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Exterior Sound for User-Car Interaction

Master's thesis in Sound and Vibration

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Cover: Visualization of the car used for emitting sound to alert a pedestrian.

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Abstract

The advent of electric and hybrid vehicles have, compared to traditional combustion engine vehicles drastically decreased the total noise emitted. One downside of lower noise levels is that it is becoming increasingly difficult for people, especially those who are visually impaired, to detect these vehicles as they hardly produce any noise. Especially when these vehicles are driven at speeds below 30 km/h, where there is not much tyre and wind noise produced by the vehicle, detecting them becomes difficult. To increase the detectability of these vehicles, various organisations across the world e.g. National Highway Traffic Safety Administration (NHTSA) in USA have come up with regulations which requires that all vehicles which are able to be be electrically driven to emit artificial sound above a certain minimum level across different third octave bands.

This thesis investigates and presents the complete process of enabling a vehicle to emit sounds. An evaluation of different sound sources is done for which artificial sounds in different categories are designed. With the chosen sound setup and the developed sounds a listening test is done to evaluate the sounds with the goal of finding the most suitable sound. Furthermore, a possible correlation of the sounds with psychoacoustic parameters should make it easier to identify suitable sounds. The thesis has three major parts which are the evaluation of the right sound source, a design process for artificial sounds and a listening test. Out of a loudspeaker setup and different shaker setups mounted on different body parts on the vehicle, the loudspeaker setup yields the best results. In the creative process of designing sounds, eight sounds with different frequency components were designed. The listening test shows that broadband sounds are perceived as very pleasant but tonal components are needed for safety reasons. A recommendation of a sound is done. The correlation of the results show similarities with the tone to noise ratio but need further investigation.

Keywords: AVAS, Sound Design, Psychoacoustic, Electric, Hybrid, Vehicle, Listening test, Shaker, Loudspeaker, Exciter.

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1 Introduction

The sound emitted by vehicles, to a certain extent ensures safety of vulnerable road users (VRU) like blind people and other pedestrians. This is because the sound alerts the people in the surroundings of the vehicles' approach. However, electric and hybrid vehicles can pose a threat to the VRUs because of the absence of engine noise. At low speeds, the road-tyre noise produced by these vehicles is not high enough to alert people about their presence.
To solve this problem, various organisations around the world e.g. NHTSA in USA have come up with regulations which makes it mandatory for electric and hybrid vehicle manufacturers to have a sound system producing exterior sound to make the vehicle more audible outside. The idea is to integrate a sound system which produces exterior sound representative of the vehicles' driving behaviour (acceleration, deceleration, active or idling, constant).
The sound that is to be produced by this system called Acoustic Vehicle Alerting System (AVAS) should not only be able to alert other road users but at the same time it also should not be annoying and should not sound out of place for the vehicle and for the environment in which it is operating. In this thesis a sound setup for an electrically driven vehicle is chosen and different sounds are designed. The aspect of a sound fulfilling all different requirements is taken care of by developing different kinds of sounds e.g. high tonal, low tonal, high rhythmic, low rhythmic etc. and then conducting a listening test in real life scenario with participants coming from different age groups, genders and backgrounds. The listening test data is analysed to come up with conclusions about the likes and dislikes of participants for different attributes of the designed sounds.

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Theory

The following sections introduce the most important topics related to the current thesis and give an insight within the thesis work into the processes used. To begin with, an overview about the legal requirements is given to verify the process of choosing a proper exterior sound generating system according to the requirements. How to figure out the right setup and which parameters to use to decide for one specific setup is explained later. With this information, the sound design work can be started. The typical approach about how that is usually done and which software was used for that is given in Chapter 2.3. To evaluate the sounds created the basics about acoustic listening tests and statistical analysis are given in Chapter 2.4.

2.1 Legal Requirements

To begin with, an introduction of the Acoustic Vehicle Alerting System (AVAS) is given and with it the most important content of the legal requirements. Those requirements set the basic framework for the investigations of a proper exterior sound setup in the following chapter according to the requirements.

2.1.1 Acoustic Vehicle Alerting System (AVAS)

AVAS are sound generating devices. Because of the upcoming legal requirements, these devices must soon be integrated in all fully electric vehicles or hybrid electric vehicles capable of running without the internal combustion engine. AVAS emits sound when the vehicle is operating at low speeds where there is not much tyre and wind noise. The emitted sound is used to alert the VRUs about the vehicles' presence. Figure 2.1 points out the main noise components of a vehicle for different speeds with different engine loads. The dotted line shows all noise sources related to a combustion engine.

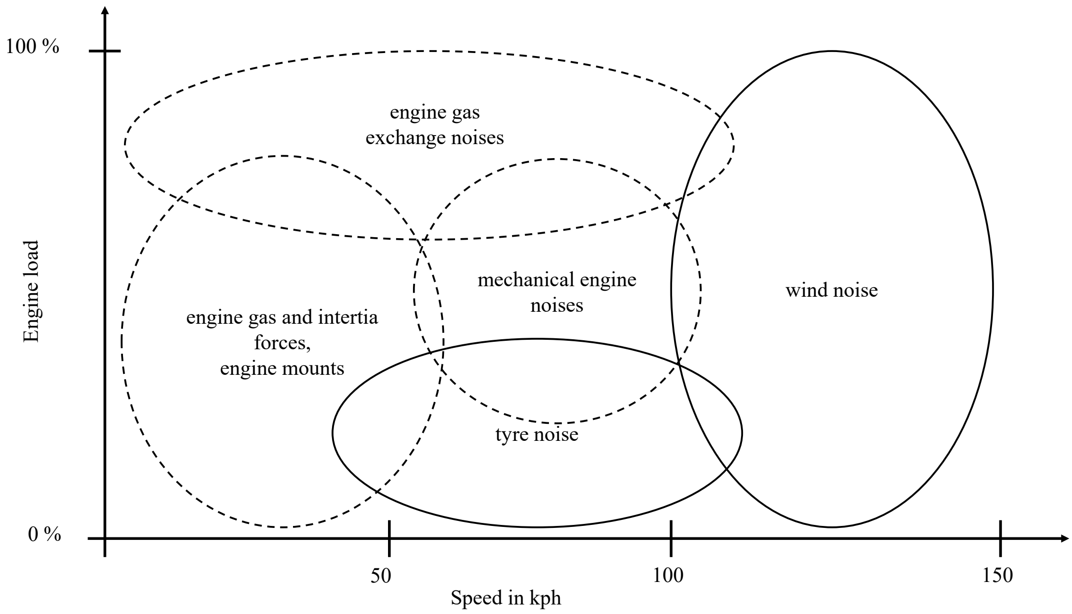


Figure 2.1: Schematic representation of the most essential components of interior vehicle noises, represented with changing speed over engine load. The dotted line emphasizes sounds related to combustion engines [1].

At low speeds for an electrically driven vehicle typical combustion engine noises are not present and the vehicle can hardly be heard. As soon as the vehicle increases speed the tyre and wind noise are most prominent and no additional sound is needed.

As per the legislation in different parts of the world e.g. Europe, US, Japan etc., all vehicles able to drive electrically have to produce an artificial sound when running at speeds up to 20 km/h or 30 km/h depending on the market. Those legislation start at different dates for different markets. In the US they are valid beginning from September 2019 but only 50% of the fleet have to fulfill the requirements in the first year [2]. In Europe, the legislations are valid from July 2019 but only for new types of vehicles [3]. The laws were made because the lack of sound of an electric vehicle approaching made it difficult for pedestrians to perceive their presence. Especially pedestrians who are visually impaired find it very difficult to hear an electric or hybrid vehicle which resulted in quite a few traffic accidents [4].

According to D. Siwiak and F. James [5], "Sound has an immediate, direct link to both the rational and emotional parts of our brain and can trigger vivid recollections of past experiences, helping us remember intricate details associated with events". It is important that the artificial sound designed for the vehicle should not sound out of place and should fit to the brand image of the vehicle and the environment as well. It should not be perceived as added, unwanted, annoying and at the same time it should not sound as if the vehicle is malfunctioning. From the safety point of view, the designed sound should give indications of changing speeds e.g. accelerating, decelerating, active idling etc. With all those parameters taken into account the sound has to fulfill the requirements explained in the following chapter.

2.1.2 Summary of most important European Legislation

With the following a short introduction about the most important legal requirements in the EU are given [3]:

1. The frequency range of interest is 160 Hz to 5000 kHz in third octave bands.
2. The artificial sound produced by the vehicle should have at least one component within or below the 1600 Hz third octave band.
3. The sound should have at least one frequency component which changes in pitch by 0.8% for every 1 km/h change in speed of the vehicle.
4. The vehicle does not need to produce any sound when at standstill or stationary condition.

2.1.3 Summary of most important US Legislation

The following are the most important legal requirements for the US market [2]:

1. The frequency range of interest is 315 Hz to 5000 kHz in third octave bands.
2. The artificial sound produced by the vehicle should have at least one component below 1000 Hz and one above or equal to 1000 Hz in third octave bands hat fulfills minimum requirements as shown in Figure 2.2. Also the chosen components must be in two non-adjacent bands.
3. The sound does not necessarily need to shift in pitch when the vehicle is changing speed but it has to change in level.
4. The vehicle need to produce sound when it is stationary as per the minimum level requirements shown in Figure 2.2.
5. An additional microphone placed at the front center as shown in Figure 2.3 is to be used to measure the stationary vehicle sound
6. The levels within the bands need to fulfill a certain bandsum.

One-third octave band center frequency, Hz	Stationary	Reverse	10km/h	20 km/h	30 km/h
315	39	42	45	52	56
400	39	41	44	51	55
500	40	43	46	52	57
630	40	43	46	53	57
800	41	44	47	53	58
1000	41	44	47	54	58
1250	42	45	48	54	59
1600	39	41	44	51	55
2000	39	42	45	51	55
2500	37	40	43	50	54
3150	34	37	40	47	51
4000	32	35	38	45	49
5000	31	33	36	43	47
Overall A-weighted SPL Range	43–47	46–50	49–53	55–59	60–64

Figure 2.2: One-third octave band SPL minimum requirements [2].

Since the legislation in the US contain more and stricter requirements compared to the other markets, the focus was mainly put on those while deciding the measurement setup. The setup was used according to the FMVSS 141 regulations [2]. The setup to measure the sound and see if it is fulfilling the legal requirements can be seen in Figure 2.3. Two microphones adjusted to a height of 1.2 m are used for measuring. For stationary sound, an additional third microphone in the front center of the vehicle is used. The left-passenger side microphone and the right driver side microphone are placed on line PP' which is passing through the front tip of the vehicle and perpendicular to the direction of travel. The distance between these microphones and line CC' which is the vehicle centerline is two meters. The front center microphone is placed on the vehicle centerline CC' and is located at a distance of two meters from the front tip of the vehicle.

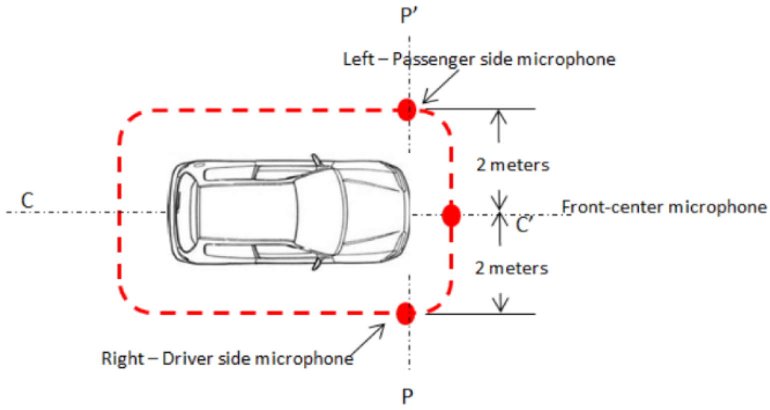


Figure 2.3: Microphone Positions for measurement setup according to NHTSA [2].

2.2 Vehicle Exterior Sound Setup

Since there is no a distinctive recipe for an exterior sound setup, all possibilities were taken into consideration to find an exterior sound setup which has to fulfill not only the legal requirements as explained before but also other restrictions regarding the price, size, weight and properties of the setup. Because it is used in the exterior it needs to be weather resistant or in the best case waterproof to ensure a smooth operation during the complete life-cycle of a vehicle and also in all conditions. The following sections give an overview about different setup ideas and in what ways they could be analyzed and discussed.

2.2.1 Different setups

The two main sound sources that were thought of were waterproof loudspeakers which do not need much of an explaination and the shakers, which need a little bit more of an introduction. The working principle of a shaker is very close to the one of a loudspeaker. But instead of the cone mounted on the coil and radiating sound, the coil is attached to a surface and excites it. In that way, surfaces and parts can be used as radiators to emit sound which could be an advantage when it comes to cars because they are many surfaces all around it which could be used for that.

2.2.2 Selecting the sound source

Designing sound is one thing, but if the sound source producing that sound is not appropriate or if it is not positioned at the appropriate position, it can result in the failure of the sound design objective. Therefore, it has to be made sure that the sound source selected is capable of producing the frequencies that the designed sound has without distortion. Therefore, while selecting the sound source, in what range it gives a flat or nearly flat frequency response must be checked. Also, the power rating of the sound source must be checked. If the sound source is not powerful enough, the sound produced by it will not be heard. Since the sound source is to be mounted on a vehicle which must operate in all weather conditions, it must be made sure that the sound source is water resistant. The size of the source should be considered. It should be small enough to fit into the vehicle e.g. at the bumper. The smaller the source, more the options to position it. Also the cost of the sound source should also be taken into account. The source which just fulfills the flat frequency response criteria and has good enough power should be selected.

2.2.3 Positioning the sound source

The position of sound source matters a lot as well. For deciding the source position, it has to be made sure that the decided position is such that the sound leakage to the interior of the vehicle is minimum and the radiation outside the vehicle is maximum. Also, the sound source must not affect the aerodynamic performance of the vehicle. Hence, it must be positioned such that it is well hidden e.g. behind the bumper but at the same time has maximum sound energy going outside the vehicle and minimum leakage inside. Also, it has to be made sure for the selected position of the sound source that the radiation is fairly omnidirectional as there could be road users approaching from all directions. An omnidirectional radiation makes it also easier to fulfill the legal requirements without pushing the speakers too much, since one speaker needs to be used on each side. The omnidirectional nature of the sound radiated can be analysed by checking the sound levels recorded at the three microphone positions as shown in 2.3. The setup is as per the FMVSS 141 regulations for the US market. If there is not much difference between the sound levels at the three microphones, it can be said that the source radiates fairly omnidirectionally. In the use case of shakers the shape and stiffness of the part the shaker is mounted on is important since the geometry and the stiffness decides how much sound a particular part will radiate. Once again the interior leakage has to be taken into account since the structure borne sound from the shaker could find ways into the vehicle's cabin and lead to a strong leakage. Additionally the radiation of a structure with the shaker on it could lead to highly non-linear radiation behaviour due to the different thicknesses, shapes and stiffness of the structure and the strong structure borne excitation of the material the shaker is mounted on.

2.2.4 Deriving the transfer function

The main idea of the transfer function is to describe the behaviour of a linear system when its input and output is known. This kind of a fingerprint could be used later on for an efficient way of creating sounds in any studio environment and convolving it with the transfer function of the system to monitor if the developed sounds fulfill certain legal requirements in actual conditions.
The transfer function H of a linear system in frequency domain is basically derived

by equation 2.1 with Y as an output of a system and X as an input. The transfer function is coupled to the impulse response via the fourier transform [6].

$$H(x) = \frac{Y(x)}{X(x)} \tag{2.1}$$

For deriving transfer functions of loudspeakers and shakers different excitation signals can be used. In this case using a sine sweep as an excitation signal seemed to be the most reasonable way. One reason for that is that the system can be investigated in terms of non-linearities which shows how reliable the transfer function is. This can be done by looking at the harmonics caused by the sweep. An easy way to see them is with plotting the spectral frequency information in a spectogram (see Figure 2.4).

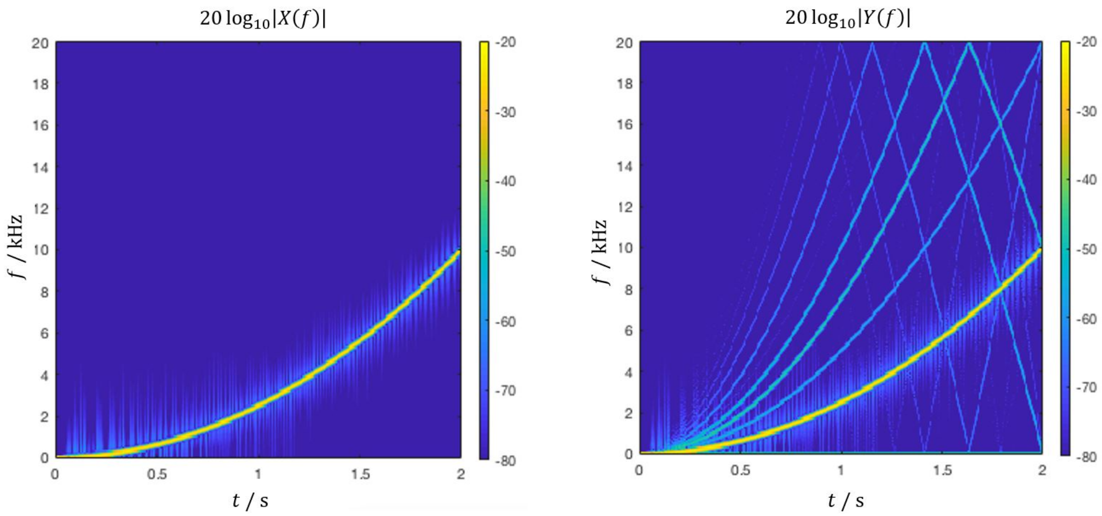


Figure 2.4: Comparison between a linear and a non-linear system with clearly visible harmonics [7].

The harmonics on the right hand side in comparison to the left hand side can clearly be seen and this intermodulation can cause aliasing and depending on how strong the harmonics are compared to the fundamental the transfer function might not represent the system in a reliable way.

2.2.5 Deriving 1/3 Octave Bands according to ANSI

According to the legal requirements which are always given in 1/3 octave band levels all the measured data is analysed in 1/3 octave bands. The way this was calculated was according to ANSI S1.1-1986 (ASA 65-1986) which filters and computes the RMS power in each band and expresses it in dB normalised to the standard reference level. Additionally the A-Weighting is added.

2.3 Sound Design

Depending on the product and the goal there are different sound design approaches for different cases. In the specific case of sound design in automotive applications the approach chosen is explained in the following sections.
Before starting with developing the sounds it is necessary to set a basic framework and goals which the sounds need to fit to. The general product design can be summarized as an interaction of the user experience, the functional structure and the technical development (see Figure 2.5). The product sound design needs to connect those values then. The user experience can be further described by aspects like the brand image or the musicality. The more functional aspects can be described with fulfilling the legal requirements and giving safety information of the vehicle in terms of audibility, localization and perception of speed changes of the vehicle. The technical side depends on the sound setup available which was explained in Chapter 2.1.

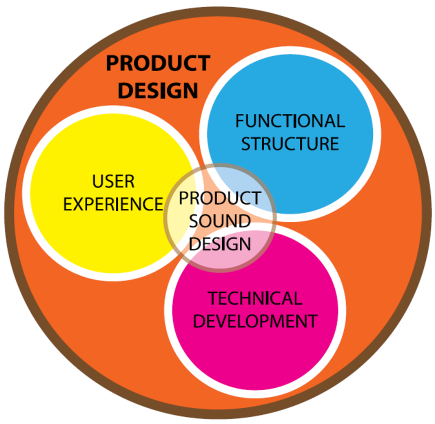


Figure 2.5: Different aspects of product sound design when applied to a general context [8].

Keeping all the factors in mind, the sound design process is started which is firstly very broad to create a range of sounds to choose from and then narrowed down to a pool of sounds which are worth evaluating further.

2.4 Listening Tests

Listening tests are essential for evaluating the subjective impressions of people about the designed sounds. An appropriately prepared test saves a lot of time and effort during the test as well as afterwards when it comes to the evaluation.

2.4.1 Category judgement test

There are several different test types for different requirements and objectives from which a suitable test needs to be chosen. In this case the so called category judge-

ment test was used because it allows to compare as many sounds as wanted with each other and it is easy to investigate in the directions of certain attributes. Furthermore a full test should not take too long due to a possible lack of focus from the participants after time and the category judgement test kept the duration of the test to the shortest possible time for our test procedure [9].
In the category judgement the sound samples are presented one by one to the participants, who then rate each sound on a scale according to different criteria. For the judgement a five-point scale with the categories "not at all", "a little bit", "difficult to say", "quite a bit" and "totally" is used. With the chosen scale one has to be aware of bias effects. This means that a sound that is judged directly after a sound that was perceived as very pleasant may be assigned to a different category compared to the one which was heard after a sound with only a little pleasantness. This effect can be avoided by presenting each sound several times in a random order. Furthermore different participants could use the scale to a different extent depending on the subjective association with the words chosen. This effect can be avoided with a sufficient amount of training of the subject. During the training, the participants can hear all or the most extreme sounds to allow them to judge accordingly. One advantage of a category judgement test is that each sound is judged more or less independently. So the difference between certain sounds can be shown. Once the analysis is done it can be presented with the mean value and the confidence intervals.

2.4.2 Conducting a listening test

After preparing the listening test some basic rules must be followed to successfully conduct the test. For selecting the right test environment it has to be taken into account that a test environment which is closest to real-life conditions lead to more meaningful results [9]. However in this case a test in real-life conditions gives also reduced control over the conditions like weather, background noise and sudden traffic. The trade off between the ecological validity and experimental control has to be taken into account and is explained later in chapter 6 .
In the beginning of the test there needs to be a proper introduction with all necessary information and explanations about the planned test. Furthermore it might be good to explain the purpose of the test. The oral instructions have to be the same for all participants. If all participants have understood the task they feel more comfortable and confident during the test and it is more likely to get reliable results. It is also important to emphasize that there is nothing right or wrong in the test, everything is subjective and the judgements can be different for different participants.
Before starting with a listening test a training can be done to show the subjects the procedure and let them read the questionnaire. After that the test can be started. During the test it is important that there is no distraction and the participants do not feel left alone. This means there should be a person in charge for inquiries (e.g. about technical problems or questions) during the test. When the test is done the person should ask the participants about their impressions regarding the procedure, the duration etc. Based on that the procedure can be changed for future tests.

2.4.3 The participants

The selection of the participants is usually limited by the sheer pool size of available participants and the time scheduled for conducting the test. However, the selection and number of participants have an influence on the result of the test, they should be chosen carefully.
In the beginning the clear objective of the listening test needs to be defined. In the specific case of this project all ages and genders are preferred because everyone could walk into the vicinity of a vehicle. Hence everyone's judgement is important and should be taken into account. A widely spread range of age and equal number of female and male participants would be in this case the most representative one. Also the level of expertise has to be taken into account. An experienced subject can solve more complicated tasks than an inexperienced one but on the other hand an expert could overrate specific aspects of sounds because of which one may discard a certain sound even though it might be perceived as acceptable by untrained participants. Hence, ideally there should be a fairly even mix of trained and untrained participants.
The number of selected participants also plays a vital role when it comes to robustness of test results. Too few participants could lead to very different results since the averaging-out of individual preferences will not be done sufficiently. In general it can be said that the more the better but of course there are restrictions. Extensive tests require much more time and a more intensive training. When it comes to the evaluation of the results it can be determined if the number of participants was sufficiently high. Various statistic examinations can be performed, so the average of different groups should not be significantly different. A way to do that is introduced in the following Chapter 2.4.4.

2.4.4 Test evaluation

After conducting the listening test the obtained results have to be evaluated. There are two main steps when it comes to the evaluation. First it needs to be proven if the results are statistically valid and can be trusted. This is done by analysing the differences among group means with an ANOVA (Analysis of Variance) investigation. Secondly the 95% confidence interval is determined to summarize and present the data in a concise form.

2.4.4.1 ANOVA Analysis

To begin with it needs to be determined if there is a significant variation between the gathered data of the different groups. For doing that there are different types of tests. Most commonly the t-test is used, which only allows analysing paired groups. In this case a bigger number of groups is used and therefore the so-called ANOVA test can be used to see the variances of the mean among groups and to determine whether any of those means have a statistically significant difference. As already mentioned differences of the mean among the groups are not desired which makes the according null hypothesis the following [12]:

$$\begin{aligned} H_0 &: \mu_1 = ... = \mu_i \\ H &: \text{Null hypothesis} \\ \mu &: \text{Mean of the groups} \end{aligned} \tag{2.2}$$

The null hypothesis in statistics is a general statement that there is no relationship between two measured phenomena or no association among groups [11]. If the null hypothesis can not be rejected the results do not show statistically significant differences. To show the probability under which the null hypothesis might or might not be fulfilled the p-value is used. If the p-value is below a certain value for example 5% it is commonly agreed that the null hypothesis is fulfilled and the probability is sufficiently low. For using the ANOVA the following prerequisits, in order of importance, need to be fulfilled [12]:

- Samples must be independent from each other
- Homogeneity of variance must be given
- Data must be normally distributed
- Loss of subjects

Those prerequisits needs to make sure an ANOVA investigation delivers reliable results.

2.4.4.2 95% Confidence Interval

If the ANOVA test gives a valid outcome it can be continued with summarising the data. To present the data in a concise way the arithmetic mean together with the 95% confidence interval (CI) is used. The CI shows a 95% chance that the confidence interval contains the true population mean. The CI can be calculated with Equation 2.3 [10].

$$CI = \overline{X} \pm t\frac{S}{\sqrt{n}} \tag{2.3}$$

As it can be seen the CI consists out of the mean of the samples X together with the intervals consisting out of the standard deviation S and the t-distribution divided by the number of data points.

To begin with the standard deviation needs to be calculated. The standard deviation is defined as the square root of the variance and is calculated in the following way:

$$\begin{aligned} S &= \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}|A_i-\mu|^2} \text{ where } \mu \text{ is the mean of } A_i\text{: } \mu = \frac{1}{N}\sum_{i=1}^{N}A_i \\ S &: \text{Standard deviation} \\ N &: \text{Number of data points} \\ A_i &: \text{Data points} \\ \mu &: \text{Mean of the samples} \end{aligned} \tag{2.4}$$

First the mean μ needs to be calculated which is done with the sum of all data points devided by the total number of data points. Then the mean is subtracted from each data point A_i which leads to zero if everything is added up do to the

negative and positive values and the definition of the mean. Because of this the square of each deviation is taken. The square values are then summed up to show the variance of the data. The variance of the data shows how spread out the data points are. The closer the variance is to zero, the more closely the data points are clustered together. With the square root of the variance the standard deviation is then determined.
With the standard deviation the Student‘s t inverse cumulative distribution function is needed:

$$t = F(x|v) = \int_{-\infty}^{x} \frac{\Gamma(\frac{v+1}{2})}{\Gamma(\frac{v}{2})} \frac{1}{\sqrt{v\pi}} \frac{1}{\left(1 + \frac{t^2}{v}\right)^{\frac{v+1}{2}}} dt \tag{2.5}$$

Γ : Gamma function

v : Degrees of freedom

Equation 2.5 contains the student’s t distribution which is a family of curves showing the probability distribution depending on the degrees of freedom v. The result t is the probability that a single observation from the student’s t distribution with v degrees of freedom will fall in the interval [-∞, x].
With S and t and the arithmetic mean the 95% confidence interval can now be calculated and used to present the data with.

3

Measurement Procedure

Based on the legal requirements two sound systems are considered. The first one is a fully enclosed loudspeaker setup (see Section 3.1) and the second one a shaker setup (see Section 3.2) as both the setups are thought to be able to emit the sound needed to fulfill the legal requirements.

3.1 Introduction of Loudspeakers

While deciding which sound source to use to produce the sound, a lot of different options were explored. The first thing that was considered while selecting the sound source was whether it has a flat or nearly flat frequency response in the frequency range where the legal requirements are supposed to be fulfilled i.e. between 315 Hz to 5000 Hz. Keeping in mind the lack of available space to mount the sound source, it was decided to shortlist sound sources which are compact enough to fit easily into the vehicle. Some of the shortlisted compact loudspeakers were discarded because they did not have a proper housing. Some of them were not waterproof. Since the vehicle is supposed to operate in different conditions e.g. rain, snow etc. it was decided to use a waterproof loudspeaker with a proper housing. Also the cost of the sound source was another factor that was considered while selecting the speaker. Keeping all these things in mind, it was decided to use the 2-way coaxial box speaker from LTC (see Figure 3.5 (a)). It is a waterproof speaker specially adapted for marine environments, bathrooms, outdoor installation etc. It has a cover of durable ABS plastic (does not oxidite in salt water) and the cone is UV resistant. The power rating is 90 Watt and has a neodymium tweeter on a 3 inch base. The specified frequency range of the speaker is 80 to 20000 Hz.

(a) LTC loudspeaker

(b) Dayton shaker

Figure 3.1: Sound sources used.

3.2 Introduction of Shakers

Ease of mounting and compact size were the main reasons why exploring the shaker as a sound source was considered. Also using the body parts of the vehicle for radiating sound would be an elegant and easy way of fulfilling the legal requirements. With the problem of lack of space out of question, it was only a matter of selecting shakers which are waterproof so that they can operate in all weather conditions. After shortlisting all waterproof shakers, the power rating of every shaker was explored. Measuring a 10 Watt shaker which was already available at the Volvo Office on the bumper, showed that the shaker radiation is powerful enough to fulfill legal requirements. Because of that it was decided to buy a not so costly, waterproof shaker with a power rating of around 10 Watts. The shaker used is a electrodynamic Dayton Audio 10 Watt waterproof shaker with a 25 millimeter exciter (see Figure 3.5 (b)). It is designed for outdoor conditions and can be used for automotive purposes.

3.3 Installation of the sound sources

To install both systems into the vehicle the place of them was chosen to be as close as possible to the two main microphone positions needed to fulfill the legal requirements.

3.3.1 Shaker Positions

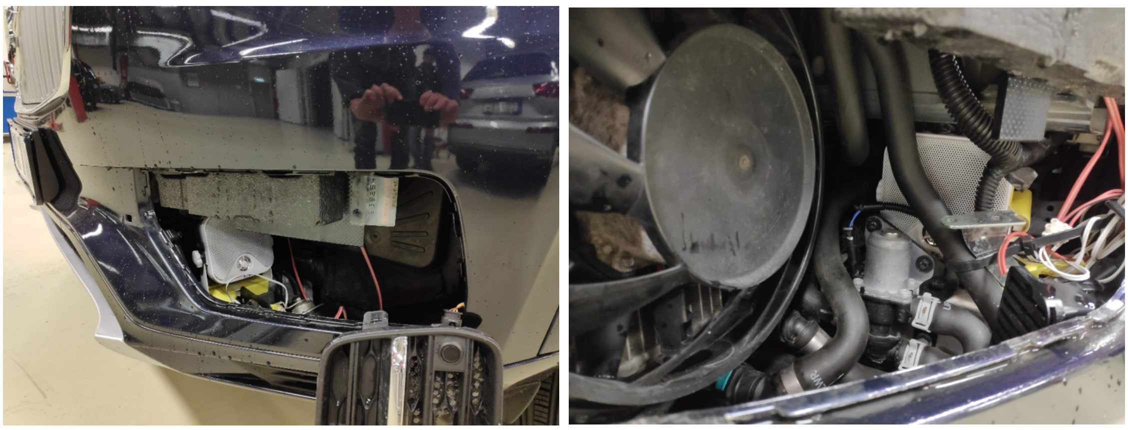
Different places were explored regarding where to put the shakers on the vehicle. After taking into account, how well the shaker can be hidden in a particular position (so that aerodynamically the mounting of the shaker does not make any difference to the vehicle), how much the part on which it is mounted can radiate sound etc., it was decided to mount the shaker at six different positions - three inside of the bumper and three close to the headlights on either side of the vehicle.

(a) Shaker on bumper (b) Shaker on lights

Figure 3.2: Mounting positions of the shakers on the bumper and on the lights.

3.3.2 Loudspeaker Positions

As with the shakers, different positions were explored to mount the speakers also. But the size of the speaker proved to be major constraint in finding positions. Finally, one position on either side of the bumper was selected to mount the pair of speakers. The speakers were mounted at the chosen position in such a way that they were oriented towards the openings in the hatches of the bumper. This helped in having minimum sound reflected back from the bumper allowing maximum sound to reach the outside of the vehicle.



(a) Loudspeaker on left side (b) Loudspeaker on right side

Figure 3.3: Loudspeaker installed behind the bumper on left and right side.

3.4 Measurement Environment

All the measurements were conducted in the semi-anechoic room at Volvo Torslanda (see Figure 3.4). The size of the room allowed putting the microphones in the positions required from the legal requirements. Also the conditions of the room allow reproduceable measurements.

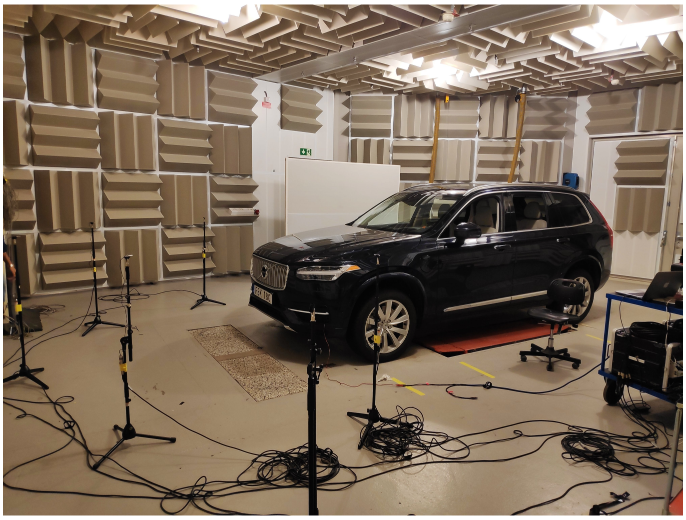


Figure 3.4: Semi-anechoic room with microphone setup.

Since the legal requirements originally should be measured outdoors this is only an approximation. A measurement outdoor was not possible due to the given time frame and much more complex measurement procedure which would be depend on the weather conditions. Also the workflow with the design of the sound in the studio and verifying it in the vehicle would be much harder to realise. Due to that is was agreed on using the semi-anechoic chamber as an alternative.

3.5 Measurement Setup/Software and Equipment

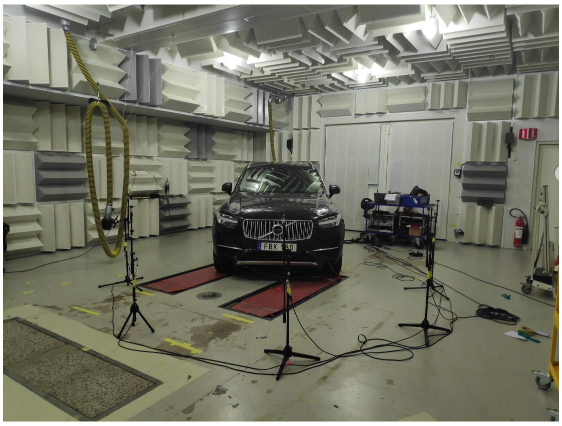
The following equipment was used:

- Audio Precision APx500 1701 transducer test interface (amplifier)
- Audio Precision APx500 586 multichannel audio analyser
- Alpine PDR-V75 amplifier
- OBD USB connector
- 9 Earthworks M50 omnidirectional condenser microphones
- 2 prepolarized microphones of type 40AE from GRAS
- 2 RME micstasy (additional amplification but was always turned off)
- Head Acoustics SquaDriga
- LTC PRobox 5inch waterproof speakers
- Dayonaudio DAEX25W-8ohm 10W waterproof shakers
- Volvo XC90 Twin engine AWD T8 hybrid
- Head Recorder, Head Artemis, MAX,MSP, Audacity, Logic, Audacity
- Audio Precision APX500 Measurement Software

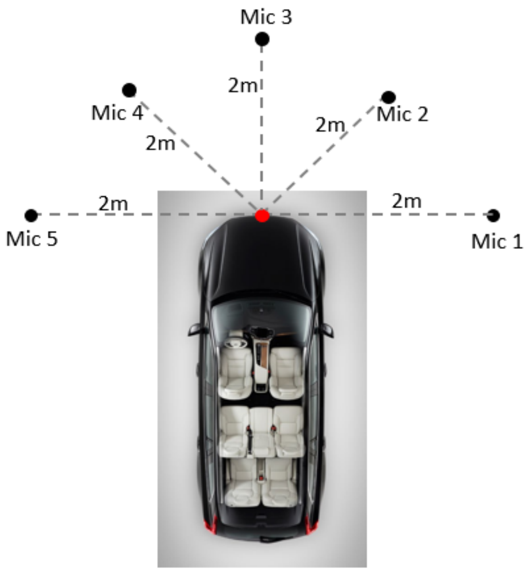
3.6 Measurements

The measurements were conducted in the semi anechoic room at Volvo Torslanda (see Section 3.4). The measurement setup is shown in Figure 3.5.

(a) Interior microphone setup



(b) Exterior microphone setup



(c) Microphone position from top view

Figure 3.5: Measurement setup in semi-anechoic chamber.

The sound sources were mounted in different locations on the vehicle as discussed in Sections 3.3.1 and 3.3.2. White noise generated by the computer software was passed to these sound sources through the Audio Precision APx500 amplifier and a recording was made through the five Earthworks M50 omnidirectional condenser microphones outside the vehicle as shown in Figure 3.5. The microphones were mounted at a height of 1.2 meters as specified in the requirements. Four microphones, two each on driver and passenger seats, were also positioned inside the vehicle to record how much sound is leaking inside the vehicle cabin (see Figure 3.5 (a)). Before the measuring process, it was made sure that all the microphones are properly calibrated. The procedure was repeated for all selected positions on the vehicle for the sound sources. In addition to this, a non-linearity check was also done for the shakers. For this, a sine sweep signal was played through the shakers and a recording was made through the five microphones positioned as shown in Figure 3.5 (c). Here, it is worth mentioning that the method using the transfer functions as described in the theory Section 2.2.4 was not used. The reason for that is there was considerable non-linearity in the shakers and hence, the transfer functions could not be trusted. The two additional microphones along with the regular positions from Figure 2.3 were positioned outside the vehicle to facilitate accurate measurement of the directivity of the sound source.

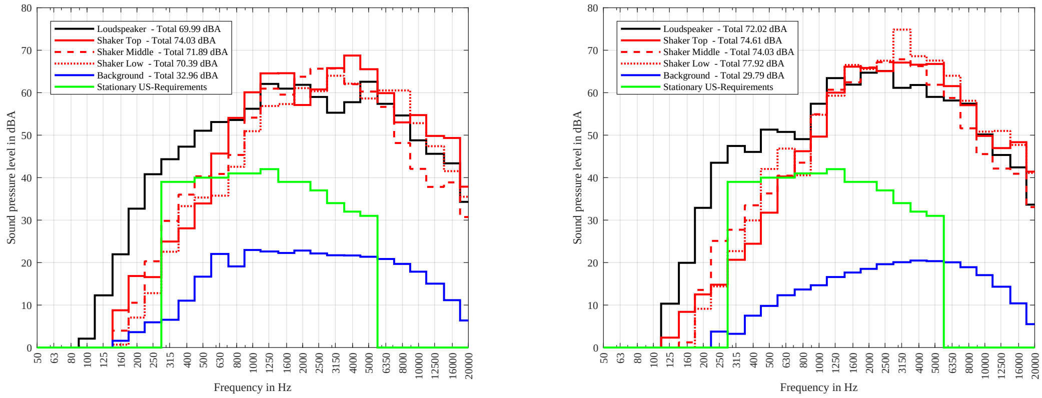
4

Measurement Results

This chapter compares the results from the two selected sound sources - shakers and speakers. Section 4.1 shows comparison of third octave band levels for shakers and speakers. Section 4.2 shows directivity comparison plots for the two sound sources and Section 4.3 shows the comparison between the amount of sound leaking into the vehicle cabin. Also, for all the results shown in this section, the reference sound pressure level is 20 μPa.

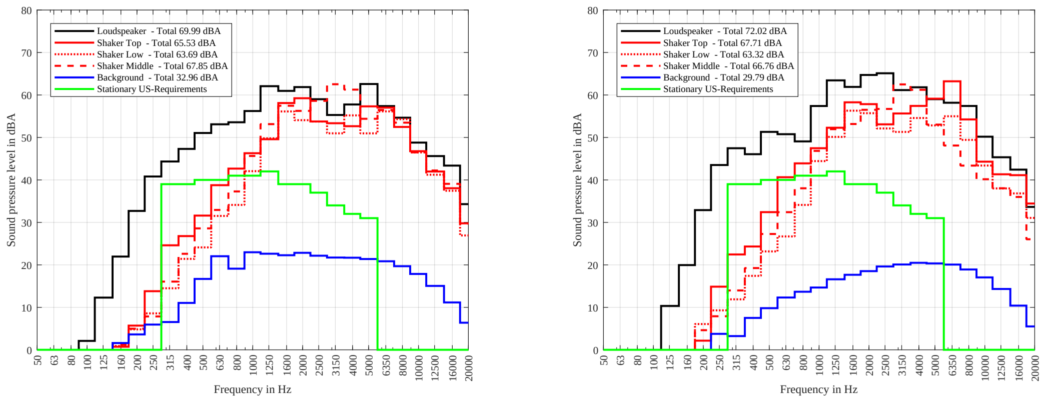
4.1 1/3 Octave Band Analysis

After analysing the data for speakers and shakers, the results for the two sound sources were compared. It must be mentioned here that the amplification used for both the shaker as well as the speaker was the same when measuring. As can be seen in Figure 4.1 and Figure 4.2 the frequency response plots of shakers and speakers show that the shaker is the weaker sound emitter of the two, especially in the lower end of the frequency range 315 Hz - 1000 Hz. To fulfill the legal requirements, the sound emitted by the sound source must have levels higher than the minimum levels (shown in green lines in Figure 4.1 and Figure 4.2) in two bands - one above and one below 1000 Hz. It would be easier to tune the designed sound to meet the legal requirement if the sound source emits strongly throughout the frequency range 315 Hz - 5000 Hz. Another thing that was not in favour of the shakers was that their acoustic response was changing when mounted on different parts. It would be difficult to have shakers as a reliable option universally because different cars will have different geometries and sizes e.g. for the bumper and thus the acoustic response would change drastically. Thus, although a shaker with a stronger radiation power could have solved the problem of weak low frequency emission, the fact that their acoustic response changes if mounted on different parts went against it and in favour of the speaker.



(a) Left microphone (b) Right microphone

Figure 4.1: Comparison between Speaker and Shaker mounted on Bumper.

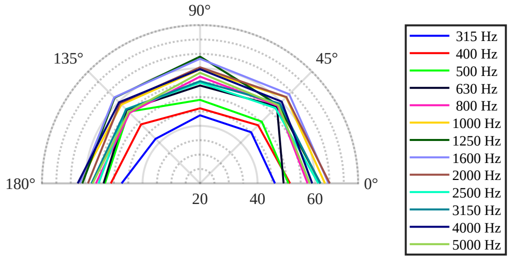


(a) Left microphone (b) Right microphone

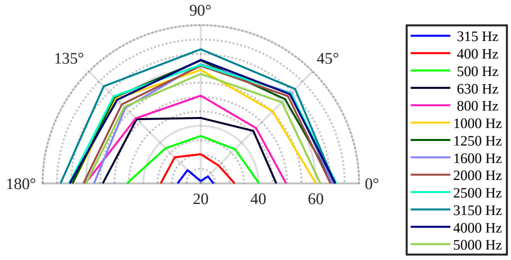
Figure 4.2: Comparison between Speaker and Shaker mounted near the Lights.

4.2 Directivity

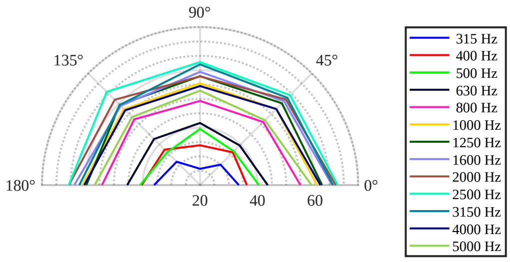
The analysis for the directivity when measured at all five microphones confirms the results from the 1/3 octave band analysis. The loudspeaker was compared to the shaker mounted on the three different bumper positions first (see Figure 4.3). It can be seen that the loudspeaker radiates sound quite omnidirectionally. When it comes to shakers, low frequencies around 315 Hz are a bit weaker than higher frequencies starting at around 630 Hz. In this range from 315 Hz to 630 Hz the biggest differences with the shaker can be found. The shaker does not radiate much sound on all three bumper position in that range. Starting at around 1000 Hz the sound gets radiated more linearly. For the shakers the radiation pattern is also not as omnidirectional as it is for the loudspeakers, there is slightly more sound radiated on the left side of the bumper. This might be most likely due to different contact points and a different mounting of the bumper on the left side than on the right side.



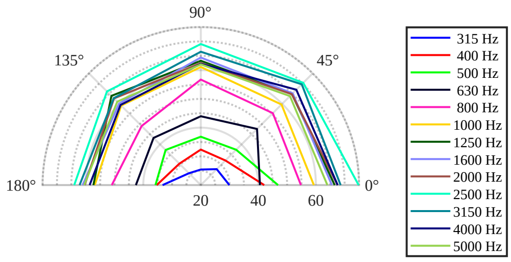
(a) Loudspeaker



(b) Shaker on Bumper Top



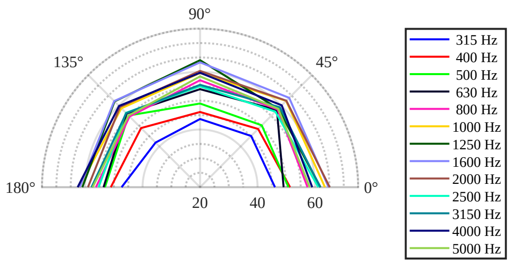
(c) Shaker on Bumper Middle



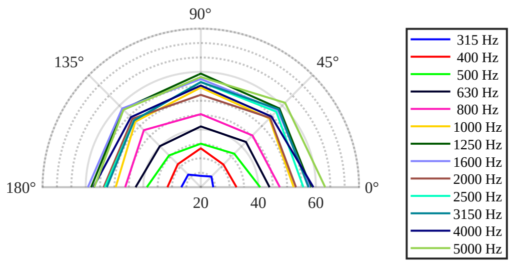
(d) Shaker on Bumper Low

Figure 4.3: Results of the directivity investigation with the total sound pressure level in dBA on the radiant axis.

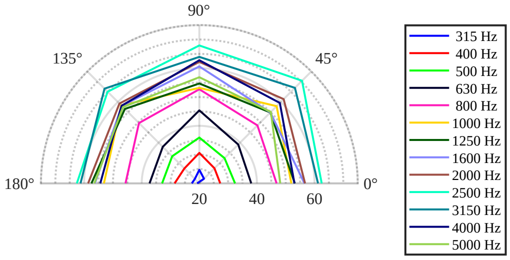
The same thing as explained before can be seen in the comparison of the loudspeaker with the shaker mounted on the light positions (see Figure 4.4). The difference here is that the radiated sound is weaker when mounting the shaker on the lights.



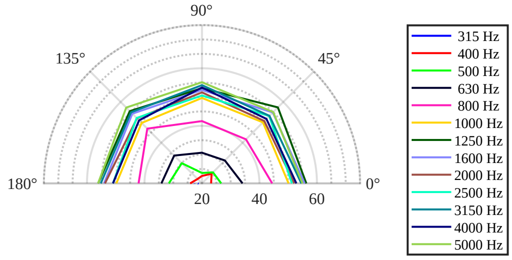
(a) Loudspeaker



(b) Shaker on Lights Top



(c) Shaker on Lights Middle



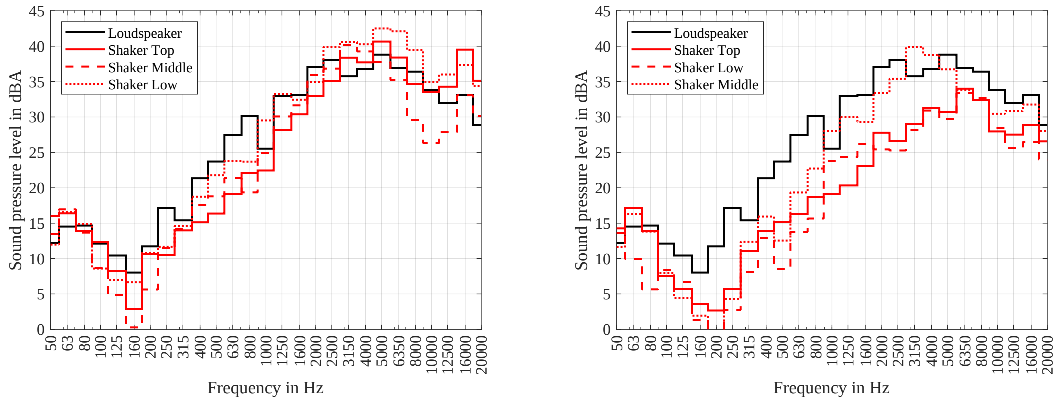
(c) Shaker on Lights Backside

Figure 4.4: Results of the directivity investigation with the total sound pressure level in dBA on the radiant axis.

The low frequency behaviour is really bad and the general sound pressure radiated is weaker than on the bumper positions. The omnidirectional pattern therefore is stronger on the bumper. If one has to decide between shakers mounted on lights or the bumper it can be clearly seen that in that case the bumper would be the better option. Overall the loudspeaker seems to be the best option in terms of directivity as well.

4.3 Interior Leakage

The following plots show the difference between the sound radiated outside vehicle to the sound leaking into the vehicle cabin for the (see Figure 4.5) for the loudspeaker position and also for different shaker positions. It can be seen that the difference between sound radiated out and that leaking into vehicle for the loudspeaker is the higher compared to the difference for shakers in different positions, especially at lower frequencies. At higher frequencies the difference between sound radiated out and sound leaking into cabin is almost the same for loudspeakers and shakers on bumper position. But when shakers are put on lights, the difference is much more for loudspeakers. This confirms once more that the loudspeakers are a better option when it comes to selecting the sound source.



(a) Shaker on Bumper (b) Shaker on Lights

Figure 4.5: Difference between sound radiated out and sound leaking in to vehicle cabin

To summarize the results from above, the loudspeakers have a good frequency response for the frequency range of interest between 315 Hz to 5000 Hz. The shaker on the other hand have a bad frequency response at the lower end of the frequency range. Secondly, the acoustic response of the shaker changes if it is mounted on different parts as the sound radiation depends on the geometry, size and stiffness of the part on which it is mounted on the contrary to the shaker, the acoustic response of the loudspeaker is not as much affected with change in mounting position. The directivity plots also show that the loudspeaker is a better sound radiator in all directions at all the frequencies between 315 to 5000 Hz whereas the shaker radiation is highly directional and the radiation magnitude is also low especially at lower frequencies. The interior leakage plots show that the amount of sound leaking into the cabin is almost the same for both shakers and speakers. For all of the above mentioned reasons, it was decided to use speaker as the sound source instead of shakers. The only positive thing about using a shaker was the ease of mounting anywhere in the vehicle.

5

Sound Design and Tuning

After determining the loudspeaker setup as the more suitable way to emit sound in this case the following chapter introduced the approach used for creating sounds and tuning them to fulfill the legal requirements.

5.1 Ideas behind the sounds

When it comes to creating sounds a wide range of aspects were considered before the sounds were created. The sounds should be functional in terms of audibility and safety but also aesthetic. Aesthetic in this case means that the sounds should represent and fit to the brand. Since Volvo as a vehicle manufacturer respects core values of having everything organic and serene, this was taken as the main framework while designing the sounds. To create nature sounds instruments like flutes, tibetian singing bowls or nature sounds like the flow of water were used. The procedure used was that sounds were first created in the listening studio and then put into the context of the vehicle with the loudspeaker. Based on that the sounds were changed again in the listening room to make them sound as desired.
After creating about 30 different sounds, they were narrowed down to eight and put in different categories which help answering the research questions of the listening test later. Those categories of sound were e.g. Dark, Bright, Sine, Noise, Low Rhythmic, High Rhythmic, Mono and Stereo sounds. To design the Dark and Bright sounds, the sound produced by tibetian singing bowls (shown in Figure 5.1) was used as the base sound. Logic Pro was used to add different virtual instruments like organs and strings. Some modifications were done to this sound using different objects in Max/MSP software for example reverb was added. As the sound from these bowls is used in different sound therapy treatments and the sound in general is known to be quite tonal and soothing, it appears to be an good option. Different sizes of the bowl produce different tones e.g. larger bowl produces more low tonal sound and a smaller bowl produces high tonal sound. The sound is produced by rubbing the hammer against the wall of the bowl.

Figure 5.1: Tibetian Singing Bowl

To get a judgement about the tonality of other sounds, pure sine tone representing sound of highest tonality and noise representing sound of very low tonality were used as anchors. To generate the sine tone sound, two sine waves - one with frequency below 1000 Hz and one with frequency above 1000 Hz were superimposed. This was done to make sure there is no trouble in fulfilling the legal requirements. Similar thing was done while generating the noise sound; band limited white noise was used for this purpose.
Another sound category that was used was the low rhythmic sound. This sound contained a subtle heartbeat intended at giving a perception that the vehicle is ready to move. It should be tested for the situation when the vehicle is stationary but active and ready to move. A layer of a heartbeat was added to layer of another sound to generate the heartbeat effect. There was another high rhythmic sound that was created especially for the stationary but active condition of the vehicle. Since the heartbeat was a very low frequency sound, it does not give a proper sense of the direction from which the sound is coming and hence had some problems with localization aspect. Hence the high rhythmic sound with higher frequency content was used. The original sound was basically an alarm signal sound picked up from the web and then modified using Audacity Software by shifting it's pitch. For the mono and stereo sound a synthesizer from Native Instruments Komplete package was used which produced a broadband wind like noise with some organ components. After adding reverb the sound was created in mono and stereo for a later investigation.

5.2 Tuning

With the selection of the eight sounds the tuning was necessary to fit them to the legal requirements. This adjusting was mainly done within Max/MSP inside of semi-anechoic chamber.

5.2.1 Preparing the sounds

The parameters that can be changed with the Max/MSP patch can be seen in the block diagram figure 5.2. There are different requirements for different speeds and Max/MSP allows to simulate the speed change of the vehicle and connect that with parameters which should be changed. Those parameters were the level of the sounds, the frequency spectra, a possible delay and the pitch shift. In the real use later in the vehicle the simulated speed change can just be replaced by the real vehicle speed received via the OBD port of the vehicle.

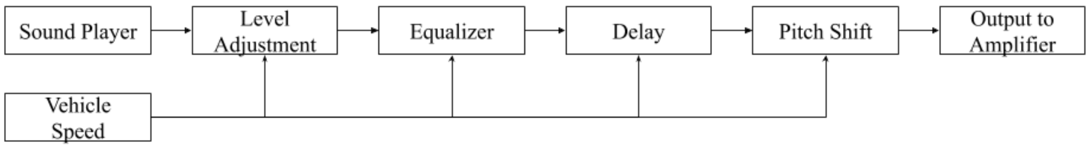


Figure 5.2: Signal processing chain of the sounds in MAX/MSP.

The created Max/MSP patch is shown in figure 5.3. The player on the right hand side shows all eight sounds and then according objects were created to achieve all the changes needed.

Figure 5.3: The GUI build in MAX/MSP to control sounds manually and automaticlly with the vehicle.

5.2.2 Pitch Requirements

As per the legislations, the pitch of the sound should shift by at least 0.8 percent for every 1 km/h change in speed. As can be seen in Figure 5.4, the frequency component is shifting from 560 Hz to 649 Hz where the minimum required shift is supposed to be at 604 Hz. This validates the fact that the frequency peak is shifting by more than 0.8 percent for change in speed which is what is required to fulfill the legal requirements. The pitch shift was done within the Max/MSP software with the in-built "pitchshift" object. The pitch object uses a ZTX based shifting by the company "zynaptiq". According to their website [13] a "...state of the art adaptive wavelet technology for high localization in both the time and frequency domains to significantly outperform traditional PSOLA or phase-vocoder based designs..." is used.

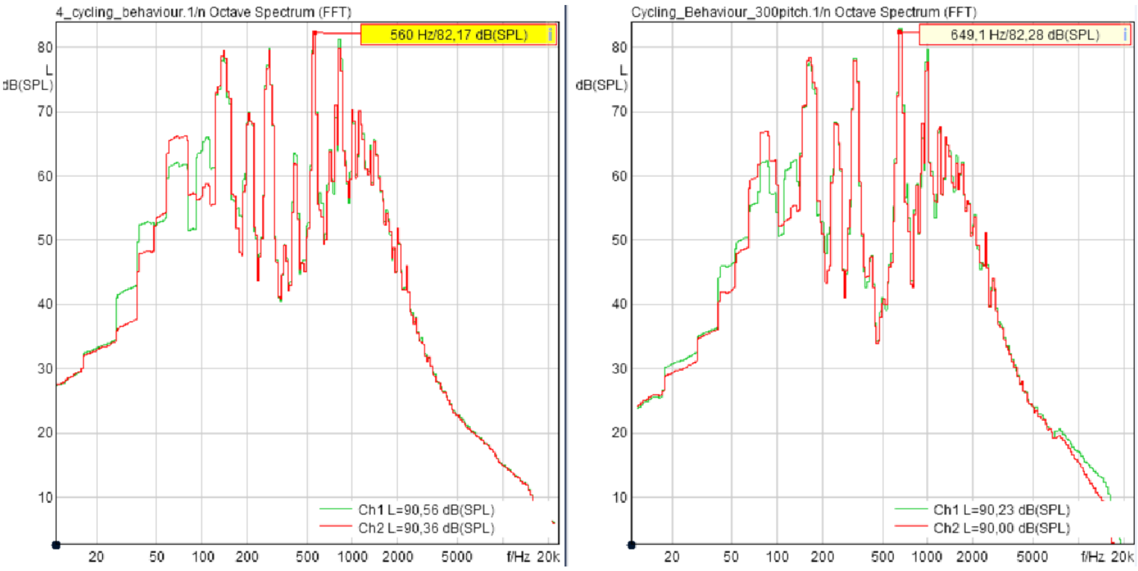


Figure 5.4: Before (left) and after (right) pitch shift. The pitch shift fulfills the requirements.

5.2.3 1/3 Octave Band Requirements

The sounds developed for AVAS were then played through the speakers and measured through the microphones. It was checked if the sounds were fulfilling the legal requirements or not. Sounds not fulfilling the legal requirements were tuned using the equalization object in MAX/MSP. The third octave band frequencies not fulfilling the legally requirements were increased in sound pressure level and third octave band frequencies way above the legally required values were reduced in sound pressure level. After tuning the sound, it was made sure that two non-adjacent third octave frequency bands, one above 1000 Hz and one below 1000 Hz were fulfilling the requirements as per the table in Figure 2.2. At the same time, it was made sure that the sound after tuning did not differ too much from what it originally was.

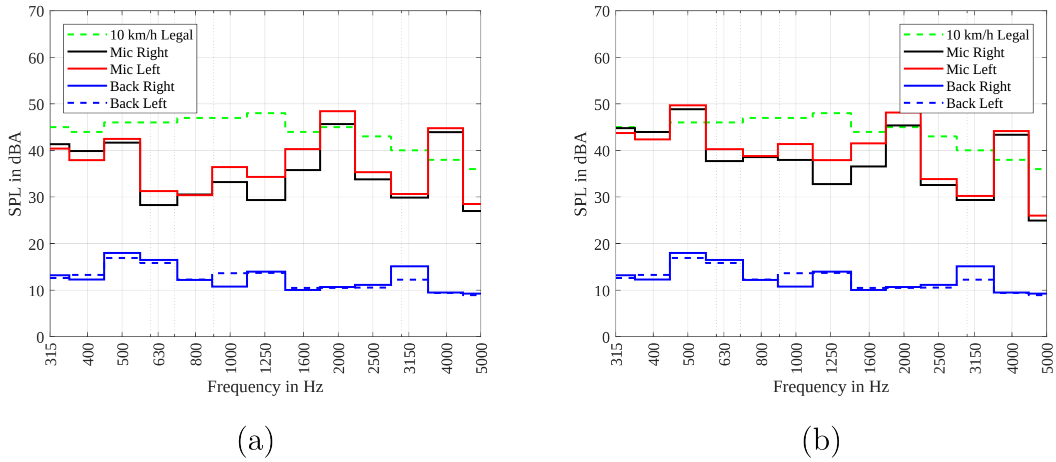


Figure 5.5: Sound not-fulfilling (a) and sound fulfilling (b) legal requirements for 10 kph with a bandsum of 50.4 dBA at the right microphone.

As can be seen in Figure 5.5 (a), the legal requirements are not fulfilled. There has to be one third octave band at or below 1000 Hz band and one third octave band above 1000 Hz which fulfills the requirements. But only the third octave bands at 2000 Hz and 4000 Hz are above the minimum requirements curve. After tuning the sound, it was made sure that at least two bands fulfill the legal requirements. As shown in Figure 5.5 (b), the third octave bands at 500 Hz, 2000 Hz and 4000 Hz fulfill the legal requirements. Furthermore the bandsum of the two bands must fulfill a certain minimum. What needed to be done basically was to calculate the bandsum for the left and right microphone for the chosen bands. Then the lower bandsum between the microphones has to fulfill the bandsum requirement. Here the bandsum is 50.4 dBA at the right microphone and the minimum has to be between 49 to 53 dBA SPL (see Figure 2.2). Hence all requirements are fulfilled and for all sounds repeated.

6
Listening Test Procedure

6.1 The goals of the test

Fulfilling the legal requirements is not the only thing a sound designer has to worry about. The acoustic subjective impressions that the vehicle makes on the customers can highly influence their decision to buy or not buy a vehicle - safety is here one of the most important things with e.g. Audiblity and Localization of the sounds. Therefore, it is important that the designed sound falls in line with the image of the product. In our case, a Volvo electrically driven vehicle. If the designed sound does not meet the customer expectations or makes a negative impression, it may result in complete failure of the product. The listening tests when designed correctly helps to get an understanding about the likes and dislikes of the people about a particular sound and in particular scenarios. For designing the listening test to evaluate the created sounds, research questions were developed to set clear investigation goals. They were investigated in two main fields. The first field was to evaluate how the sounds behave in terms of safety, aesthetic and appropriateness to the environment. And secondly a direct comparison between the sounds was done. The research questions are:

- How are sounds with low or high tonal components perceived?
- How are tonal sounds perceived compared to non-tonal sounds like noise?
- How are sounds perceived with a rhythmic component in the low frequencies compared to sounds with a rhythmic component in higher frequencies especially when the vehicle is stationary and idling?
- Since to loudspeakers are used on each side of the vehicle the question arises if a stereo sound makes a difference compared to a mono sound in terms of Localization?
- Which sound do most people prefer?
- Which sound can be localized the best?
- For which sound is a speed changed recognised the easiest?
- Are sounds perceived differently depending in in which scenario you here them?
- Is there good correlation between test results and psychoacoustic parameters like sharpness, tonality etc.

6.2 The design of the test

It was ideal to have as many people for the test as possible. But because of time constraint, it was decided to have around 30 people with a good mix of both males

and females from different age groups. It was also decided to include extreme sounds representing different categories like tonal and non-tonal, noise and sine tone, rhythmic and non rhythmic in the test to ensure good quality of the results. The extreme sounds would be used as anchors for different categories. An example of this would be to use a sine tone representing extreme tonal sound and a white noise representing a non tonal sound. Judging the tonality of different sounds if we have sine and white noise as the anchor.
The test was designed to have four different scenarios. It was important to understand how the sound is perceived in different vehicle conditions like accelerating, decelerating, stationary and constant speed. It was also important to understand if people are able to perceive the change in speed of the vehicle as it is an important safety parameter. Out of the four scenarios a rough test procedure was created as shown later in Figure 6.3.
The questionnaire prepared for the listening test was designed in such a way that clues about the sound from the point of view of safety, aesthetics etc.could be extracted. For example questions about ease of Localization, Audibility and Speed Change could extract information which is important from safety point of view. At the same time, questions about Pleasantness, Annoyance, Personal Preference could provide information about aesthetics of the sound.
The same set of questions were applied to all the scenarios to ensure quality and cross verification. For example the question about the perception of change of speed was the same in the constant speed scenario as well as in the acceleration and deceleration scenarios. An effort was made to ensure the questions were framed in an uncomplicated manner so that they are easy to understand and answer. The length of the test was also kept as short as possible to avoid improper answers out of desperation to finish the test quickly from the participants. Each of the questions had to be answered by choosing one of the five options - first option being complete disagreement with the question, the fifth option of complete agreement with the question. The scale was the following:

1. not at all
2. a little bit
3. difficult to say
4. quite a bit
5. totally

It is important to point out that the scales do only reflect the participants' judgement of their perceptions. It is not a general way in how the attributes e.g. audibility or localisation is derived and it does not contain information about how well the participants do or how right their answers are. The test was designed using Google forms and the participants gave their feedback using their smartphones.

6.3 Test environment

The listening test was conducted at the Johanneberg campus of Chalmers. The street where the test was conducted has a dead end with a turning circle. This allowed us to divide the test into different scenarios because the vehicle could be stopped at several locations without disturbing anyone. Furthermore there was enough space for placing the participants and keeping the same distance from them independent of the direction in which the vehicle went. It was decided to conduct the test there as it is a calm locality. So the vehicle sounds are easily heard and at the same time there is a low level of background noise from the city. There is a tennis court on the side of the road and a soccer field. So there was low level noise from people playing tennis in a few cases and a lawnmower mowing the field. These were good conditions for testing out the sounds as they closely replicated practical situation.

Figure 6.1: View of the test environment with a turning circle at the end.

6.4 How was the test conducted?

Thirty people with ages ranging from twelve years to fifty-nine years participated in the listening test. The test consisted of 20 male and 10 female participants. The participants were divided into six different groups. Each group had on an average five participants. The listening test was conducted seperately for all the six groups across two days. The surrounding sound and conditions were almost the same for all the groups except for the first when there was a constant noise from a lawn mower in the surrounding area.
The participants were asked to stand on one side of the road on which the vehicle was driven as shown in Figure 6.2 .

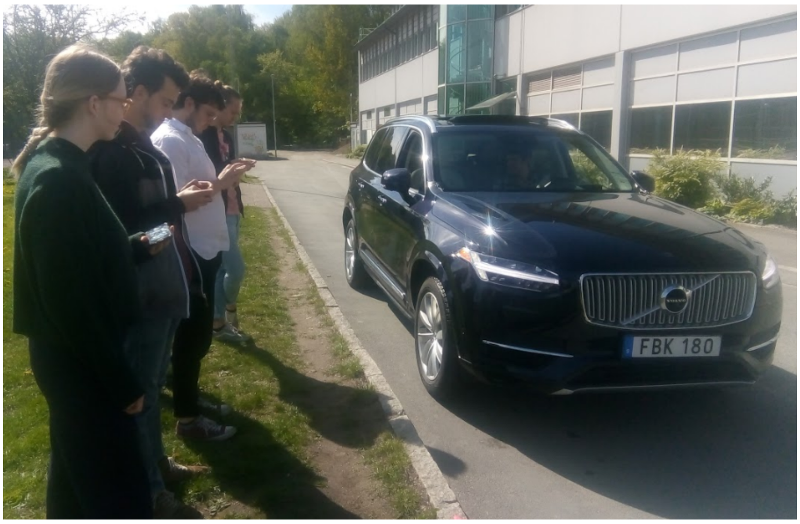


Figure 6.2: Participants evaluating the vehicle sounds.

The test was divided into four different scenarios as shown in Figure 6.3

1. Scenario one : The vehicle was driven at a constant speed of 10 km/h
2. Scenario two : The vehicle was decelerating towards the participants
3. Scenario three : The vehicle was stationary
4. Scenario four : The vehicle was accelerating towards and past the participants

In the beginning of the test all participants got the same introduction and they got to listen to the eight sounds chosen with the vehicle stationary. With that they got an overview about the variety of sounds which makes it easier to judge about extreme cases. During the test there was always a supervisor ready to answer questions and to avoid the feeling of helplessness. For each of the four scenarios, the participants were asked to fill up a questionnaire (see Appendix A). The questionnaire consisted of questions about the pleasantness, annoyance, localization etc. of the sound based on the research questions created in Section 6.1. The sound was to be judged independently for different scenarios. The order of the sounds for each group was randomised to ensure reliable results.

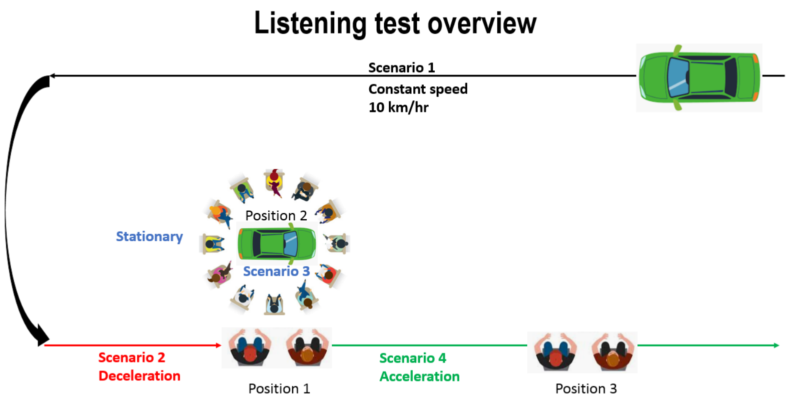


Figure 6.3: Schematics of the order of scenarios in the listening test.

7

Listening Test Results

The following chapter explains the analysis of the data from the listening test and correlates the outcome with psychoacoustic parameters. After giving some information about the analysis the results are shown. The results are answering the research questions of safety, aesthetics and appropriateness to the environment and after that sounds are compared to each other before at last the correlation with psychoacoustic parameters is done.

7.1 Analysis of Data

Before the results are presented a short information about the statistical reliability is given in the following lines. It ensures the quality of the data shown and helps understand the way the data is presented as well. The analysis of the data was completely done in MATLAB and is described as following. First the data needed to be rearranged to check it for any order effects due to the randomised order for the six different groups of participants. Then all groups are summarised into one big group which contains then all participants. After that the answers of the participants are assigned to numbers from -1 to 1 which correspond to their judgements. Hence the data can be easily handled now and tested. To test the data for statistical significant differences the ANOVA test was done. Before that it was checked if the data fulfills the prerequisites for ANOVA (see section 2.4.4).
One prerequisite is that the samples should be independent from each other which was achieved in the best way possible by having six random groups of participants evaluating each sound, scenario and attribute independent from each other. None of the participants participated twice in the test. Also the order of sounds was randomised for each group to avoid biased judgements. With that an sufficient independence of the participants is given. To test the data for a homogeneity of variance the test by Levene was chosen because it is more stable in case of non-normal distibutions. As a result of the test a p-value is determined which states how much the variances around the mean of the groups are differing. This test needs to be done for each of the eight sounds, eleven attributes and four scenarios with the 6 groups of participants. This leads to a total number of 352 tests. As a result out of the 352 p-values 89 are below the 5% threshold which says that not all samples show a homogeneity of variance. To test the data for a normal distribution different tests are available e.g. Kolmogorov-Smirnov in different forms, Anderson-Darling Test, Cramer von Mises test and Shapiro-Wilk test which show different results for the achieved data. Since the data is on an interval scale it is questionable

if and how the data can be normal distributed. With that in mind it was still decided to use ANOVA since its function is quite stable even if the prerequisites are not completely fulfilled.

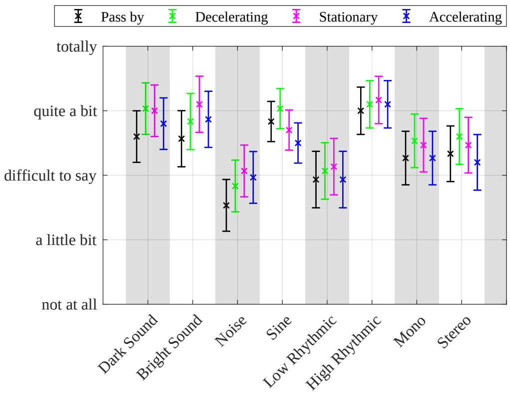
The results of ANOVA between all 30 participants show that 20 p-values out of 352 are below 5%. In these cases the probability of the mean being not independent is higher. With that statistical significant differences are identified. A reason for these values could be the incidents during the test which are the lawnmower and the activities on the tennis court during some groups. Also the tests in the evening contained significantly more wind and a colder environment. All those factors can lead to different perception of the sounds hence a different rating. Since the amount of statistical significances is still low it was continued with the next test.
For the second ANOVA test between the scenarios one thing is to mention because there could be a statistical significant difference identified for one attribute between the scenarios. This difference was expected since in scenario 3, a different question was used which lead to different answers compared to the other three scenarios. The question asked was about the perception of change of speed in scenario 1, scenario 2 and scenario 4. But for scenario 3, the question was asked about the perception of active-idling of vehicle. This question was implemented because the vehicle was stationary in scenario 3 (see Appendix A). With the obviously low p-value a correct working principle of the test could be proved and the quality of the results ensured. For now the results can be trusted and a further analysis of the mean and the the 95% confidence intervals according to section 2.4.4 was done. The reliability of the used tests is further discussed in 8.3.

7.2 Results of the research questions

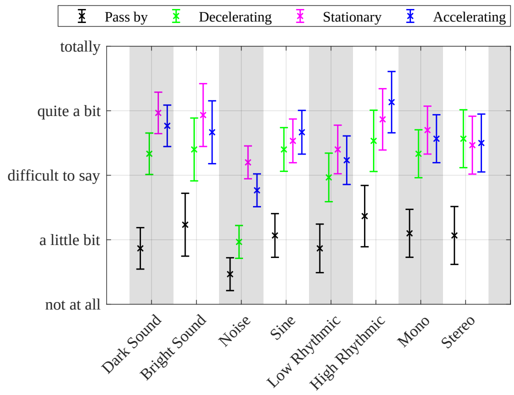
The following chapter gives information about the three main research questions for the best sound in terms of safety, aesthetics and appropriateness to the environment point of view. The figures shown in this section have eight sounds on the x-axis and the rating in words on the y-axis. The four colors represent the four driving scenarios. The whiskers show the 95% coincidence intervals with the arithmetic mean as a marker between them. For different aspects like safety, aesthetics and appropriateness to the environment the according results where chosen and compared.

7.2.1 Safety

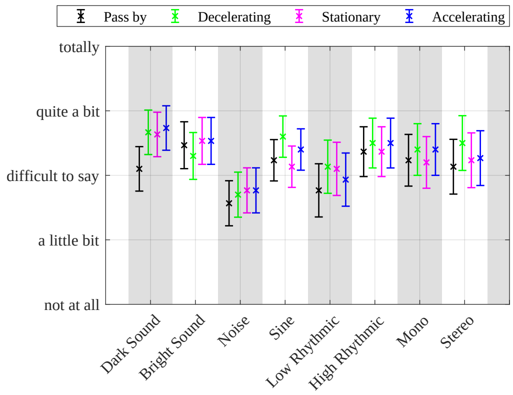
With the research question of the best sound in terms of safety the attributes of Audibility, Speed Change and Localization are evaluated. The results can be seen in Figure 7.1.



(a) Audibility



(b) Speed Change



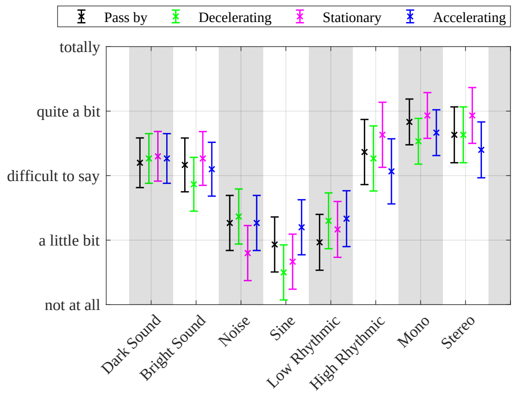
(c) Localization

Figure 7.1: Safety attributes compared.

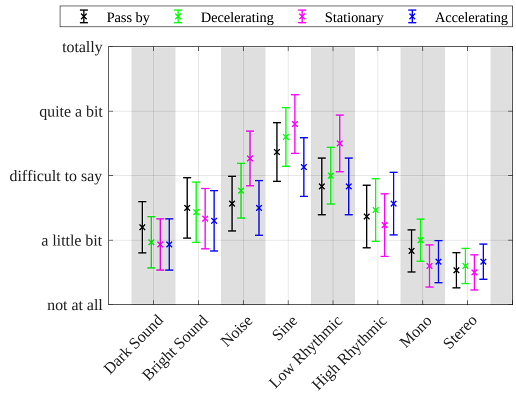
For the Audibility it can be seen that sounds with a broad frequency spectrum like the Dark Sound, the Bright Sound and the High Rhythmic sound are best and also the Sine leads to a high audibility. The Noise and the Low Rhythmic sound are the opposite and less audible. This can be due to the easier masking by the surroundings and wind. The Mono and Stereo sounds are most likely due o their broad but more low frequency spectrum also not that audible. For the attribute of the Speed Change it is the Dark Sound, Bright Sound and High Rhythmic sound that show the best perception of a speed change. The Noise shows again the worst behaviour. This gets once more verified by the attribute of the Localization where the Dark Sound, the Bright Sound, the High Rhythmic sound, the Mono and Stereo sounds also show the best results. In terms of safety it can be said that the Dark Sound, Bright Sound and High Rhythmic sound are the best. Hence a broad frequency spectrum which contains tonal components leads to better ratings in terms of safety.

7.2.2 Aesthetics

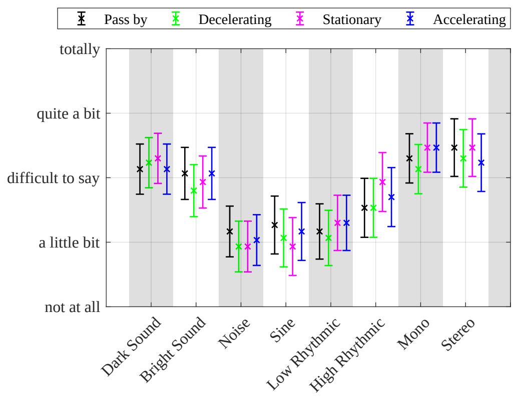
To answer the research question of aesthetics the attributes of Pleasantness, Annoyance, how premium the sound is perceived and the Personal Preference are checked. Just comparing the first two attributes (see Figure 7.2 (a) and (b)) shows a mirroring effect which verifies the analysis of the test. It can be seen what is perceived as pleasant is also perceived as less annoying.



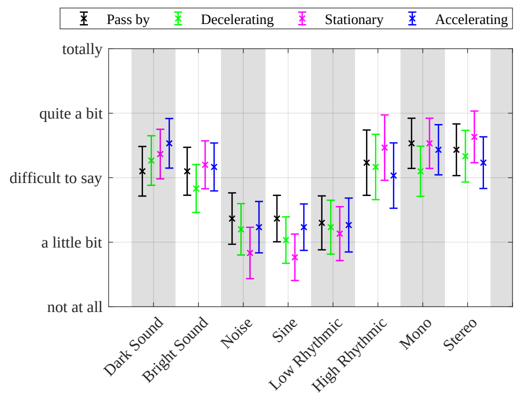
(a) Pleasantness



(b) Annoyance



(c) Premium



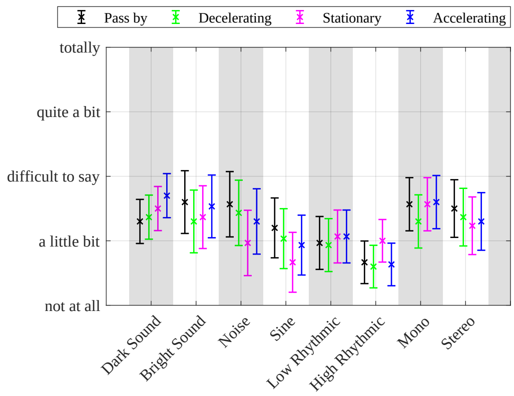
(d) Personal Preference

Figure 7.2: Aesthetics attributes compared.

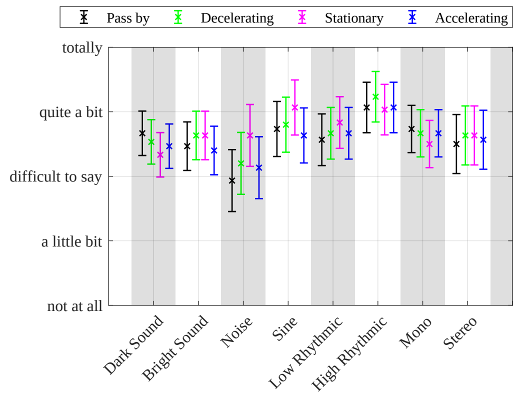
Here this is the Dark Sound, the Bright Sound, the Mono and Stereo sounds together with the High Rhythmic sound which show the best results. The same trend can be seen for the attributes of how premium the sound is perceived for the Personal Preference. The pattern from the Pleasantness can be seen for the Premium and Personal Preference attribute as well just a bit weaker. Out of the aesthetic point of view it can be said that a pure tonal component which is the case for the Sine leads to a bad aesthetic rating. Also the Noise is not rated as very aesthetic over all four attributes same as the Low Rhythmic sound. Therefore the Dark Sound, the Bright Sound, the High Rhythmic sound and the Mono and Stereo sounds can be recommended out of aesthetic point of view.

7.2.3 Appropriateness to the environment

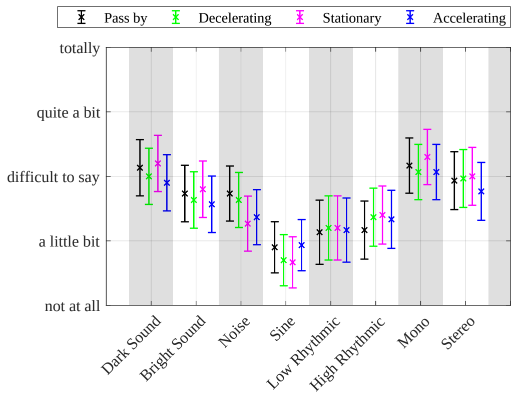
To evaluate the results for the question of the appropriateness to the environment, the attributes Organic, Artificial, Forest Environment and City Environment are presented in Figure 7.3. Looking into the Organic attribute plot, it can be seen that no sound has a good rating. All of them are around or below the "difficult to say" mark.



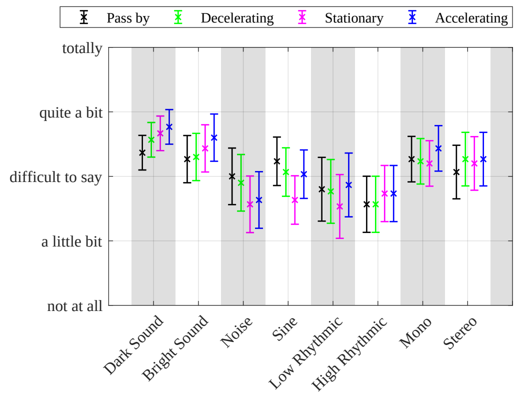
(a) Organic



(b) Artificial



(c) Forest Environment



(d) City Environment

Figure 7.3: Appropriateness to the environment attributes compared.

The question here is if a vehicle can even sound organic or if an organic sound means the same to all participants. The results here show that a closer look into the attribute of Organic could be good. Nevertheless the Dark and Bright Sound as well as the Mono and Stereo sound resulted in the best ratings. The results of the Artificial attribute show more or less the mirrored behaviour then the Organic attribute. Almost all sounds were rated above the "difficult to say" mark. In a way this makes sense since in this test a vehicle emits artificially created sound which is most likely in all cases perceived as artificial for the participants. The most artificial sounds would be the Sine sound and the High Rhythmic sound because they are hard to connect with any existing vehicle sound and catch a lot of attention. The results of the Forest Environment show a similar trend compared to some aesthetic values of Pleasantness, Premium and Personal Preference with the Dark and Bright sound and the both Mono and Stereo sounds are the ones with the highest ranking. This trend can slightly be seen for the City Environment as well. In both cases, the Forest Environment and the City Environment, the Dark and Bright Sound and the Mono and Stereo sound are rated best. The idea of correlating the organic results with the results of how well the sound fits into a forest can hardly be made since the similarities are too vague. The same applies to the artificial value correlated with how well a sound fits into a city environment. To find a reliable connection here is not possible, for getting a reliable correlation a deeper insight has to be gained in what defines those values to allow to connect them with each other.

7.3 Comparison of the sounds

The data presented below in Figure 7.4 (a) - (c) shows the comparison between the Dark Sound and the Bright Sound sound, the Sine and Noise sound, the Mono and Stereo sound and the Low and High Rhythmic sounds.

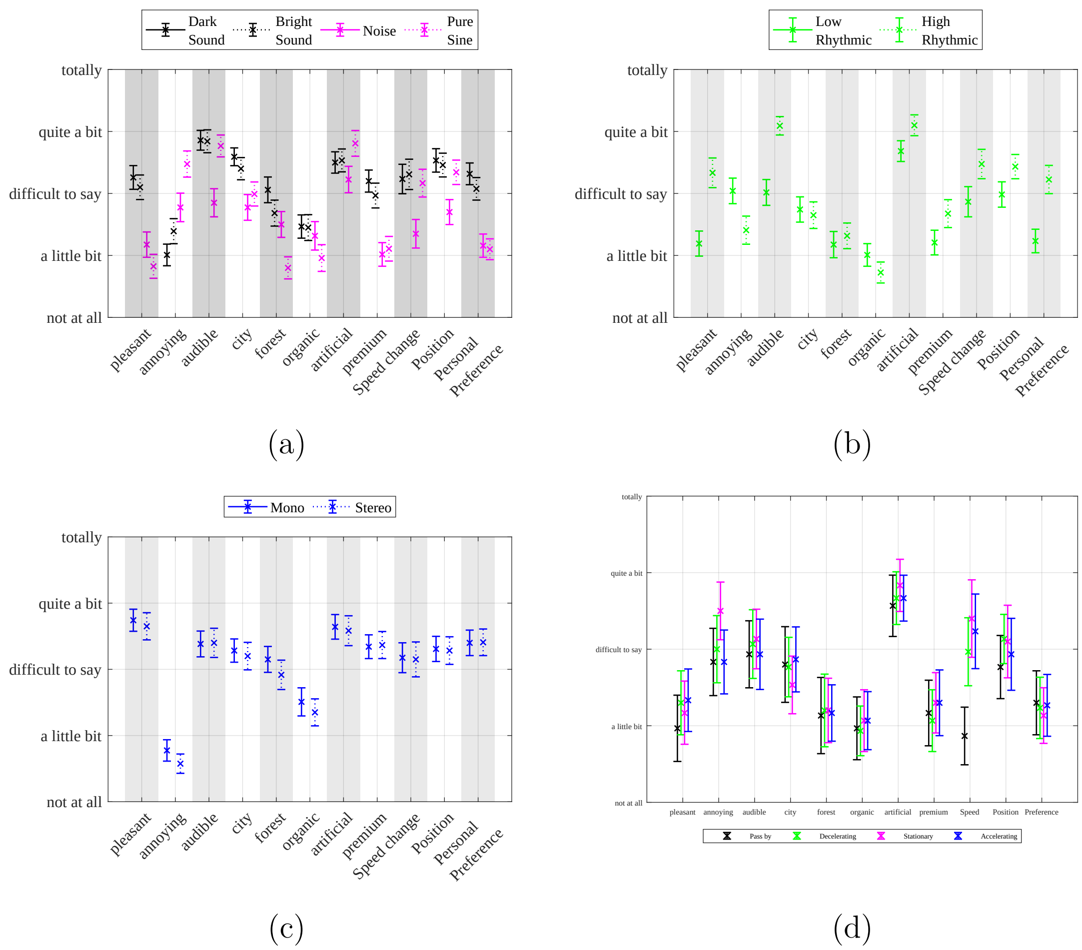


Figure 7.4: Comparison between sounds and scenarios

Figure 7.4 (d) shows the comparison between the four scenarios where the vehicle is accelerating, decelerating, passing by at constant speed and remaining stationary for one of the sounds (all sounds are shown in Appendix B). It can be clearly seen that the judgement about different scenarios does not differ much. For example, the sound is perceived almost equally pleasant for the four different scenarios. Hence one sound can be used for all four scenarios.

While comparing the Dark Sound and Bright Sound sound, it is clear that the Dark Sound is perceived slightly more pleasant compared to the Bright Sound. This gets confirmed from the Annoyance which is rated high for the Bright Sound. In terms of Audibility, both sounds are perceived equal. The Dark Sound sound is perceived to fit well both in the city and in forest compared to Bright Sound. Both sounds are perceived the same in terms of organic and artificial nature but the Dark Sound sound is rated higher in terms of premium quality. This could be because sounds with high frequency content give a feeling that something is fragile but the one with more low frequency content give a perception of something very solid. Also, with the Bright Sound sound, it is easier to perceive the speed change. Participants rated the Dark Sound as being easier to localise. This could be explained by the fact that some of the participants had their eyes open which influenced their answer and made the judgement less truthworthy. Finally the personal preference confirms the overall likeability of the Dark Sound sound compared to the Bright Sound one. This correlates with the results from Pleasantness. To sum up, the Dark Sound sound is recommended over the Bright Sound.

Comparing the Sine sound with the Noise, the Noise is preferred over the Sine sound from the aesthetics view point. The Noise sound was given higher ratings for Pleasantness and lower value for Annoyance compared to the Sine sound. From safety point of view, the Sine is clearly better as it is rated higher for attributes like Audibility, perception of Speed Change and Localization. On the contrary, the Noise fits better into both the Forest and the City environment. It is also perceived more natural compared to the Sine which can be seen from the higher ratings given for the organic nature attribute. This could be because of the fact that people are not familiar with a Sine tone coming out of a vehicle and hence rated it not natural i.e. artificial and hence less organic. In terms of personal preference Noise is slightly more preferred.

Next comes the comparison between Low and High Rhythmic sounds especially when the vehicle is stationary and idling. Beginning with aesthetics, the High Rhythmic sound is perceived more pleasant and less annoying than the Low Rhythmic sound. The safety attributes (Audibility, Speed Change and Localization) clearly show that a High Rhythmic sound is more audible and also better in terms of Speed Change and Localization. High rhythmic is perceived more artificial and premium and less organic because people are most likely not used to a vehicle sounding like that. This also applies to the perception of the vehicle in a city which is lower for High Rhythmic sound. None of the rhythmic sounds is well perceived in city and forest. The High Rhythmic sound was rated higher in terms of Preference. This could be because of the fun factor associated with that sound.

The comparison between the mono and stereo versions of the same sound gave almost identical results. According to our own observation, a big difference was perceived in Localization between the Mono and Stereo sound inside the semi-anechoic room. But when the Mono and Stereo sound were played in outdoor conditions the participants were not able to perceive any difference. This can be seen Figure 7.3 (c).

Coming to the question of the overall preference, the sounds most liked by the test participants were the Dark sound and both of the Mono and Stereo ones. Those sounds were rated quite pleasant and premium and not so much annoying. Apparently the high rating for the artificial attribute for those sounds is not influencing the personal preference so much.

7.4 Correlation with psychoacoustic parameters

For the correlation of the results with psychoacoustic parameters the focus was set on the parameter of tonality. Therefore the Tone to Noise Ratio (TNR) was calculated with the software Artemis. The results can be seen in the table 7.1. The TNR is then compared with the results of annoyance (see Figure 7.5) from the listening test.

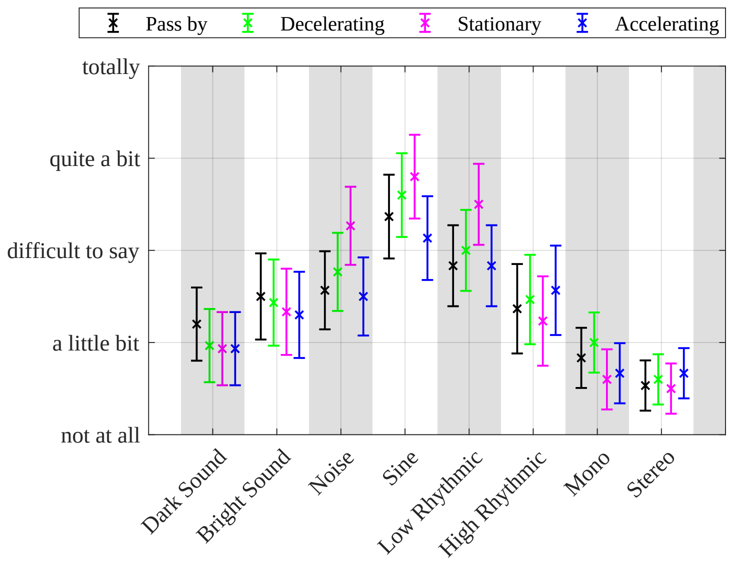


Figure 7.5: Annoyance plot of all sounds for different scenarios

The sound with highest TNR is the Sine sound which can be found in the annoyance plot as the most annoying one. That states that tones with only tonal components are not so good because they are perceived as highly annoying. On the other hand the Noise sound with the lowest TNR is not rated as much less annoying compared to the Sine. Out of that it can be said that a mixture out of tonal and broad sounds might be the most suitable solution.

	Channel	Stationary TNR in dB	10 km/h TNR in dB
Dark Sound	Right	29,23	30,74
	Left	21,41	22,76
Bright Sound	Right	28,85	22,60
	Left	25,80	25,58
Low Rhythmic	Right	28,36	25,93
	Left	29,18	33,28
High Rhythmic	Right	20,22	28,17
	Left	16,65	16,74
Mono	Right	18,52	26,58
	Left	14,55	20,55
Stereo	Right	18,45	25,79
	Left	16,01	22,58
Noise	Right	5,12	3,87
	Left	2,65	4,23
Sine	Right	50,8	39,22
	Left	49,37	43,61

Table 7.1: The calculated TNR values for all sounds.

All the other values have a TNR somewhere in between the extreme cases of the Noise and the Sine and they get also a less annoying rating. As found out before the Dark and Bright sound together with the Mono and Stereo sound are perceived as less annoying, the TNR for those is between 15 dB and 30 dB. A TNR in that level could be a way to identify and avoid very annoying sounds. The TNR for the rhythmic sounds are also in that range but the rhythmic component is most likely not taken into account while calculating the TNR. Therefore one has to be careful with completely relying on the TNR to identify annoying sounds.

8
Discussion

8.1 Measurements

The first part of the discussion is about the position of the loudspeaker. The most important thing that was considered while positioning the loudspeaker was that the emitted sound should most efficiently reach the measurement microphones. The chosen position on the bumper is the closest on the vehicle to the measurement microphones. Also, the hatch on the bumper behind which the loudspeaker is mounted has holes in it. The holes allow sound to easily pass through (without reflecting it backwards) and reach the measurement microphones. Another advantage of positioning the loudspeaker in the chosen position is that it is properly hidden there.
The second point to discuss is about the shakers. Using shakers was a very good option as it is very easy to mount anywhere on the vehicle. The power output from the shaker was also not bad. But the fact that the acoustic response of the shaker is different when mounted on different parts of the vehicle is a major concern when it comes to fulfilling legal requirements across different third octave bands. Because of different frequency response, the shaker is not a universal solution as the same shaker cannot be used on different cars. Different cars will have parts of different geometries, size, weight and hence the acoustic reposnse will be different when the shaker is mounted on those parts. Thus it will be difficult to make different cars fulfill the legal requirements.
The third point to discuss is about the use of transfer function or rather the reason for not using it. Transfer function which is the ratio of the sound output from the sound source to the sound input to the sound source was initially thought of to make it easy to check if the designed sound would fulfill the legal requirements without actually measuring the output sound. But because of the non-linearities that were observed mainly in the shakers and to a small extent in the speakers, the method was discarded.

8.2 Sound Design

It is worth mentioning that while tuning the sounds to fulfill legal requirements, the measurements were done inside the semi anechoic room which had no wind and hardly any background noise. These are not the practical conditions that the vehicle would encounter. Secondly, while measuring the sounds, the vehicle is supposed to be moving at 10 km/h, 20 km/h except for the case when it is stationary. But because of time constraint and ease of measurements, our measurements were done in controlled environment of semi anechoic room with the vehicle stationary. Also, the frequency peak shift that is supposed to happen with change in vehicle speed was not measured in real condtions.

8.3 Listening test

When it comes to the listening test different things have to be discussed. One thing would be the test design by itself and a second thing is the analysis with the ANOVA test and the form of presentation with 95% confidence intervals. The ANOVA test was used to decide if there were a statistically significant differences in the mean values obtained from the six groups that participated in the listening test. As explained in the theory part (see Section 2.4.4) some prerequisites must be fulfilled to allow this. In Section 7.1 it is shown that not all prerequisites are fulfilled which means the reliability of the ANOVA results have to be carefully considered and can not be blindly trusted. The ANOVA was still used because it is considered as a quite stable way of investigating for statistical significant differences. The results of the ANOVA test itself showed with 20 out of 352 p-values below 5% a good result which allows to trust the derived averages and the CI. But still the averages should not be seen as completely reliable, that would need a more detailed investigation.
It is also important to check whether the scale used to rate the questions in the experiment is non-linear or linear. If the scale is non linear, it may give rise to a bias due to perceptually non-linear scale. For example, in the questionnnaire, the labels that have been used are "not at all", "a little bit", "difficult to say", "quite a bit" and "totally". The question whether the label "difficult to say" lies exactly in between "a little bit" and "quite a bit" or not is worth further exploration. If it does not, the listening test results may be affected. Unfortunately, because of time constraint, this bias could not be explored. A solution to get rid of this bias could be using only two labels e.g. "not at all" and "totally" ignoring all the other in-between labels.
Another thing that could give rise to the non-linear scale bias is the difference in the way people of different cultures interpret the labels. As people of different nationalities, religions, ethnicities and cultures participated in this test, it is highly possible that for one person the label is not as extreme as it is for another person coming from a different culture and speaking a different language. For example, the label 'a little bit' may be understood to be very close to the label 'not at all' by a person from one culture whereas a person from a different culture might find not find it as close giving rise to the non linearity bias. To get rid of this bias, numbers could be used as labels instead of words.
The third important point to discuss is about the judgement of the young 12 year old participants. After checking their answers to different questions in the questionnaire, it was found out that their ratings to different questions were falling fairly in line with what the other participants answered. This confirmed that their judgement was not to be discarded because of immaturity.
The 95% confidence interval is quite narrow as can be seen in the plots in the results section. This confirms the fact that the number test participants which is 30 for this experiment is sufficient.

It is worth mentioning that the listening test was conducted outdoors. For different groups doing the listening test, the external conditions varied a bit. For example, in the evenings on both the days, it was colder and windy. Some of the participants were not wearing jackets and were feeling a bit cold. This could definitely have a little bit influence on the answers they gave. Also, there was a lawn mover producing background sound for some of the batches. This could also make the sound produced by the vehicle sound a bit more annoying.
The question about how organic or artificial the vehicle sounds is a bit difficult to answer. The reason being, since the sound is externally added, it will never be natural and always sound artificial. Hence the participants must be informed in advance about what exactly is expected of them while answering that question.
The question about the ease of localization of the vehicle for a particular sound is a bit tricky to answer. It has to be made clear to the participants before hand that the intention of asking that question is to know how well the emitted sound is giving cues about the exact location of the vehicle. But for many participants who had their eyes open, the visual inputs were making it easier to localize the vehicle and hence the test results for that particular question could be biased. Hence, it would be a good practice to put a mask on the eyes of the participants while answering they answer the question about localization. This would completely eliminate the visual cues and help the participants make judgement only based on what they hear.

9 Conclusion

To conclude the thesis, the loudspeaker was identified as the better sound source compared to the shaker. The position of the loudspeaker on the bumper behind the hatch was identified to be the most practical one in terms of fulfilling the legal requirements.
In the sound design process eight sounds representing different categories were created and the listening test was carried out to evaluate the sounds with the help of the participants.
From the results of the listening test, it would be apt to say the Noise was considered less intrusive by the participants than the Sine. It matched better with the sound they are used to hearing from a vehicle with a combustion engine. Coming to the Low and High Rhythmic sounds, the High Rhythmic sound was rated higher in terms of preference compared to the Low Rhythmic sound. Also in the aspects of safety and appropriateness to the environment it received a better rating. The comparison between the Mono and Stereo sounds gave almost identical results, which means the participants could not differentiate between the two. The comparison between the Dark and Bright Sound yielded most of the results in favour of the Dark Sound. The Dark Sound with a lot more low frequency content compared to the Bright Sound was the preferred sound and was rated higher in terms of Premium Quality. The sounds most preferenced overall were the Dark sound and both of the Mono and Stereo ones.
For future investigations several things could be done, beginning with an investigation for stronger shakers. Furthermore investigations about an expanded setup with a sound source at the back of the car could be done to fulfill the legal requirements when the vehicle is reversing. Based on the current outcome, a new set of sounds could be created for future use. The current psychoacoustic investigation could be expanded to parameters like Harshness, Sharpness and Roughness and the TNR could be improved. For certain attributes e.g. Organic further insight could be gained with a deeper investigation and trained participants.

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A

Questionnaire

Sound Evaluation Test

Welcome to our sound evaluation test!

*Required

1. **How old are you?** *

2. **Gender:** *
   Mark only one oval.
   - Male
   - Female
   - Prefer not to say

3. **Do you have a hearing impairment?** *
   Mark only one oval.
   - Yes
   - No
   - Prefer not to say

4. **Do you have any experience in acoustics and sound evaluations?** *
   Mark only one oval.
   - NOT from the field of acoustics and have NOT done a sound evaluation test
   - NOT from the field of acoustics and have done a sound evaluation test
   - From the field of acoustics and have NOT done a sound evaluation test
   - From the field of acoustics and have done a sound evaluation test

5. **What did/do you study ?** *

6. **E-mail address (if you are interested in the test outcome)**

Sound 1 - Scenario 1:

7. **I think the sound is ...** *
   Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
pleasant					
annoying					
audible					

8. **How well do you think the sound fits into ...** *
Mark only one oval per row.

	not at all	rather not	neither of both	fits well	fits very well
a city?	◯	◯	◯	◯	◯
a forest?	◯	◯	◯	◯	◯

9. **To what extent does the car sound ...** *
Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
organic?	◯	◯	◯	◯	◯
artificial?	◯	◯	◯	◯	◯
premium?	◯	◯	◯	◯	◯

10. **Could you sense that the car is changing speed?** *
Mark only one oval.

	1	2	3	4	5	
not perceptible	◯	◯	◯	◯	◯	easily perceptible

11. **How sure were you about the exact position of the car?** *
Mark only one oval.

	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very sure

12. **How much do you like the sound ?** *
Mark only one oval.

	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very much

Sound 1 - Scenario 2:

13. **I think the sound is ...** *
Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
pleasant	◯	◯	◯	◯	◯
annoying	◯	◯	◯	◯	◯
audible	◯	◯	◯	◯	◯

14. **How well do you think the sound fits into ...** *
Mark only one oval per row.

	not at all	rather not	neither of both	fits well	fits very well
a city?	◯	◯	◯	◯	◯
a forest?	◯	◯	◯	◯	◯

15. **To what extent does the car sound ... ***
Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
organic?	◯	◯	◯	◯	◯
artificial?	◯	◯	◯	◯	◯
premium?	◯	◯	◯	◯	◯

16. **Could you sense that the car is changing speed? ***
Mark only one oval.

	1	2	3	4	5	
not perceptible	◯	◯	◯	◯	◯	easily perceptible

17. **How sure were you about the exact position of the car? ***
Mark only one oval.

	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very sure

18. **How much do you like the sound ? ***
Mark only one oval.

	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very much

Sound 1 - Scenario 3:

19. **I think the sound is ***
Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
pleasant	◯	◯	◯	◯	◯
annoying	◯	◯	◯	◯	◯
audible	◯	◯	◯	◯	◯

20. **How well do you think the sound fits into ... ***
Mark only one oval per row.

	not at all	rather not	neither of both	fits well	fits very well
a city?	◯	◯	◯	◯	◯
a forest?	◯	◯	◯	◯	◯

21. **To what extent does the car sound... ***
Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
organic?	◯	◯	◯	◯	◯
artificial?	◯	◯	◯	◯	◯
premium?	◯	◯	◯	◯	◯

22. **How sure are you about the exact position of the car?** *
Mark only one oval.

	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very sure

23. **To what extent do you feel the car is active/idling?** *
Mark only one oval.

	1	2	3	4	5	
not perceptible	◯	◯	◯	◯	◯	easy perceptible

24. **How much do you like the sound ?** *
Mark only one oval.

	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very much

Sound 1 - Scenario 4:

25. **I think the sound is ...** *
Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
pleasant	◯	◯	◯	◯	◯
annoying	◯	◯	◯	◯	◯
audible	◯	◯	◯	◯	◯

26. **How well do you think the sound fits into ...** *
Mark only one oval per row.

	not at all	rather not	neither of both	fits well	fits very well
a city?	◯	◯	◯	◯	◯
a forest?	◯	◯	◯	◯	◯

27. **To what extent does the car sound ...** *
Mark only one oval per row.

	not at all	a little bit	difficult to say	quite a bit	totally
organic?	◯	◯	◯	◯	◯
artificial?	◯	◯	◯	◯	◯
premium?	◯	◯	◯	◯	◯

28. **Could you sense that the car is changing speed?** *
Mark only one oval.

	1	2	3	4	5	
not perceptible	◯	◯	◯	◯	◯	easily perceptible

29. **How sure were you about the exact position of the car?** *

Mark only one oval.

	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very sure

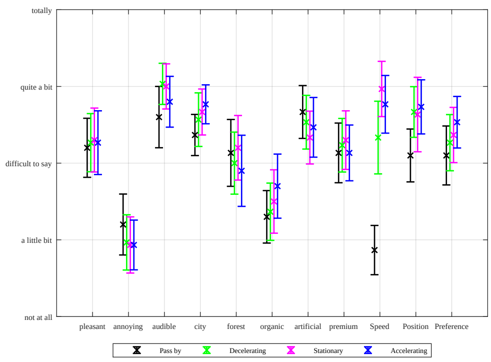
30. **How much do you like the sound ?** *

Mark only one oval.

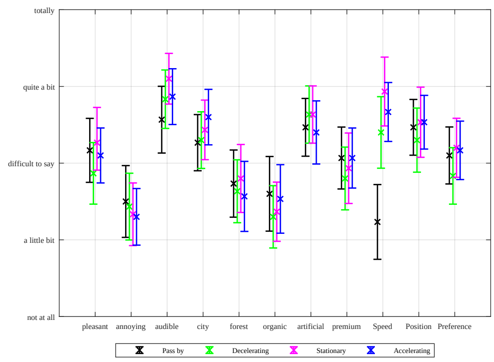
	1	2	3	4	5	
not at all	◯	◯	◯	◯	◯	very much

B

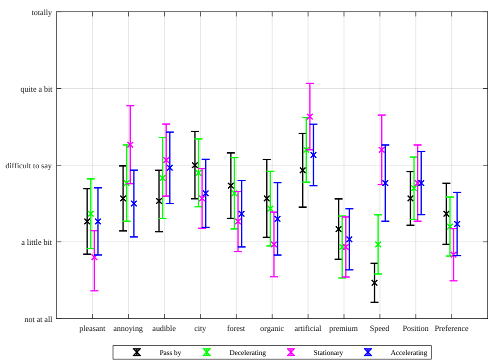
Comparison of scenarios



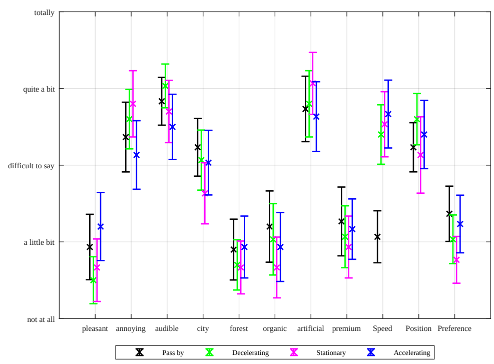
(a) Dark Sound



(b) Bright Sound

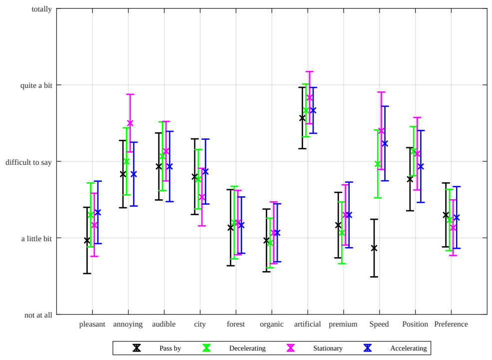


(c) Noise

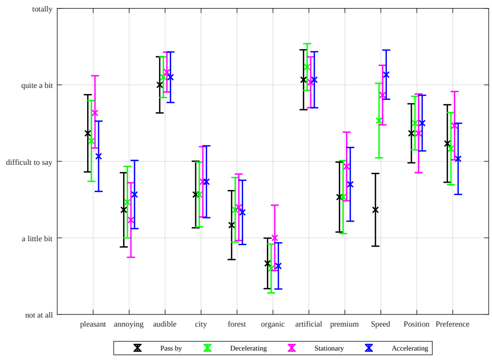


(d) Sine

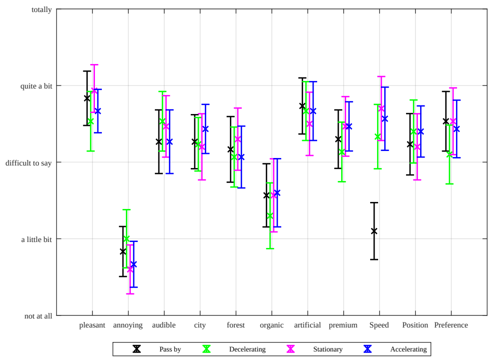
Figure B.1: Comparison between scenarios 1 to 4.



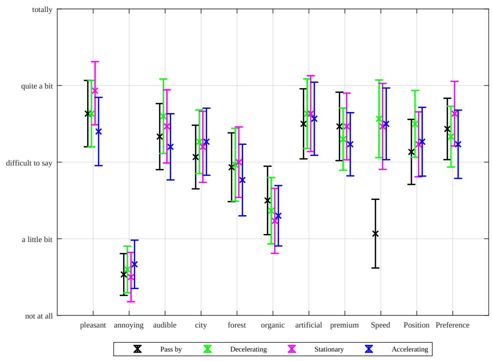
(a) Low Rhythmic



(b) High Rhythmic



(c) Mono



(d) Stereo

Figure B.2: Comparison between scenarios 5 to 8.

C

Contribution Report

This is a short contribution report that explains who worked on what part of this master thesis. The thesis work could mainly be divided into literature review, sound source research, selection and positioning in the car, developing sound design concepts and implementation in car, listening test and statistical analysis of the results.

- Literature review: Both Anand and Markus read all the literature relevant to this master thesis including the legal requirements necessary for AVAS.
- Sound source research, setup and positioning: Both Anand and Markus carried out the research to find out the most suitable sound sources for this project.
- Deciding a proper position for the sound sources required doing a lot of sound measurements which were carried out together by the two of us. The measurement systems to use were also setup together. Markus worked more on the measurement software part (Audio Presicion APX500, Head Recorder and Artemis) and Anand worked more on arranging the hardware as per the standards e.g. microphone positions etc.
- Developing sound design concepts and implementation: Anand spent more time on developing different sound design concepts mainly with Audacity and Logic whereas Markus focused more on implementing those designed sounds in the car using softwares like Ableton and Max/MSP.
- Listening test and statistical analysis of results: A discussion was made together to decide how the listening test would be carried out and, why it has to be carried out and what is required to carry it out. The location of the listening test, what participants to invite, when to carry it out, the setup of the listening test were all decided together. Anand worked more on designing the questions and the options for the listening test. During the test, Markus was driving the car and Anand was directing and helping the participants understand things in case of any problem. The statistical analysis of the test data was carried out by Markus.