

Auralization of road traffic scenes: Investigating perceived effects of heavy vehicle proportion

Master's Thesis in MSc Programme Sound and Vibration

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Cover: A spectrogram of a created traffic scene signal in this project.

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Abstract

For vehicles with internal combustion engines, the main types of noise when driving are tyre-road noise and propulsion noise. According to the Nord 2000 model, light and heavy vehicles have different noise levels and spectrum at different speeds. In urban traffic scenes, the number of light and heavy vehicles varies, and people may perceive the scenes differently even if they have the same equivalent A-weighted level (L_{Aeq}) but various proportions of light and heavy vehicles. To investigate the effect of the proportion of heavy vehicles on human psychological perception, the noise signals of five individual vehicles (two heavy and three light) at different speeds were auralized based on the combined model proposed in the LISTEN project and applied to compose eight traffic scene signals containing different proportions of heavy vehicles. These signals are used in the listening test where participants were asked to make category judgments and paired comparisons. The results of the category judgment part of the listening test showed that the signals containing heavy vehicles were indeed more disturbing than the signal only consisting of light vehicle noise, and scoring higher in loudness, sharpness and roughness. However, the stress and annoyance felt by the participants when listening to the signals did not increase with the proportion of heavy vehicles in the signal. From the paired comparison part of the test, it can be found that for heavy vehicles, participants felt more disturbed by the lower speed signals when the perceived loudness of the signals was constant. As for the plausibility of the traffic scene signals created, all eight signals scored similarly, between 5 and 6 on a scale of plausibility, which means that the traffic scene signals created are somewhat plausible, but still need to be improved.

Keywords: Auralization, Acoustics modelling, Simulation, Tyre/road noise, Traffic noise, Heavy vehicles, Psychoacoustics, Perception.

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1

Introduction

1.1 Background and Problem Description

With the widespread use of different types of vehicles in human society, traffic noise is becoming a significant and growing environmental problem in urban areas. Traffic noise in the urban landscape is a severe threat to human health, both physically and psychologically. For example, the World Health Organization (WHO) found that noise from traffic contributes to irritability and sleep disruption, increases the risk of ischemic heart disease, and may also be associated with other cardiometabolic diseases like stroke, obesity, and diabetes.[1] Over the past few decades, a lot of research has been done to reduce traffic noise and its effects on the urban environment. Numerous noise reduction techniques, including noise barriers, sound absorbing materials and access time limitations, have been researched and put to use in order to reduce the impact of road noise on surrounding inhabitants.

Three components make up the entire noise transmission process: the sound source, the propagation path, and the receiving point. Therefore, the prevention and control of noise are mainly from these three perspectives. From the standpoint of sound source, low-noise materials can be used for the road surface and traffic flow can be controlled to reduce the noise; from the perspective of the propagation path, green noise reduction forests, sound barriers, and other solutions can attenuate the noise during the propagation; regarding to noise reduction measurements at receiving points, sound-insulating windows are usually adopted to lower the indoor noise level, electronic products such as noise-cancelling headphones have also been developed and widely used. In order to predict the traffic noise level of the urban environment and take measurements to lower the noise level in the planning and design stage, effects of different urban morphology as well as vegetation surfaces on facades and roofs on noise exposure were investigated [4], a quantitative comparison, using a single-number indicator which is called the DALY (Disability-Adjusted Life Year) [10], is used to compare the noise impact of the different cases.

The concept of "Auralization", which means to simulate the sound field of a sound source in space by physically or mathematically modelling it and providing a binaural listening experience at a location in the modelled space, was first proposed by Kleiner.[5] The goal of auralization is not only to reproduce the perception of speech or music, but also to allow the aural impression of spatial acoustic properties to be reproduced, whether outdoors or indoors. The ability to recreate any arbitrary

soundscape on demand allows people to understand the limitations and practicalities of noise attenuation and control. Thus, auralisation become a very important part of the acoustic designer's toolbox. In previous research, many researchers proposed some prediction models for sound source of road vehicles, such as Harmonoise [6], CNOSSOS [8], and Nord2000 [9], to auralize the road vehicle noise so that the designers are able to predict the noise level and sound environment of the road in the planning stage.

A demonstrator of an auralization tool, which allows architectural, noise control and design solutions for improving urban soundscapes can be auralized at the planning stage, was developed in LISTEN project by Mats and Jens and etc..[2] The schematic diagram of LISTEN-Demonstrator is shown in Fig1.1. The following are the key outcomes of this project: for the auralization of vehicle noise from both rail and road traffic, a generic methodology was created; A technique for auralizing the effects of noise barriers on train and road traffic noise has been devised; a real-time implementation of the acoustic models was accomplished; based on casual listening, acoustic analysis, and formal listening experiments, a methodology for the perceptual validation of auralizations was developed. Based on these results from the project's research on acoustic modeling, auralization and perceptual evaluation, the LISTEN-Demonstrator enables real-time listening to the effects of road-traffic noise on a variety of environmental factors, such as the listener's distance to the road, the density and speed of the traffic, the presence of a noise barrier between the listener and the traffic, and the effects of various window types on the perception of indoor noise.

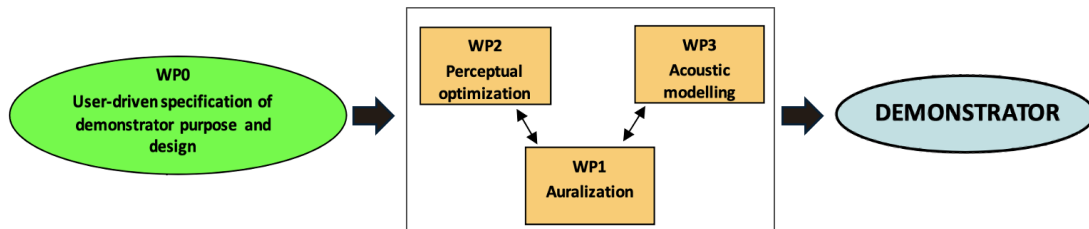


Figure 1.1: Schematic diagram of the LISTEN-Demonstrator.

Heavy vehicles are taking on an increasingly important role in transport in modern society. The noise of heavy-duty road vehicles has been the focus of much research over the last few decades. Tyre-road noise is the main noise source of road traffic noise when the driving speeds exceed 30km/h for light vehicles, and 50km/h for heavy vehicles, respectively. For heavy vehicles on urban roads with a speed limit of 40km/h, the main noise source of the traffic noise is from the engine of the vehicles. Serious traffic noise problems cause a lot of economic damage and affect the physical and mental health of residents. Therefore, it is essential that the reduction of the noise from heavy vehicles is carried out as efficiently as possible. In the 2018 work of Prof. Jens Forssén, an auralization tool for tyre-road noise of vehicles in a pass-by situation was developed by combining two models: The first model, developed in

the LISTEN project, enables the source signals of engine and tyre-road interactions constructed from the recorded data to be separated from the propagation effects; The second model approach, which is known as the SPERoN model, predicts the third-octave band levels of rolling noise for different tyre-road combinations. As long as dense road surfaces are taken into account, the combination of both models enables simulation and auralization of pass-by sounds for arbitrary tyre-road combination.[3] The details of the auralization process are shown in Fig1.2. Results from the initial listening tests are promising. In terms of pleasantness, the sounds produced by the final model are thought to be comparable to recordings. The auralization of tire-road noise is therefore made possible, and a potentially effective tool is offered. However, the final model needs to be further developed, for example, including heavy-duty road vehicles and accelerating vehicles. The work of this report will focus on the topic of auralization models for heavy vehicles.

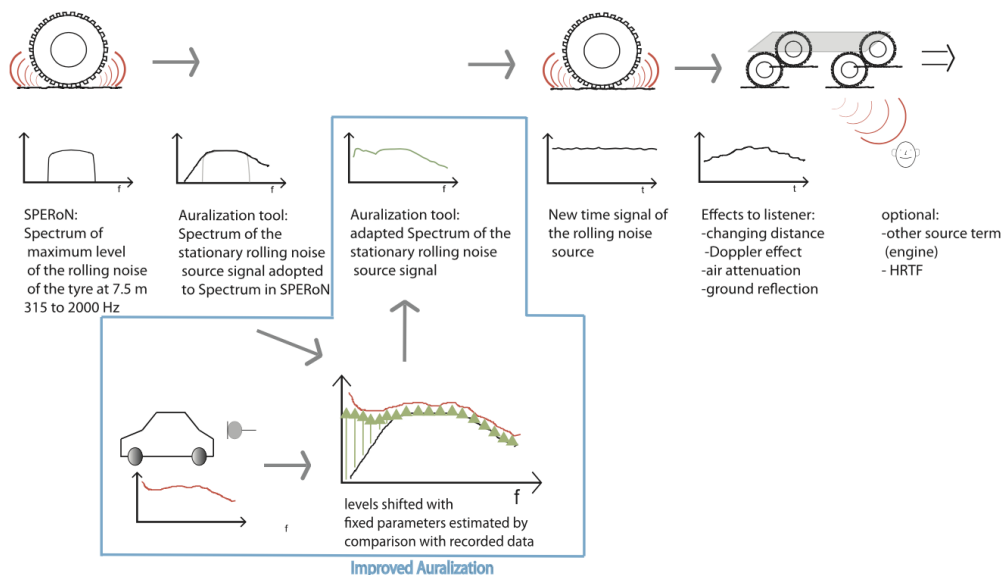


Figure 1.2: Illustration of the auralization process.

1.2 Goals and Objectives

This thesis investigates the perceptions of auralization for heavy vehicles and the impacts of noise from traffic scenes which are in the same A-weighted equivalent level, L_{Aeq} , but contain different percentages of heavy vehicles. Also, differences in people's perceptions of the noise generated by individual vehicles of the same type (e.g. light and heavy vehicles) when travelling at different speeds.

In the past, the A-weighted level is used to evaluate how loud the noise is. It can be easily obtained and is universally used in measurements and simulations. However, people's perception of sound signals can be evaluated in several ways, on the one hand as an objective assessment of the properties of the sound itself (e.g. loudness, sharpness, roughness), and on the other hand as an assessment of the

psychological factors (e.g. stressful, angry, annoying, etc.) that the sound signal brings to the participants. In this listening experiment, a metric called plausibility was introduced, intended to indicate how similar the generated noise signal is to the signal perceived in a real scene.

1.3 Approach and Outline

1. **Introduction:** A brief overview of this thesis. Introduce the problem needs to be solved, the objectives, scopes, relevant researches and approaches of this master thesis project.
2. **Theory:** Introduce some basic concepts and calculation methods. The methodology of auralization and the basic approaches to modeling traffic sound sources and sound transmission are also briefly introduced in this chapter.
3. **Implementation and testing:** This chapter of this report aims at the implementation listening test, including the preparation of the sound signals and the introduction of the procedure. The prepared calculation and the generation of traffic scene signals are processed in MATLAB.
4. **Results:** In this section, the A-weighted equivalent levels (L_{Aeq}) of the signals of different vehicle types and driving speeds are compared to the models Nord 96 and Nord 2000. Also, the results of the traffic scene signals, including the loudness and frequency analysis for each signal, and the perceived results of the listening test from the ArtemiS Suite are illustrated and analyzed.
5. **Conclusion:** Presents a discussion on the results of the listening experiment and a summary of this thesis, including the conclusion of this study and possible improvements.

2

Theory

2.1 Sound prediction of road traffic

2.1.1 A-weighted sound pressure level

There is a difference between the subjective perceived 'loudness' of a sound and the objective sound pressure level of a sound. The subjective perception of sound is complex and is determined by many factors, such as the frequency and bandwidth of the sound signal.

A-Weighted is a standard weighting curve used in audio measurements to reflect the response characteristics of the human ear, describing how sensitive the human ear is to changes in sound in different frequency bands. In practical applications, the dB(A)-value is measured using the A-weighting filter. The frequency response function of the A-filter is drawn in Fig2.1.[12] The sound pressure level of each vehicle noise signal in this experiment was measured by A-weighting filter.

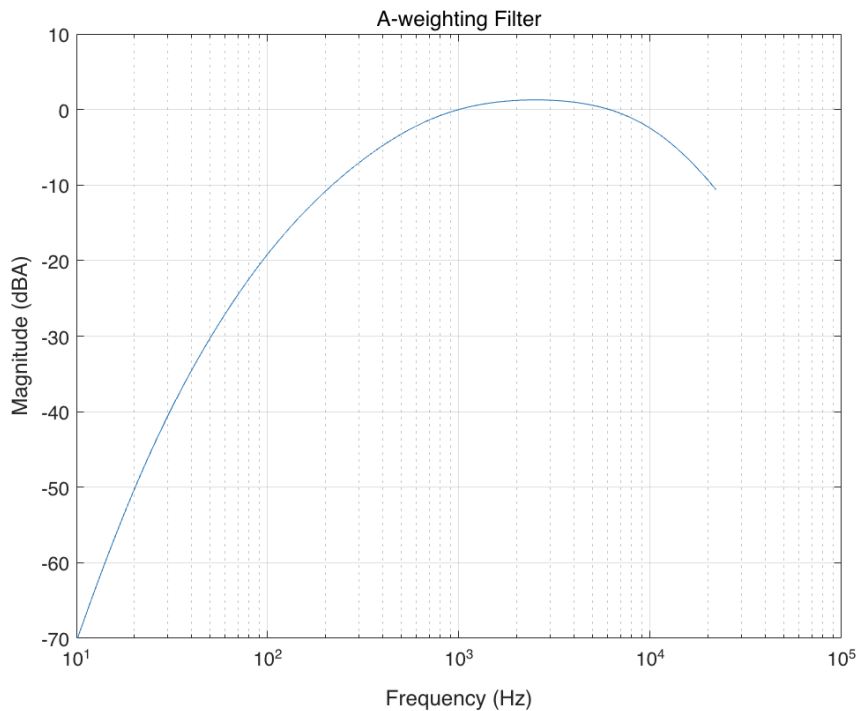


Figure 2.1: A-filter curve with frequencies

2.1.2 Equivalent level

Most of the limit values for European traffic noise as well as from other regions are not related to the peak or maximum level, but are related to the equivalent level L_{Eq} , which represents the sound pressure level obtained by testing a sound signal with uneven energy over a period of time and dividing its total energy equally over the test time period. For example, for traffic noise on a road section, the total energy of vehicle noise over a 24-hour period can be equally distributed over that period of time to obtain the equivalent sound pressure for that day on that road section.

In the case that the A-weighted sound pressure level L_{pA} at a given time can be measured, then the energy-equivalent A-weighted sound pressure level, $L_{AEq,T}$, can be defined as:

$$L_{AEq,T} = 10 \log \left(\frac{1}{T} \int_0^T \frac{\tilde{p}^2}{p_{\text{ref}}^2} dt \right) = 10 \log \left(\frac{1}{T} \int_0^T 10^{L_{pA}/10} dt \right) \quad (2.1)$$

where T is the measurement period (usually in hours), $p(t)$ is the short time averaged A-weighted rms sound pressure and L_{pA} is the short time averaged A-weighted sound level.[12] When processing the measured vehicle noise signals, the A-weighted sound pressure level curve can be calculated, then the A-weighted sound pressure level can be integrated over the time interval and divided by the measurement period to obtain the $L_{AEq,T}$. Usually, 8 and 24 hours are typical integration times for many environmental noise measurements. For example, the Nord 96 model is applied to the energy-equivalent A-weighted sound pressure level of the vehicles passing in a 24-hour period.

2.1.3 Sound Prediction Models

2.1.3.1 The Nordic model

Nord 2000, a new Nordic method to predict road traffic noise, is based on a complete separation of source emission and sound propagation. Each vehicle is modeled as a point source with a certain sound power with or without directivity. The source model, connecting to point source sound propagation theory, to obtain the sound pressure level at an arbitrary receiver position. The propagation model is based on accurate analytical models and is able to predict the effects of propagation both with and without the influence of meteorological parameters. The Nordic model is based on A-weighted sound levels and therefore only A-weighted sound levels can be compared and discussed as output indicators. The results of the calculations depend on the input data and how much sound attenuation is present.

In the 1996 model, the input data are the sound exposure and maximum sound pressure levels of light and heavy vehicles, which are given as a function of speed. These data are used to calculate the L_{Aeq} at 10 m from the middle of the road. heavy vehicles are defined as those with a mass of more than 3500 kg. The A-weighted exposure level L_{AE} of single light or heavy vehicle passing at 10 meters can be described as:

$$L_{AE10m \text{ Light}} = 73.5 + 25 \log(v/50) \quad (2.2)$$

$$L_{AE 10m \text{ Heavy}} = 80.5 + 30 \log(v/50) \quad (2.3)$$

where v is the driving speed in km/h, with 50 km/h being the reference speed. And the equivalent levels are given by inserting the number of vehicles per second (N_{Light} and N_{Heavy}):

$$L_{AEq10m \text{ Light}} = L_{AE10m \text{ Light}} + 10 \log N_{\text{Light}} \quad (2.4)$$

$$L_{AEq10m \text{ Heavy}} = L_{AE10m \text{ Heavy}} + 10 \log N_{\text{Heavy}} \quad (2.5)$$

And the total sound pressure level can be calculated by the energy sum of light and heavy vehicles:

$$L_{AEq10m \text{ Mixed}} = 10 \log \left(10^{L_{AEq10m \text{ Light}} / 10} + 10^{L_{AEq10m \text{ Heavy}} / 10} \right) \quad (2.6)$$

Unlike the Nord 96, in the Nord 2000 the sound power levels are output as a function of speed and the vehicles are divided into various types according to the number of wheels and axles. When there is a number N of vehicles with speed U along a straight road, within a given angle α from the listener, the distance from the listener to the vehicle line is L , and the mean distance between vehicles is $d = U/N$. The sound power level L_W of the vehicles is known. Then the equivalent level $L_{Eq,free}$ can be estimated as:

$$L_{Eq, \text{ free}} = L_W + 10 \log \left(\frac{N}{4LU} \right) + 10 \log \left(\frac{\alpha}{\pi} \right) \quad (2.7)$$

When assuming the vehicles are in an infinitely long, straight and unshielded road,

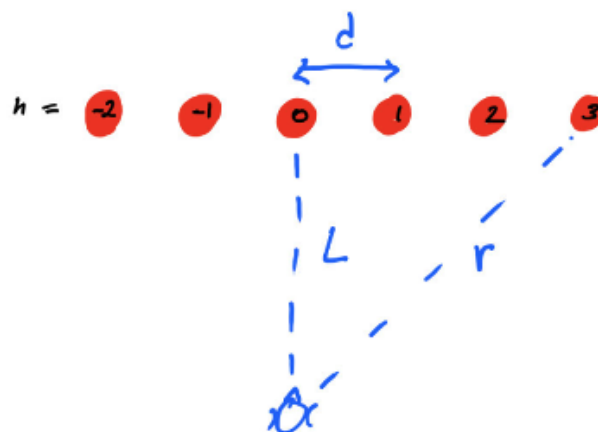


Figure 2.2: Diagram of calculation of $L_{Eq,free}$ in Nord2000

thus the angle $\alpha = \pi$, so the last term becomes zero. The theoretical equivalent

level can be calculated using the sound power level given by the Nordic model (Nord 2000). The noticeable thing is that the sound power level given by Nord 2000 is for single vehicle, so the N equals to 1.

2.1.3.2 Harmonoise model

Harmonoise is an engineering model similar to the Nord 2000 for predicting environmental noise level, which is predicting the sound pressure level at the receiver position in one-third octave bands from 25 Hz to 10 kHz from the sound power level of the source.

Several factors have effects on the sound propagation, such as spherical divergence, air absorption, reflections from the ground and diffraction from barriers, energy losses during side reflections and effects of scattering zones. The effects of these factors can be calculated separately (in dB) and subtracted from the sound power level. However, the method used to calculate the factors in the Harmonoise model is partially different from that used in the Nordic model, which results in predictions using Harmonoise that are quite consistent with the reference data, while the Nord2000 predictions never exceed 6 dB with respect to the free field.[13]

2.2 Auralization approach

The methodology of auralization and the basic approaches to modeling traffic sound sources and sound transmission are briefly introduced in this chapter. A number of parameters need to be taken into account when auralizing road traffic noise for a person standing outside of the vehicle. The sound path from a vehicle to the listener can be considered as starting from a set of sources with properties concerning directivity and spectral content. Changes of the parameters of the sound source and propagation paths can significantly affect the characteristics and levels of the sound, leading to the difference of the perceived realism.

In previous research, multiple ways of acoustics modeling are proposed and applied to traffic noise prediction. The auralization approach with modeling of multiple sound sources proposed in LISTEN project has been successfully validated to have a wide capability to light vehicles at constant speed by Forssén et al. In this work, the feasibility of this approach on heavy vehicles will be investigated.

2.2.1 General approach

According to the linear acoustics theory, the source signal and the effects of propagation can be separated, which is the core of auralization. For an omnidirectional point source, the sound pressure at the receiving point, $p(t)$, can be obtained by convolution of the time signal, $s(t)$, and the impulse response due to the propagation, $h(\tau)$. The calculation can be expressed as:

$$p(t) = \int_0^{\infty} s(t - \tau)h(\tau)d\tau \quad (2.8)$$

For example, for the free-field propagation in three-dimensional space, the impulse response can be calculated as:

$$h(\tau) = \delta(\tau - R/c)/4\pi R \quad (2.9)$$

where the $\delta(\tau)$ is the Dirac delta function, R is the propagation distance and c is the speed of sound, resulting in the sound pressure at the receiver expressed as:

$$p(t) = \frac{s(t - R/c)}{4\pi R} \quad (2.10)$$

The source signal is delayed in time by an amount equal to R/c and its amplitude is reduced by a factor that is inversely proportional to R . For a moving source (i.e. moving vehicles), the distance becomes a function of time, $R(t)$, and the retarded time $t - R(t)/c$ is used in LISTEN approach to model the Doppler shift by re-sampling the time signal.

In the process of the sound propagation from the source to a receiver, the amplitude of the sound can be influenced by these factors: spherical spreading, air attenuation

(which results in a greater reduction at higher frequencies than at lower frequencies), and ground reflection (leading to an interference pattern over frequency). Also, the perception will be affected by listener's head and torso when the sound finally entering listener's ears, which is modeled using the head related transfer functions (HRTFs). So the process of auralization can be regarded as starting from modeling the factors and ending with the HRTFs.

2.2.2 Modelling of sound propagation

The sound propagation modelling, including the decay due to air attenuation, refraction, ground effect and diffraction by barriers of infinite length, can generally be easily implemented in computer codes.[11] The refraction of the sound which means sound speed changing (i.e. due to wind or varying temperature with height) leads to the curving of the propagation path, and the diffraction by infinite-long barriers, are not considered in this project due to the short propagating distance and no use of screens.

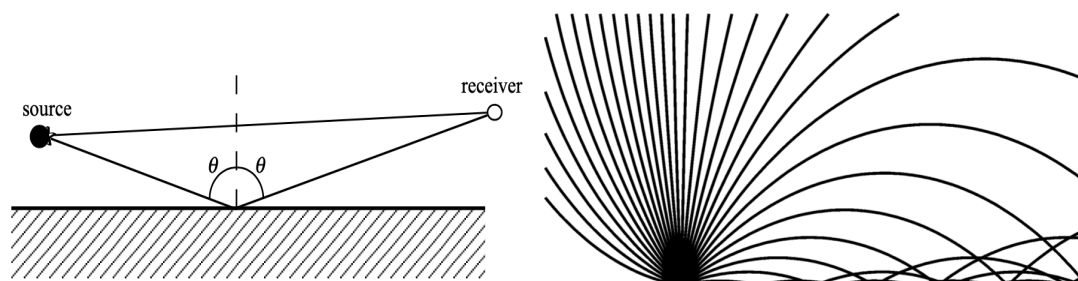


Figure 2.3: (a) ground effect of sound. (b) refraction of sound

In the previous research, the outcomes of the Nord2000 project and the EU project Harmonoise provide a practical and reliable physical foundation for sound propagation modeling. The effects of ground reflection, as well as the air attenuation, can be modeled and calculated in frequency domain, according to the ISO-9613 standard.[14] For air attenuation, 40 % relative humidity, temperature 24 °C, and a static atmospheric pressure of 101.325 hPa (one atmosphere) are used in this project.

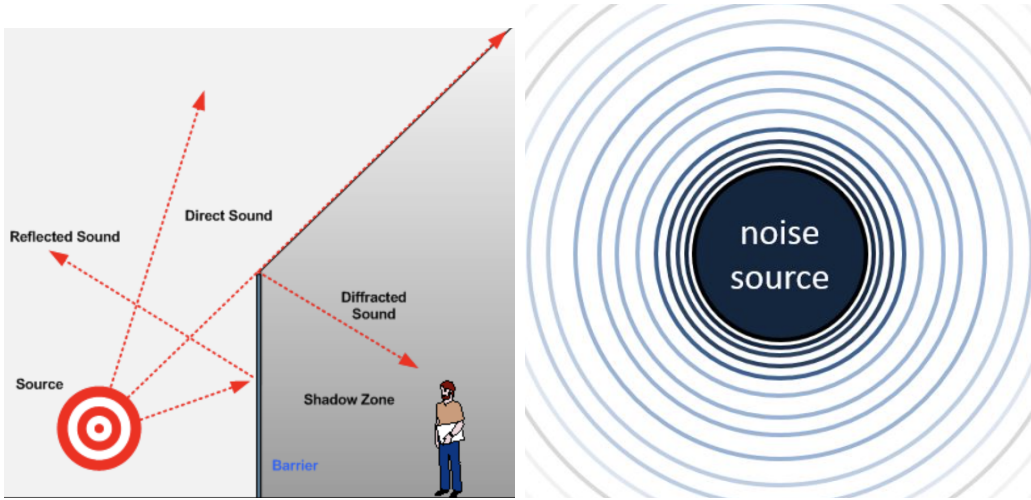


Figure 2.4: (c) sound diffraction. (d) sound attenuation.

The atmosphere absorption of sound is mainly depends on the attenuation coefficient α in decibels per meter, which can be calculated with the Eq.2.11, according to ISO-9613:

$$\begin{aligned}\alpha &= 8.686f^2 \left(X + \left(\frac{T}{T_0} \right)^{-5/2} \times (0.01275Y + 0.1068Z) \right) \\ X &= \left[1.84 \times 10^{-11} \left(\frac{p_a}{p_r} \right)^{-1} \left(\frac{T}{T_0} \right)^{1/2} \right] \\ Y &= \left[\exp \left(\frac{2239.1}{T} \right) \right] \left[f_{rO} + \left(\frac{f^2}{f_{rO}} \right) \right]^{-1} \\ Z &= \left[\exp \left(\frac{-3352.0}{T} \right) \right] \left[f_{rN} + \left(\frac{f^2}{f_{rN}} \right) \right]^{-1}\end{aligned}\quad (2.11)$$

where $p_r = 101.325\text{kPa}$ is the reference atmospheric pressure, p_a is the actual atmospheric pressure when measuring, $T_0 = 293.15\text{ K}$ is the reference temperature and T is the actual atmospheric temperature, f is the frequency. The variables f_{rO} and f_{rN} are relaxation frequencies of oxygen and nitrogen, which can also be calculated according to the below equations:

$$f_{rO} = \frac{p_a}{p_r} \left(24 + 4.04 \times 10^4 h \frac{0.02 + h}{0.391 + h} \right) \quad (2.12)$$

$$f_{rN} = \frac{p_a}{p_r} \left(\frac{p_a}{p_r} \right)^{-1/2} \times \left(9 + 280h \times \exp \left(-4.170 \left[\left(\frac{T}{T_0} \right)^{-1/3} - 1 \right] \right) \right) \quad (2.13)$$

where h is the molar concentration of water vapour in percentage and can be expressed as:

$$h = h_r \left(\frac{p_{sat}}{p_r} \right) / \left(\frac{p_a}{p_r} \right) \quad (2.14)$$

where hr is the relative humidity and p_{sat} is the saturation vapour pressure. The value of p_{sat}/p_r can be calculated by Eq.2.15:

$$\frac{p_{sat}}{p_a} = 10^C \quad (2.15)$$

where the constant C equals to $-6.8346 (T_{01}/T)^{1.261} + 4.6151$, where $T_{01} = 273.16$ K, which is the triple-point isotherm temperature.

For ground effects, the effective flow resistivity of $2 \cdot 10^8 \text{Nsm}^{-4}$ is used as dense asphalt in ground modelling, and the used sound speed is $c = 340 \text{m/s}$. The normalized impedance model by Delany and Bazely, with effective flow resistivity σ is:

$$Z = 1 + 9.08 \left(\frac{1000f}{\sigma} \right)^{-0.75} - j11.9 \left(\frac{1000f}{\sigma} \right)^{-0.73} \quad (2.16)$$

The plane wave reflection coefficient can be calculated with the impedance Z :

$$R(\theta) = \frac{Z \cos(\theta) - 1}{Z \cos(\theta) + 1} \quad (2.17)$$

where the θ is the sound incidence angle, and then the spherical wave reflection coefficient can be expressed as:

$$Q = R(\theta) + [1 - R(\theta)]E(\rho) \quad (2.18)$$

where the $E(\rho)$ is related to the normalized impedance Z and incidence angle θ :

$$\begin{aligned} p(x, t) &= \left(\frac{e^{-jkR_1}}{R_1} + Q \frac{e^{-jkR_2}}{R_2} \right) e^{j\omega t} \\ E(\rho) &= 1 + j\sqrt{\pi}\rho e^{-\rho^2} \text{erfc}(-j\rho) \\ \text{erfc}(x) &= \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt \\ \rho &= \frac{1+j}{2} \sqrt{kR_2} \left(\frac{1}{Z} + \cos \theta \right) \end{aligned} \quad (2.19)$$

2.2.3 Modelling of acoustic sources of road vehicles

When developing the auralization model for the acoustic sources of road vehicles, mono recordings for three speeds (30km/h, 40km/h, 50km/h) of light vehicles and two speeds (40km/h, 50km/h) of heavy vehicles are used. And an inverse process is applied here to transfer the mono recordings to source signals by inverting or undoing the effects of the Doppler shift, the spherical spreading, the air-attenuation and the ground effect. The similar approach is previously used by Kaczmarek and Tomasz,[15] here the inverse of this method is used. Assuming that there is a noise

source moving at a constant velocity along the centerline of the driving lane, as the noise source passes the receiver, the distance from the receiver to the source and the velocity of the source can be used as input parameters to calculate the propagation effect at any point in time. The Doppler effect is inverted by re-sampling the signal, and the effect of spherical spreading on amplitude can be inverted by multiplying the signal by the distance.

For road vehicles, the noise comes from two main sources: 1) propulsion sources (e.g. vehicle's engine, exhaust fan, compressor, etc.); 2) tire-road noise, generated when the tires are in contact with the road. According to the current engineering methods (Harmonoise and Nord 2000),[16] as for the vertical height of noise sources of passing vehicles, the heights of light vehicles are 1) 0.3m and 2) 0.01m, while the height of propulsion source for heavy and medium heavy vehicles is 0.75m.

When modelling the tonal characteristics of the passenger cars, a methodology called spectral modelling synthesis (SMS), which based on the granular synthesis.[17] This approach is also valid for modelling the tonal characteristics of heavier vehicles, which is more complex than that of light vehicles. Furthermore, it allows the amplitudes of noise and tones as well as the frequency of the tones to vary with time.[18] For the tyre-road noise, Jens Forssén et al. created a combined model which based on the LISTEN approach and the SPERoN model for tyre noise levels, and psychoacoustic judgements are designed to validate the quality and accuracy of the combined model with respect to perceived pleasantness. The listening tests designed in Forssén's project showed promising results and validated the high accuracy of the model. This method is applied in this project to evaluate the psychoacoustic perception regarding to heavy vehicles.

2.3 Head Related Transfer Function (HRTF)

Head Related Transfer Function (HRTF) is a response that characterizes how an ear receives a sound from a point in space. A sound wave moves through space in all directions, and expands outward from the sound source in every direction, like a rapidly expanding sphere. The listener receives sound waves from many different directions as they reverberate off nearby objects. By changing the frequency profile of a sound, for example, boosting some frequencies and attenuating others, the size and mass of the head, the shape of the ear, the length and diameter of the ear canal, and the dimensions of the oral and sinus cavities can all manipulate the incoming sound waves. Thus, the sound with specific frequency characteristics gives unique perspective and perception for the listener and help the listener locate the sound source.

Empirical HRTF measurements are often conducted by inserting tiny microphones into the subject's eardrums and then recording the subject's reaction to a stimulus signal played at a specific azimuth and elevation. HRTF can also be calculated using artificial geometric models of the upper human body. Knowles Electronic Manikin for Acoustic Research (KEMAR), Neumann KU-100, Bruel and Kjaer Type 4100, Head Acoustics, and Cortex Electronic Manikin MK1 are a few examples of the models utilized for these studies.[19] In this project, open source KEMAR dummy head recordings were used, taking the effect of the ear canal into consideration.[20] An angular resolution of 5 degrees in the horizontal plane is made available to HRTFs by these recordings. The angle between the listener and the sound source is calculated to apply the proper HRTF for each sample of the sound source. Then these values are rounded to the given five-degree steps. As a result, the appropriate HRTF is selected for each sample.

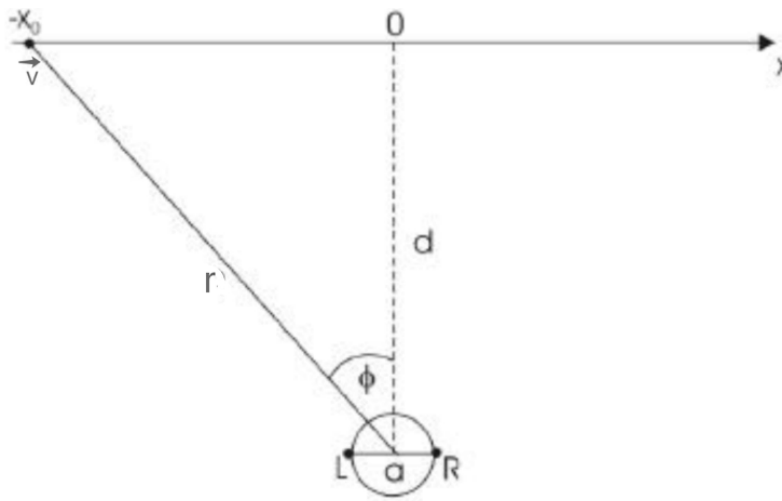


Figure 2.5: Geometry of motion

According to the method proposed by Kaczmarek and Tomasz [15], as the motion diagram showed in Fig2.5, L , R represents left and right ear, a is the diameter of

the head, d is the distance between head and motion trajectory, v , the velocity of sound source and x_0 represents the starting point of the source. ϕ describes the angular location of the source. When an omni-directional point source in the free field which emits a pure tone, the instantaneous sound pressure at points on either side of the sphere [21], $p_L(t)$ and $p_R(t)$, which represents left and right ear, can be expressed as follows:

$$\begin{aligned} p_L(t) &= HRTF_L(t) \cdot A(t) \cdot \sin\left(\theta(t) - \frac{\theta_{ITD}(t)}{2}\right) \\ p_R(t) &= HRTF_R(t) \cdot A(t) \cdot \sin\left(\theta(t) + \frac{\theta_{ITD}(t)}{2}\right). \end{aligned} \quad (2.20)$$

Where $HRTF_L(t)$ and $HRTF_R(t)$ shows the impact of the amplitude correction for a given source frequency and for actual source position at time t , $A(t)$ represents changes in amplitude over time, $\theta(t)$ is the instantaneous phase and $\theta_{ITD}(t)$ is the additional phase shift related to interaural time difference (ITD) between the left and right ear. $A(t)$ can be calculated approximately as:

$$A(t) = \frac{\eta}{r(t)} \left[1 + \frac{v}{c} \sin(\phi(t))\right]^{-2} \quad (2.21)$$

where η is a constant related to the acoustical power of the source and the air impedance, c is the speed of the sound, v is the velocity of the sound source, $r(t)$ is the instantaneous distance between the source and the center of the dummy head, and $\phi(t)$ is the instantaneous angular location of the source defined in Fig2.5.

The instantaneous phase $\phi(t)$, including Doppler effect information, and phase shift between the ears $\theta_{ITD}(t)$ can be calculated as:

$$\begin{aligned} \theta(t) &= 2\pi f_0 \int \frac{1}{1 + \frac{v}{c} \sin(\phi(t))} dt \\ \theta_{ITD}(t) &= 2\pi f(t) ITD(t) \\ ITD(t) &= \frac{3a}{c} \sin(\phi(t)) \end{aligned} \quad (2.22)$$

where the a is usually calculated as the average of the head (8.5 cm).

2.4 Perception validation

In many previous studies, listening tests have been used effectively to verify people's perception of auralized signals. In listening tests, participants are asked to make psychological judgements about the signals provided, usually by paired comparisons and categories judgments of signals. The combined model proposed by the LISTEN project is also validated by comparing the simulated signals to recorded signals.[23]

3

Implementation and Listening Test

This chapter of this report aims at the implementation listening test, including the preparation of the sound signals and the introduction of the procedure. The prepared calculation and the generation of traffic scene signals are processed in MATLAB. The listening test is performed in the department of Applied Acoustics, Chalmers University of Technology.

3.1 MATLAB Implementation

The entire auralization coding for modelling of the different acoustical sources and propagation effects and creating the binaural signals based on the HRTF are implemented in MATLAB. First, the recordings of light and heavy ICE vehicles driving in 30, 40 and 50 km/h are used to create the mono signals which contain the information of distance between the receiver and the noise source and Doppler effect. Then, the KEMAR HRIR data for the standard large and small pinnae, containing the data of horizontal-plane, is used to create binaural signals.

To create the signals which are in the same A-weighted equivalent level but contain different percentages of heavy vehicles, the L_{AEq} of mono signals of different vehicle type and speed are calculated in MATLAB by using the audioread function and Fast Fourier Transfer method. The L_{AEq} of each mono signal is listed in the following table:

Table 3.1: The $L_{AEq,10m}$ for single vehicle of different types and speeds.

Vehicle type	Engine type	Velocity (km/h)	$L_{AEq,10m}$ (dBA)
light	ice	30	61.10
light	ice	40	62.60
light	ice	50	64.85
heavy	ice	40	71.48
heavy	ice	50	69.85

The goal of $L_{AEq,1min}$ of each traffic scene signal is 75 ± 0.5 dBA, so the next step is to calculate how many signals should be contained to reach the goal. The mentioned

3. Implementantation and Listening Test

five single-vehicle signals are selected at random to be added to the traffic scene signals since the kind and speed of vehicles in a traffic scene are highly unpredictable. The steps to generate a traffic signal are still done in MATLAB. First, the signals are randomly selected and the number of times each signal is used is calculated, and then it is placed in a one-minute long blank signal at any position, in order to simulate the realism of vehicles breaking into the traffic scene at any point in time. The $L_{Aeq,1min}$ of the generated traffic scene signal will be calculated again to check if it is in the aimed range ($75 \pm 0.5\text{dBA}$). Finally, 8 sets of numbers are calculated and 8 traffic scene signals are correspondingly generated, the percentages of heavy vehicles of the 8 one-minute signals vary from 0% to 100%, containing the extreme situations (all light vehicles and all heavy vehicles in a traffic scene). The total L_{Aeq} of the 8 signals are also calculated, all values reach the goal of $75 \pm 0.5\text{dBA}$, and are shown in the Fig 3.1.

Group set	Numbers of different signals					Heavy vehicle percentage(%)	Total LAEq,10m (dBA)
	light (30 km/h)	light (40 km/h)	light (50 km/h)	heavy (40km/h)	heavy (50km/h)		
1	29	22	31	0	0	0	74.58
2	12	8	10	4	6	25	74.64
3	14	9	7	6	4	25	74.74
4	4	5	4	7	6	50	74.84
5	4	2	6	9	3	50	74.83
6	3	0	2	5	10	75	74.70
7	0	1	3	10	2	75	74.55
8	0	0	0	8	6	100	74.53

Figure 3.1: The compositions, percentage of heavy vehicles and total $L_{Aeq,10m}$ of each group.

3.2 Listening Test

In this listening test, participants were required to complete the listening test independently in a sound-isolated laboratory alone in order to avoid others interfering with the participants' perception. 14 participants with normal hearing enrolled in the listening test, 10 male and 4 female (all students from Chalmers, with different professional backgrounds and personal experiences), and their average age was 24.5 years, with a standard derivation of 1.5 years. The majority of participants had less than or equal to two listening tests, and only four participants had 3-5 listening test sessions.

3.2.1 Test Setup

This listening test was conducted in the listening test lab, which is a sound-insulated lab furnished as a lecture room, at the department of Applied Acoustics, Chalmers University of Technology. The hardware used in this listening test are listed:

- Dell Laptop
- LG Monitor Flatron W2753VC
- Lucid D/A Converter DA9624
- Sennheiser HD650 Headphones
- Several cables

The setup of hardware components for this listening test is illustrated in Fig3.2. The D/A Converter was used to convert the digital signal from the computer to analog signal for headphones with a sampling rate of 88.2 kHz. Then the amplification of the converter was adjusted until an ideal level was reached.

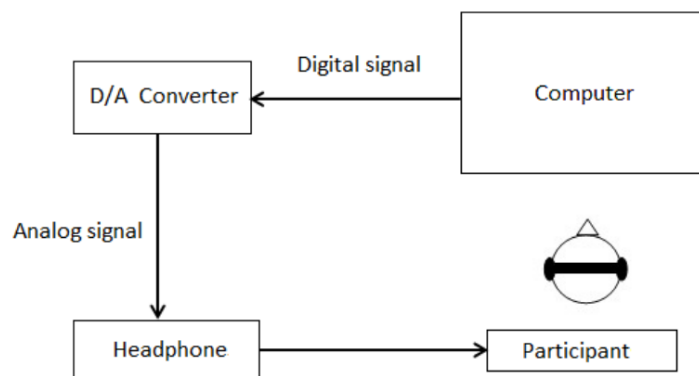


Figure 3.2: Block diagram of the test setup.

3.2.2 ArtemiS Suite SQala

The software used in this listening test is SQala from the ArtemiS Suite. It is a modular jury testing software which can be used to set up and perform jury tests.

3. Implementation and Listening Test

Jury tests can be conducted with SQala quickly and efficiently, either on a single-user workstation or in a listening studio. SQala offers flexible and accurate product or background noise ratings wherever and whenever they occur. It also supports the playback of binaural recordings. The following jury testing techniques are provided by SQala: semantic differential, ranking, paired comparison, simultaneous category judgment, and category judgment. The test coordinator can monitor, organize, and control jury tests using interactive tools. The SQala Server stores the results, which can be precisely and efficiently exported. The main functions used in this test are category judgement and paired comparison. Figure 3.3 shows the interface of SQala software.

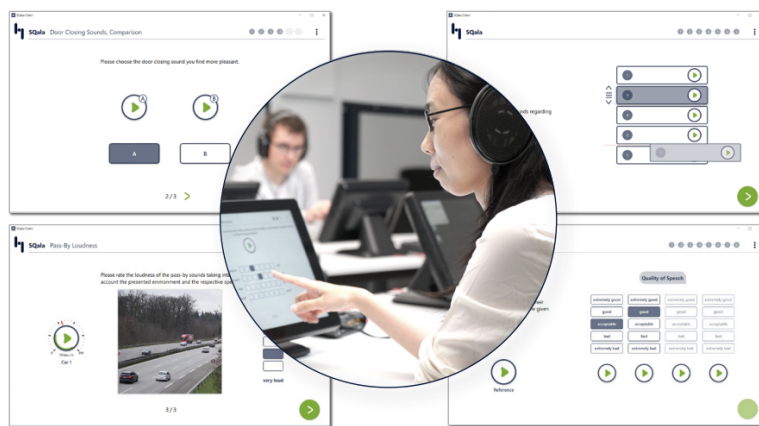


Figure 3.3: Interface of SQala software.

When participants enter the interface of the SQala Listening Session, they are required to fill their personal information, such as name, gender, age and whether they have normal hearing. In the second part, the category judgment part, 6 categories (loudness, roughness, sharpness, plausibility, annoyance and stressful) for each traffic scene signal are scaled from 0 (not at all) to 10 (extremely). According to ISO-15666 standard[22], the questions with verbal rating are graded in 5 scales: not at all, slightly, moderately, very and extremely. Otherwise, the questions can also be scaled with numerical rating, 0-to-10 opinion scale is used for how much the sound bothers, disturbs or annoys. Participants should choose 0 when they are not at all annoyed, choose 10 if they are extremely annoyed, and if they are somewhere in between, then choose a number between 0 and 10. The two judgement methods can be conducted simultaneously, however, in this listening test, only numerical rating is applied. In order to avoid participants' inertial thinking, eight traffic scene signals with different proportions of heavy vehicles were arranged in the category judgment part in a shuffled order.

4

Results and Analysis

In this section, the A-weighted equivalent levels (L_{AEq}) of the signals of different vehicle types and driving speeds are compared to the models Nord 96 and Nord 2000. Also, the results of the traffic scene signals, including the loudness and frequency analysis for each signal, and the perceived results of the listening test from the ArtemiS Suite are illustrated and analyzed.

4.1 Comparison with Nordic models

4.1.1 comparison of Nord 96 and Nord 2000

In the Nord 96 model, $L_{AEq,10m}$ is calculated for vehicles passing in a 24-hour period. This model sets the traffic flow for light and heavy vehicles as the total number of vehicles passing is 100000, with the percentage of heavy vehicles being 8 % and the speed range being 30 km/h to 70 km/h. According to the Equation 2.2 to 2.6 of Nord 96 model, the curve of $L_{AEq,10m}$ for the light, heavy and mixed vehicles varies with the driving speed can be calculated and shown in the Fig 4.1.

As the figure shows, for light vehicles, when the speed is no more than 40 km/h, the curve of $L_{AEq,10m}$ is shown as a straight line, which means the $L_{AEq,10m}$ is keep as the value of around 71.4 dBA and doesn't change with the driving speed. As the driving speed increases, the $L_{AEq,10m}$ tends to increase linearly with speed. While for the heavy vehicles, the $L_{AEq,10m}$ starts changing with driving speed from 50 km/h, and the $L_{AEq,10m}$ when the driving speed under 50 km/h is 70.2 dBA, which is 1.2 dBA lower than that of the light vehicles. The reason for this result is that the heavy vehicle percentage is only 8 %, so the amount of light vehicles is much larger than the heavy vehicles. The linear increase in $L_{AEq,10m}$ with speed is almost identical for light and heavy vehicles, which also means that the linearly increasing parts of the two curves are almost parallel. For the mixed vehicles, the initial $L_{AEq,10m}$ is much higher than in the case of heavy vehicles only and light vehicles only, which is 73.9 dBA, and the increasing rate for mixed vehicles at the range of 40-50 km/h is slightly lower.

In the Nord 2000, the A-weighted sound power levels, L_{WA} , are output as a function of driving speed, which are illustrated in Fig 4.2. From this figure, the rolling noise and engine noise sound power level curves of light cars can be found to be very different from those of heavy vehicles. Therefore, it can be tentatively inferred that

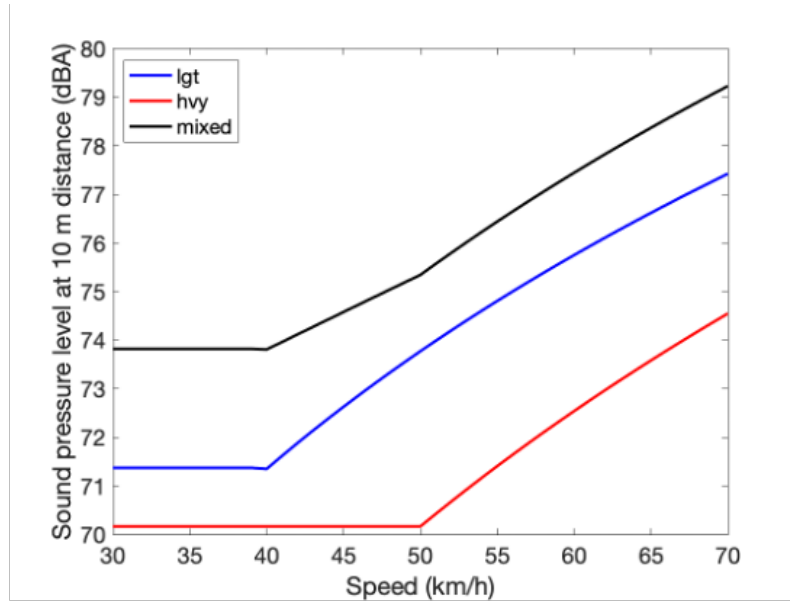


Figure 4.1: $L_{AEq,10m}$ calculated used Nord 96.

the frequency characteristics of light vehicles and heavy vehicles are quite different. It is noticeable that the engine noise curve and the rolling noise curve have a point of intersection in both figures. With the increase of speed, the sound power level of engine noise increases linearly, while the sound power level of rolling noise has a non-linear growth trend. The sound power level of rolling noise gradually surpasses that of engine noise after the intersection of the two curves and takes up the majority of the total sound power level.

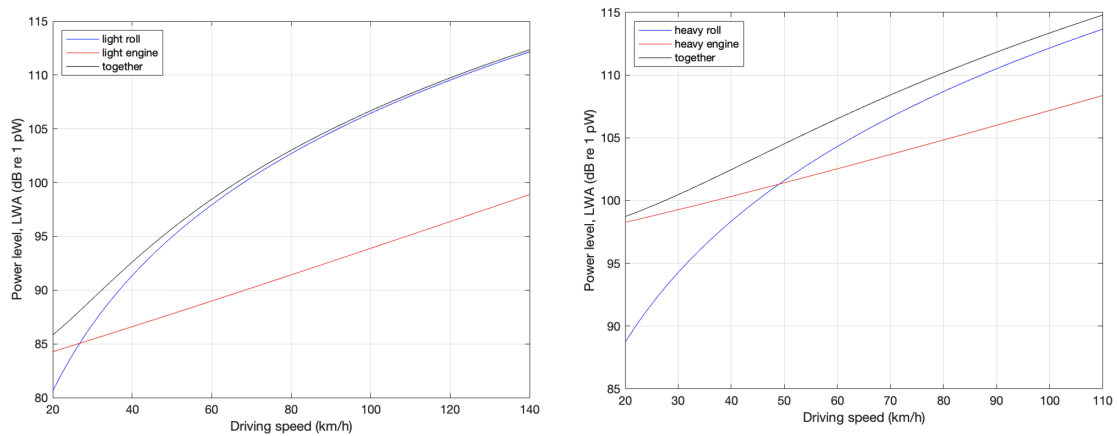


Figure 4.2: L_{WA} calculated used Nord 2000.

According to the Equation 2.7, the A-weighted equivalent levels can be obtained by the given A-weighted sound power levels. It can be seen from the Fig 4.3, the $L_{AEq,10m}$ of light vehicles succeeds that of heavy vehicles when the driving speed is higher than 34 km/h. To compare the Nord 2000 with Nord 96, the numbers of the vehicles are exactly equal to the vehicle amount in Nord 96, which are 8,000 heavy

vehicles and 92,000 light vehicles passing in 24 h. That's why the $L_{AEq,10m}$ of light vehicles is higher than that of heavy vehicles with the speed increasing. Thus, the two Nordic models can be compared in the same situation, and it can be found that the initial $L_{AEq,10m}$ s of the vehicles for both models are similar, while the $L_{AEq,10m}$ shown in Nord 2000 is approximately 0.7 dB higher than that in Nord 96 at the end of the curves. The advantage of the Nord 2000 model is that it can calculate the $L_{AEq,10m}$ for any traffic volume in any time period and over all speed ranges. In contrast, the Nord 96 model limits the volume of traffic to a certain number of vehicles in a 24-hour period and the $L_{AEq,10m}$ is considered constant at lower speeds, which limits the study of vehicle noise on urban roads with speed limits.

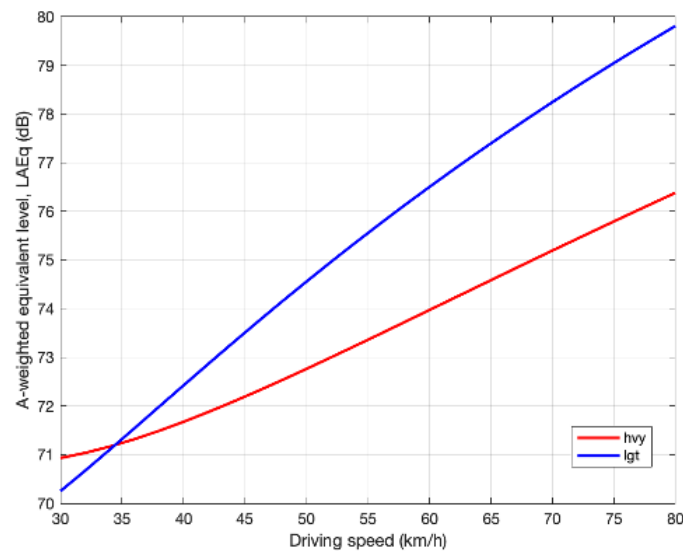


Figure 4.3: $L_{AEq,10m}$ calculated used Nord 2000.

4.1.2 Comparison for L_{AEq} of created signals with Nord 2000

In order to check the $L_{AEq,10m}$ of the generated signals, Equation 2.7 is used to calculate the $L_{AEq,10m}$ of a single vehicle. Using the N equals to 1, and the T is 10 seconds for each signal, then the $L_{AEq,10m}$ of created mono signals can be compared to the calculated $L_{AEq,10m}$. Comparing the $L_{AEq,10m}$ of the individual vehicles listed in the Table 3.1 for different types and travel speeds, which is marked in Figure 4.4, with the calculated $L_{AEq,10m}$ curves.

As the Figure 4.4 illustrates, the $L_{AEq,10m}$ s of the light vehicle in the speed of 30 km/h, 40 km/h and 50 km/h fit the light vehicle curve well. However, for heavy vehicles, only the mono signal for heavy vehicle in 40 km/h approximates to the heavy vehicle curve, the $L_{AEq,10m}$ for the heavy vehicle driving in 50 km/h is nearly 3 dBA lower than the corresponding value on the calculated curve. The reasons for this result may be that 1) there were accidental errors when recording the initial noise and 2) the propulsion noise (i.e the engine noise) has a greater effect on the total $L_{AEq,10m}$ when the heavy vehicle is traveling at low speeds, according to the Figure 4.2.

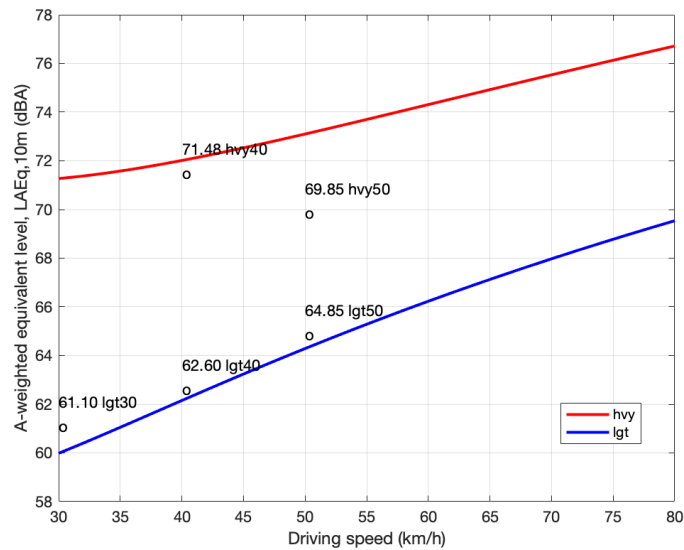


Figure 4.4: L_{AEq} calculated used Nord 2000 for single vehicle.

4.2 Analysis of characteristics of binaural signals

The binaural signals created by MATLAB are analyzed in this section, including the signals of single vehicle and the composed signals of random traffic scenes (the components are shown in Figure 3.1). The loudness and Fast Fourier Transform (FFT) results of the binaural signals are obtained from the software ArtemiS Suite.

4.2.1 Loudness and frequency analysis of individual vehicle signals

Figure 4.5 and 4.6 show the loudness curves of the signals for light vehicles in 30, 40 and 50 km/h and heavy vehicles in 40 and 50 km/h, respectively. The sound pressure levels (SPL) for two channels of each binaural signal are also labeled under the corresponding curves. It can be found that the sound pressure levels (SPL) of the binaural signals analyzed by the software ArtemiS Suite are slightly different from the calculated SPL of mono signals. The SPLs of two channels for the light vehicle signals marked in Figure 4.5 are obviously lower than the calculated SPLs listed in the Table 3.1, while the results for heavy vehicles shown in the Figure 4.6 are similar to the calculated ones.

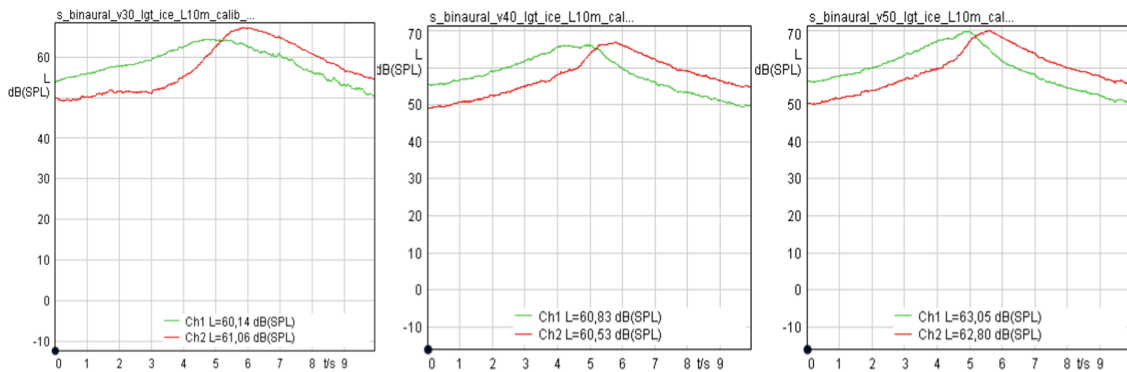


Figure 4.5: Loudness curve of the signal for light vehicle at speeds 30 km/h, 40 km/h and 50 km/h.

Figure 4.7 and 4.8 illustrate the amplitude spectrums of the individual vehicle in different speeds for light and heavy types, respectively. Figure 4.9 and 4.10 present the spectrograms of the channel 1 of the binaural signals for light vehicles in 30, 40 and 50 km/h and heavy vehicles in 40 and 50 km/h, respectively. A spectrogram is a visual representation of the spectrum of frequencies of a signal as it varies with time. The horizontal coordinate of the spectrum graph represents the time of the signal, the vertical coordinate shows the frequency of the signal, and the color of the color bar below from dark to light represents the sound pressure level from low to high.

It can be illustrated from the spectrums that the energy power for the individual vehicle signals are concentrated on the frequency range of 30 Hz to 20000 Hz, and the amplitude in the frequency 50 Hz is obviously high. Comparing the spectrums

4. Results and Analysis

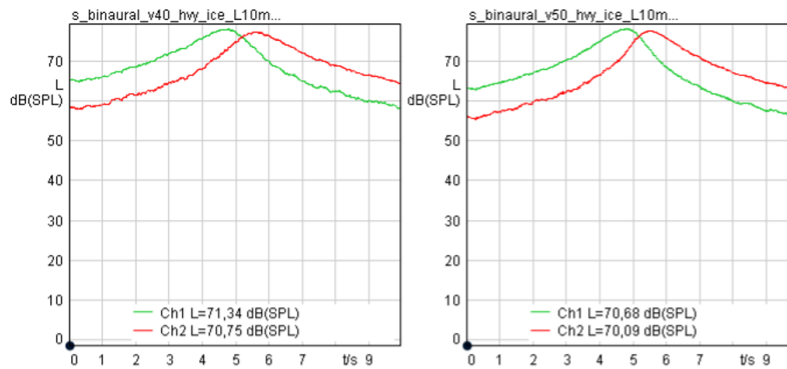


Figure 4.6: Loudness curve of the signal of heavy vehicle at speeds 40 km/h and 50 km/h.

for light and heavy vehicles, when they are driving in the same speed, the energy power of heavy vehicles is much more than that of light vehicles.

By comparing the three spectrograms of the light vehicle at different speeds in Figure 4.9, the 50-100 Hz and 1000 Hz frequency bands are where this light vehicle generates the most significant noise. Combined with the analysis in Figure 4.2, it can be found that for light vehicles, the increase in engine noise is not very significant when the speed increases from 30 to 50 km/h, while the tyre-road noise has a noticeable increase. Since the noise in the frequency band of 50-100 Hz is less affected by changing of the speed, while the spectrogram of the noise in the frequency band of 200-5000 Hz is obviously more yellow as the speed increasing, it can be inferred that the noise in the 50-100 Hz band is propulsion noise (i.e engine noise), while the noise in the 200-5000 Hz is the tyre-road noise. For heavy vehicles, at speeds of 40-50 km/h, the sound power of rolling noise is relatively close to that of engine noise, and it can be observed from the spectrograms that the noise is distributed over a wide range of frequency bands from 20 to 5000 Hz with no particularly significant noise bands.

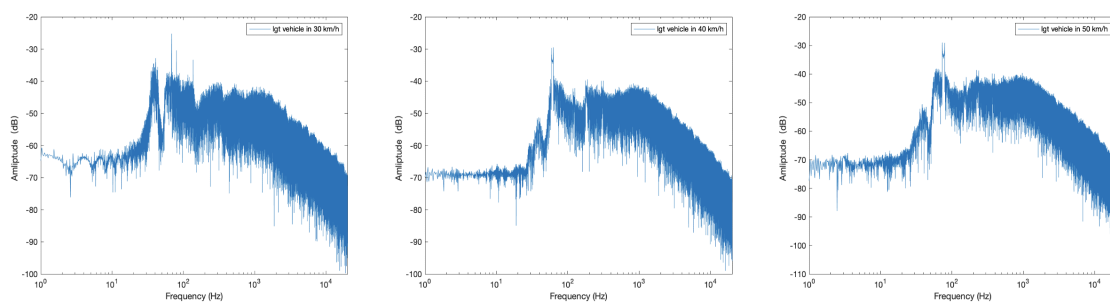


Figure 4.7: Spectra of individual light vehicles at speeds 30 km/h, 40 km/h and 50 km/h.

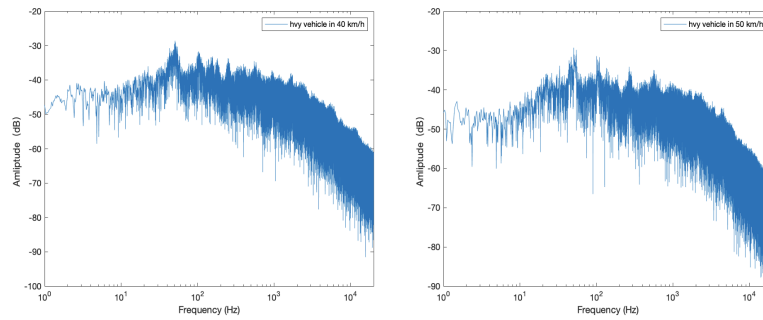


Figure 4.8: Spectra of individual heavy vehicles at speeds 40 km/h and 50 km/h.

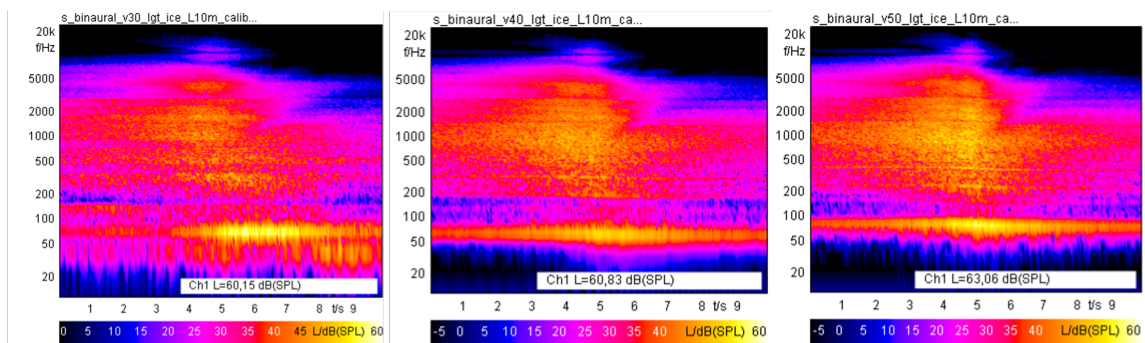


Figure 4.9: Spectrograms of individual light vehicle at speeds 30 km/h, 40 km/h and 50 km/h.

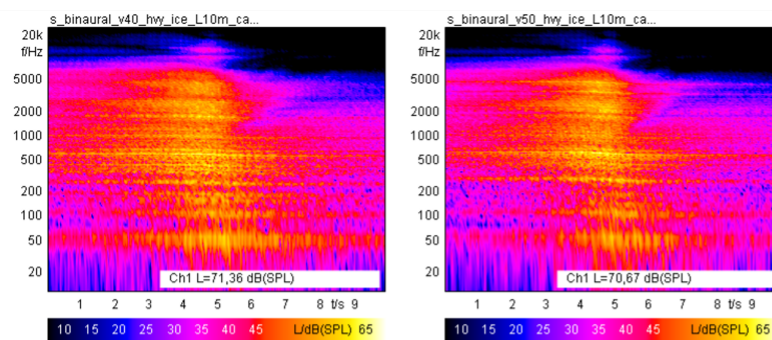


Figure 4.10: Spectrograms of individual heavy vehicle at speeds 40 km/h and 50 km/h.

4.2.2 Loudness and frequency analysis of composed signals

In this part, the results of loudness curves and spectrograms for composed binaural signals are displayed. The sound pressure levels of 2 channels of composed binaural signals calculated in ArtemiS Suite differ from the calculated ones listed in Figure 3.1. The reason may be that the methodology of calculation in ArtemiS Suite is different from that used in MATLAB. Although the SPLs of a few channels are slightly below 74.5 dB, the signals still make sense and can be tested in the listening test as the range of most SPLs is still in 75 ± 0.5 dB.

Figure 4.11 presents two loudness curves over time in green and red, representing the two channels of the first set of binaural signal containing 0 % heavy vehicles. It can be seen that The sound pressure levels of both channels are mainly stabilized at about 75dB in the majority of the time.

The spectrograms of two channels for this signal are presented in Figure 4.12. Since this set of the signal only composed with several signals of light vehicles, the frequency characteristics of the spectrogram of this signal are relatively significant and homogeneous. The spectrograms of this signal is clearly divided into two parts, the upper part (200-5000 Hz) showing mainly the tyre-ground frequency characteristics and the lower part (20-100 Hz) showing that of the engine noise. Tyre-road noise shows a not very light colour, but it is spread over a very large frequency range, whereas engine noise is concentrated in the frequency band around 50 Hz and shows a very bright colour, which means the sound pressure level is very high.

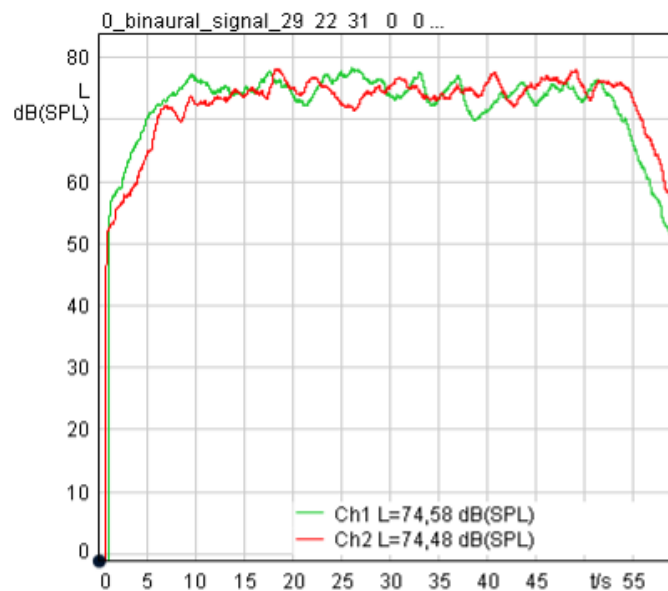


Figure 4.11: Loudness curves of Group 1 (0 % heavy vehicles).

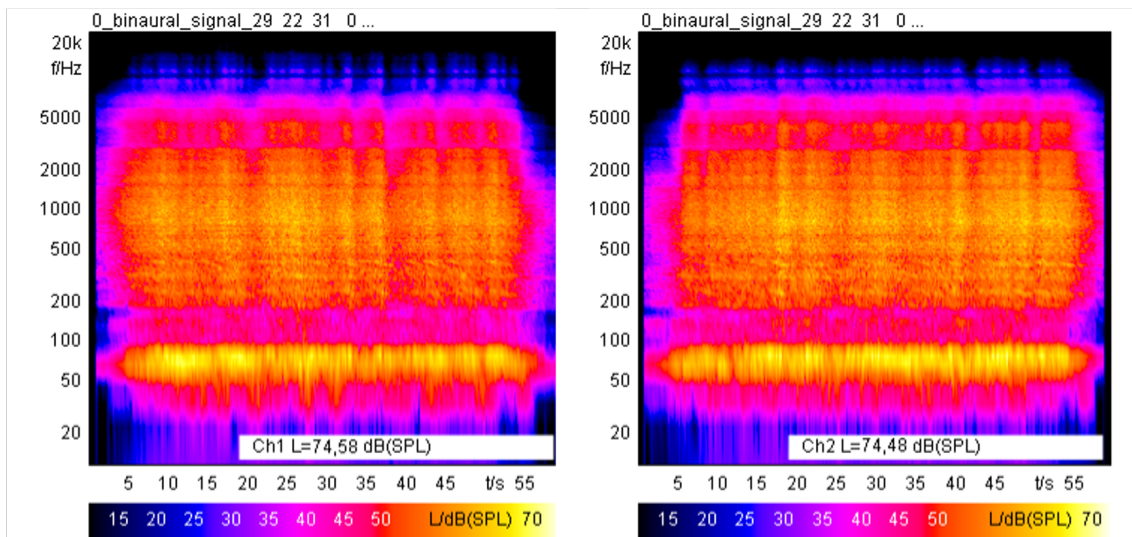


Figure 4.12: Spectrogram of Group 1 (0 % heavy vehicles).

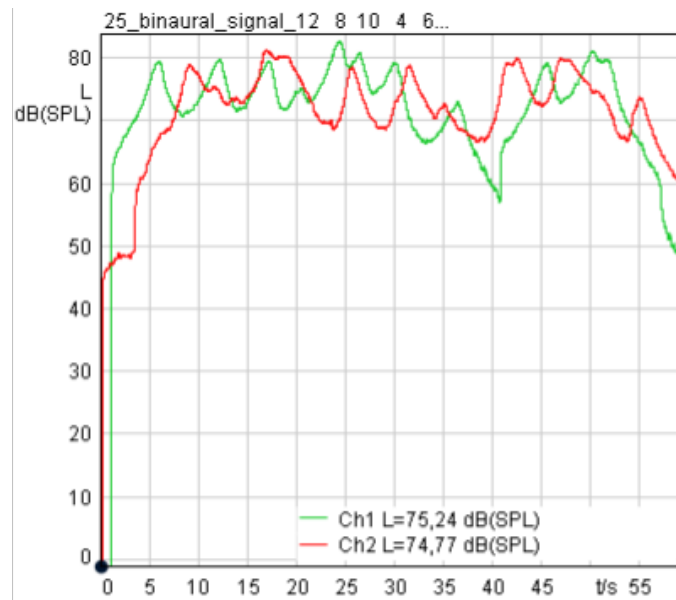


Figure 4.13: Loudness curves of Group 2 (25 % heavy vehicles).

4. Results and Analysis

Figure 4.13 presents the loudness curves of the binaural signal which contains 25 % heavy vehicles. It is obviously that, comparing with the loudness curves of the signal composed with all light vehicles, the two curves have significant amplitude fluctuations around 75 dB.

Figure 4.14 presents the spectrograms of both channels for the binaural signal with heavy vehicles making up 25 % of the entire vehicles. Comparing with the spectrograms of the binaural signal containing only light vehicle noise, it can be seen that when the noise signal from heavy vehicles is added, there is not a clear demarcation between high and low frequencies in the spectrograms as in Figure 4.12. The noise is distributed over the entire range from 20 Hz to 5000 Hz, but at the frequency of 5000, 2000, 1000, 500, 200 and 50 Hz the noise is obviously higher in decibels.

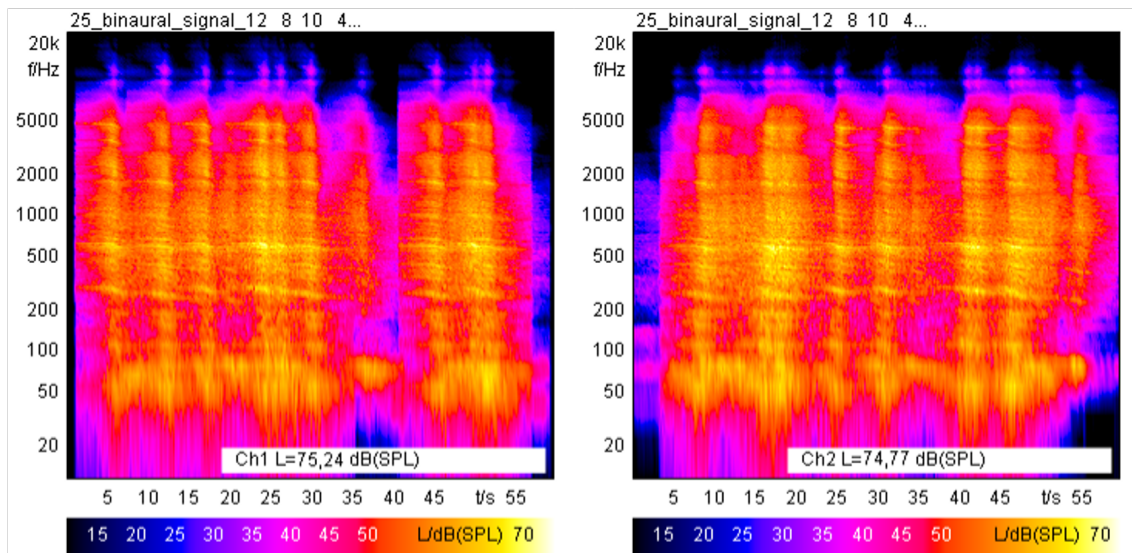


Figure 4.14: Spectrogram of Group 2 (25 % heavy vehicles).

Figure 4.15 presents the loudness curves of the signal Group 3 which also contains 25 % heavy vehicles, and even has the same number of light vehicles and heavy vehicles as the Group 2. However, it can be seen from the figure that the loudness curves of Group 3 fluctuates more strongly than that of Group 2. As can be seen from the spectrograms shown in Figure 4.16, the vehicles in the signal of Group 3 are more densely distributed in the one-minute traffic scene than in the second group of signals. Thus, even though they have the same number of vehicles and the same proportion of heavy vehicles, the distributions of the spectrograms are very different. The spectrograms of the Group 3 is visually more 'blurred' than the second group.

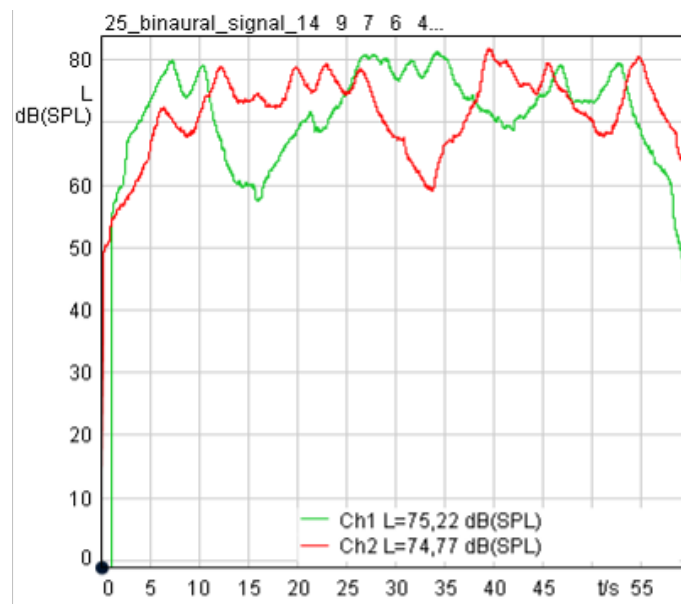


Figure 4.15: Loudness curve of Group 3 (25 % heavy vehicles).

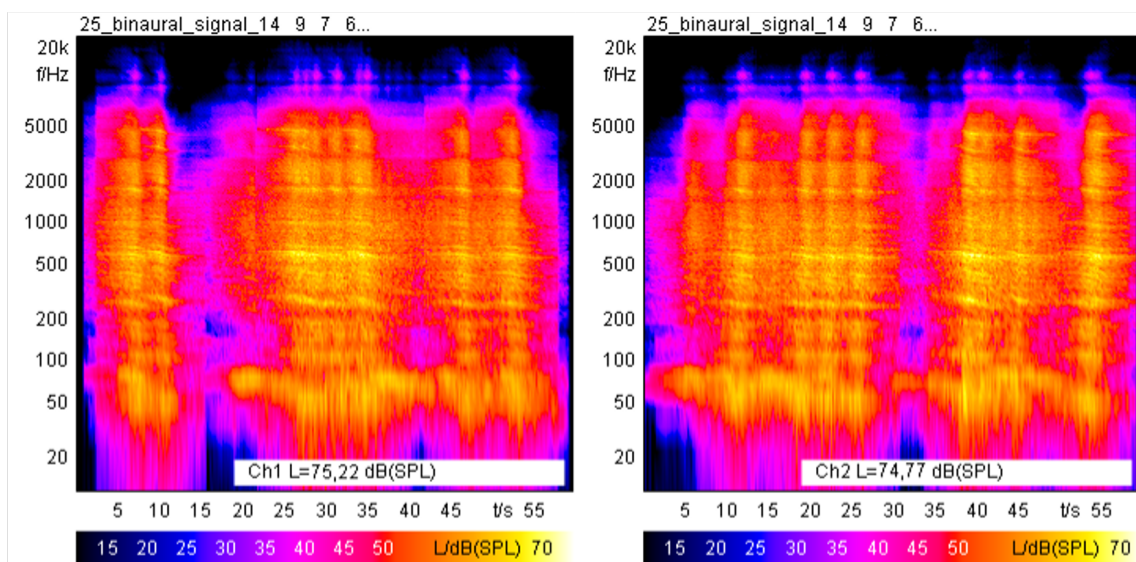


Figure 4.16: Spectrogram of Group 3 (25 % heavy vehicles).

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Figure 4.17 and Figure 4.19 illustrate the loudness curves of Group 4 and Group 5, respectively. It is noticeable that the loudness curve of channel 2 in Figure 4.17 has a 5-second delay in time, the difference in sound pressure level between channel 2 and channel 1 is greater, comparing to the other groups.

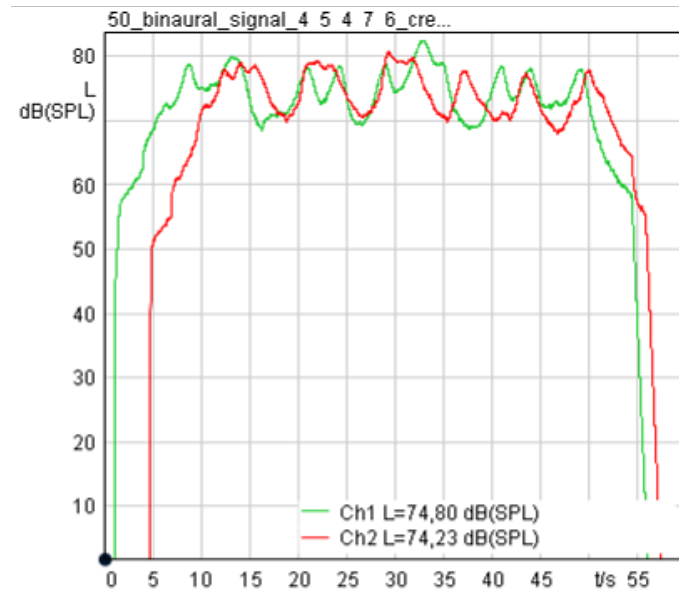


Figure 4.17: Loudness curve of Group 4 (50 % heavy vehicles).

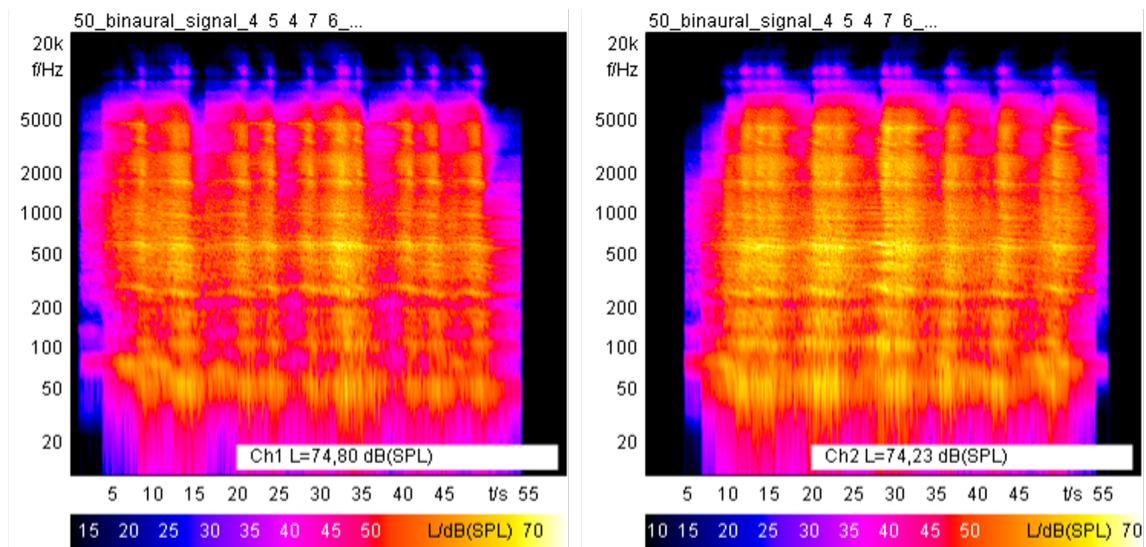


Figure 4.18: Spectrogram of Group 4 (50 % heavy vehicles).

Figure 4.18 and Figure 4.20 show the spectrograms of Group 4 and Group 5, respectively. The two groups of signals have the same percentage of heavy vehicles, although the number of vehicles and their distribution in the whole signal are not identical, the two signals have very close SPL values.

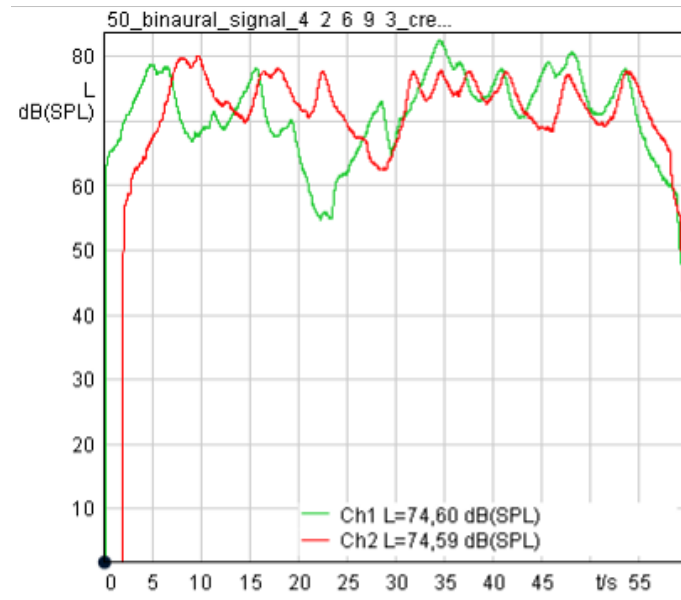


Figure 4.19: Loudness curve of Group 5 (50 % heavy vehicles).

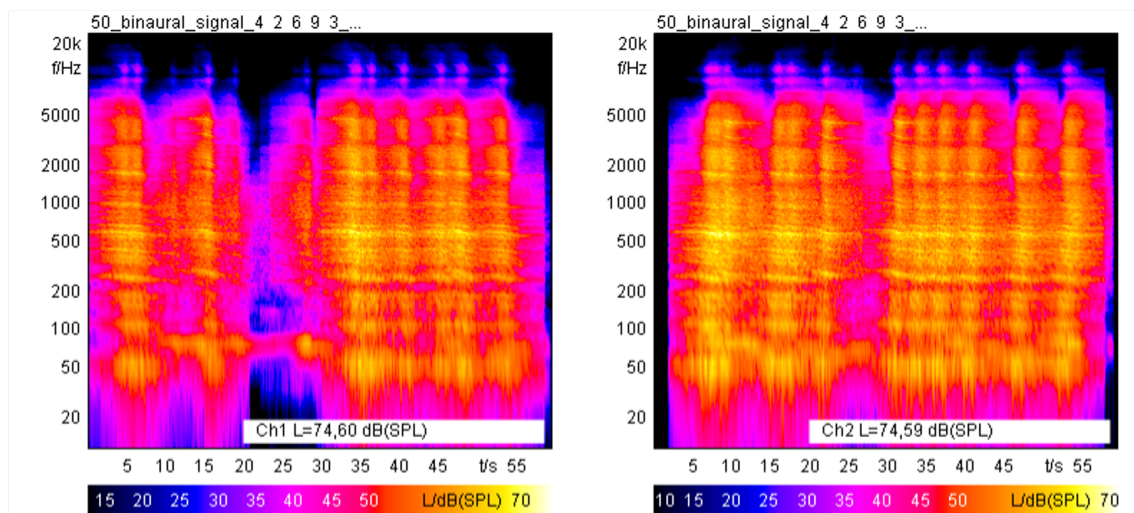


Figure 4.20: Spectrogram of Group 5 (50 % heavy vehicles).

4. Results and Analysis

Figure 4.21 and 4.23 present the loudness curves of signals of Group 6 and Group 7, in which heavy vehicles account for 75 % of all vehicles. Figure 4.22 and 4.24 show the spectrograms of these two groups.

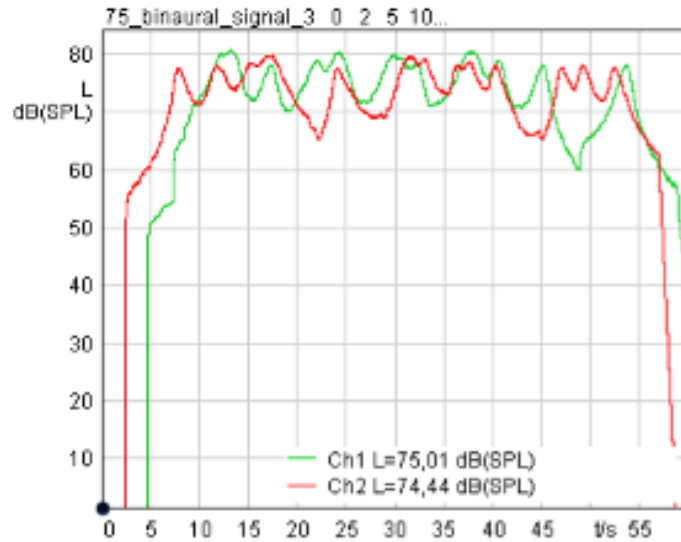


Figure 4.21: Loudness curve of Group 6 (75 % heavy vehicles).

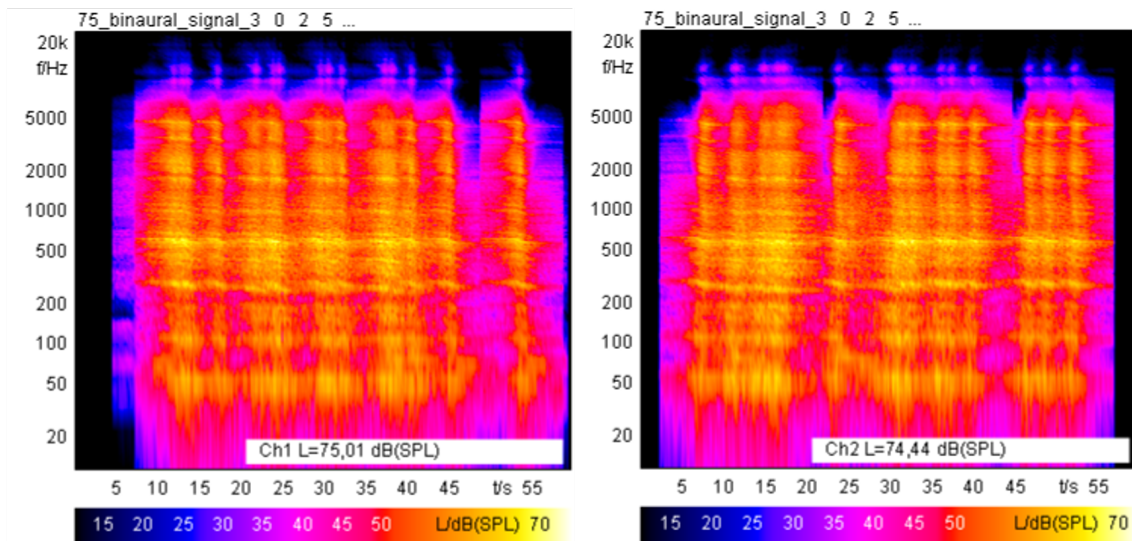


Figure 4.22: Spectrogram of Group 6 (75 % heavy vehicles).

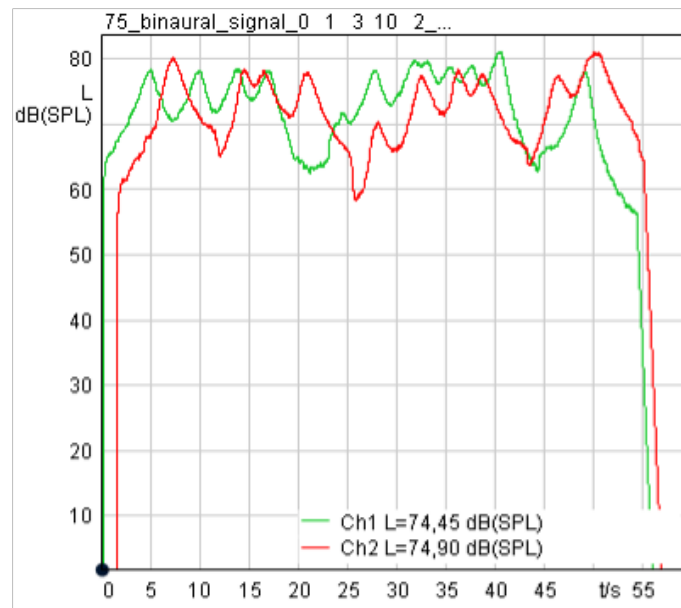


Figure 4.23: Loudness curve of Group 7 (75 % heavy vehicles).

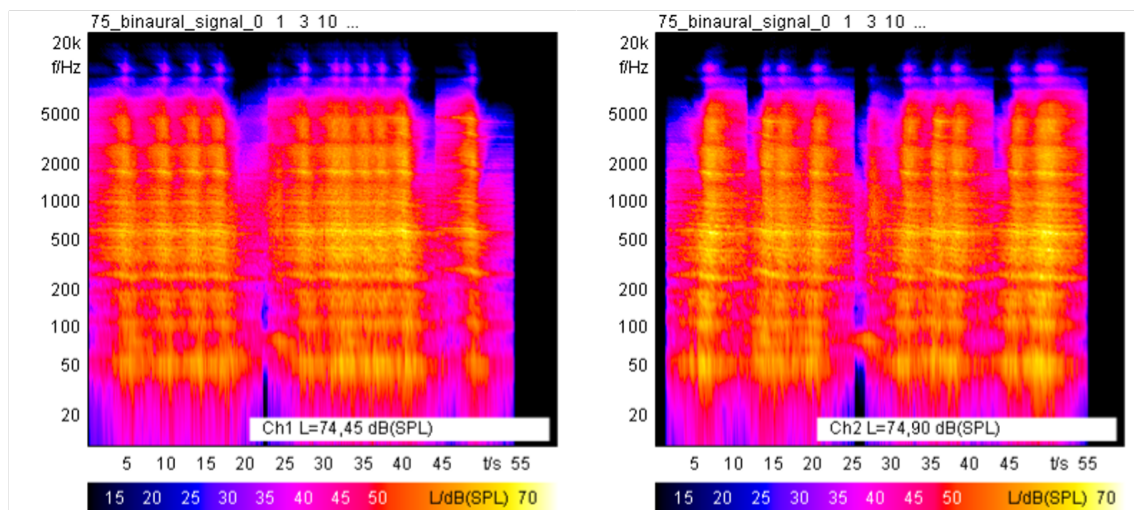


Figure 4.24: Spectrogram of Group 7 (75 % heavy vehicles).

4. Results and Analysis

In contrast to the first group of signals, the signal of Group 8 consists only of heavy vehicle noise. In the Figure 4.25, there is a significant drop of the loudness curve for the channel 1 at the time of 40s. By analyzing the spectrograms shown in the Figure 4.26, it can be found that at the time of 40s in the signal, no vehicles pass by, which could explain the above phenomenon. The delay at the beginning may be the cause of the channel 2's loudness being 0.58 dB less than that of the channel 1.

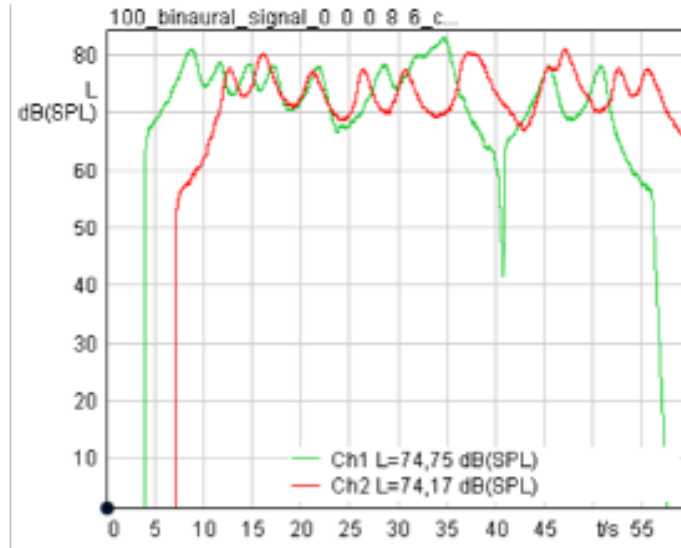


Figure 4.25: Loudness curve of Group 8 (100 % heavy vehicles).

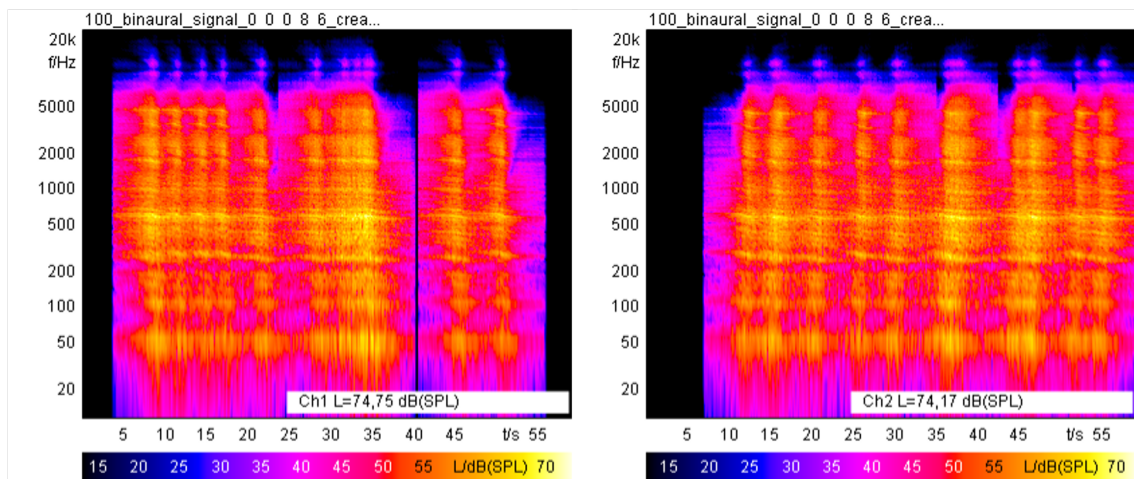


Figure 4.26: Spectrogram of Group 8 (100 % heavy vehicles).

4.3 Results of listening tests

4.3.1 Arithmetic mean values

Figure 4.27, 4.28, 4.29, 4.30, 4.31 and 4.32 respectively presents the perceived results of 6 categories: loudness, sharpness, roughness, plausibility, stressful and annoyance. Furthermore, the error bar shows a of 95 % confidence interval for the arithmetic mean value for all the groups data combined. The 8 groups are simplified as the shown abscissa label, the sequence is exactly the same as that of Table 3.1.

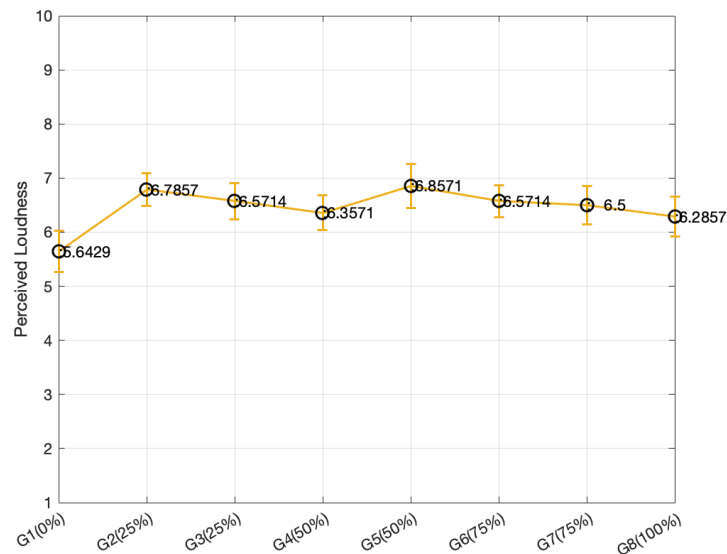


Figure 4.27: Perceived loudness values for 8 groups.

Figure 4.27 presents the mean values of the perceived loudness of 8 binaural signals for 14 participants. Group 5 is perceived as the loudest signal (6.8571/10), while the group 1 is perceived the quietest (5.6429/10). It is noticeable that signal which contains more heavy vehicles is not louder than the signal contains less heavy vehicles. Signals contain the same percentage of heavy vehicles do not show the same loudness here.

Figure 4.28 presents the mean values of the perceived sharpness of the 8 binaural signals. Group 1 which consists entirely light vehicles gets the lowest score in sharpness (4.4286/10), whereas, the sharpest signal is group 6 which contains 75 % of heavy vehicles. Comparing Group 4 with Group 5, Group 6 with Group 7, it can be seen that although they contain the same percentage of heavy vehicles, there is a sizable difference in their perceived sharpness results. Analysis of the spectrograms suggests that the reason for this result may be that the signals of Group 7 and 5 have a gap at some point in time, causing participants to get a short break while listening to them. In contrast, the signals of Group 6 and 4 output high frequency sounds continuously and without interruption.

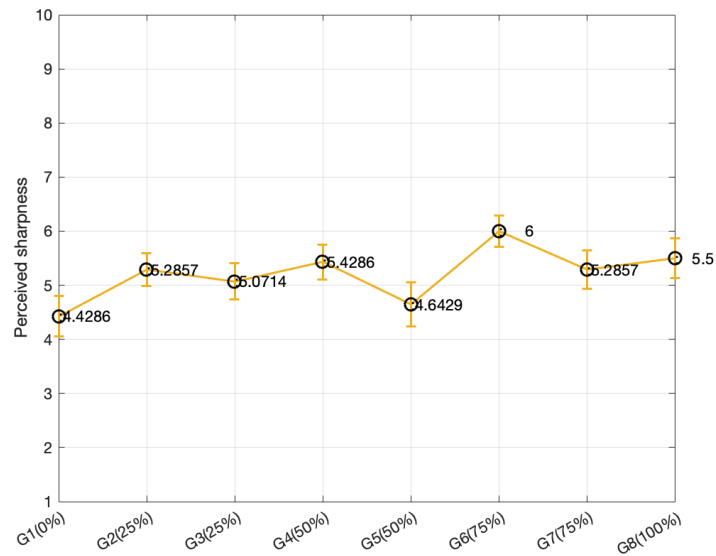


Figure 4.28: Perceived sharpness values for 8 groups.

Figure 4.29 illustrates the mean values of the perceived roughness of the 8 binaural signals. As the results shown in the figure, the signal which only composed by light vehicles is scored the lowest on the roughness scale. It's interesting to note that although the Group 2 and Group 3 have different proportions of heavy vehicles, they are both evaluated the equal score for roughness. The roughest of the eight signals was the signal of Group 5, which received a score of 6.2857.

For the characteristics of plausibility, which means the extent to which the created binaural signals is similar to the noise perceived in real life. From the results shown in Figure 4.30, the mean values of perceived plausibility for all eight groups of signals are distributed between 5 and 6 and do not differ much. This result shows that these composed signals do have some plausibility, but still need to be improved. In the implementation of composing signals, although all the single-vehicle signals are made to fade in and out at the beginning and end, there are still obvious breakpoints when vehicles enter and leave the traffic scene, which may have a significant impact on plausibility.

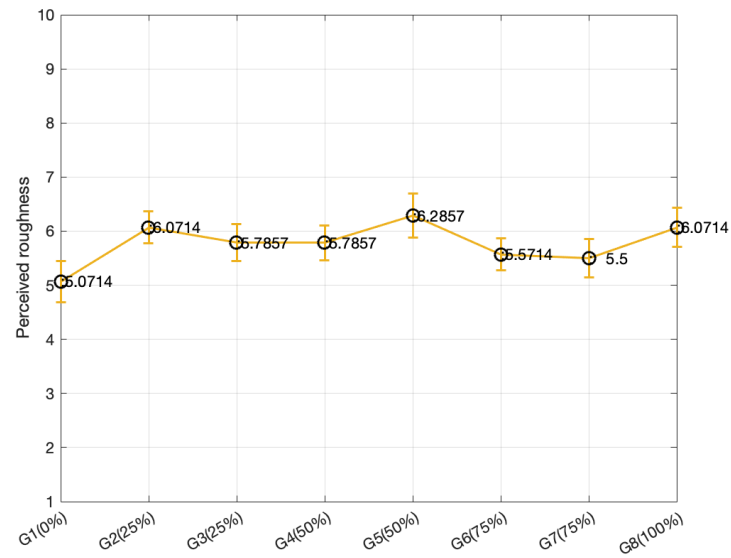


Figure 4.29: Perceived roughness values for 8 groups.

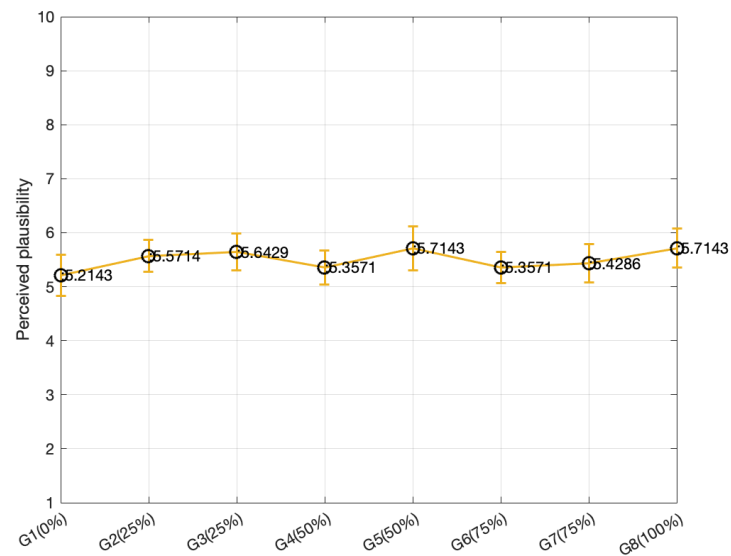


Figure 4.30: Perceived plausibility values for 8 groups.

The above results are evaluated for the own characteristics of the signals. In addition, to explore the psychological effects of the signals on the participants, two indicators, stress perception and annoyance, are also included in the listening test.

Figure 4.31 and Figure 4.32 show the mean values of how much the 14 participants feel stressful and annoyed for the 8 signals. It can be seen from the figures that, regarding to the extent of how participants feel stressful and annoyed to the traffic scene signals, the signal of Group 1 which composed by all light vehicles got the lowest scores, while the Group 2 containing 25 % heavy vehicles got the highest

4. Results and Analysis

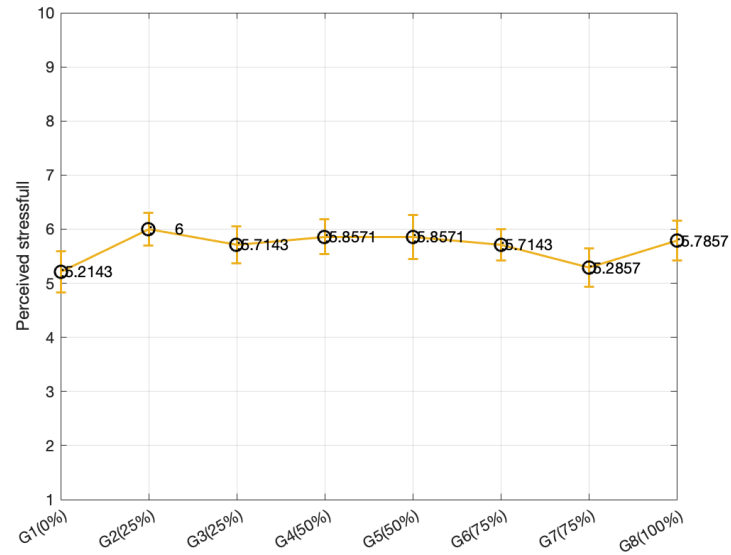


Figure 4.31: Perceived stressfull values for 8 groups.

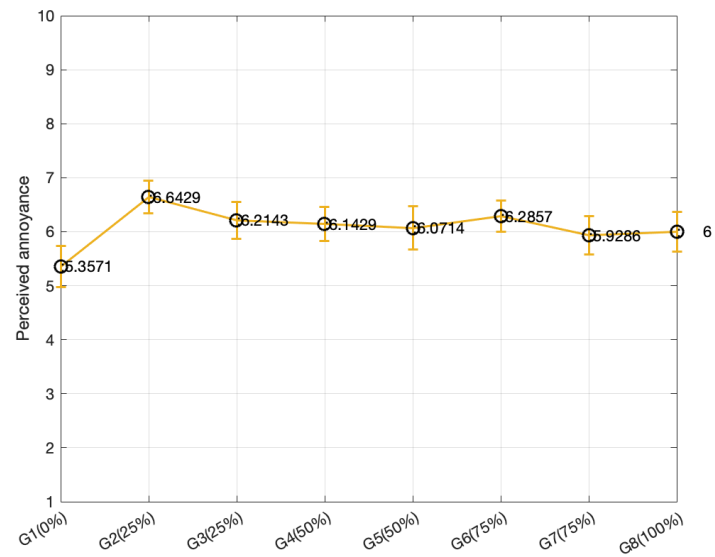


Figure 4.32: Perceived annoyance values for 8 groups.

scores in both evaluations.

Compared to the above four evaluation indicators: loudness, sharpness, roughness, reasonableness, the evaluation results of sense of stress and annoyance are more subjective, and also related to each participant's own perceptual function and personal experiences. Furthermore, the order in which the signals were tested in the listening experiment also affected the results of the experiment unavoidably, even though all the signals had been randomized in this listening test. People are more inclined to make a moderate assessment when faced with something that is unknown in its entirety, therefore, the first signal (in this listening test the first signal is Group 7) tested is more likely to get a biased score.

4.3.2 Results of Paired Comparison

In the second part of the listening test, the 14 participants were required to compare two signals of the same vehicle type but at different speeds and choose the one that disturbed them more. Generally speaking, signals with a higher loudness are more annoying. However, vehicles have different tyre-road noise and engine noise when travelling at different speeds, which means that even if the signals have the same loudness (same soneGF), they have different frequency compositions. This test aims at investigating the effect on human perception of signals with similar psychological loudness but different noise compositions. Thus, to avoid the influence of loudness on the test results, the psychological loudness of each signal was adjusted to be very close to each other.

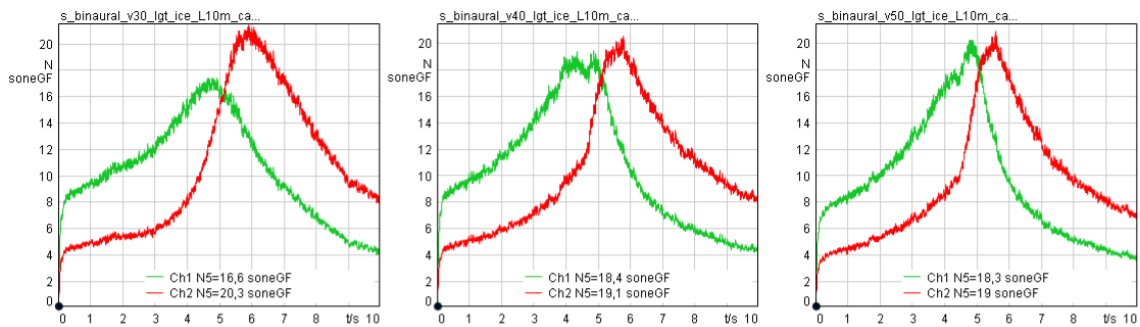


Figure 4.33: Subjective loudness curves of individual light vehicle at 30, 40 and 50 km/h.

Figure 4.33 and Figure 4.34 present the psychological loudness curves of the signals in different speeds for light vehicles and heavy vehicles, respectively. Figure 4.35 and Figure 4.36 show the proportion of each single-vehicle signal of different vehicle type and driving speed selected by participants as the most disturbing.

It can be seen from the Figure 4.35 that in the paired comparison test, the signal of light vehicle driving in 30 km/h is selected the largest proportion of the total number of times, while the other two signals are selected a similar number of times. The two signals of heavy vehicles driving in 40 km/h and 50 km/h have almost the

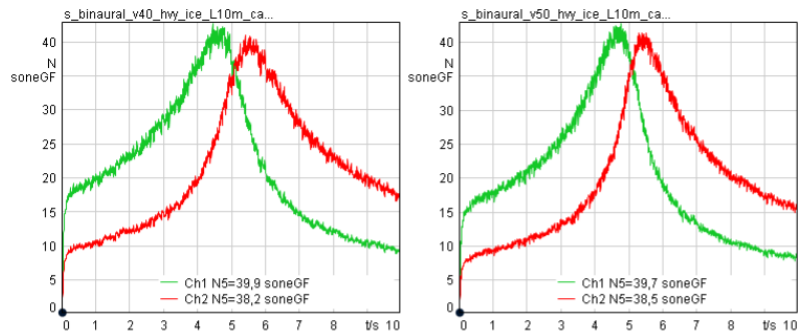


Figure 4.34: Subjective loudness curves of individual heavy vehicle at 40 and 50 km/h.

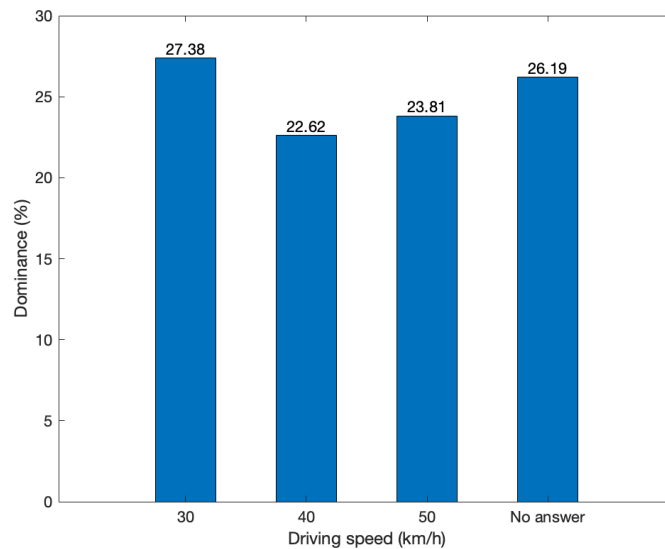


Figure 4.35: Results from paired comparison test on which sound is more disturbing, for light vehicle at three driving speeds.

same perceived loudness, but as can be seen from the results in Figure 4.36, there is a large difference in the proportion of times they are selected. It is noticeable that the sum of the proportions of the signals is not 100 %, the missing answers account for a part of the proportion. This may be caused by inconsistent judgements of participants in paired comparison tests. For example, when comparing signal A and B, participants may give different answers in repeat comparisons. Also, it may be due to an issue in the design of the listening test process that participants were able to skip the test without giving an answer.

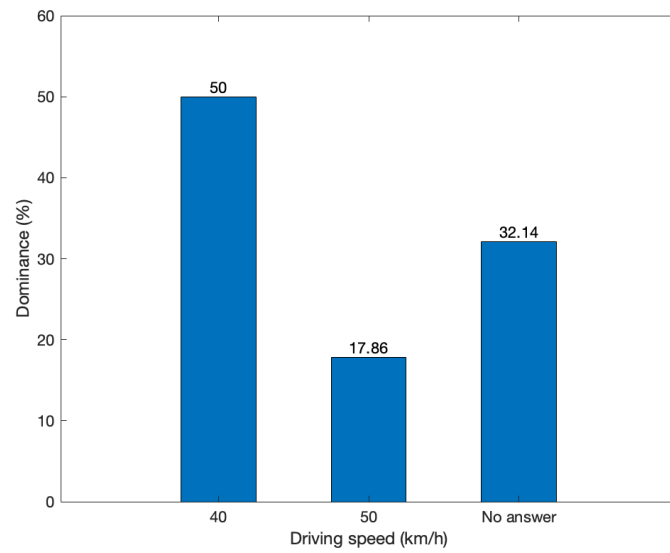


Figure 4.36: Results from paired comparison test on which sound is more disturbing, for heavy vehicle at two driving speeds.

5

Discussion

In this project, the noise of the vehicles driving in different speeds in urban roads for both light and heavy types is auralized. Noise signals from light vehicles at 30 40 and 50 km/h and heavy vehicles at 40 and 50 km/h are modelled and used to compose 8 one-minute-long traffic scene signals with various percentages of heavy vehicles. As the Figure 5.1 shows, the L_{AEq} of each traffic scene signal is controlled at the range of 75 ± 0.5 dBA.

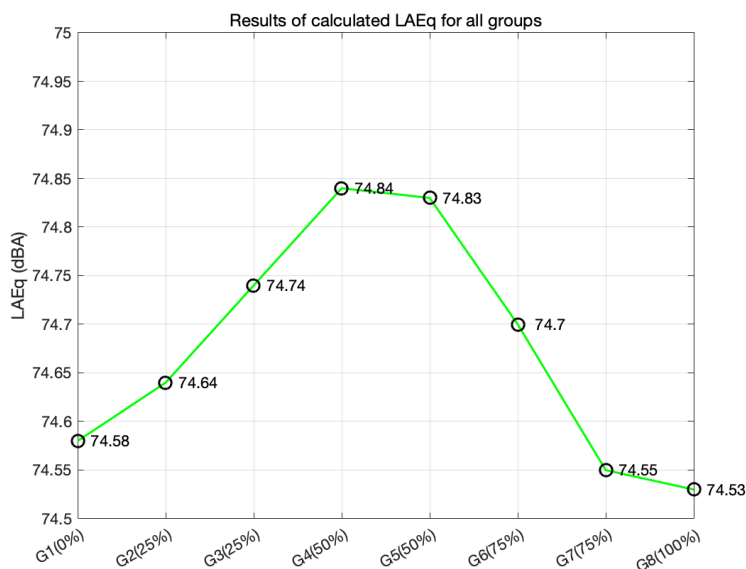


Figure 5.1: LAEq values of all groups.

To investigate the effect of the proportion of heavy vehicles in the signal on human perception, a listening test was designed and implemented in the teaching room in the Division of Applied Acoustics, at Chalmers University of Technology. 14 participants showed their willingness to take the listening test and gave their feedback. It can be seen from the results shown in the last chapter, the signal of Group 1 which composed by only light vehicles received the lowest scores in the evaluations for loudness, sharpness and roughness, even though the A-weighted equivalent level is the same (within 75 ± 0.5 dBA for all situation). It was also the least stressful and annoying than the other signals containing heavy vehicles. This leads to the conclusion that traffic scenes containing heavy vehicles do have a greater impact on human perceptions than traffic scenes with only light vehicles.

However, in this listening test, the proportion of heavy vehicles varies from 25 % to 100 % in traffic scenes signals of the same L_{Aeq} did not show much differences in human perception. For group pairs 2 and 3, 4 and 5, and 6 and 7, each pair had the same proportion of heavy vehicles, but participants rated them differently in terms of loudness, sharpness, roughness and the extent to which they felt stressed and annoyed by them. Additionally, for the groups with proportions of heavy vehicles varying from 25 % to 100 %, the evaluations of the participants showed no correlation between the proportion of heavy vehicle signals and the stress and annoyance people felt. By analyzing the signals with the same proportion of heavy vehicles in the results (e.g. Group 2 and 3, 4 and 5, 6 and 7) it can be seen that even if the signals have the same proportion of light and heavy vehicles or even the same total number of vehicles (e.g. Group 2 and 3), they still have a different impact on human perception.

One of the participants gave feedback that high frequency noise makes signals perceived more annoying. However, another participant suggested that the roughness of the signal had a greater effect on annoyance, while sharpness had a less significant effect on human perception. To validate which statement is more reliable, the results of Group 6 and 7, which had the same proportion of heavy vehicles (75 %), are used as comparative examples. The objective results were calculated and exported by ArtemiS Suite. As follows, Figure 5.2 and Figure 5.3 show the sharpness changing over time for both channels of Group 6 and Group 7. For Group 6, the values of sharpness for two channels are 2.97 acum and 3.01 acum, while for Group 7, they are 2.86 and 2.81 acum. Thus, it is proved that the objective sharpness of Group 6 is higher than that of Group 7. The objective roughness results for Group 6 and 7 are shown in the Figure 5.4 and 5.5, which illustrates that the roughness value of Group 6 is 0.013 asper lower than that of Group 7. According to You and Jeon [24], who researched the Just Noticeable Differences (JND) in several sound quality metrics, the JND of sharpness and roughness are 0.08 acum and 0.04 asper, respectively. Thus, objectively, for Group 6 and 7, the difference of sharpness is noticeable while the difference of roughness is not. Referring to the perceived results of the two groups, the perceived values for sharpness and roughness fit the objective results well. The perceived values of the two test indicators, annoyance and stress, showed that the one with the higher sharpness was more disturbing. The reason for this can be that, unlike Group 6, which continually and uninterruptedly outputs high frequency noises, while the signal of Group 7 occasionally has a gap, allowing participants to take a short rest while still listening to the annoying noise. but this inference could not be validly confirmed by the results of this listening test. Therefore, the investigation of time gaps between vehicles in a traffic scene can be conducted in the future research.

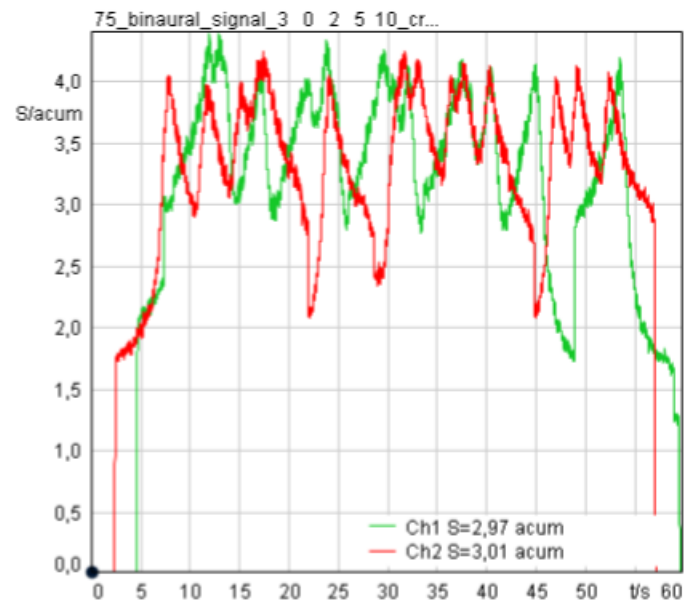


Figure 5.2: Sharpness for Group 6

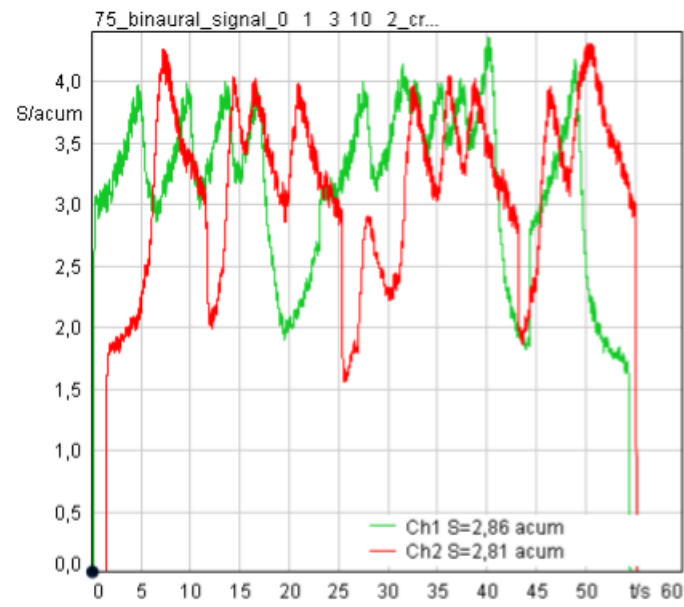


Figure 5.3: Sharpness for Group 7

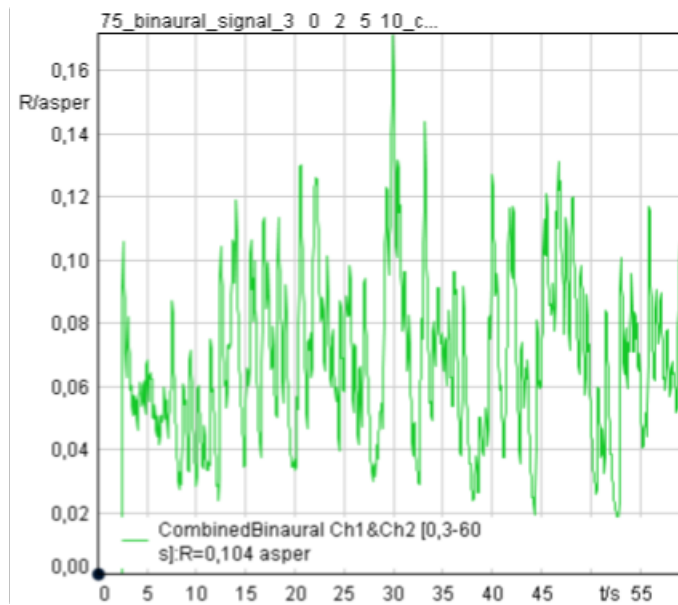


Figure 5.4: Roughness for Group 6

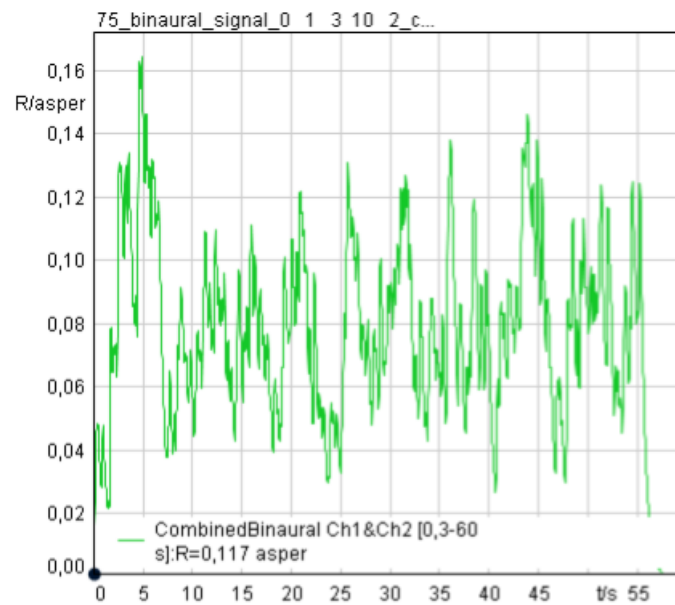


Figure 5.5: Roughness for Group 7

6

Conclusion

The results of the first part of the listening test showed that the signals containing heavy vehicles were indeed more disturbing than the signal consisting entirely of light vehicle noise at same L_{AEq} , and scoring higher in perceived loudness, sharpness and roughness. However, the stress and annoyance felt by the participants when listening to the signals did not increase with the proportion of heavy vehicles in the signal. Therefore, based on the results and the above analysis, it can be tentatively inferred that continuous high frequency noise in the signal increases perceived stress and perceived annoyance and reduces pleasure. In future studies, more listening experiments could be designed to be tested. Traffic scene noise with the same L_{AEq} and the same proportion of light and heavy vehicles, but with widely varying high and low frequency distributions, can be created based on the principle of controlled variables. It is also possible to vary the distribution of vehicles in the given traffic scene, with some signals having continuous and uninterrupted vehicle noise and others having intermittent vehicle noise, and these created signals can be used in listening experiments to further investigate more factors in traffic noise that affect human perception.

For the second part of the listening test, the results of the paired comparisons for heavy vehicles showed that participants felt more disturbed by the lower speed signals when the measured loudness in Sone of the signals was constant. However, for light-vehicle signals, the results can not show a clear relationship between the driving speeds and the annoyance of people. According to the Figure 4.2, it can be seen that for heavy vehicles, the proportion of rolling noise to total noise increases as speed increases, which means that propulsion noise accounts for a greater proportion of the total noise generated when the vehicle is travelling at lower speeds. It can be inferred that when signals have the same perceived loudness, the signal with a greater proportion of propulsion noise is more disturbing for a single passing vehicle.

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