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# **Auralization of Road Traffic**

A study of finite length noise barriers

Master's thesis in Master Programme Sound and Vibration

**MAN-SHIN TAN**

**DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING**

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MASTER'S THESIS 2022

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MAN-SHIN TAN

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Examiner and supervisor: Jens Forssén, Department of Architecture and Civil  
Engineering, Chalmers

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Department of Architecture and Civil Engineering  
Division of Applied Acoustics  
Chalmers University of Technology  
SE-412 96 Gothenburg  
Telephone +46 31 772 1000

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MAN-SHIN TAN  
Department of Architecture and Civil Engineering  
Chalmers University of Technology

## Abstract

Road-traffic noise is one of the dominating noise sources in urban areas and consequently creates problems for health and wellbeing. Engineers and architects often use mathematical models (auralization) to simulate sound during the planning and design process of buildings e.g., simulate sound fields in virtual spaces indoors. At the division of Applied Acoustics at Chalmers a toolbox to auralize sound outdoors has been developed, with which it is possible to simulate sounds of a vehicle passing by with or without a noise barrier. A further study of noise barriers is conducted in this work. The aim was to investigate the Harmonoise model for noise barriers and to evaluate the perception of the sounds created with the model. The Harmonoise model was added into the existing toolbox and auralized sounds for different receiver locations, both with and without noise barrier, were evaluated in a listening test together with real recorded sounds without noise barrier. The participants in the listening test noticed a difference in plausibility between the recorded and the auralized sounds. The auralized sounds with and without noise barrier gave a similar plausibility at 27 km/h and 45 km/h. The sounds with noise barrier had higher average plausibility than the sounds without noise barrier, when the receiver was placed nearest to the edge of the noise barrier. The participants perceived that the sounds with noise barrier were most plausible when the distance between the receiver and the road was 7.5 m whereas the plausibility decreased when the distances increased to 15 m and 30 m. Whereas the average plausibility decreased when a large portion of the sound clip consisted of sound screened by the noise barrier, a higher average plausibility was obtained when a shorter time of the sound clip consisted of sound screened by the noise barrier.

Keywords: urban acoustics, auralization, noise barrier



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Man-Shin Tan, Gothenburg, June 2022



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# 1

## Introduction

Road-traffic noise is one of the dominating noise sources in urban areas and consequently creates problems for human health. Noise could disturb sleep, provoke annoyance responses and reduce performance of people [1]. Engineers and architects often use mathematical models (auralization) to simulate sound during the planning process and design process of buildings. Using software to auralize sound indoors is common. Engineers often use such software to evaluate the acoustics in buildings. Software to auralize sound outdoors is not as common [2].

At the division of Applied Acoustics at Chalmers a toolbox to auralize sound outdoors has been developed. It is possible to auralize railway noise and road traffic noise with different setups e.g., auralize outdoor sound reaching inside buildings and sound reaching behind buildings [2]. In the setup for road traffic noise, it is possible to auralize sounds of a vehicle passing by a person either with noise barrier or without noise barrier shielding the person (receiver). The noise barrier (screen) could be of either finite length or infinite length [2]. The purpose of the a noise barrier is to reduce noise.

The toolbox that was developed in house enables the possibility to auralize the effect of noise barriers. However, the noise barrier and the perception of the sounds created with and without the noise barrier can be explored further.

### 1.1 Purpose and aim of work

The purpose of this work is to develop the toolbox for noise barrier further. The aim is to study the effect (of a vehicle passing by with a noise barrier screening the sound) of receivers placed on different positions behind the noise barrier and on different distances from the source. The aim is also to investigate the Harmonoise model for noise barriers and to evaluate the perception of the sounds created using the Harmonoise model.

The following questions are investigated in this thesis work:

- Is it possible to distinguish between an auralized sound and a real sound?
- Are the real sound and the auralized sounds perceived similarly?

- Is there any difference in perception (plausibility) of the sound when the receiver is located on different positions behind a finite-length noise barrier?
- Is there any difference in perception (plausibility) of the sound when the distance from receiver and road is different?

The main goal of this work is to improve the noise mapping and auralization.

## 1.2 Limitations

This work focuses on developing noise barriers. The toolbox has many setups and it is possible to auralize different scenarios. However, the scope of this work is limited to a noise barrier with finite length and one height. There are many screen models such as the Piece model and the Harmonoise model. There are also different calculation methods for thin screens and thick screens. The work is limited to using the Harmonoise model for a thin screen. It is possible to hear several vehicles passing by at the same time for a usual road traffic environment. This work is limited to sounds of one vehicle passing by the receiver and the vehicle type is limited light-weight vehicle (car). This work is limited to the effect of noise on humans, other environmental factors are excluded.

# 2

## Theory

### 2.1 Auralized sounds of a vehicle passing by

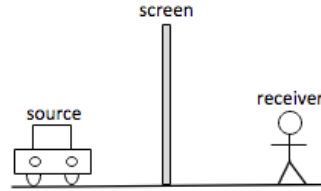
The method of creating sound files from numerical data, either simulated or measured data, is called auralization. The sound files can be used to simulate sound fields in virtual spaces. The output signals of the sound files are often binaural, to give a realistic impression of the sound [3]. Auralized sounds are often used by architects and engineers in the design and planning process of buildings.

The perception of sound is called psychoacoustics. Sounds are not only perceived as high sound pressure level or low sound pressure level. Sounds can also be perceived as e.g, sharp or rough, and lead to different feelings and emotions. Auditory perception is the conscious and unconscious processing of sounds that leads to understanding of the acoustic environment. Response is the emotion and reaction to the sound. The response can change the context of the sound [5]. Sounds (e.g., auralized sounds) can be evaluated on a listening test. This type of test is called jury testing. There are different ways to evaluate the sounds in the test. In one type, a group of people listen to the sounds and rank or rate the sounds on scales [5].

Humans have binaural hearing which enables localization of the sounds. It is possible for a person to distinguish if the sound is approaching from the front, back or from above. The sound wave is reflected and diffracted along the travel distance. A sound wave from a known direction will be distorted when the wave approaches to the head and the torso, and arrive to the ears in different amplitude and time. The brain will notice the difference and localise the direction of the sound [5].

Figure 2.1 shows a vehicle passing by a person on the road. The vehicle is the sound source and the person is the sound receiver, and there is a screen in-between. There are two main sound sources in vehicles, propulsion noise and road-tyre noise. Propulsion noise is generated by e.g., the engine, the exhaust and the compressor of the vehicle and is located at different heights for light-weight vehicles and heavy vehicles. The sound sources are due to this modelled differently for the vehicles [6]. The sound waves generated by the vehicle will be affected by the source, the screen, the ground, refraction (change of sound velocity caused by temperature and wind), air attenuation (depends on temperature, relative humidity and static pressure in the air), turbulence (unpredictable fluctuations caused by temperature and wind) and the Doppler effect due to the moving vehicle (a frequency change of the sound

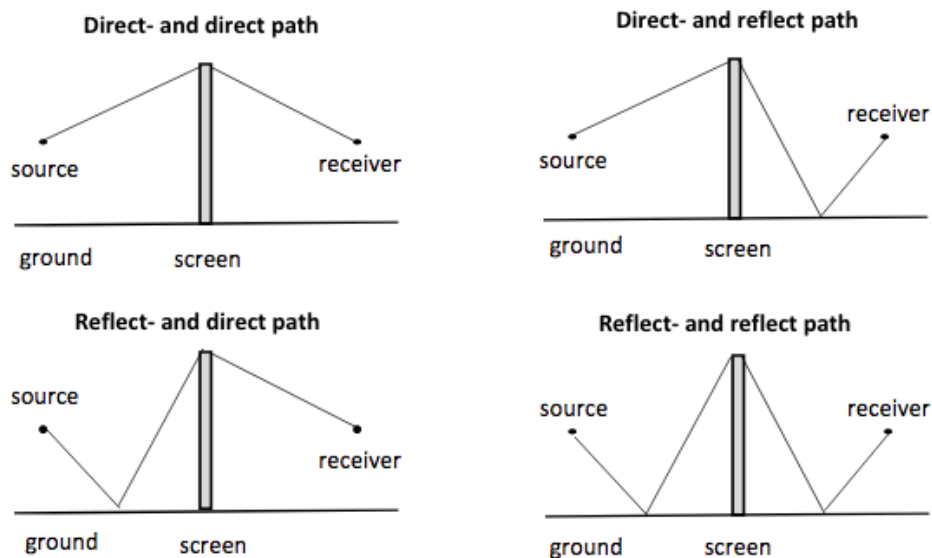
wave caused by the movement of the vehicle, and the relative motion between the person and the vehicle) [8][9]. Vehicle velocity, distance between the sound source and receiver, and height of screen also affect the sound propagation.



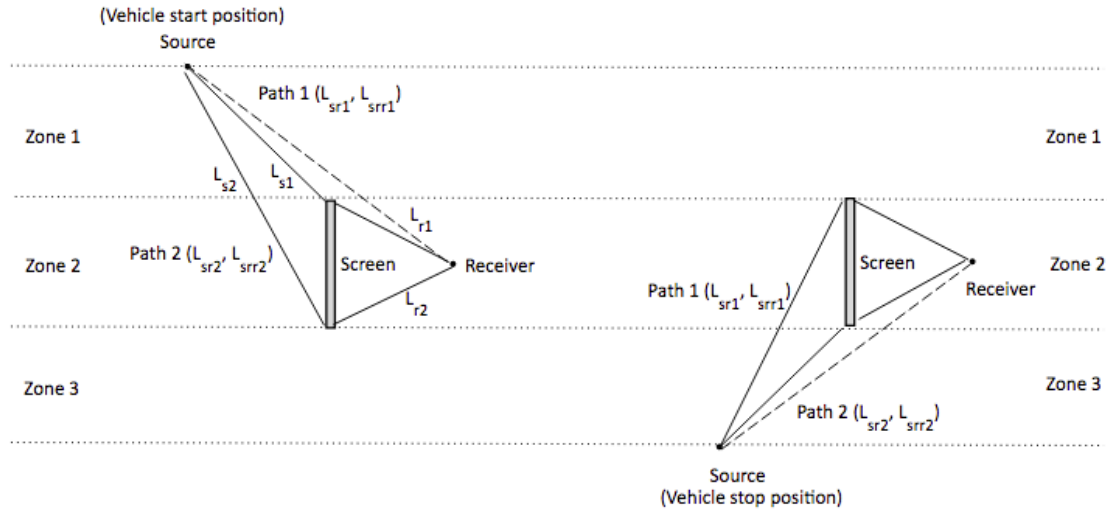
**Figure 2.1:** Vehicle passing by a person with a sound screen in-between.

## 2.2 Sound paths

The purpose of the noise barriers is to reduce noise from the road. The person (receiver) behind the screen hears a lower sound pressure level. Humans hear frequencies from 20 Hz to 20 000 Hz. The sound from the source will go different paths before it reaches the receiver. The paths could e.g., go above the screen and/or around the screen. Figure 2.2 shows the paths when the sound goes above the screen. Figure 2.3 shows the paths when the sound goes around the screen. Ray tracing is a method to find sound paths from the source to the receiver. Different models can be used to calculate the paths, e.g., Harmonoise model or Pierce model [8]. This section describes Harmonoise model for thin screen. It also describes the calculations of sound paths going above the screen and around the screen.



**Figure 2.2:** Four sound paths going over the screen. [8]



**Figure 2.3:** Sound paths going around the screen. (Screen viewed from above.) Path 1 and path 2 consist of the reflected-direct paths ( $L_{srr1}$  and  $L_{srr2}$ ) and direct-direct paths ( $L_{sr1}$  and  $L_{sr2}$ ), via the screen edges. The dashed lines indicate line-of-sight paths.

### 2.2.1 Ray tracing of sound rays going above the screen and through the screen

The sound source (vehicle) is moving from the start position to the stop position.  $X1_{small}$  is the distance the sound source is moving (Figure 2.4).  $L_{slan.s}$  is the distance between the source and the screen.  $L_{slan.r}$  is the distance between the screen and the receiver.  $L_{slan.s}$  and  $L_{slan.r}$  are calculated as

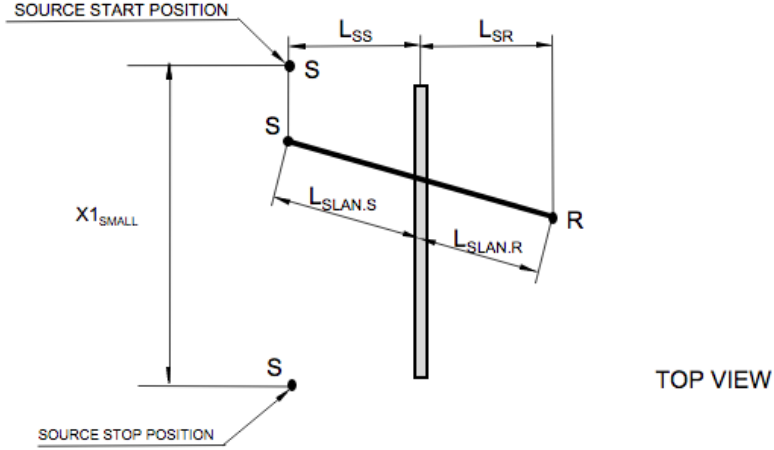
$$L_{slan.s} = \left( \frac{L_{ss}}{L_{ss} + L_{sr}} \cdot L_{slan} \right) \quad (2.1)$$

$$L_{slan.r} = \left( \frac{L_{sr}}{L_{ss} + L_{sr}} \cdot L_{slan} \right) \quad (2.2)$$

where  $L_{slan}$  is the slanted distance between the source and receiver. The distance is slanted due to the moving source.  $L_{slan}$  is calculated as

$$L_{slan} = \sqrt{(L_{ss} + L_{sr})^2 + (X1_{small})^2} \quad (2.3)$$

Figure 2.4 shows the variables used in the equations.



**Figure 2.4:** Slanted distance between source and receiver due to moving vehicle.

Four sound paths are shown in Figure 2.5: the direct-direct path, the direct-reflect path, the reflect-direct path and the reflect-reflect path. The reflected paths are shown as an image source,  $S'$  in Figure 2.5.  $L_{dd}$  is the shortest direct-direct path going above the screen and is  $L_{rr}$  the shortest reflect-reflect path going above the screen.  $L_{rd}$  is the shortest reflect-direct path going above the screen and  $L_{dr}$  is the shortest direct-reflect path going on above the screen.  $L_{dd}$ ,  $L_{rr}$ ,  $L_{rd}$  and  $L_{dr}$  are calculated as

$$L_{dd} = H_{ssdd} + H_{srdd} \quad (2.4)$$

$$L_{rr} = H_{ssrr} + H_{srrr} \quad (2.5)$$

$$L_{dr} = H_{ssdd} + H_{srrr} \quad (2.6)$$

$$L_{rd} = H_{ssrr} + H_{srdd} \quad (2.7)$$

where  $H_{ssdd}$  is the direct path from the source to the screen, and  $H_{srdd}$  is the path from the screen to the receiver.  $H_{ssrr}$  and  $H_{srrr}$  are their corresponding reflected paths.  $H_{ssdd}$ ,  $H_{srdd}$ ,  $H_{ssrr}$  and  $H_{srrr}$  are calculated as

$$H_{ssdd} = \sqrt{(H_{\text{screen}} - H_s)^2 + (L_{\text{slan.s}})^2} \quad (2.8)$$

$$H_{srdd} = \sqrt{(H_{\text{screen}} - H_r)^2 + (L_{\text{slan.r}})^2} \quad (2.9)$$

$$H_{ssrr} = \sqrt{(H_{\text{screen}} + H_s)^2 + (L_{\text{slan.s}})^2} \quad (2.10)$$

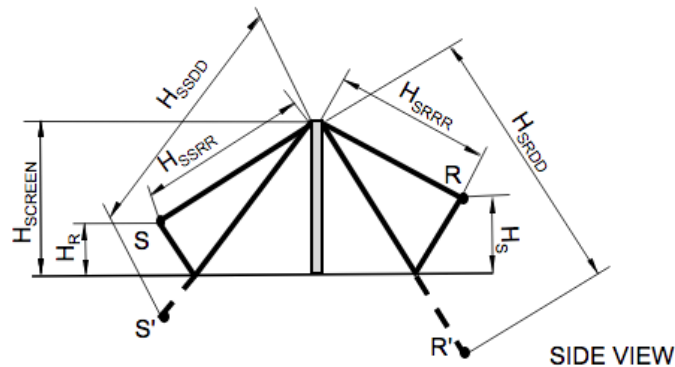
$$H_{srrr} = \sqrt{(H_{\text{screen}} + H_r)^2 + (L_{\text{slan.r}})^2} \quad (2.11)$$

$R$  is the shortest path through the screen.  $R_{\text{direct}}$  is used for the direct-direct path and the reflect-reflect path.  $R_{\text{reflect}}$  is used for the reflect-direct path and the direct-reflect path.  $R_{\text{direct}}$  and  $R_{\text{reflect}}$  are calculated as

$$R_{\text{direct}} = \left( \sqrt{H_r - H_s} \right)^2 + \left( \sqrt{L_{\text{slan}}} \right)^2 \quad (2.12)$$

$$R_{\text{reflect}} = \left( \sqrt{H_r + H_s} \right)^2 + \left( \sqrt{L_{\text{slan}}} \right)^2 \quad (2.13)$$

Equations 2.4 to 2.13 are from these sources [11] [12].



**Figure 2.5:** Four sound paths going above of the screen.

## 2.2.2 Position of the screen

The position of the screen is required to enable calculations on sound rays going around the screen, and to find the angles the sound rays start to hit the screen and stop to hit the screen.  $S_{start}$ , is the start position of the screen and  $S_{stop}$ , is the stop position of the screen.  $S_{start}$  and  $S_{stop}$  are calculated as

$$S_{start} = S_{mid} - \frac{L_{screen}}{2} \quad (2.14)$$

$$S_{stop} = S_{mid} + \frac{L_{screen}}{2} \quad (2.15)$$

Figure 2.6 shows the variables that are used in equation 2.14 and 2.15. The position of the screen is also required to move the screen in relation to the receiver. The receiver is not movable and it is located at  $X1_{small} = 0$ .

## 2.2.3 Angles where the sound rays start and stop to hit the screen

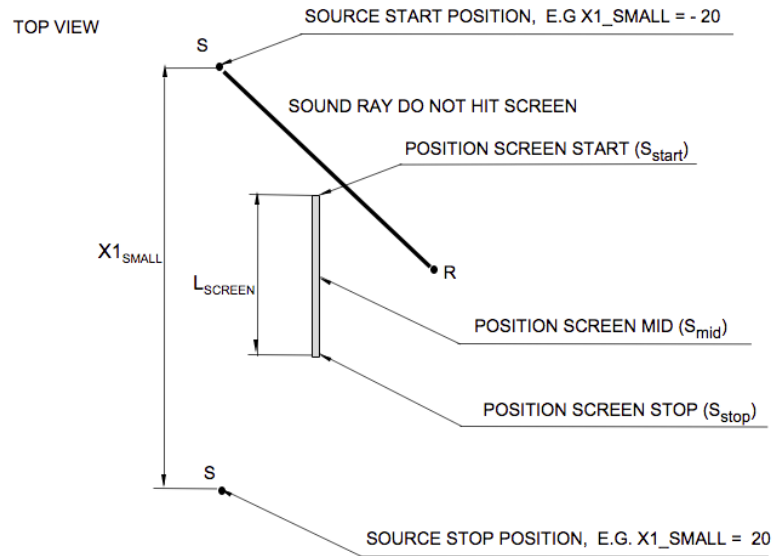
The angle where the sound rays start and stop to hit the screen is required, since the sound source is moving (Figure 2.6). The sound rays going above the screen do no hit the screen at the starting position (zone 1, Figure 2.3). The sound rays start to hit the screen at a certain position of the moving sound source (zone 2, Figure 2.3). They stop to hit the screen when sound source has passed the screen. The sound rays do no hit screen at the end position (zone 3, Figure 2.3).

The angle  $u_1 = u_2$  (Figure 2.7).  $u_2$  is the angle where the sound ray starts to hit the screen.  $u_1$  is calculated as

$$u_1 = \tan^{-1} \left( \frac{S_{start}}{L_{sr}} \right) \quad (2.16)$$

The sound rays start to hit the screen at the distance  $x_1$  from the screen.  $x_1$  is calculated as

$$x_1 = L_{ss} \tan(u_1) \quad (2.17)$$



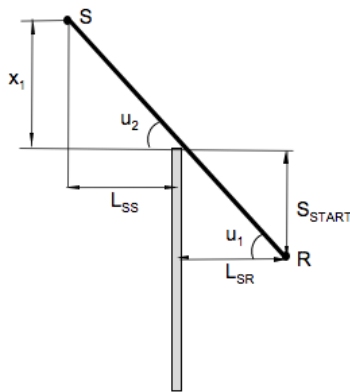
**Figure 2.6:** Screen viewed from above.

The angle  $u_3 = u_4$  (Figure 2.8).  $u_4$  is the angle the sound ray stops to hit the screen.  $u_4$  is calculated as

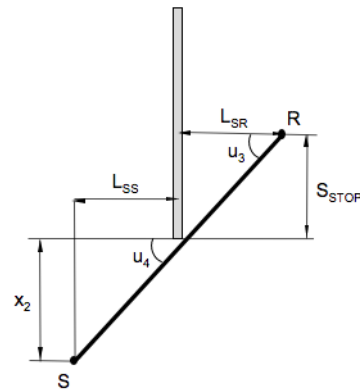
$$u_3 = \tan^{-1} \left( \frac{S_{stop}}{L_{SR}} \right) \quad (2.18)$$

The sound ray stops to hit the screen at the distance  $x_2$  from the screen.  $x_2$  is calculated as

$$x_2 = L_{SS} \tan(u_3) \quad (2.19)$$



**Figure 2.7:** The angle and distance the sound ray starts to hit the screen.



**Figure 2.8:** The angle and distance the sound ray stops to hit the screen.

### 2.2.4 Ray tracing of sound rays going around the screen

The sound rays going around the screen are shown in Figure 2.3.  $L_{SR1}$  is the distance of the direct path and  $L_{SRR1}$  is the distance of the reflected path.  $L_{SR1}$  and  $L_{SRR1}$  are calculated as

$$L_{sr1} = \sqrt{(L_{s1} + L_{r1})^2 + (H_s - H_r)^2} \quad (2.20)$$

$$L_{srr1} = \sqrt{(L_{s1} + L_{r1})^2 + (H_s + H_r)^2} \quad (2.21)$$

where  $L_{s1}$  is the distance from the source to the screen and  $L_{r1}$  is the distance from the screen to the receiver.  $L_{s1}$  and  $L_{r1}$  are calculated as

$$L_{s1} = \sqrt{(L_{ss})^2 + (S_{start} - X1_{small})^2} \quad (2.22)$$

$$L_{r1} = \sqrt{(L_{sr})^2 + (S_{start})^2} \quad (2.23)$$

Figure 2.4, 2.5 and 2.6 show the variables that are used in the equations 2.20 to 2.23.

The sound rays going around the screen (path 2) are shown in Figure 2.3.  $L_{sr2}$  is the distance of the direct path and  $L_{srr2}$  is the distance of the reflected path.  $L_{sr2}$  and  $L_{srr2}$  are calculated as

$$L_{sr2} = \sqrt{(L_{s2} + L_{r2})^2 + (H_s - H_r)^2} \quad (2.24)$$

$$L_{srr2} = \sqrt{(L_{s2} + L_{r2})^2 + (H_s + H_r)^2} \quad (2.25)$$

where  $L_{s2}$  is the distance from the source to the screen and  $L_{r2}$  is the distance from the screen to the receiver.  $L_{s2}$  and  $L_{r2}$  are calculated as

$$L_{s2} = \sqrt{(L_{ss})^2 + (S_{stop} - X1_{small})^2} \quad (2.26)$$

$$L_{r2} = \sqrt{(L_{sr})^2 + (S_{stop})^2} \quad (2.27)$$

Figure 2.4, 2.5 and 2.6 show the variables that are used in the equations 2.24 to 2.27.

## 2.2.5 The Fresnel number

The Fresnel numbers are the following for the paths going around the screen:  $N_{sr1}$  and  $N_{sr2}$  are the Fresnel numbers of the direct-direct path 1 and path 2 respectively.  $N_{srr1}$  and  $N_{srr2}$  are the Fresnel numbers of the direct-reflect path 1 and path 2 respectively.  $N_{sr1}$ ,  $N_{sr2}$ ,  $N_{srr1}$  and  $N_{srr2}$  are calculated as

$$N_{sr1} = \frac{\Delta_{sr1}}{\lambda} \quad (2.28)$$

$$N_{sr2} = \frac{\Delta_{sr2}}{\lambda} \quad (2.29)$$

$$N_{srr1} = \frac{\Delta_{srr1}}{\lambda} \quad (2.30)$$

$$N_{srr2} = \frac{\Delta_{srr2}}{\lambda} \quad (2.31)$$

Equations 2.28 to 2.31 are based on equations from the following sources [11] [12].

When the sound rays do not hit the screen. The variables  $\Delta_{\text{sr1}}$ ,  $\Delta_{\text{sr2}}$ ,  $\Delta_{\text{srr1}}$  and  $\Delta_{\text{srr2}}$  are calculated as

$$\Delta_{\text{sr1}} = -(L_{\text{sr1}} - R_{\text{direct}}) \quad (2.32)$$

$$\Delta_{\text{sr2}} = -(L_{\text{sr2}} - R_{\text{direct}}) \quad (2.33)$$

$$\Delta_{\text{srr1}} = -(L_{\text{srr1}} - R_{\text{reflect}}) \quad (2.34)$$

$$\Delta_{\text{srr2}} = -(L_{\text{srr2}} - R_{\text{reflect}}) \quad (2.35)$$

When the rays hit the screen. The variables  $\Delta_{\text{sr1}}$ ,  $\Delta_{\text{sr2}}$ ,  $\Delta_{\text{srr1}}$  and  $\Delta_{\text{srr2}}$  are calculated as

$$\Delta_{\text{sr1}} = L_{\text{sr1}} - R_{\text{direct}} \quad (2.36)$$

$$\Delta_{\text{sr2}} = L_{\text{sr2}} - R_{\text{direct}} \quad (2.37)$$

$$\Delta_{\text{srr1}} = L_{\text{srr1}} - R_{\text{reflect}} \quad (2.38)$$

$$\Delta_{\text{srr2}} = L_{\text{srr2}} - R_{\text{reflect}} \quad (2.39)$$

The Fresnel numbers are the following for the paths going above the screen.  $N_{\text{dd}}$  is for the direct-direct path and  $N_{\text{dr}}$  is for the direct-reflect path.  $N_{\text{rd}}$  is for the reflect-direct path and  $N_{\text{rr}}$  is for the reflect-reflect path.  $N_{\text{dd}}$ ,  $N_{\text{dr}}$ ,  $N_{\text{rd}}$  and  $N_{\text{rr}}$  are calculated as

$$N_{\text{dd}} = \frac{\Delta_{\text{dd}}}{\lambda} \quad (2.40)$$

$$N_{\text{rr}} = \frac{\Delta_{\text{rr}}}{\lambda} \quad (2.41)$$

$$N_{\text{rd}} = \frac{\Delta_{\text{rd}}}{\lambda} \quad (2.42)$$

$$N_{\text{dr}} = \frac{\Delta_{\text{dr}}}{\lambda} \quad (2.43)$$

Equations 2.40 to 2.31 are based on equations from the following sources [11] [12].

The variable  $\Delta_{\text{dd}}$  is for the direct-direct path and  $\Delta_{\text{rr}}$  for the reflect-reflect path. The variable  $\Delta_{\text{dr}}$  is for the direct-reflect path and  $\Delta_{\text{rd}}$  for the reflect-direct path. When the sound rays do not hit the screen (zone 1 and zone 3 in Figure 2.3),  $\Delta_{\text{dd}}$ ,  $\Delta_{\text{rr}}$ ,  $\Delta_{\text{dr}}$  and  $\Delta_{\text{rd}}$  are calculated as

$$\Delta_{\text{dd}} = -R_{\text{direct}} \quad (2.44)$$

$$\Delta_{\text{rr}} = -R_{\text{direct}} \quad (2.45)$$

$$\Delta_{\text{dr}} = -R_{\text{reflect}} \quad (2.46)$$

$$\Delta_{\text{rd}} = -R_{\text{reflect}} \quad (2.47)$$

When the sound rays hit the screen (zone 2 in Figure 2.3),  $\Delta_{\text{dd}}$ ,  $\Delta_{\text{rr}}$ ,  $\Delta_{\text{dr}}$  and  $\Delta_{\text{rd}}$  are calculated as

$$\Delta_{\text{dd}} = L_{\text{dd}} - R_{\text{direct}} \quad (2.48)$$

$$\Delta_{\text{rr}} = L_{\text{rr}} - R_{\text{direct}} \quad (2.49)$$

$$\Delta_{\text{dr}} = L_{\text{dr}} - R_{\text{reflect}} \quad (2.50)$$

$$\Delta_{rd} = L_{rd} - R_{reflect} \quad (2.51)$$

The Harmonoise model takes attenuation into account and attenuation is obtained for each sound ray. There are eight sound-ray paths in total: four paths going above the screen and four paths going around the screen. The following applies for the Fresnel number. When  $N \leq -0.25$  the attenuation,  $A_{diff}$  is

$$A_{diff} = 0 \quad (2.52)$$

when  $-0.25 \leq N < 0$  attenuation is

$$A_{diff} = 6 - 12\sqrt{-N} \quad (2.53)$$

when  $0 \leq N < 0.25$  attenuation is

$$A_{diff} = 6 + 12\sqrt{N} \quad (2.54)$$

when  $0.25 \leq N < 1$  attenuation is

$$A_{diff} = 8 + 8\sqrt{N} \quad (2.55)$$

when  $N \geq 1$  attenuation is

$$A_{diff} = 16 + 10\log N \quad (2.56)$$

The equations 2.52 to 2.56 are from this source [10].

The variable  $p_{factor}$  is the factor for the eight rays.  $p_{factor}$  is calculated as

$$p_{factor} = 10^{\frac{-A_{diff}}{20}} \quad (2.57)$$

Equation 2.57 is from this source [13].

The sound rays going above the screen and the sound rays going around the screen hit the screen in zone 2 (Figure 2.3). Only the sound rays going around the screen hit the screen in zone 1 and zone 3 (Figure 2.3). The following applies for path 1 in zone 1 and zone 3:  $p_{sr1}$  is the pressure from the direct-direct path and  $p_{srr1}$  is the pressure from the direct-reflect path. The following applies for path 2 in zone 1 and zone 3:  $p_{sr2}$  is the pressure from the direct-direct path and  $p_{srr2}$  is the pressure for the direct-reflected for path.  $p_{sr1}$ ,  $p_{srr1}$ ,  $p_{sr2}$  and  $p_{srr2}$  are calculated as

$$p_{srr1} = \left( \frac{e^{-ikL_{srr1}}}{L_{srr1}} \right) p_{factor.srr1} Q_s \quad (2.58)$$

$$p_{sr1} = \left( \frac{e^{-ikL_{sr1}}}{L_{sr1}} \right) p_{factor.sr1} \quad (2.59)$$

$$p_{srr2} = \left( \frac{e^{-ikL_{srr2}}}{L_{srr2}} \right) p_{factor.srr2} Q_s \quad (2.60)$$

$$p_{sr2} = \left( \frac{e^{-ikL_{sr2}}}{L_{sr2}} \right) p_{factor.sr2} \quad (2.61)$$

The equations 2.58 to 2.61 are from this source [13].

When the ground is asphalt:  $Q_s = 1$  and  $Q_r = 1$ .  $Q_s$  and  $Q_r$  are reflections on the source side and the receiver side respectively.

The total pressure  $p_{\text{tot}}$  for paths going around the screen (zone 1 and 3) is calculated as

$$|p_{\text{tot}}|^2 = |(p_{\text{sr1}} + p_{\text{srr1}})^2| + |(p_{\text{sr2}} + p_{\text{srr2}})^2| \quad (2.62)$$

The following applies in zone 2: The pressure of the paths going around the screen is calculated with equations 2.58 to 2.61. The paths going above the screen are calculated as following:  $p_{\text{dd}}$  and  $p_{\text{rr}}$  are the pressures from the direct-direct path and the reflect-reflect path respectively.  $p_{\text{rd}}$  and  $p_{\text{dr}}$  are the pressures from the reflect-direct path and the direct-reflect path respectively.  $p_{\text{dd}}$ ,  $p_{\text{rr}}$ ,  $p_{\text{rd}}$  and  $p_{\text{dr}}$  are calculated as

$$p_{\text{dd}} = \left( \frac{e^{-ikL_{\text{dd}}}}{L_{\text{dd}}} \right) p_{\text{factor.dd}} \quad (2.63)$$

$$p_{\text{rr}} = \left( \frac{e^{-ikL_{\text{rr}}}}{L_{\text{rr}}} \right) p_{\text{factor.rr}} Q_s Q_r \quad (2.64)$$

$$p_{\text{rd}} = \left( \frac{e^{-ikL_{\text{rd1}}}}{L_{\text{rd}}} \right) p_{\text{factor.rd}} Q_s \quad (2.65)$$

$$p_{\text{dr}} = \left( \frac{e^{-ikL_{\text{dr}}}}{L_{\text{dr}}} \right) p_{\text{factor.dr}} Q_r \quad (2.66)$$

The equations 2.63 to 2.66 are from this source [13].

The total pressure,  $p_{\text{tot}}$ , in zone 2 is calculated as

$$|p_{\text{tot}}|^2 = |(p_{\text{dd}} + p_{\text{rr}} + p_{\text{rd}} + p_{\text{dr}})^2| + |(p_{\text{sr1}} + p_{\text{srr1}})^2| + |(p_{\text{sr2}} + p_{\text{srr2}})^2| \quad (2.67)$$

The sound pressure level is obtained by converting the pressure into sound pressure level. The sound pressure level relative to free field,  $L_{\text{p rel.free field}}$  is calculated as

$$L_{\text{p rel.free field}} = \log_{10} \frac{|p_{\text{tot}}|^2}{|p_{\text{ref}}|^2} \quad (2.68)$$

where  $p_{\text{ref}}$  is the reference pressure

$$p_{\text{ref}} = \frac{e^{-ikR_{\text{direct}}}}{R_{\text{direct}}} \quad (2.69)$$

Amplification caused by diffraction is given by the amplification factor  $a_{\text{factor}}$  and is calculated as

$$a_{\text{factor}} = 10^{\frac{L_{\text{p rel. free field}}}{20}} \quad (2.70)$$

The equation 2.70 is from this source [9].

The influence of the screen (when the vehicle is passing by the receiver) is calculated with the amplification factor.

### 2.2.6 Statistical hypothesis test

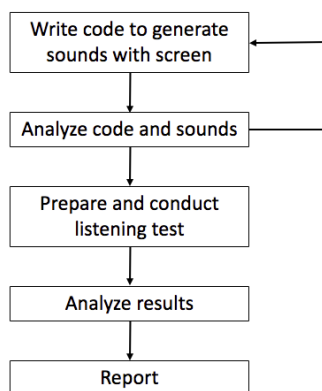
The hypothesis that the recorded sounds are similar to the auralized sounds can be tested in a statistical hypothesis test. Matlab has the functions t-test and rank test. The t-test function assumes that the data is normal distributed. The hypothesis is rejected if  $h = 1$  and the hypothesis is not rejected if  $h = 0$ . A significance level of 5% is the default test setting. The p-value is the probability for the result to occur under the hypothesis. P-value is obtained from both the t-test and rank test. [14] [15]



# 3

## Methods

The two main parts of this thesis work were the code and the listening test. Figure 3.1 shows the work process.



**Figure 3.1:** Flow chart of the work process.

The first step was the pre-study and to understand the existing code (to be able to add a noise barrier). At the second step, the code for the finite-length noise barrier was written in Matlab and sounds were generated and analysed. The code was rewritten several times to assure that the sounds were correct. At the third step, the listening test was prepared in ArtemiS SUITE 13.1 and the test was performed. At the final step, the results were analysed and presented in a report and at a seminar.

### 3.1 The code

The code for vehicle passing by the receiver already exists. In that code, the sound source is from a light-weight vehicle. Ground effect, air attenuation and turbulence exist in the model[9]. The Harmonoise model for thin screen was added to the existing model. Ray tracing was used to find the sound paths going from the source to the receiver. There are sound rays going above the screen and around the screen. Figure 2.2 shows the paths going above the screen (the direct-direct path, the direct-reflect path, the reflect-direct path and the reflect-reflect path). Figure 2.3 shows the paths going around the screen (the direct-direct path and the direct-reflected path for each side of the screen). The code for the screen was built with the following parts.

- The sound rays going above the screen were calculated. The distance between the source and the receiver was slanted due to the moving vehicle. Equations 2.1 to 2.3 were used to calculate the slanted distance (Figure 2.4). The shortest paths from the source to the receiver,  $L$ , were calculated for the four paths going above the screen. The equations 2.4 to 2.7 were used. Sound rays going through the screen,  $R$ , were calculated with equation 2.12 and equation 2.13.
- The position of the screen was required to enable calculations on the sound rays going around the screen and above the screen. Equations 2.14 and 2.15 were used to calculate the start position and the stop position of the screen. It was assumed that the sound rays going around the screen, hit the screen on all positions of the sound source (zone 1, zone 2 and zone 3 in Figure 2.3). It was assumed the sound rays going above the screen did not hit the screen at the start position and stop position of the sound source (zone 1 and zone 3 in Figure 2.3).
- The receiver was located at  $X1_{\text{small}} = 0$  and it was not movable. To adjust the start position of the screen, the centre point of the screen was shifted (to the left or to the right) in relation to the position of the source (Figure 2.6). Equations 2.14 and 2.15 were used to adjust the position of the screen in the calculations. In the listening test there were different cases, where the screen was moved in relation to the receiver (Figure 2.6). The same equations were used to move the screen in relation to the receiver.
- The angle where the sound rays going above the screen started and stopped to hit the screen, was calculated with equations 2.16 to 2.19.
- The paths that were going around the screen were divided into two paths, path 1 and path 2 (Figure 2.3). Both path 1 and path 2 consisted of a direct-reflect path and direct-direct path. Equations 2.20 to 2.27 were used to calculate the paths around the screen.
- Fresnel number was calculated for all the eight paths. Equations 2.28 to 2.31 were used to calculate the paths going round the screen. Equations 2.40 to 2.43 were used to calculate the paths going above the screen.
- The Harmonoise model takes attenuation into account. The attenuation was calculated with equations 2.52 to 2.56. The factor was calculated with equation 2.57.
- It was only the sound rays going around the screen that hit the screen in zone 1 and 3 (Figure 2.3). The pressure caused by diffraction was calculated with equations 2.58 to 2.61. The ground was assumed to be asphalt and the total pressure was calculated with equation 2.62.

- Both the sound rays going above the screen and sound rays going around the screen hit the screen in zone 2 (Figure 2.3). Equations 2.58 to 2.61 were used to calculate the pressure for the sound rays going around the screen. Equations 2.63 to 2.66 were used to calculate pressure for sound rays going above the screen. The total pressure was calculated with equation 2.67.
- The sound pressure level was obtained by converting the sound pressure into sound pressure level. The sound pressure level relative to free field was calculated with equation 2.68. The amplification caused by diffraction of the screen was given by the amplification factor in equation 2.70.

The code (with screen) was written in the existing Matlab code. The auralized sound were generated at 28 km/h, 46 km/h and 66 km/h (the speeds were determined by existing recordings). The distances between centre line of road and receiver were 7.5 m, 15 m and 30 m. The height of the screen was 3 m. The screen was placed in four different positions in relation to the receiver: the receiver was on the half length of the screen, on the edge behind the screen, on the edge of the screen and on a location where the receiver was not shielded by the screen (Figure 3.4 to 3.7). The sounds were cut into 6 s clips. The results (with the screen) were analysed in Matlab. The analysis was made on the code to assure that the screen reduced the sound pressure level on the right vehicle positions. The sounds with screen and without screen were exported from Matlab and the listening test was prepared in ArtemiS SUITE 13.

## 3.2 The listening test

The plausibility of the sounds was investigated in the listening test. Parameters such as roughness, fluctuation strength could support the results, but was not designed into the test due to time limitation. The aim was to keep the test short for the participants. It was difficult design a short test with specific questions, since it was difficult to predict which sounds would have high plausibility (by analysing the graphs in Matlab).

### 3.2.1 Equipment and set-up

The test was performed in a lecture room at Chalmers. The participants listened on the sounds on the headphones and answered the questions on a computer. Figure 3.2 shows the set-up. The following equipment and software were used:

- Headphones from SENHEISER HD 650 (no. 1 to 3 and no. 20 to 24)
- Amplifier from HEAD Acoustics (no. 1 to 3 and no. 20 to 24)
- One computer was used by the test leader and eight computers (no. 1 to 3 and no. 20 to 24) were set-up for the participants
- ArtemiS SUITE 13.1 and SQala Server 2.1x64 were used on the test leader's computer. SQala Client Distributed Test was used on the participants computers.

The plausibility of the sounds was evaluated by nine participants. The test was kept short since the participants were volunteers. Each sound clip was 6 s and 54 sounds were evaluated in the test. The duration of the test session was 20 minutes. The test was performed in two sessions with three participants in each session. Three participants performed the test individually at different test sessions.

The participants listened to the sounds and answered the question "How plausible is the vehicle passing by sound?". They rated the sound on a scale "not plausible" to "plausible". "Not plausible" corresponded to 1 on the scale and "plausible" corresponded to 10 on the scale. The test was divided into two parts. The sounds without screen were evaluated in part one and the sounds with screen were evaluated in part two.

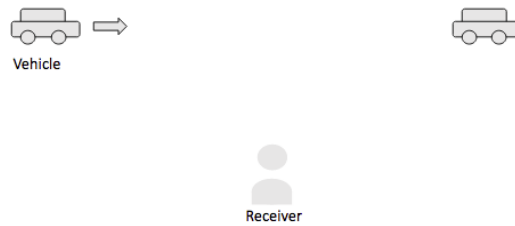


**Figure 3.2:** The participants performed the test in the class room and each participant had their own equipment (computer, amplifier and headphones).

#### 3.2.2 Listening test - part 1

The recorded sounds were evaluated together with the auralized sounds. The vehicle (an Opel Astra) had the velocities: 27 km/h, 45 km/h and 65 km/h during the recording. The distance between the centre line of the road and the receiver was 7.5 m. The recordings of the real sounds were not made at this thesis work.

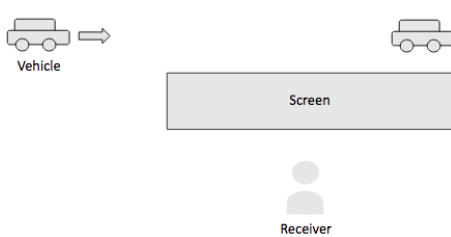
The vehicle had the velocities: 28 km/h, 46 km/h and 66 km/h in the auralized sounds. The difference in velocity between the recorded sounds and the auralized sounds were caused by the code. The velocity was adjustable in steps of 2 km/h in the code. The distances between centre line of the road and the receiver were: 7.5 m, 15 m and 30 m. The receiver was placed on the half length of the screen (Figure 3.3). The recorded sounds and the auralized sounds were mono sounds. They were not converted to binaural sounds in the listening test, since a comparison close to the recorded sound was desired.



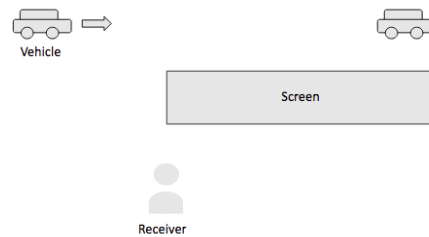
**Figure 3.3:** Part 1, sound without screen.

### 3.2.3 Listening test - part 2

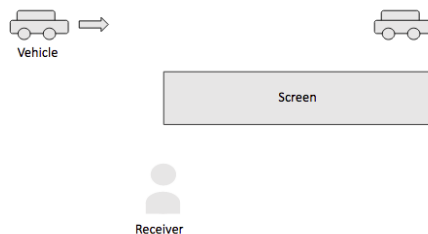
The auralized sounds with screen were evaluated in part two. The auralised sounds were generated in the same velocities (28 km/h, 46 km/h and 66 km/h) and the same distances (7.5 m, 15 m and 30 m) as in part one. The height of the screen was 3 m and the screen was placed at four different locations in relation to the receiver: on the half length of the screen, on the edge behind the screen, on the edge of the screen and on a location where the receiver was not shielded by the screen (Figure 3.4 to 3.7). The data were extracted from ArtemiS SUITE and exported to Excel and Matlab after the test. The data was analysed in Matlab.



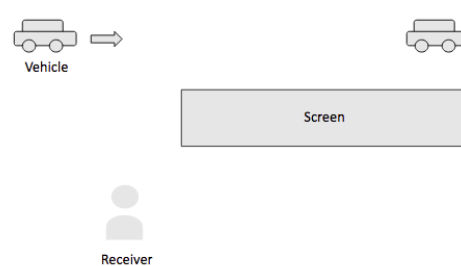
**Figure 3.4:** Part 2, position 1. The receiver is placed on the half length of the screen.



**Figure 3.5:** Part 2, position 2. The receiver placed on the edge behind the screen.



**Figure 3.6:** Part 2, position 3. The receiver is placed on the edge of the screen.



**Figure 3.7:** Part 2, position 4. The receiver not shielded by the screen.

#### **3.2.4 Analyzing the results**

The results from the listening test were analyzed in Matlab. The results of the recorded sounds were compared with the results of the auralized sounds. A statistical hypothesis test was made for the recorded and the auralized sounds. The hypothesis was that the recorded sounds were similar to the auralized sounds. The different velocities of the vehicle and the different positions of the receiver in relation to the screen were compared and analyzed. The results were obtained and plotted in Matlab.

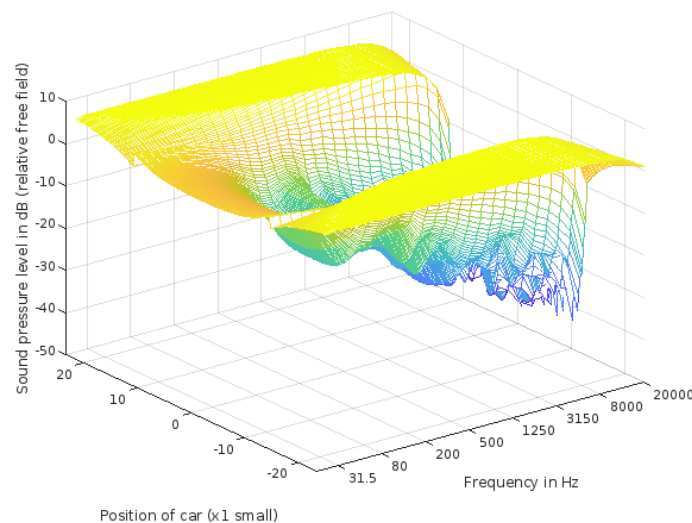
# 4

## Results and discussion

### 4.1 Modelling results

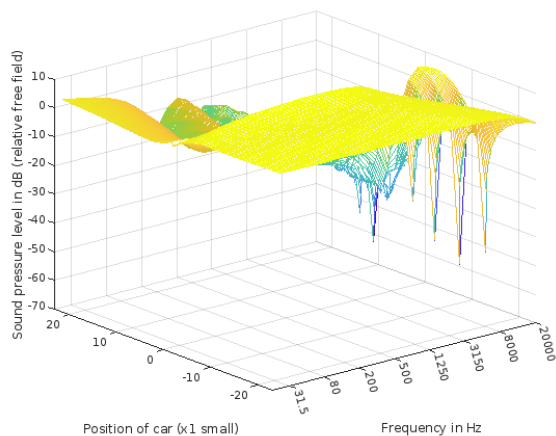
Figure 4.1 shows the resulting change in sound pressure level for a vehicle passing by the receiver with a finite-length screen in-between the receiver and the road. The receiver is placed in the half length of the screen, which corresponds to "x1 small" = 0 in Figure 3.4. In the beginning of the sound (when position of car is at "x1 small" = -23 to "x1 small" = -13) the line of sight is not shielded by the screen. The sound pressure level increases by 6 dB according to the Harmonoise model. At the position "x1 small" = -13 to "x1 small" = 13 of the car, the line of sight is shielded by the screen. The screen is largely effective in decreasing the sound pressure level between 200 Hz to 20 000 Hz, which is within the frequency range of human hearing. The screen decreases the sound pressure level in the desired frequency range and fulfills its purpose. The screen is most effective, and decreases the sound pressure level with 30 dB to 40 dB, when the car is in the same x-position as the receiver ("x1 small" = 0).

The corresponding graphs that were obtained when changing velocity, receiver position and distances between centre line of road and the receiver had all different appearances (Figures 4.2 to 4.7).

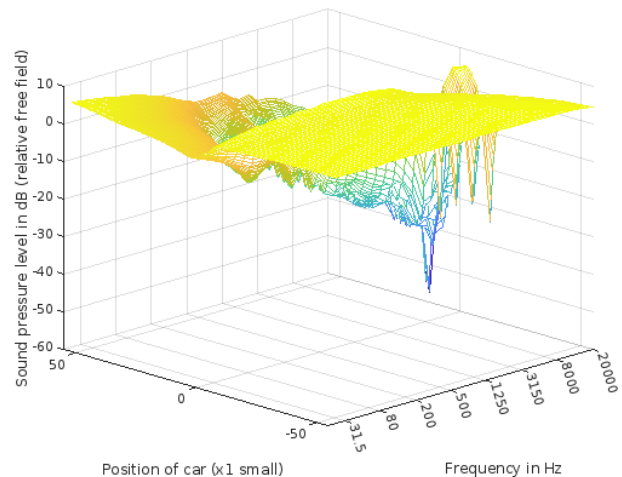


**Figure 4.1:** Position 1, 28 km/h and 15 m between centre line of road and receiver.

## 4. Results and discussion



**Figure 4.2:** Position 3, 28 km/h and 7.5 m between centre line of road and receiver.

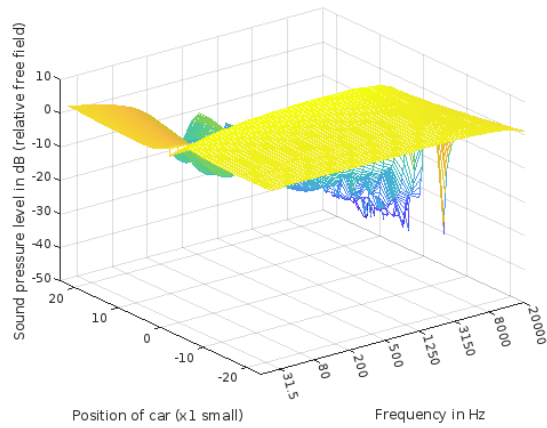


**Figure 4.3:** Position 3, 66 km/h and 7.5 m between centre line of road and receiver.

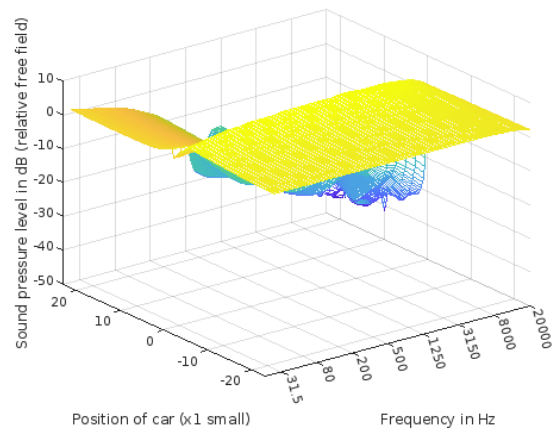
The results for position 2 (receiver on the edge behind the screen), position 3 (receiver on the edge) and position 4 (receiver not shielded by the screen) shared the same appearances in the graphs. The similarities are presented for position 3 as an example.

- When the sound ray starts to hit the screen (when position of car is "x1 small" = -13), the sound pressure level fluctuates at 15 000 Hz to 20 000 Hz. The fluctuations create dips and peaks in the graphs (interference pattern). The dips are more prominent at 28 km/h (Figure 4.2) than at 66 km/h (Figure 4.3) when the distance between the receiver and the centre line of road is 7.5 m. The dips in the interference pattern decrease when the velocity increases.
- There are several dips at 15 000 Hz to 20 000 Hz, when the distance between the receiver and the centre line of road is 7.5 m and the velocity is 28 km/h (Figure 4.2). It is only one dip at 15 m (Figure 4.4) and there is no dip at 30 m (Figure 4.5). The dips in the interference pattern decrease when the distance between the receiver and the centre line of road increases. The dips will occur at lower frequencies when the distances between the source and the receiver decrease. The dips will occur at higher frequencies when the distances between the source and the receiver increase.

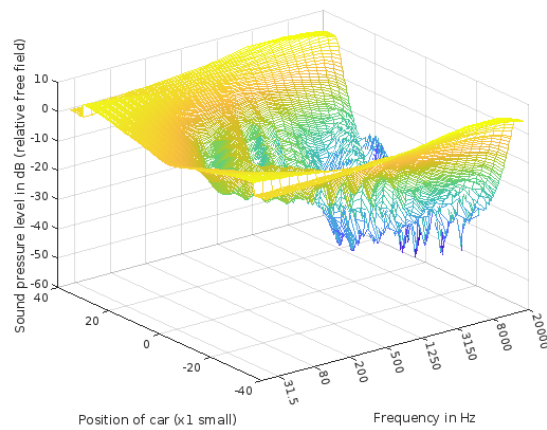
The graph for position 1 (the receiver is placed on the half length of the screen) is different in appearance from the other positions (Figure 4.6 and Figure 4.7). There are no dips at frequencies between 15 000 Hz and 20 000 Hz when the sound ray starts to hit the screen, regardless velocity and distance. The distance between the source and the receiver is long when the sound ray does not hit the screen, and due to this there are no interference dips at 15 000 and 20 000 Hz. The interference dips occur at higher frequencies when the distance increases. The graphs only show up to 20 000 Hz.



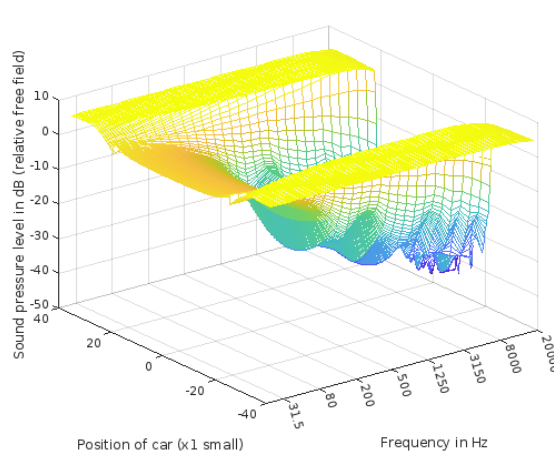
**Figure 4.4:** Position 3, 28 km/h and 15 m between centre line of road and receiver.



**Figure 4.5:** Position 3, 28 km/h and 30 m at between centre line of road and receiver.



**Figure 4.6:** Position 1, 46 km/h and 7.5 m between centre line of road and receiver.



**Figure 4.7:** Position 1, 46 km/h and 30 m between centre line of road and receiver.

#### 4.1.1 Analyzing the sounds by listening

It is predicted that the participants in the listening test would distinguish between auralized sounds and recorded sounds by listening on the sounds. It is possible to hear that the sounds without screen are more dynamic, than the sounds with screen shielding most of the passage. The graphs show the reduction of the sound pressure levels and show that the screen decreases sound pressure levels at the correct vehicle positions. However, more parameters affect the human perception of sound. It is not possible to predict which setting would give the most plausible sound in the listening test, by only analysing the graphs above.

## 4.2 The listening test

This section shows the results from the listening test and the graphs show the average plausibility. High average (e.g., 10) means "plausible sound" and low average (e.g., 1) means "not plausible sound". The vehicle velocities 27 km/h, 45 km/h and 65 km/h are the auralized vehicle velocities. The velocities 28 km/h, 46 km/h and 66 km/h are the recorded vehicle velocities. The velocities 30 km/h, 50 km/h and 70 km/h are shown in the graphs and these are the nominal values. 5 females and 4 males participated on the listening test. The average age was 30 year.

### 4.2.1 Statistical hypothesis test for the recorded sounds and the auralized sounds without screen

The hypothesis that the recorded sounds are similar to the auralized sounds is tested in a statistical hypothesis test. If the test result is  $h = 1$ , it means that the hypothesis is rejected. If  $h = 0$  the hypothesis is not rejected. The test is made with 5% significant level. Table 4.1 shows the results of the paired sample t-test from Matlab. The table shows that the hypothesis is rejected at 27 km/h (Figure 4.8) and 45 km/h (Figure 4.9). The sounds are not similar at 27 km/h and 45 km/h. The hypothesis is not rejected at 65 km/h (Figure 4.10) and the p-value is 0.1322 (Table 4.1). It means that the probability for this result to occur is 13% under the hypothesis. The tests were made under the assumption that the results are normal distributed. The results are not normal distributed. This is shown in Figure 4.12 to Figure 4.17. Therefore, a rank test was also performed. The results are shown in Table 4.2. The results show that the recorded and the auralized sounds are similar, and the probability for this result to occur is 100% under the hypothesis.

**Table 4.1:** Results for recorded sounds versus auralized sounds, from the paired-sample t-test in Matlab

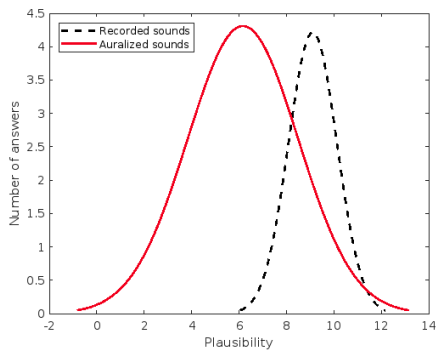
	27 km/h	45 km/h	65 km/h	All velocities
h	1	1	0	1
p-value	1.1E-4	0.0085	0.1322	3.5E-06

**Table 4.2:** Results for recorded sounds versus auralized sounds, from the paired-sample rank-test in Matlab

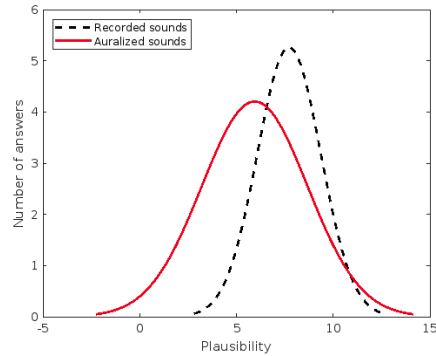
	27 km/h	45 km/h	45 km/h
h	0	0	0
p-value	1	1	1

A possible reason for these results (from the rank-test and t-test) is that there are too small amount of data. The number of answers are too few to draw conclusions. An attempt to increase the data was made by comparing the data from all velocities

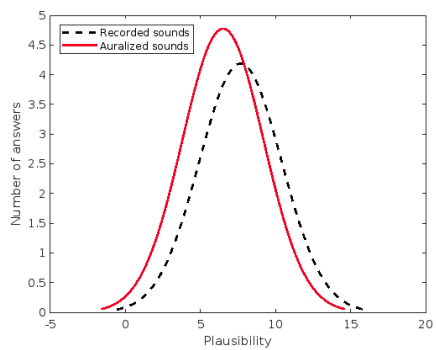
in the same graph (Figure 4.11). The hypothesis is still rejected (Table 4.1 "All velocities"). The results from the rank-test and t-test can not be used, since the amount of data are too small, to draw conclusions. The average plausibility of the sounds is therefore analyzed instead.



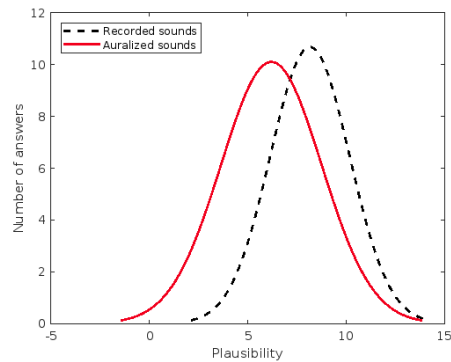
**Figure 4.8:** 5% significance level is rejected 27 km/h.



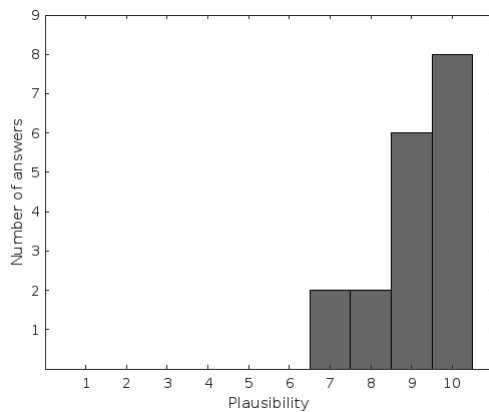
**Figure 4.9:** 5% significance level is rejected at 45 km/h.



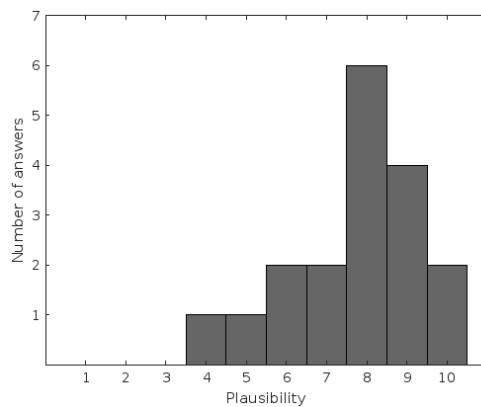
**Figure 4.10:** 5% significance level is not rejected 65 km/h.



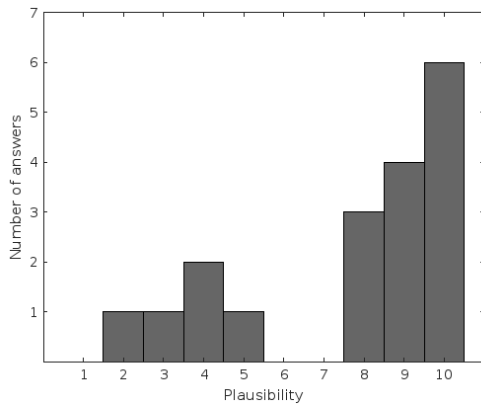
**Figure 4.11:** Data from all the velocities is the same graph is rejected on 5% significance level.



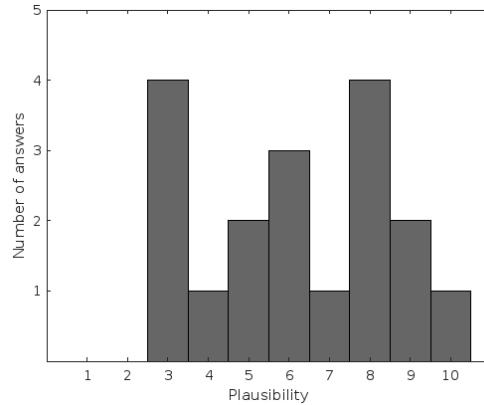
**Figure 4.12:** Recorded sound at 27 km/h, distance 7.5 m.



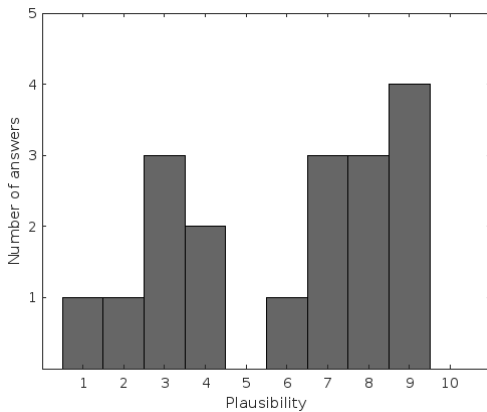
**Figure 4.13:** Recorded sound at 45 km/h, distance 7.5 m.



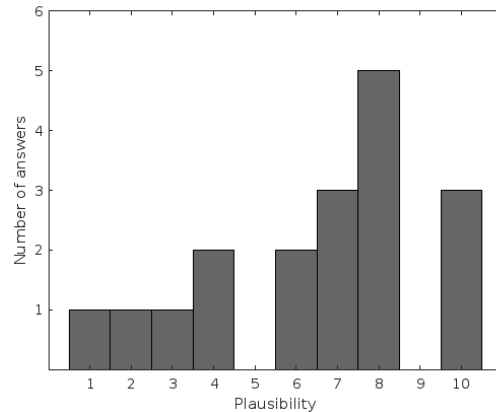
**Figure 4.14:** Recorded sounds at 65 km/h, distance 7.5 m.



**Figure 4.15:** Auralized sounds at 28 km/h, distance 7.5 m.



**Figure 4.16:** Auralized sounds at 46 km/h, distance 7.5 m.

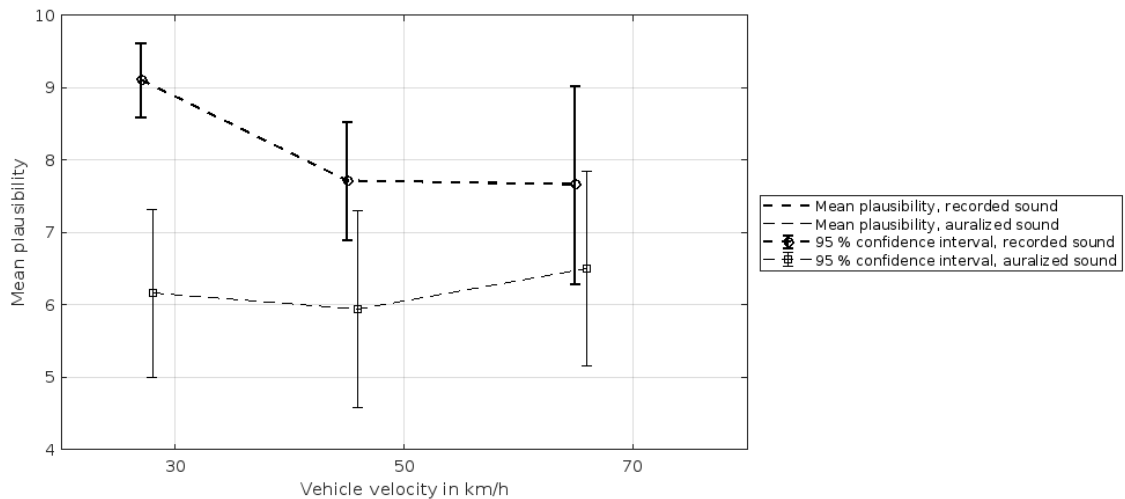


**Figure 4.17:** Auralized sounds at 66 km/h, distance 7.5 m.

### 4.2.2 The average plausibility of the recorded and the auralized sounds

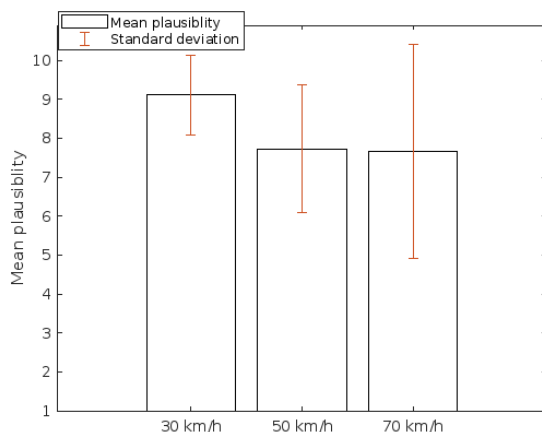
Figure 4.18 shows the average plausibility of the recorded sounds and the auralized sounds. The recorded sounds have higher average plausibility than the auralized sounds. The average plausibility for the recorded sounds are 9.1 for 27 km/h, 7.7 for 45 km/h and 7.7 for 65 km/h (Figure 4.18). The corresponding average plausibility for the auralized sounds are 6.2 for 28 km/h, 5.9 for 46 km/h and 6.5 for 66 km/h (Figure 4.18). The participants notice a difference in plausibility between the recorded sounds and the auralized sounds.

It was expected that the participants would notice a difference between the auralized sounds and the recorded sounds. The lowest average plausibility of the recorded sound is 7.7 (Figure 4.18). The average plausibility of the auralized sounds is approximately 6 for all the velocities (Figure 4.18), which is slightly lower than the recorded sound with the lowest average. The auralized sounds are perceived quite realistic.

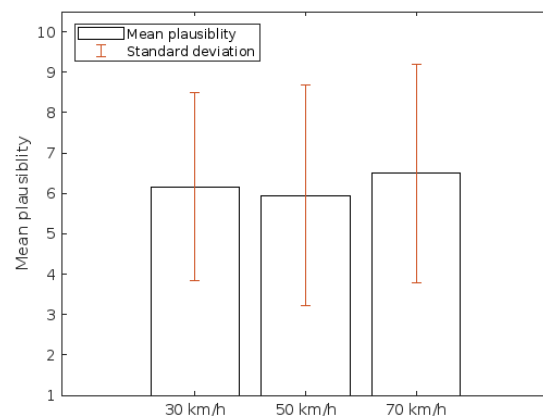


**Figure 4.18:** The average plausibility for the recorded sounds at 30 km/h, 50 km/h and 70 km/h without screen. The distance is 7.5 m.

Figure 4.19 and Figure 4.20 show the average plausibility with one standard deviation. The standard deviation is estimated for the mean value assuming a normal distribution. The recorded sound for velocity 27 km/h has the smallest standard deviation. The standard deviations increase when the velocities increase (Figure 4.19). The standard deviation is larger for all velocities for the auralized sounds (Figure 4.20). Figure 4.12 to Figure 4.17 show the number of answers for each sound. The answers from the recorded sounds are located on the higher end of the plausibility scale. Several answers have the plausibility between 8 and 10 (Figure 4.12 to Figure 4.14). The answers from the auralized sounds are between 2 and 10 on the plausibility scale (Figure 4.15 to Figure 4.17). The reason could be that the real (recorded) sounds are easy to recognise, but it is difficult for the participants to determine the plausibility of the auralized sounds.



**Figure 4.19:** The average plausibility for the recorded sounds at 28 km/h, 45 km/h and 65 km/h without screen. The distance is 7.5 m.



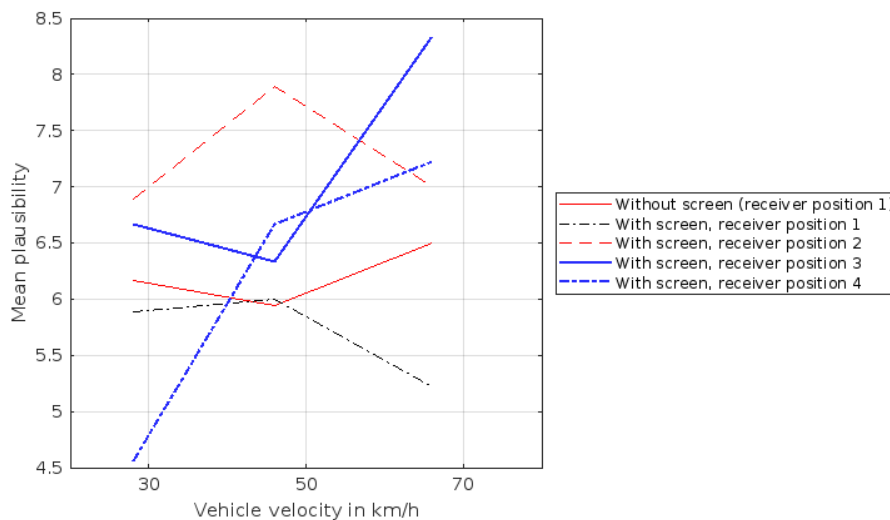
**Figure 4.20:** The average plausibility for the auralized sounds at 28 km/h, 46 km/h and 66 km/h without screen. The distance is 7.5 m.

Appendix A shows the results for the auralized sounds with screen. The standard deviation is larger for the auralized sounds (figure A.1 to A.12) than for the recorded sounds (Figure 4.19), except from one auralized sound (Figure A.4 in appendix A).

### 4.2.3 Auralized sounds with screen and without screen

The listening test results "without screen" and "with screen, receiver position 1" in Figure 4.21 show that the auralized sounds with screen have approximately the same average plausibility as the auralized sounds without screen. The auralized sounds with screen are perceived as plausible as the auralized sounds without screen at velocity 27 km/h and 45 km/h (Figure 4.21).

Figure 4.21 shows that the sounds with screen have higher average plausibility than the sounds without screen when the receiver is placed on position 2 and position 3 (Figure 3.5 and Figure 3.6). A possible explanation could be that the sounds from position 2 and position 3 are perceived as more dynamic and due to this more plausible. A short part of the sound is covered by the screen in these sounds. The sounds without screen are more dynamic than the sounds with screen, when the screen is influential during the main part of the pass-by (as discussed in section 4.1.1. "Analyzing the sounds by listening")



**Figure 4.21:** The average plausibility of the auralized sounds at different receiver positions. The distance is 7.5 m.

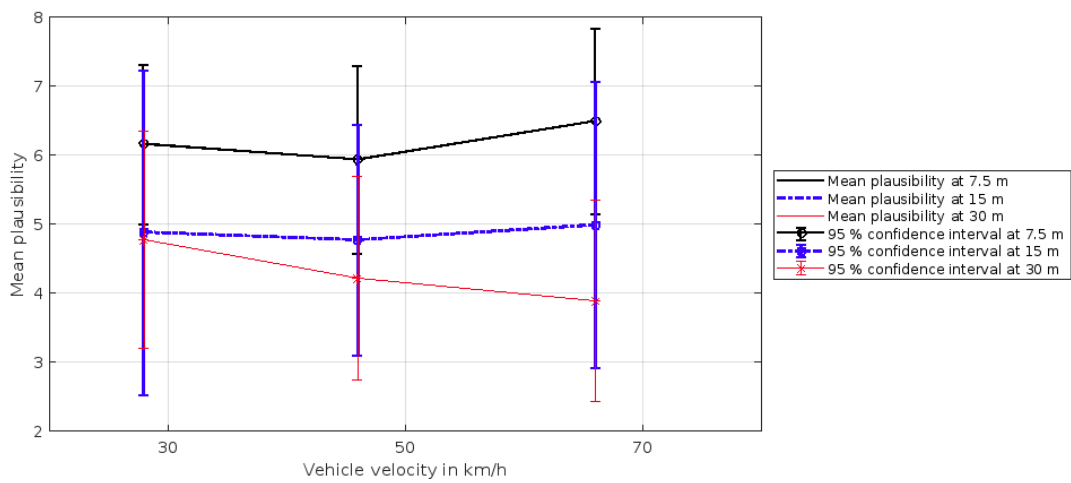
### 4.2.4 Vehicle velocity

Figure 4.18 shows the recorded sounds at 27 km/h, 45 km/h and 65 km/h without screen. 27 km/h has higher plausibility than 45 km/h and 65 km/h (Figure 4.18). The recorded sounds have high plausibility at low velocity.

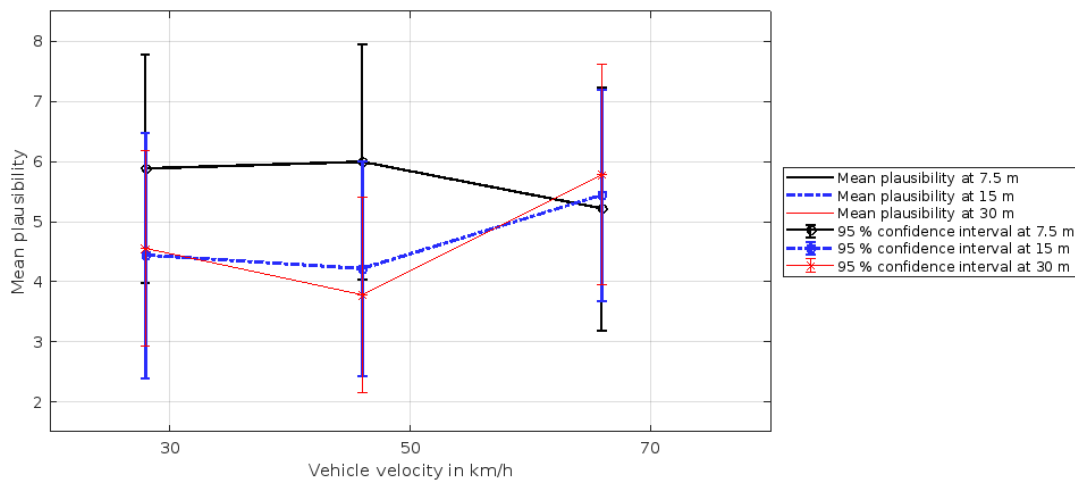
Figure 4.22 to Figure 4.26 show the auralized sounds with and without screen at 28 km/h, 46 km/h and 66 km/h. 66 km/h has the highest plausibility at 7.5 m in

Figure 4.22, Figure 4.25 and Figure 4.26. 46 km/h has the highest plausibility at 7.5 m in Figure 4.23 and Figure 4.24. The auralized sounds have higher plausibility at high velocity (66 km/h and 46 km/h) than at low velocity (28 km/h).

The auralised sounds are perceived as more plausible at higher velocity. A possible explanation could be that the sounds are not normalised in sound pressure level. The high velocity sounds are in higher sound pressure level than the low velocity sounds in the listening test. It could be easier for the participants to hear the characteristics of the sound when it is louder and that might affect the plausibility of the sound. It might lead to higher or lower plausibility, when the participants hear the sounds clearly.

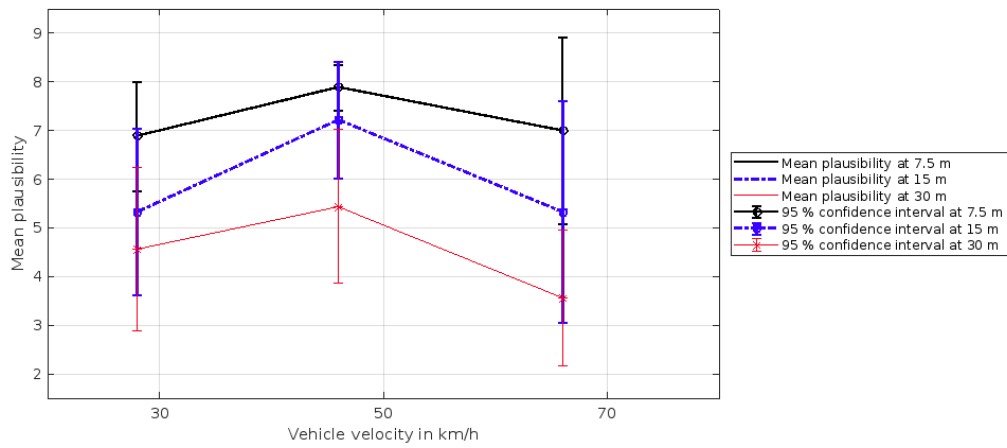


**Figure 4.22:** The average plausibility of auralized sounds without screen.

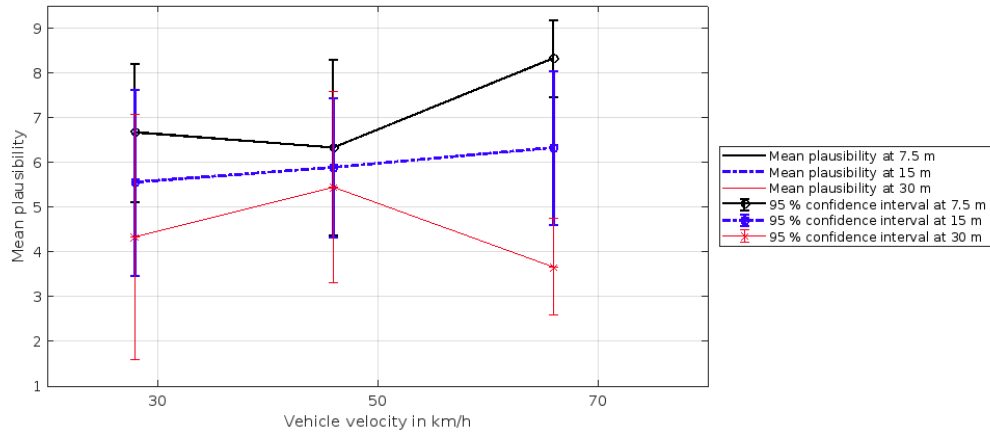


**Figure 4.23:** The average plausibility of auralized sounds with screen, position 1.

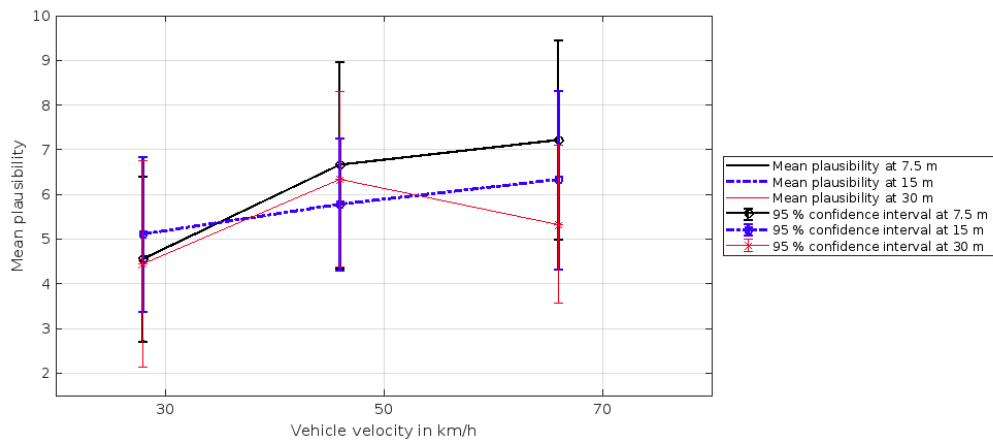
## 4. Results and discussion



**Figure 4.24:** The average plausibility of auralized sounds with screen, position 2.



**Figure 4.25:** The average plausibility for auralized sounds with screen, position 3.



**Figure 4.26:** The average plausibility of auralized sounds with screen, position 4.

### 4.2.5 Distance between the receiver and road

Figure 4.22 to Figure 4.26 show the results for 7.5 m, 15 m and 30 m between the receiver and the centre line of road. The 7.5 m distance (black curves) have higher average plausibility than 15 m (red curves) and 30 m (blue curves). This trend in results is obtained without screen (Figure 4.22), and also at all receiver positions with screen (Figures 4.23 to Figure 4.26). The participants perceive that the sounds are most plausible when the distance is 7.5 m. When the distance between the receiver and the centre line of road increase to 15 m and 30 m, the participants perceive the sounds as less plausible.

The reason could be that the auralized sounds are created based on recordings made on 7.5 m distance. Therefore, the sounds from 7.5 m are perceived more plausible than the 15 m and 30 m sounds. When the distance increases to 15 m and 30 m in the code, the characteristics of the sounds change and the sound is perceived as less plausible by the participants.

### 4.2.6 Position of the receiver

The comparison of position of the screen edge is made on 7.5 m, since this distance has the most plausible sounds. Figure 4.21 shows that position 2 (red dotted curve) and position 3 (thick blue curve) have higher average plausibility than position 1 (black dotted curve) and position 4 (blue dotted curve). Position 1 has the lowest average plausibility (the least plausible sounds). The average plausibility decreases, when a long time of the sound clip consists of sound with screen (as in position 1). A higher average plausibility is obtained when a smaller portion of the sound clip consist of sound screened by the sound barrier (as in positions 2, 3 and 4).

The reason could be that the sounds from positions 2, 3 and 4 are perceived as more dynamic, since a shorter part of the sound is covered by the screen. The sound is possibly perceived as less dynamic and thereby less realistic/plausible when a large portion of the sound is screened by the sound barrier.

## 4.3 Further work

The sample size was too small to draw any conclusions from the statistical test. As a further work more listening tests could be performed to increase the sample size. The auralized sounds are created based on 7.5 m recordings. Auralized sounds created based on longer distance e.g., 15 m and 30 m as well as including screen could be investigated further. It would also be interesting to investigate if the plausibility increases when more surfaces and sound sources are added into to the code. The specific parameters e.g., roughness and fluctuation strength could be investigated further in a listening test, to investigate the perception of sounds and the connection to plausibility.



# 5

## Conclusion

A 3 m high finite-length noise barrier was modelled using the Harmomonoise model for thin screen. A listening test was performed to evaluate the perception (plausibility) of the auralized and the recorded sounds with and without noise barrier. The sounds were auralized with three vehicle velocities: 28 km/h, 46 km/h and 66 km/h (which were determined by existing recordings, where the vehicle was in the velocities 27 km/h, 45 km/h and 65 km/h). The screen was placed in four different positions in relation to the receiver: on the half length of the screen (position 1), on the edge behind the screen (position 2), on the edge of the screen (position 3) and on a location where the receiver was not shielded by the screen (position 4). The auralized sound were also generated at different distances (between the receiver and the centre line of the road): 7.5 m, 15 m and 30 m. The aim was to investigate: if it was possible to distinguish between auralized and real recorded sounds, if the sounds were perceived similarly and if there were any difference in perception (plausibility) when the receiver was placed on different locations behind the noise barrier and placed on different distances from the source.

A statistical hypothesis test was made for the recorded and the auralized sounds. The hypothesis was that the recorded sounds were similar to the auralized sounds. The results from the statistical hypothesis test could not be used, since the amount of data was too small to draw conclusions. The average plausibility was analyzed instead. The participants in the listening test noticed a difference in plausibility between the recorded and the auralized sounds. The recorded sounds had higher average plausibility than the auralised sounds at the same distance. The lowest average plausibility of the recorded sound was 7.7. The average plausibility of the auralized sounds was approximately 6 (for all velocities), which is slightly lower than for the recorded sound with the lowest average. The auralized sounds were perceived fairly realistic. However, the recorded sounds were perceived as more plausible at low velocity and the auralized sounds were perceived as more plausible at high velocity.

When a comparison was made between the results with and without noise barrier for auralized sounds, it was found that the sounds with noise barrier were perceived as plausible as the sounds without noise barrier at 27 km/h and 45 km/h. The auralized sounds were perceived similarly at these velocities for position 1. However, the sounds with noise barrier had higher average plausibility than the sounds without noise barrier, when the receiver was placed on position 2 and position 3.

The participants perceived that the sounds with noise barrier were most plausible when the distance between the receiver and the centre line of road was 7.5 m. The participants perceived the sounds as less plausible when the distances increased to 15 m and 30 m. The average plausibility decreased when a large portion of the sound clip consisted of sound screened by the noise barrier (as in position 1). This may be due to that these sounds were less dynamic in terms of noise level radiation. A higher average plausibility was obtained when a shorter time of the sound clip consisted of sound screened by the noise barrier (as in position 2, position 3 and position 4).

For further work, auralized sounds created based on longer distance e.g., 15 m and 30 m as well as including screen could be investigated. The specific parameters e.g., roughness and fluctuation strength could be investigated in a listening test, to investigate the perception of sounds and the connection to plausibility.

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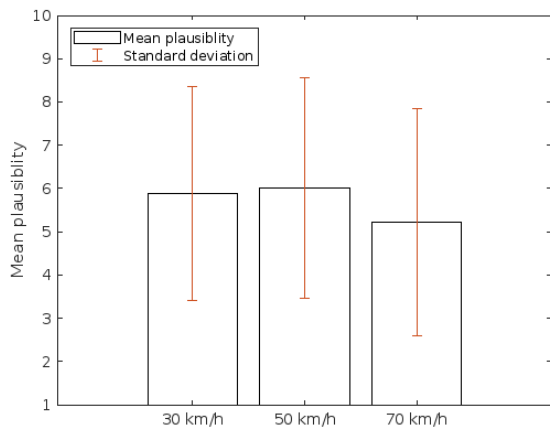
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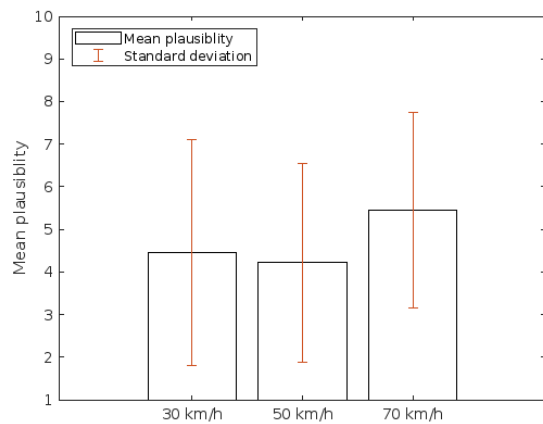
# A

## Results of auralized sounds

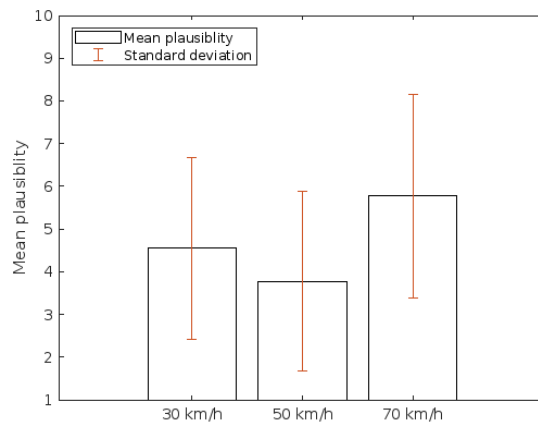
Figure A.1 to Figure A.3 show the average plausibility of the auralized sounds at position 1 at 7.5 m, 30 m and 15 m respectively.



**Figure A.1:** The average plausibility of the auralized sounds at position 1 and 7.5 m distance.



**Figure A.2:** The average plausibility of the auralized sounds at position 1 and 15 m distance.

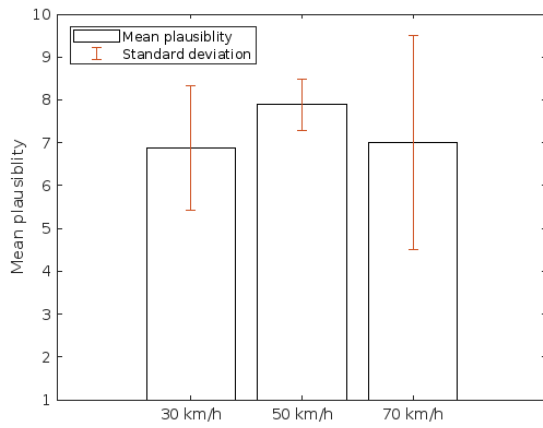


**Figure A.3:** The average plausibility for auralized sounds at receiver position 1 and 30 m distance.

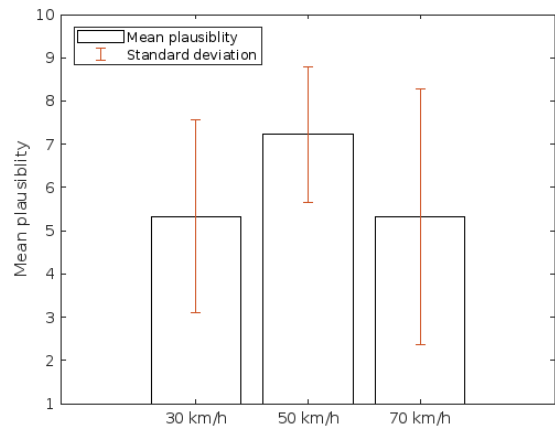
## A. Results of auralized sounds

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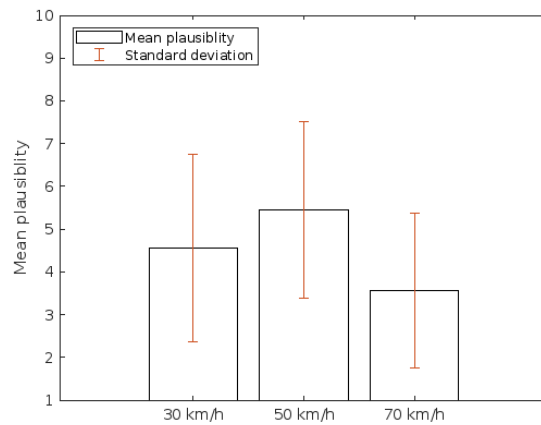
Figure A.4 to Figure A.6 show the average plausibility of the auralized sounds at position 2 at 7.5 m, 30 m and 15 m respectively.



**Figure A.4:** The average plausibility of the auralized sounds at position 2 and 7.5 m distance.

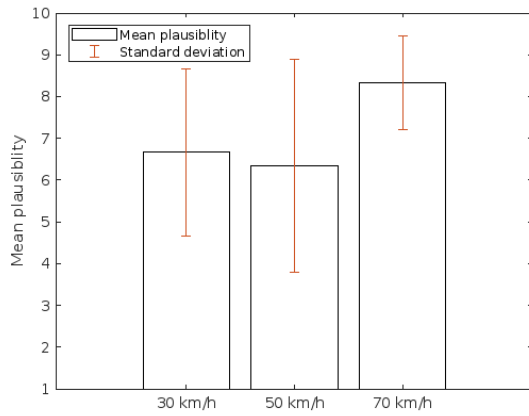


**Figure A.5:** The average plausibility of the auralized sounds at position 2 and 15 m distance.

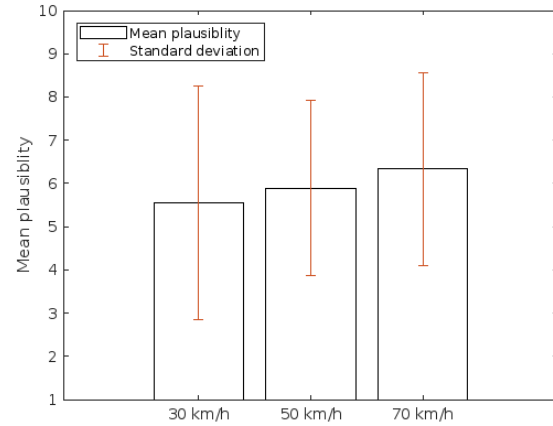


**Figure A.6:** The average plausibility of the auralized sounds at position 2 and 30 m distance.

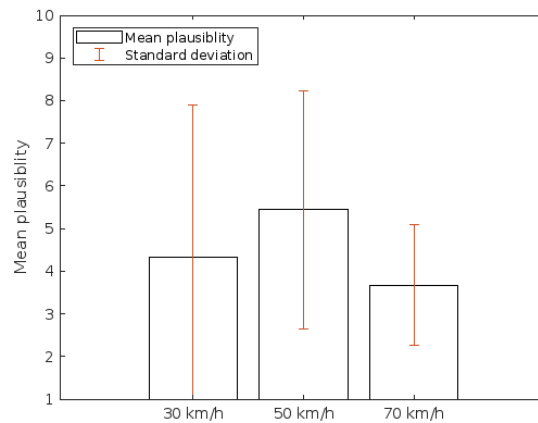
Figure A.7 to Figure A.9 show the average plausibility of the auralized sounds at position 3 at 7.5 m, 30 m and 15 m respectively.



**Figure A.7:** The average plausibility of the auralized sounds at position 3 and 7.5 m distance.



**Figure A.8:** The average plausibility of the auralized sounds at position 3 and 15 m distance.

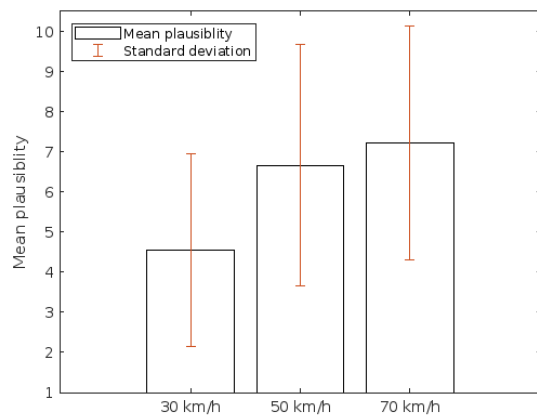


**Figure A.9:** The average plausibility of the auralized sounds at position 3 and 30 m distance.

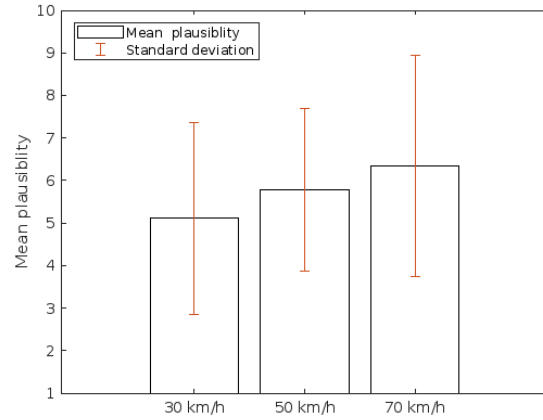
## A. Results of auralized sounds

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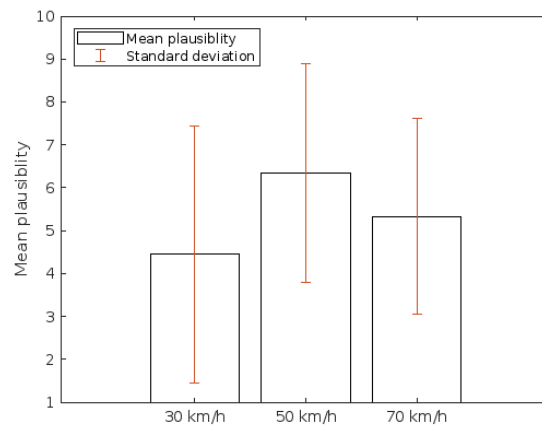
Figure A.10 to Figure A.12 show the average plausibility of the auralized sounds at position 3 at 7.5 m, 30 m and 15 m respectively.



**Figure A.10:** The average plausibility of the auralized sounds at position 4 and 7.5 m distance.



**Figure A.11:** The average plausibility of the auralized sounds at position 4 and 15 m distance.



**Figure A.12:** The average plausibility of the auralized sounds at position 4 and 30 m distance.

DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING  
CHALMERS UNIVERSITY OF TECHNOLOGY  
Gothenburg, Sweden  
[www.chalmers.se](http://www.chalmers.se)



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