not fulfill step 4, increase the loudspeaker output power and repeat step 4.

Results

Center Frequency [Hz]	D_{Rear}	D_{Right}	D_{Left}
80	9,42	9,02	9,96
100	10,93	13,51	11,30
125	10,66	14,25	13,11
160	22,30	20,04	21,67
200	23,34	20,92	22,93
250	23,58	22,18	25,69
315	26,18	24,48	29,67
400	25,13	27,04	27,29
500	29,68	31,26	32,19
630	28,16	26	30,24
800	31,18	27,77	32,79

Center Frequency [Hz]	D_{Rear}	D_{Right}	D_{Left}
1000	30,64	23,28	32,38
1250	33,34	28,58	35,07
1600	33,04	30,28	37,94
2000	32,29	31,66	35,91
2500	33,07	31,31	33,51
3150	34,98	31,01	35,99
4000	31,89	30,45	33,14
5000	32,47	31,75	33,59
6300	30,31	30,35	31,95
8000	32,86	32,41	33,94
10000	34,35	33,27	34,88
12500	33,36	32,17	33,73

Table B.3: Results of the airborne sound insulation measurement. Level difference D for the three facades given in one-third octave bands with the listed center frequencies.

Appendix C

Measurement Report: Facade Leakage

The purpose of this measurement report is to locate leakage areas of the ambulance facades. This is not a sound insulation measurement, but a measurement that is used to find places on the surface with bad insulation. The results of this measurement report will be a map showing where the weakest insulation is located on the three facades of the ambulance.

Measurement Theory

This section describes the theory behind the facade leakage measurement. The idea of this measurement is to locate critical areas of the surface of the ambulance. This measurement is made using a sound level meter, measuring in a number of points on the surface. The measurement is made outside the ambulance, where a loudspeaker is placed inside the ambulance playing a white noise signal.

Measurement Considerations

The measurement of the leakage areas will be made as point measurements, where the SPL will be measured at the chosen points. The distance from the facade to the microphone is set to be 0.05 m.

Outdoor Measurement Positions

The outdoor measurement positions is shown in figure C.1, C.2 and C.3. They are listed in table C.1 and C.2.

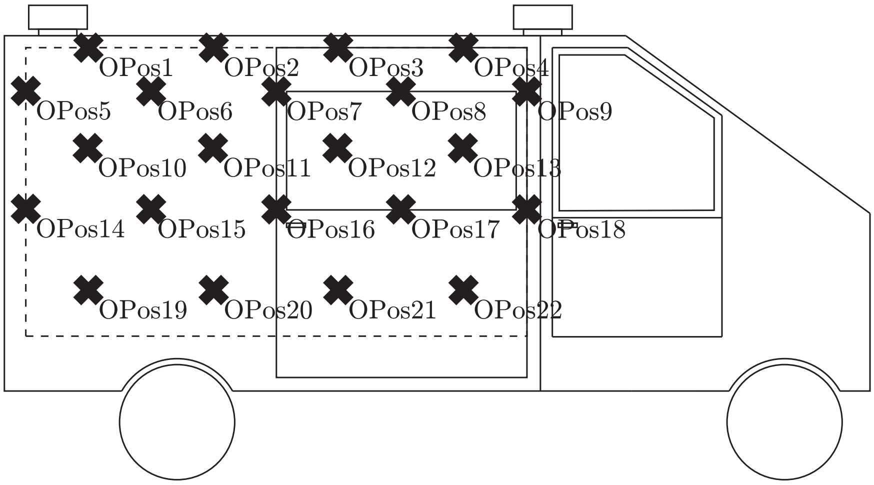

Figure C.1: Measurement positions for the facade leakage measurement for the right side of the ambulance.

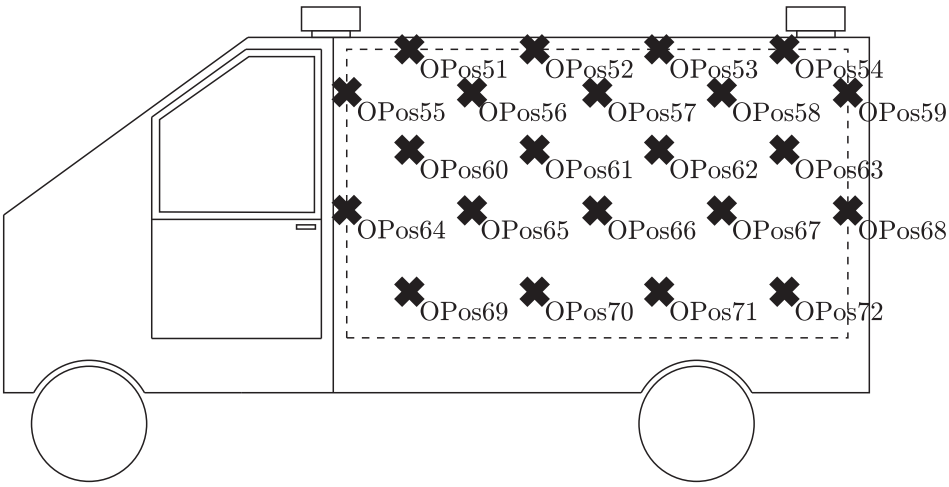

Figure C.2: Measurement positions for the facade leakage measurement for the left side of the ambulance.

	Dist from rear end [m]	Dist from clearance [m]
OPos1	0.60	2.10
OPos2	1.40	2.10
OPos3	2.20	2.10
OPos4	3.00	2.10
OPos5	0.20	1.80
OPos6	1.00	1.80
OPos7	1.80	1.80
OPos8	2.60	1.80
OPos9	3.40	1.80
OPos10	0.60	1.50
OPos11	1.40	1.50
OPos12	2.20	1.50
OPos13	3.00	1.50
OPos14	0.20	1.10
OPos15	1.00	1.10
OPos16	1.80	1.10
OPos17	2.60	1.10
OPos18	3.40	1.10
OPos19	0.60	0.50
OPos20	1.40	0.50
OPos21	2.20	0.50
OPos22	3.00	0.50

	Dist from rear end [m]	Dist from clearance [m]
OPos51	3.00	2.10
OPos52	2.20	2.10
OPos53	1.40	2.10
OPos54	0.60	2.10
OPos55	3.40	1.80
OPos56	2.60	1.80
OPos57	1.80	1.80
OPos58	1.00	1.80
OPos59	0.20	1.80
OPos60	3.00	1.50
OPos61	2.20	1.50
OPos62	1.40	1.50
OPos63	0.60	1.50
OPos64	3.40	1.10
OPos65	2.60	1.10
OPos66	1.80	1.10
OPos67	1.00	1.10
OPos68	0.20	1.10
OPos69	3.00	0.50
OPos70	2.20	0.50
OPos71	1.40	0.50
OPos72	0.60	0.50

Table C.1: Measurement positions for the facade leakage measurement for the left and right side.

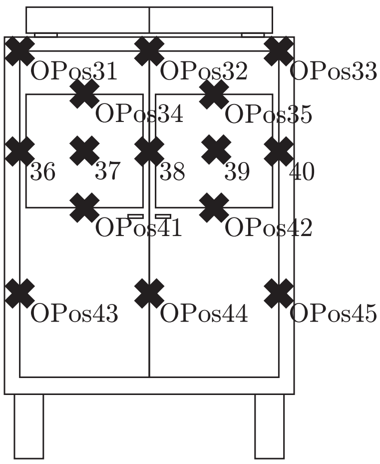

Figure C.3: Measurement positions for the facade leakage measurement for the rear end.

	Dist from left side [m]	Dist from clearance [m]
OPos31	0.10	2.10
OPos32	0.95	2.10
OPos33	1.80	2.10
OPos34	0.53	1.80
OPos35	1.37	1.80
OPos36	0.10	1.50
OPos37	0.53	1.50
OPos38	0.95	1.50
OPos39	1.37	1.50
OPos40	1.80	1.50
OPos41	0.53	1.10
OPos42	1.37	1.10
OPos43	0.10	0.50
OPos44	0.95	0.50
OPos45	1.80	0.50

Table C.2: Measurement positions for the facade leakage measurement for the rear end.

Measurement Setup

During measurements, the setup on figure C.4 will be used.

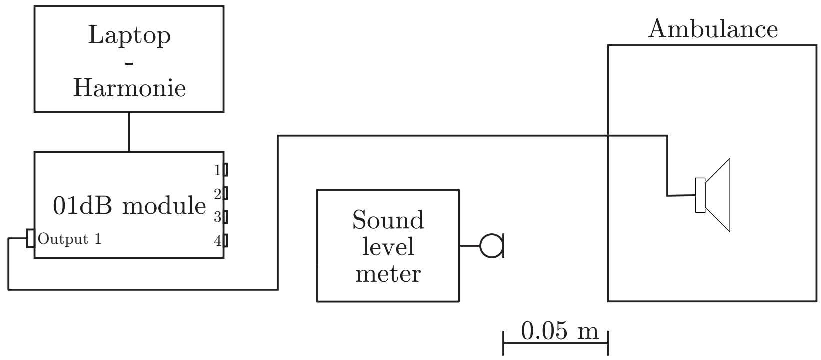

Figure C.4: Measurement setup for the facade leakage measurement.

Calibration

Calibrate the sound level meter to 94 dB with the calibrator.

Equipment

Description:	Type:	AAU number:
Sound level meter.	B&K type 2231	8236
Harmonie	4 channel measurement system	56524
Measurement laptop for Harmonie	HP OmniBook6000	47200
Calibrator	B&K 4231	33691
Omnidirectional loudspeaker	B&K 4296	33949

Table C.3: Equipment used for the facade leakage measurement.

Measurement Procedure

1. Place the loudspeaker inside the ambulance.
2. Start the white noise generator in Harmonie.
3. Increase the power to the loudspeaker to a level so it is at least 60 dB on the suspected most insulating place of the ambulance.

4. Start measuring at position OPos1.
5. Read the SPL for the position.
6. Move to the next measuring point, and redo step 5 and 6 until position OPos72 is measured.

Results

The measured SPL for each point of the facade leakage measurement is listed in table C.4.

Right side		Left side		Rear end	
OPos	SPL [dB]	OPos	SPL [dB]	OPos	SPL [dB]
1	61.4	51	60.3	31	67.5
2	63.3	52	60.3	32	69
3	65.2	53	61.2	33	67.3
4	65	54	61.2	34	68.8
5	61.6	55	60	35	68.8
6	62.7	56	60	36	67
7	67.3	57	61.2	37	69
8	67	58	61	38	72.1
9	67.3	59	62	39	68.9
10	62.3	60	60	40	67.5
11	63.7	61	60.3	41	68.5
12	69.5	62	60.4	42	68.4
13	69.8	63	60.5	43	66.4
14	62	64	60	44	67
15	62	65	60	45	64.7
16	68	66	60.8		
17	68	67	60.6		
18	66.5	68	61.2		
19	61.7	69	60.2		
20	62	70	61.4		
21	63	71	61.3		
22	63.6	72	62.7		

Table C.4: Measured SPLs at the positions (OPos) for the facade leakage measurement.

Appendix D

Measurement Report: Noise from Closing Doors

The purpose of this measurement is to determine the noise generated by closing the ambulance doors.

Measurement Theory

To determine the noise generated by closing the ambulance doors, the SPL is measured in the patient head position accordingly with the ISO 5128 standard [ISO 5128, 1980]. The resulting values are given as the A-weighted SPL, L_{pA} expressed in dB in one-third octave bands from 100 Hz to 5 kHz. After measuring the response L_{pA} from 5 repetitive door slams, the one with the highest maximum SPL is chosen to represent the worst-case scenario for that door. This measurement will be performed with one person present inside the ambulance holding the microphone to reduce the effect of vibrations.

Measurement Positions

The measurement will be performed using one microphone placed at the position of the patients head marked by "**X**" shown on figure D.1. The specific position is given in table D.1.

	Distance from floor [m]	Distance from left wall [m]	Distance from rear wall [m]
Pos1	1.00	1.20	1.90

Table D.1: Position of the microphone (Pos1).

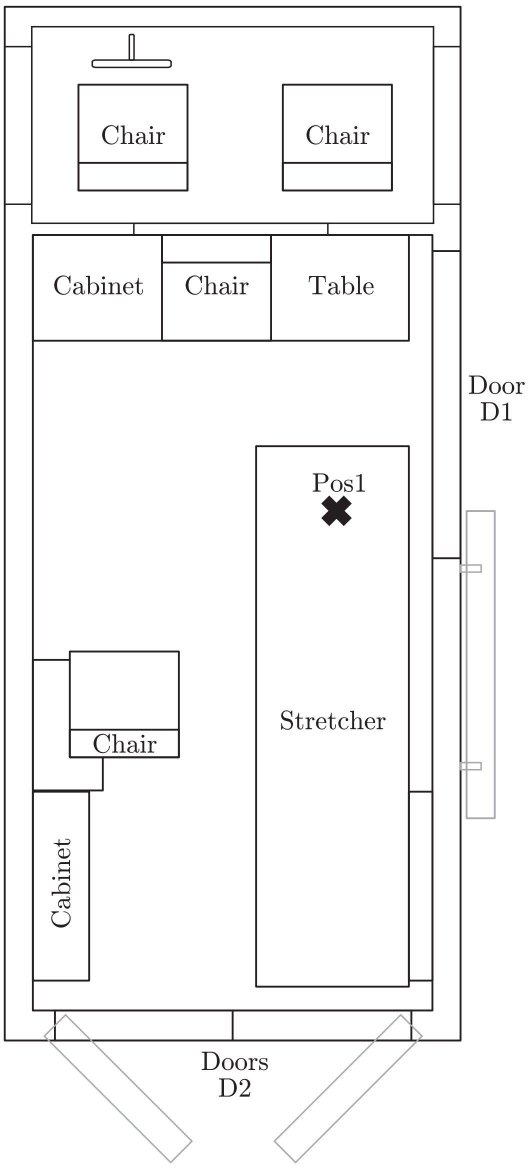

Figure D.1: Top view of the ambulance with the microphone position marked by **X**. Door D1 is a sliding door, and its opened position is sketched in gray. Door D2 is a two-part swinging door and its opened position is marked in gray.

Measurement Considerations

All windows and the doors not currently being tested must be closed.

Ambulance engine and siren

Ambulance engine and siren must be turned off.

Measurement Location Conditions

The measurement location was inside the garage at Falck, Aalborg, and thus it is an indoor measurements.

Background Noise

The background noise is measured before the actual measurement to ensure that no undesired sound sources affect the measurements.

Measurement Setup

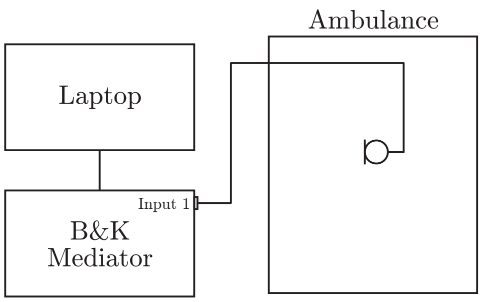

Figure D.2: Measurement setup for the closing door measurement.

Calibration

First, the mediator is placed at the measurement position shown on figure D.1 and connected to the laptop. The calibrator is then mounted on the mediator and the calibration procedure on the mediator is initiated. The output is also recorded on the laptop for later scaling. When the calibration is complete, the calibrator is removed.

Equipment

Description:	Type:	AAU number:
Measurement laptop	Lenovo T500	-
Mediator	B&K 2238	33948
Calibrator	B&K 4231	33691

Table D.2: Equipment used for the closing door measurement.

Measurement Procedure

1. Make the setup shown on figure D.2 with the microphone placed as shown on figure D.1.
2. Ensure that ambulance engine and siren are turned off.
3. Close all doors.
4. Calibrate the microphone.
5. Measure the background noise.
6. Open door ”D2”.
7. Start the record function in the wave recorder ”Audacity” installed on the laptop.
8. Close door ”D2” with the force representing a worst-case scenario.
9. Repeat step 6 through 8 five times.
10. Close door ”D2”, open door ”D1” and go through step 7 through 9 again using door ”D1” instead of ”D2”.

Results

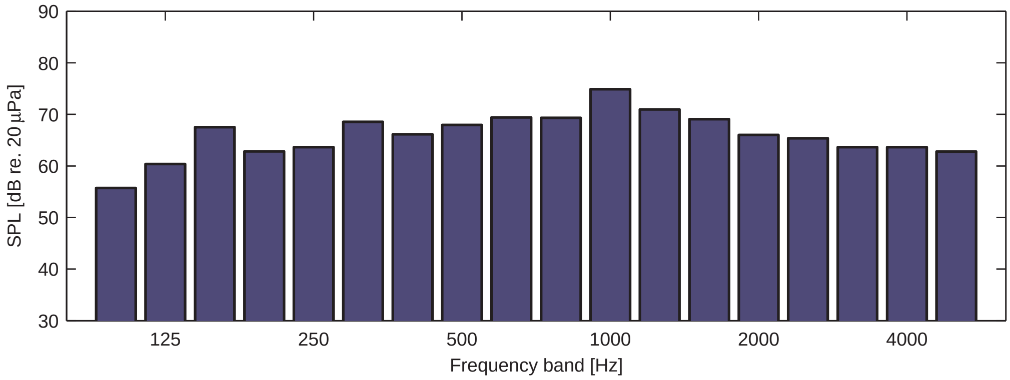

Figure D.3: Measured SPL in one-third octave bands from closing the side door of the ambulance.

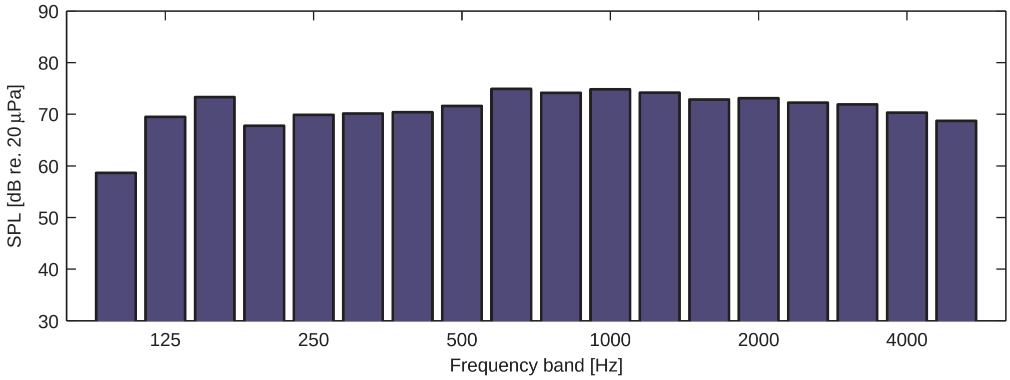

Figure D.4: Measured SPL in one-third octave bands from closing the rear left door of the ambulance.

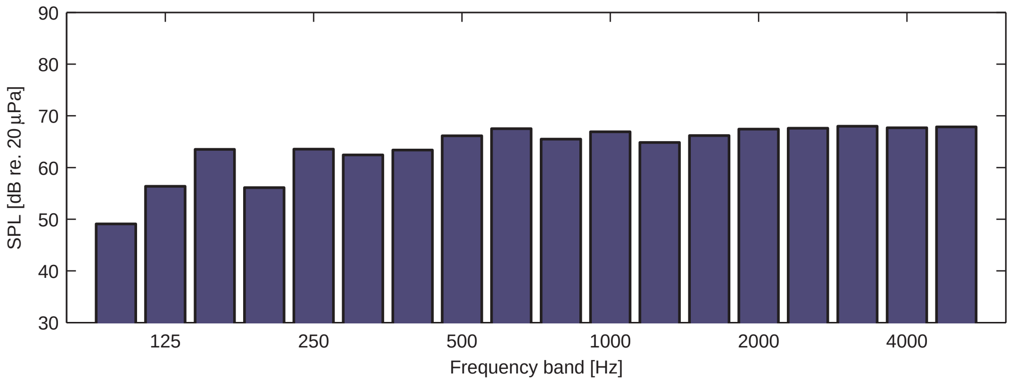

Figure D.5: Measured SPL in one-third octave bands from closing the rear right door of the ambulance.

Appendix E

Measurement Report: Noise Exposure during Emergency Response

The purpose of this measurement is to determine the noise present inside the ambulance during emergency response where the siren is in use.

Measurement Theory

To obtain a measure of the noise inside the ambulance during emergency response, a raw signal is measured in the position of the patients head accordingly with the ISO 5128 standard [ISO 5128, 1980].

It is desired to obtain these measurements for the following scenarios

1. The ambulance is stationary with the siren turned on and the engine idling.
2. During city transport at a speed of 60 km/h and siren on. A road paved with cobblestones will be used for this scenario to get a noisy environment inside the ambulance.
3. During freeway transport at a speed of 130 km/h also with siren on.
4. During highway transport at a speed of 80 km/h also with siren on.

It is desired to reproduce the conditions of an emergency response for these measurements, and therefore two persons will be part of the measurement setup acting as patient and paramedic respectively.

Measurement Positions

ISO 5128 [ISO 5128, 1980] gives specifications for microphone positions inside motor vehicles and is therefore adopted.

The sound pressure inside the ambulance is measured in the position marked by "**X**" shown on figure E.1. The specific position is given in table E.1.

	Distance from floor [m]	Distance from left wall [m]	Distance from rear wall [m]
Pos1	1.00	1.20	1.90

Table E.1: Position of the microphone.

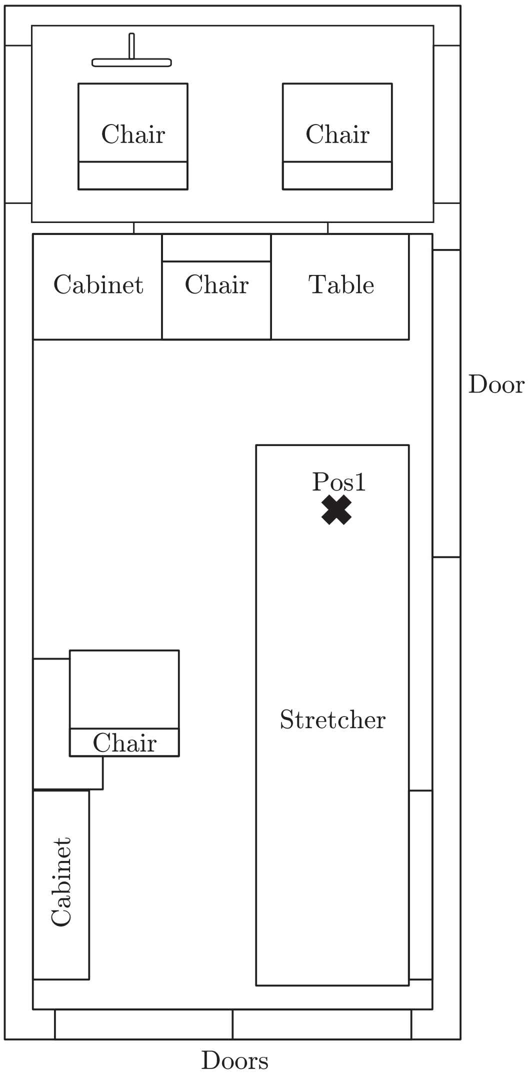

Figure E.1: Top view of the ambulance with the microphone position marked by **X**

Measurement Considerations

All doors and windows in the ambulance must be closed.

Engine and Siren

In scenario 1, where the ambulance is stationary, the engine must be running idle and siren switched on. The siren has three different modes, and the two frequently used ones are used in turn throughout this measurement to obtain recordings of both.

In scenario 2, the ambulance is driving at 60 km/h, or as close to as possible depending on traffic with the siren turned on, and again the two different siren modes are used in turn.

In scenario 3, where the ambulance is driving on the freeway maintaining a speed of 130 km/h, or as close to as possible depending on traffic, the siren is turned on and the two different modes are used as well.

In scenario 4, where the ambulance is driving at 80 km/h on a highway, the siren will be used in its two different modes in turn as well.

Measurement Location Conditions

The road on which the measurements are performed shall be dry and free from snow, dirt, stones, leaves etc. to the extent this is possible. However since an actual city, highway and freeway road will be used as measurement locations, the only factors that is decided to be critical is that the road shall be dry and free from snow.

In scenario 2 it is desired to determine the noise levels inside the ambulance when the road is in a poor condition, thus a street paved with cobblestones was chosen for this measurement.

For scenario 3 and 4, the quality of the road itself must not be too poor either, that is, a road with holes and bumps should be avoided.

Background Noise

The background noise is measured in appendix D and is considered representative for this measurement.

Measurement Setup

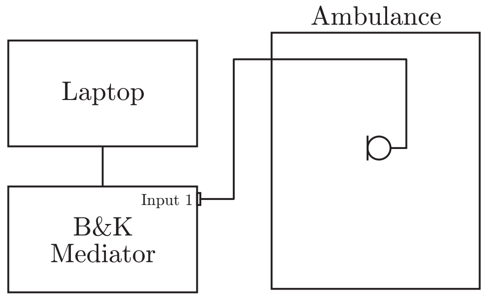

Figure E.2: Measurement setup for noise exposure measurement.

Calibration

The calibration procedure for the B&K mediator used in this measurement must be carried out with ambulance engine and siren turned off. First, the mediator is placed at the measurement position shown on figure E.1. The calibrator is then mounted on the mediator and the calibration function is activated. When the calibration is complete, reaching 94 dB SPL, the calibrator is removed and the calibration signal is recorded by the mediator and captured on the laptop with the record function in the wave recorder "Audacity" as a reference.

Equipment

Description:	Type:	AAU number:
Measurement laptop	Lenovo T500	-
Mediator	B&K 2238	33948
Calibrator	B&K 4231	33691

Table E.2: Equipment used for the noise exposure measurement.

Measurement Procedure

The measurement procedure for scenario 1 where the ambulance is stationary:

1. Make the setup shown on figure E.1.
2. Ensure that ambulance engine and siren are turned off.
3. Calibrate the mediator.
4. Turn on the ambulance siren and engine and let it idle.

5. Start the record function on the mediator and capture the data on the laptop with record function in the wave recorder ”Audacity”, while the two siren modes are used in turn each for a minimum of 5 s.
6. Turn off the siren and record the noise in the ambulance.

The measurement procedure for scenario 2 where the ambulance is driving in the city at 60 km/h:

1. Keeping the setup from scenario 1, the ambulance is driven to the measurement location.
2. Accelerate to 60 km/h or as close to as possible dependent on traffic and start the siren.
3. Start the record function on the mediator and capture the data on the laptop with record function in the wave recorder ”Audacity”, while the two siren modes are used in turn each for a minimum of 5 s.

The measurement procedure for scenario 3 where the ambulance is driving on the freeway at 130 km/h:

1. Keeping the setup from scenario 2, the ambulance is driven to the measurement location.
2. Accelerate to 130 km/h or as close to as possible dependent on traffic and start the siren.
3. Start the record function on the mediator and capture the data on the laptop with record function in the wave recorder ”Audacity”, while the two siren modes are used in turn each for a minimum of 5 s.
4. Turn off the siren and record the noise in the ambulance.

The measurement procedure for scenario 4 where the ambulance is driving on the highway at 80 km/h:

1. Keeping the setup from scenario 3, the ambulance is driven to the measurement location.
2. Accelerate to 80 km/h or as close to as possible dependent on traffic and start the siren.
3. Start the record function on the mediator and capture the data on the laptop with record function in the wave recorder ”Audacity”, while the two siren modes are used in turn each for a minimum of 5 s.
4. Turn off the siren and record the noise in the ambulance.

Results

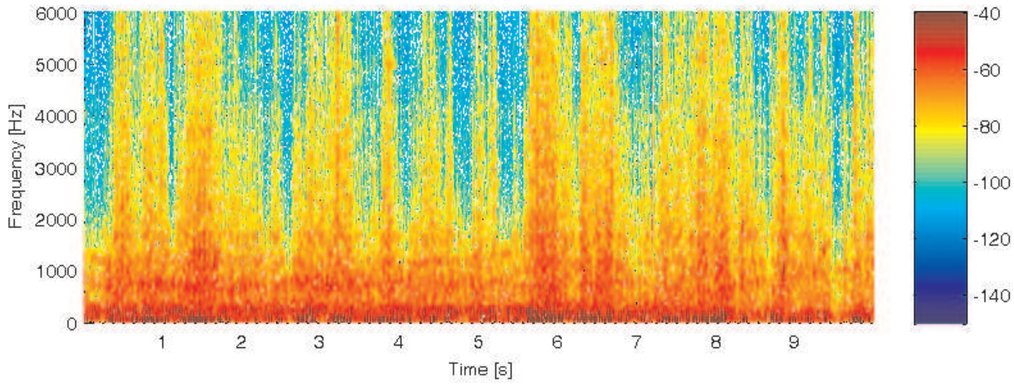

Figure E.3: Noise measured in the cabin when driving in the city with siren 1 on.

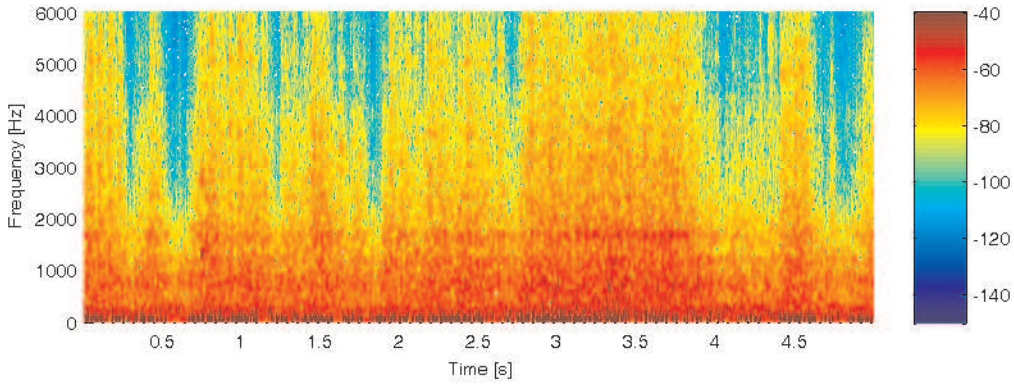

Figure E.4: Noise measured in the cabin when driving in the city with siren 2 on.

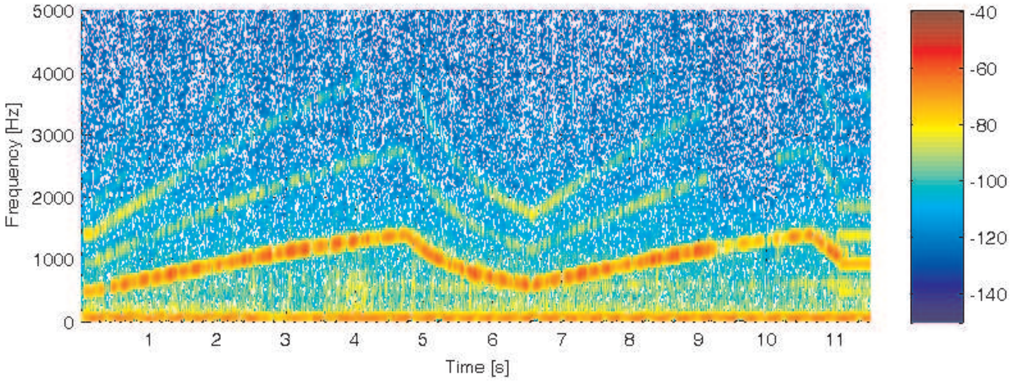

Figure E.5: Noise measured in the cabin where the ambulance is stationary and siren 1 turned on.

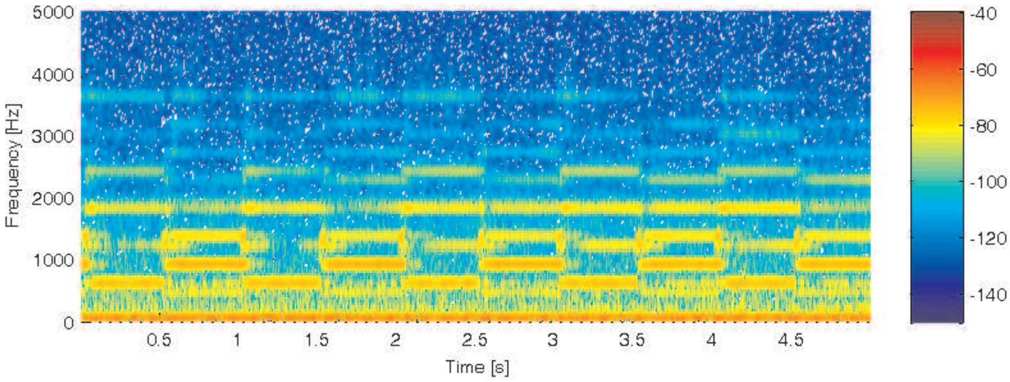

Figure E.6: Noise measured in the cabin where the ambulance is stationary and siren 2 turned on.

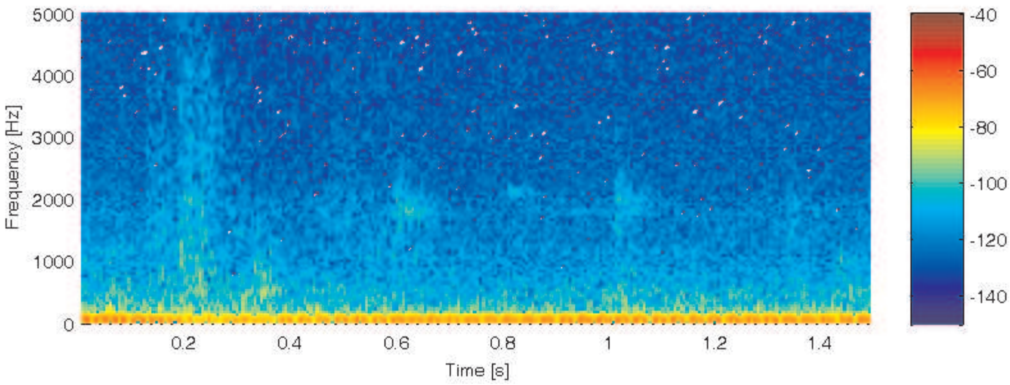

Figure E.7: Noise measured in the cabin where the ambulance is stationary.

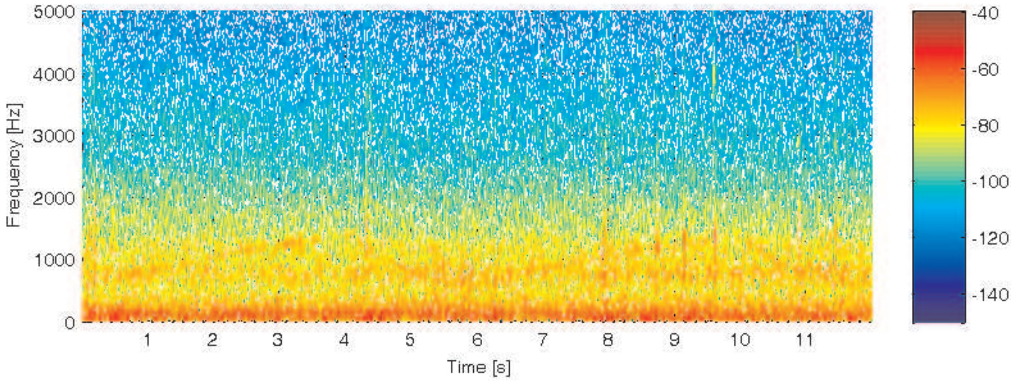

Figure E.8: Noise measured in the cabin when driving in on the freeway with siren 1 on.

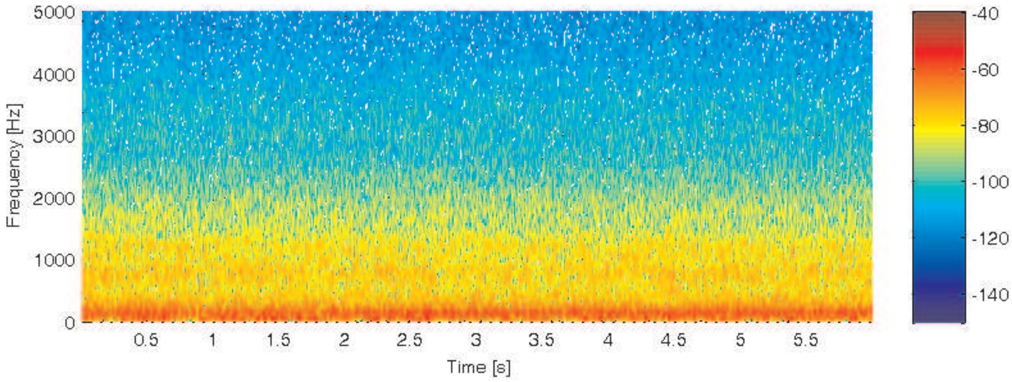

Figure E.9: Noise measured in the cabin when driving in on the freeway with siren 2 on.

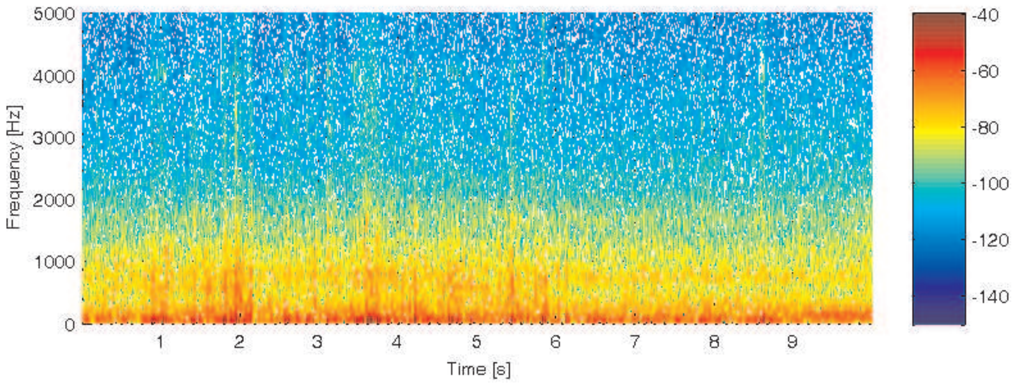

Figure E.10: Noise measured in the cabin when driving on freeway with the siren turned off.

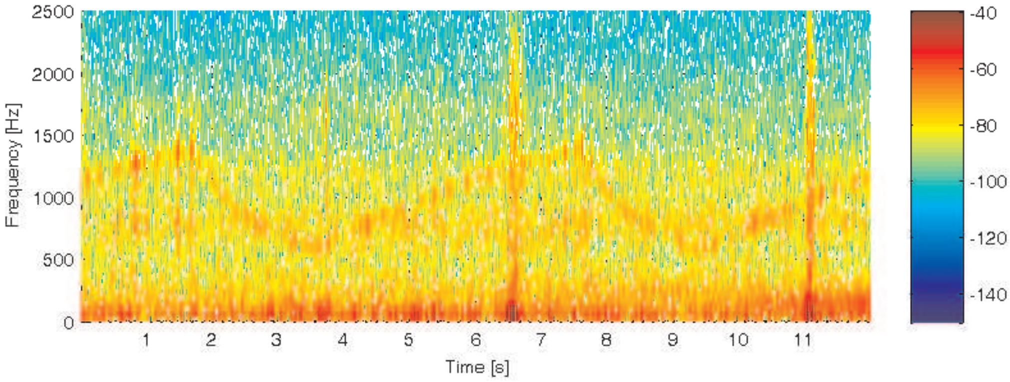

Figure E.11: Noise measured in the cabin when driving on highway with siren 1 turned on.

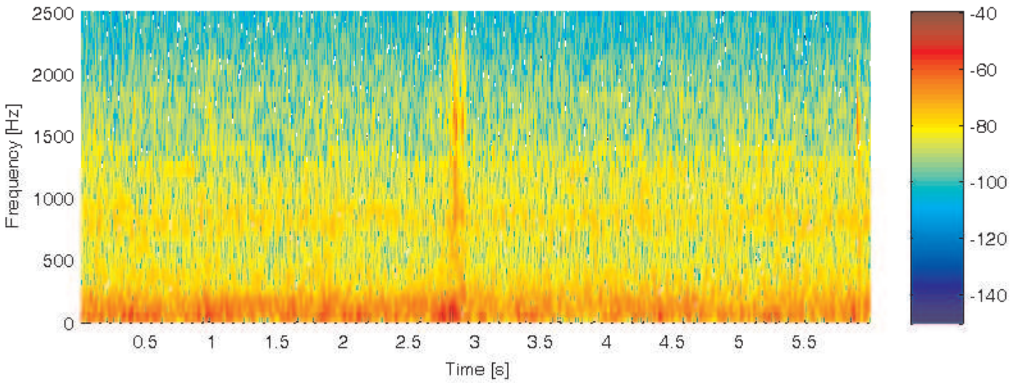

Figure E.12: Noise measured in the cabin when driving on highway with siren 2 turned on.

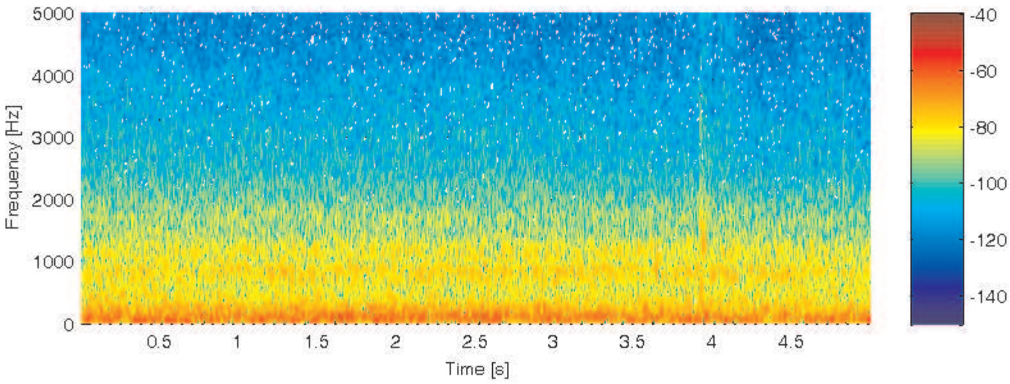

Figure E.13: Noise measured in the cabin when driving on highway with the siren turned off.

Enclosure: CD

As enclosure a CD is attached. This CD contains information to be studied if the reader desires additional insight into the different topics of the report.

Contents of the CD:

- Additional literature
- MATLAB scripts
- Measurement data
- Pictures of ambulance
- Project proposal
- Project report (PDF & PS format)