THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

PERCEPTION OF ROLLING NOISE

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Abstract

Due to improvements on combustion-engines and electric-engines for cars, tyre noise has become the prominent noise source at low and medium speeds. Models exist that simulate the noise produced by a rolling tyre, as do models that auralize different traffic situations from a basic data set. When constructing a tyre it is of interest if improvements and planned changes are not only physically measurable, but that they also can be perceived. Focussing on that, two aims were followed in this thesis. The first aim was to combine an established model for tyre noise (SPERoN) with an auralization tool. The combined model can predict the spectrum of the sound at 7.5 m, as well as reproduce the sound for a given listener position. The auralization uses a methodology where recorded sounds are converted to source signals for engine and tyre/road-interaction. These can be shaped by the spectra estimated in SPERoN and synthesized back into a pass-by signal. Psychoacoustic judgements were used to compare the modelled signals with recorded signals. To see how well the modelled signals match the real recorded signals for perception, two listening-tests were performed. The simulated and recorded signals were rated by pleasantness, loudness, roughness and sharpness using semantic differentials. It was found that responses for simulated and recorded signals correlate for all cases, but rankings could not be reproduced exactly. The model can be further improved to be more applicable for listening tests. The model has been optimized after a first validation. The second aim laid focus on the perception of tyre/road noise. When designing tyre sounds, the main aim should be to increase the pleasantness of the total vehicle sound while maintaining the carried information and reducing the sound level. To be able to do this an understanding of how physical changes in a tyre are reflected in the perception of the same tyre is essential. Thus, the second aim was to see if the rolling noise of a tyre can be both differentiated and characterized by its perceptual qualities. The focus is on the perception of the sound outside the car, perceived by for example a pedestrian. Listeners have judged different road tyre combinations and their perception in terms of their emotional responses (pleasantness, activation and stress) and their psychoacoustic responses (loudness, sharpness, roughness, and pitch). The results confirmed that rolling noise can be perceptually differentiated. It is further possible to differentiate between the effects of the street and the effects of the tyre on all emotional and most psychoacoustic parameters. The results suggest that changes to road surfaces or tyres can affect both emotional and psychoacoustic perceptual qualities.

Keywords: *Psychoacoustics, Auralization, Perception, Tyre/Road Noise, Rolling Noise*

List of publications

This thesis is based on the work contained in the following appended papers:

Paper I
Auralization of simulated tyre noise: psychoacoustic validation of a combined model.
A. Hoffmann, W. Kropp
To be submitted, 2015.

Paper II
Perception of tyre noise: Can tyre noise be differentiated and characterized by the perception of a listener outside the car?
A. Hoffmann, P. Bergman, W. Kropp
To be submitted, 2015.

The following papers are not included in the thesis due to an overlap in content or due to being published in another language:

Auralization of tyre/road noise based on the SPERoN prediction tool.
A. Hoffmann, J. Forssén, W. Kropp
Proceedings of AIA-DAGA 2013 Conference on Acoustics, Meran, Italy, March 18-21, 2013.

Optimierung der Auralisierung von Reifengeräuschen basierend auf dem Modellierungs-Tool SPERoN
A. Hoffmann, J. Forssén, W. Kropp
DAGA 2014, Fortschritte der Akustik, 40. Deutsche Jahrestagung für Akustik, 10.–13. März 2014, Oldenburg.

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Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Background

Road traffic noise has historically been dominated by the noise of the engine. Modern car engines have become more and more silent, due to improvements of combustion-engines and especially the upcoming electric alternatives for car-engines. This has led to nowadays tyre/road noise being the most prominent noise source for the speed range from about 30 km/h up to 100 km/h [97], [105]. Consequently, today tyre/road noise is the main source of road traffic noise.

For car-manufacturers the main focus concerning noise and vibration properties towards perception is on how the customer perceives the interior sound quality of the car. Focusing on the problem of environmental noise the area of noise perception has to be widened to the noise radiated by the car to the environment. A report of the Word Health Organization (WHO) [34] estimates environmental noise to be responsible for the loss of about 1 million healthy life years in Europe. Environmental noise has been shown to increase the risk of cardiovascular diseases, cognitive impairment in children and sleep disturbances. Tyre/road noise as a main contributor to road traffic noise is one of the main sources of environmental noise and thus a major factor for its health effects. As a consequence, in order to reduce the severe health effects of road traffic noise, it is essential to reduce the negative impact of tyre/road noise.

Most of the ongoing work focuses on the reduction of tyre/road noise at the source by using low noise road surfaces ([96] , [97]) and low noise tyres ([107], [90]). Noise barriers and a series of innovative noise control measures could be used to reduce the propagation of traffic noise from source to receiver [4]. Finally increased façade and window isolation is used as a rather desperate final solution to scope with the noise problem. However, praxis has shown that this work is cumbersome and progress is slow.

A design tool that can auralize the noise produced by the designed tyre or road would be of great help in the process. For this, both a model for the sound generation process is needed as well as a method to generate a realistic audio signal for e.g. a pass-by situation under desired conditions. Such a tool would help to make tyre and road design more cost efficient.

On the other side there are discussions about single cars becoming too silent and thus increasing the risk of accidents, especially for blind people. This was brought forward by the American Highway Traffic Safety Administration in a study on accidents involving electric vehicles [87] and led to a legal Act in the USA [78] that demands a minimum sound level for new electric and hybrid vehicles. This is done by adding alert sounds to help pedestrians perceive the presence, direction, location and operation of the vehicle. The different viewpoints on noise requirements might lead to a conflict of interests, where on the one hand there are health risks by noise emitted by passenger cars, on the other hand if this noise is reduced there is an increasing risk of accidents due to non-detection. To overcome this conflict of interests, further knowledge in the field of perception of vehicle noise is needed.

1.2 Aim

The overall hypothesis behind the work presented here, is that tyre/road noise varies in the perception of a listener outside the car, depending on road and tyre selection and that this could be utilized as a complementary action to the ongoing work to reduce the negative consequences of tyre/road noise without loosing information carried by the sound needed for identification and detection of the sound source.

There are two aims pursued in this work. For both the focus was set only on passenger cars. The first aim is to model an authentic pass-by situation of a passenger car from the point of view of a listener on the roadside. The concept of the applied model is to combine the SPERoN prediction model [63] for tyre noise and the Listen Demonstrator [85]. In this work both approaches are combined to create a tool for the auralization of tyre/road noise. The combined model can predict the spectrum of the sound close to the tyre, as well as reproduce the sound at a given listener position. This tool needs a set of parameters that define the properties of the tyre and the road as input data.

The second aim in this work is to verify that there is a perceptual difference for different tyre/road combinations and to show how these differences can be described. By investigating the perceptual space of tyre/road noise, one gains information about the main parameters that influence the perception and the possible spread in those parameters for tyre/road noise. This will provide a framework for possible changes and improvements.

1.3 Outline

The thesis is divided into three parts. It starts with a general introduction. The field of perception of tyre/road noise has been dealt with from two aspects. The first is the development of an auralization model, its validation and extensions. The second aspect is the psychoacoustic investigation of tyre/road noise. Both aspects are studied based on the same listening tests, but using different view points and methods.

In Chapter 2 a literature review on the perception of rolling noise is given. The field of tyre/road noise and the field of psychoacoustics are described in more detail. The general information about the methodology of the presented studies is collected in Chapter 3. The psychoacoustic methodology applied in the studies is presented and the applied statistical analysis model ANOVA is described. The utilized tyres and roads and their sources are also described in this chapter.

In Chapter 4 the auralization method is introduced and validated. This corresponds to the content of the first paper. The introduced auralization method is a combination of the SPERoN prediction model [63] for tyre noise and the Listen Demonstrator [85]. To verify the model, the perceived sound quality of the modelled signals as well as real recordings were rated by a set of listeners. The recorded and the simulated signals incorporated the same tyres, roads and speeds. The listeners were asked to rate pleasantness, loudness, roughness and sharpness of each signal. These properties are commonly seen to be important for sound quality perception in general [118]. It is shown that the combined model provides an estimate of how the real situation is perceived. If the pass-by situations are similar, the modelling uncertainties lead to differences in the judgements.

In Chapter 5 the auralization method is developed further and some weaknesses are investigated and improved, namely the treatment of low frequencies and the treatment of tonal components.

In Chapter 6 the focus of the work is moved to the perception of rolling noise. A listening test and its statistical analysis is presented. This corresponds to the second paper. As a basis for this work, the psycho-acoustical annoyance defined by Zwicker and Fastl [118] has been used, and the components defining it. These parameters are commonly used in comparable studies for different kind of sound sources. Additionally, emotional responses have been tested, since research [34] indicates that emotional reactions to sounds are related to health effects. Västfjäll et all [111] evaluated the use of emotional measures on interior and exterior vehicle auditory quality, and found them well fitting. This motivates the inclusion of emotional measures in the evaluation of tyre/road noise.

A summery of the conclusions and an outlook on possible future work are presented in Chapter 7.

Chapter 2

Overview of the involved fields

This thesis is placed at an intersection of different fields, namely tyre/road noise generation and modelling, auralization and psychoacoustics. Thus a literature review investigating the state of the art in the different fields concerning the presented studies and an introduction to the field of tyre/road noise, the field of auralization and to the field of psychoacoustics are included.

2.1 Literature review

The field of perception of tyre/road noise interacts with different areas. A set of studies focuses on the perception of noise inside the car. An example is the study by Bergeron et all [12]. They developed a method to describe the perception of internal automotive road noise. For this, they designed a sensory grid and a predictive tool where calculated sound metrics are related to perceptual dimensions.

If the focus is more on noise and noise pollution in urban areas, the interest is not on the perception of interior noise in a car, but mainly on exterior noise. A field of ongoing studies is to apply psychoacoustics on car pass-by and traffic noise. Pörschmann et all[86] evaluated the velocity and distance perception by moving sources to find the important cues. Park and Lee [81] analysed booming sounds and investigated which psychoacoustic parameters that are related to this sound characteristic. Gärtner et all [36] modified car pass-by sounds to investigate the perception of sound quality and to find basic parameters affecting the sound quality. Lee et all [67] used another approach to investigate sound quality by investigating the connection between the electrical brain signal on the sound of an accelerating car to the perceived sound quality. Still another method has been developed by Cik [23]. Here the health effects of traffic noise are related to sleep disturbance and annoyance, and a method has been developed to investigate these factors in situ.

A quite new field is to combine the different approaches of tyre/road noise research and psychoacoustics. Keulen suggests in an inventory study of basic knowledge on tyre/road noise [105] that the use of psychoacoustics might give new insights into tyre noise. He used this approach to find explanations for disagreements in measurements and subjective ratings on noisiness of silent roads. The use of the psychoacoustic concept of coloration helped to explain the emerging differences. Buss [21] follows this idea and investigates pattern noise as a part of tyre/road noise by evaluating sound quality assessments of professional subjective testers.

2.2 Tyre/road noise

Tyre/road noise describes the noise produced by a tyre rolling on a surface. It is the most prominent noise source for the speed range from typically 30 km/h up to 100 km/h ([97], [105]) for passenger cars, and it depends strongly on the speed of the car.

The start of the research on tyre/road noise generation dates back to the sixties and seventies. A very first workshop on tyre/road noise generation was held in Stockholm 1979 [77]. At that time two mechanisms were identified as main contributors to tyre/road noise: tyre vibrations and air-pumping. This view has been extended over time. The most important effects will be discussed in more detail as follows:

Tyre vibrations Tyre vibrations are caused by the interaction between road and tyre. Due to the tread pattern and due to the roughness of the road surface the contact geometry between road and tyre is varying. Consequently the contact forces are varying over time as well as the tyre vibrations. The time varying tyre vibrations lead to sound radiation.

The response of the tyre to the varying contact forces depends strongly on the tyre properties, i.e. the geometry and material properties. An extensive study of the influence of different parameters on the tyre properties can for instance be found in [43].

Research showed that tyre vibrations can be responsible for the radiated sound within a wide frequency range. This can also be true for frequencies above 1 kHz. In this range the radiation is mainly determined by the motion of low order modes on the tyre structure due to the time varying contact shape [61].

Flow-related processes Traditional literature tends to use the term air-pumping which was introduced by Hayden. Air-pumping refers to a time varying air flow, which creates monopole sources at the leading and the trailing edge of the tyre during rolling. However, the mechanisms leading to the time varying flow are not very well understood and are largely speculative. The following phenomenological mechanisms are suggested:

In 1971 Hayden [42] suggested that, as the tread enters the leading edge of the road contact area, the tread is compressed and penetrates into the road surface. This leads to the air being squeezed out of the void. At the trailing edge, the tread is decompressed and lifts up from the road surface, with the result that air flows back to fill the void.

Deffayet and Hamet [39] assumed that the opening and closing of cavities in the contact leads to sound generation. They measured the pressure in cylindrical cavities of different dimensions as a slick tyre rolled over the opening.

Ronneberger [89] assumed that when the tread was deformed by roughness asperities intruding into the rubber, there is air displaced due to the changing gap between rubber and road surface. He considered this flow as a monopole source and estimated the radiated sound.

None of these suggestions is able to explain the air-pumping measured in the field in a satisfactory way. The meagre result might be due to that experimental investigation is very difficult, since it is hard to directly observe the exact process in the contact between tyre and road during rolling without disturbing the process.

Less speculative was the work by Conte [24] who actually made a very first complete non-linear model of the flow in between tyre and road when the tyre is passing cavities in the road.

Much of the literature claims that air-pumping is responsible for tyre/road noise above 1 kHz (see e.g. [97]). This is based on the observation that below 1 kHz the speed dependency is normally U^2 while above the dependency it is around U^4 which indicates that the sound generation mechanism is airflow related (monopole source). Winroth and Kropp [115] showed however, that this U^4 dependency can even be obtained when only taking into account tyre vibrations in the simulations. Further they observed this dependency even at lower frequencies. A fact which hardly can be explained by traditional air-pumping models. Therefore they introduced the expression air-flow related mechanism, which is broader and in this context maybe more accurate.

Other processes Other processes can be found in literature, but they play only a minor role in very specialized situations. For very smooth surfaces one might find stick-slip and stick-snap processes where friction and adhesion is involved.

Stick-slips occurs when individual parts of the tread (e.g. a block) come into contact. Tangential stresses are then built up while this section travels through the contact. At the end of the contact patch the tangential stresses will exceed the frictional force and the section will start to slide (snap out) as described e.g. in [73]. This process is mainly related to high frequency sound radiation, but is normally not so important.

Stick-snap describes forces occurring when the adhesive bonds between rubber and road change. If the tyre is sticky the adhesive bonds may break up and cause vibrations. It can also happen that the adhesive bonds are increased, which leads to an increase of the excitation at the trailing edge of the tyre footprint [73]. Also the stick-snap does not seem to contribute strongly to the sound radiation.

Propagation processes The propagation of the tyre/road noise is influenced by different circumstances. The cavity formed by tire and road in and opposing the rolling direction is shaped like a horn. It is exponentially growing and thus gives a smooth impedance matching from the contact area to the surrounding. This leads to very effective sound radiation, specially in the region of 2 kHz [98]. The strength of the horn effect depends strongly on tire width and the road surface and the structure of the road surface. The narrower the tyre width and the more porous the road surface, the smaller the horn effect becomes ([58] and [38]).

The sound radiation is dependent on the absorptive parameters of the different media along the radiation path. One main consideration being the parts of the car surrounding the tyre, and the road surface. The more sound absorbent these parts are, the less sound is radiated.

Another aspect is that the tyre can not be seen as a spherical source. The levels in front of the tyre are higher than at the back of the tyre. These differences are presumably due to stick-snap phenomena [97]. The radiation to the side is even less than to the back, due to the horn effect mainly working in the frontward and backward directions.

2.2.1 Model approaches

Today, independent models of different complexity exist for predicting different phenomena involved in tyre/road interaction. In most of the models tyre/road contact is substantial simplified, considering e.g. only stationary contact or rather crude contact models. In many cases tyre dynamics, tyre profile and road surface profiles are neglected, i.e. a smooth static tyre rolling on smooth surface is modelled. The quality of a tyre/road interaction model depends on the quality of the tyre model, the road model and the contact model used for the simulation. In the following an overview of the state of the art for these models is given.

Contact between tyre and road For calculating the contact between two surfaces, typically a third body approach is introduced. This third body approach has the task of characterizing the local deformation of the involved bodies. One of the most common methods is to model the tread as a set of uncoupled springs with constant stiffness (e.g. [56]). A more advanced method is to use an elastic half-space formulation (e.g. [116]). Kalker's classical model for 3D contact between rolling bodies [52] follows this approach. It is applied in many practical applications, especially for wheel/rail contact. However, both approaches are far from being sufficient for describing the contact between tyre and road. Uncoupled springs neglect the coupling of displacements within the tread. The elastic half-space includes this coupling, but demands that the contact area is small in comparison to a typical dimension of the body (e.g. the diameter of the minimum curvature radius of the involved bodies). Instead of a third body model, the two bodies in contact could be modelled by taking into account the local elasticity of the structure.

In most of these approaches the solution of the contact problem is carried out in two steps [19]. First the contact problem for stationary rolling, i.e. a smooth tyre rolling on a smooth surface is solved. After fixing the obtained contact geometry the influence of road roughness is then applied as external forces acting on the deformed tyre structure. This is only valid for very small roughnesses, where the roughness does not alter the contact area - an assumption, which for the tyre/road interaction is hardly correct.

Tyre models Tyres are composite structures with frequency-, temperature-, load- and strain-dependent properties. From a modelling point of view, complexity is added by the inflation which alters the undeformed tyre shape and is the origin of additional pre-tension forces acting on the side-walls and belt. Acoustic pressure fluctuations within the enclosed air cavity also induce vibrations on the tyre structure and vice versa, yielding a coupled fluid/structure problem. Models for the simulation of tyre dynamics range from analytical approaches, based on coarse ([22] and [80]) simplifications in the description of the physical tyre properties, to highly elaborate numerical models, which take into account the very details of the complicated tyre features [19]. In the 1980s and 1990s, two-dimensional models with focus on noise generation from tyres were developed. These also covered the medium and high frequencies (e.g. [55] and [72]). A further step forward was the model by Larsson and Kropp [65] consisting of two elastic layers. It is one of the few tyre models that have been demonstrated to capture the high-frequency response of the tread and especially its local deformation. A similar model but with curvature in the circumference has later been suggested by O´Boy [76]. In parallel to these models, from the mid 1980s on, finite element models have been used to describe tyre dynamics (e.g. [88], [83], [68] and [64]). Although capturing more geometrical details, they have been limited to the low frequency region due to the computational cost at that time. Often, they are directly combined with a contact model (see [29], [19], [40] and [69]). Nilsson [74] presented a model based on Wave Guide Finite Element Method (WFEM). Fraggstedt [33] developed this model further. The WFEM is one of the most advanced tyre models. Sabiniarz and Kropp used this model to discuss the vibration properties of tyres [95].

Sound radiation Typically, the Boundary Element Method (BEM) is utilized to calculate the radiated sound from tyre vibrations. For example in [18] and [38] the amplification due to the horn effect was modelled with BEM, while for instance, in [94] and [113] calculated radiation from a rolling tyre was simulated. An interesting alternative to BEM is based on so-called 'infinite elements' as described in e.g. [19]. The idea is to model the near-field close to the tyre in terms of conventional finite elements, which are coupled to 'infinite elements' describing wave propagation outside the near-field zone. The infinite elements are easily incorporated into existing Finite Element software and preserve the banded matrix structure of standard FE-models. The latter feature is a great advantage over BEM since efficient numerical algorithms developed for standard FE-problems can be utilized [109]. In addition, the very narrow gap building the horn might create problems in standard BEM packages. Most of the calculations were made for smooth tread pattern. In the case of normal tread pattern the geometry between tyre and road is given by a complex system of narrow channels and cavities, creating viscous losses and groove resonances. Work related to this subject includes e.g. [37], where Graf modelled the transfer function from a point source in a groove to the far field radiation including the horn effect. Recently Hoever and Kropp [44] published calculated sound pressure spectra for truck tyres rolling on different road surfaces (simulated with the model developed at Chalmers) and found very good agreement with measurements.

Hybrid models Beside typical statistical models not discussed here, there are so-called hybrid models. These models combine deterministic calculations (e.g. contact forces) based on physics with a statistical approach, e.g. correlation of calculated contact forces with measured sound pressure levels. This approach has been used by Beckenbauer and Kuijpers [10] and was used in the form of the SPERoN Prediction model [35] in the presented studies. This model will be described in detail in Chapter 2.1.1.

2.3 Auralization

The term auralization had been introduced by Kleiner et all in 1991 [54]. In [53] they define auralization as "*the process of rendering audible, by physical or mathematical modelling, the sound field of a source in a space, in such a way as to simulate the binaural listening experience at a given position in the modelled space*". Another, newer definition is by Vorländer. He defines auralization as the technique of creating audible sound files from numerical (simulated, measured, or synthesized) data [110]. In general one can say that auralization describes different techniques that recreate sounds in such a way that they represent different acoustic situations either from basic recordings, or by the use of information about the sound source and the sound propagation in the surrounding environment.

There have been some efforts to develop models that auralize different traffic situations from a basic data set. Eerden et all [104] used a monitoring system to investigate the sound level distribution in different urban areas. These measurements were used to create dynamic noise maps of different areas. Another method has been used in the Swedish Listen Project [85]. Here the aim was to develop a demonstrator that simulates and auralizes the sound environment in urban areas [82]. The demonstrator is based on a set of single vehicle passages [70].

A useful step that has not been accomplished yet, is to combine the tyre noise modelling with the auralization approach. This combination would create a design tool that can play back the noise produced by the designed tyre or road. In this way the acoustic effects of a newly developed tyre or road can be analysed even prior to the start of production.

2.4 Psychoacoustics

In the Encyclopedia Britannica Psychoacoustics is defined as the study of the physical effects of sound on biological systems [20]. This means that Psychoacoustics deal with the relation of physical properties of stimuli like sounds and vibrations and their effect on the human body as well as the subjective experience of those stimuli.

In psychoacoustics the relation between the physical signals and their interaction with the auditory system all the way to the interpretation and reaction to the signals (perception) is studied. Models are derived for different stages of this relationship. Psychoacoustics is an interdisciplinary field, and thus different models follow different approaches and concepts.

Some models focus on the relation between stimuli and percept, like Zwicker and Fastl [118] or Moore [71]. Zwicker and Fastl describe sounds by different parameters like pitch, loudness, roughness, fluctuation-strength, pleasantness/annoyance, subjective duration and rhythm and try to find mathematical models describing them. These parameters will be discussed in detail in a separate section. Moore uses a slightly different approach by analysing the sound processing from the ear into the brain and how this leads to the perception of loudness, and how frequency selectivity and temporal processing explain pitch, space, object and speech perception. For that he follows the neuronal responses on the auditory pathway and describes them in models. Based on Moore's approach models like PEMO ([41] and [45]) have been derived, that apply a model of the auditory signal processing in order to estimate the perceived similarity between two audio signals.

Another way is to focus on the emotional reaction on the sound [15]. With this approach the focus is on the subjective experience of a feeling (emotion) induced by a stimulus like a sound. For this, common parameters for different emotional reactions have to be found. The most common are valence (pleasantness) and activation but, depending on the question, there can be found more parameters that represent different stages of interaction between the two, like annoyance, stress, happiness, relaxation and many more [91]. This approach has been used by Västfjäll et all to investigate the affective evaluation of vehicle auditory quality [111].

In product design the focus is often on sound quality. Here the different approaches mix up, depending on the purpose of the product and the type of sound. Quite often, a mix of emotional measures and psychoacoustic measures is used, that is fitting to the sound and understandable for the evaluating person. Depending on the sound, specific measures are used, like comfort, booming and many more. Finding a suitable measure is often a challenge and often approached by free verbalization interviews [2].

2.4.1 Psychoacoustic measures

Psychoacoustic measures describe the perception of the characteristics of a sound by a listener. They are properties of an acoustical signal that are rated and recognized in a consistent way by listeners and can be used to characterize a sound.

The psychoacoustic measures used in a certain situation should reflect properties that are relevant for the problem at hand. For example dieselness (describes the specific sound characteristics of a diesel engine that is often related to poor engine quality and thus often undesired) can be an important measure for car engines, but it would not be a well-chosen measure for air-plane cabin noise. Other examples are that booming would not fit to describe bird singing, whereas sharpness would not fit to describe noises of huge engines.

The measures used in this study are described in more detail in the next paragraphs.

Loudness is defined in ANSI [3] as "*the intensive attribute of an auditory sensation in terms of which sounds may be ordered on a scale from soft to loud*". It has to be differed between loudness and loudness level. The unit related loudness is called sone and the unit related to loudness level is called phone.

The loudness level of a specific tone is defined as the level in dB SPL of a 1 kHz reference tone that sounds equally as loud as the specific tone [49]. Thus a 1 kHz tone at 60 dB SPL has 60 phone. The loudness is defined as the estimate between the strength of a sound compared to a sound with a loudness level of 40 phone [48]. A pure 1 kHz tone at 40 dB SPL has a loudness of 1 sone if presented binaurally from the front in free field. Loudness is additive. A sound of 2 sone is twice as loud as one of 1 sone. Loudness does not only depend on the magnitude of the signal, but also on the frequency, the bandwidth of the signal and the duration.

The relation between loudness and loudness level is linear for levels over 20 phone, but non-linear for lower levels. It has been described the first time by Fletcher [31].

Calculation methods for loudness have been developed and are defined in different standards ([26] [47]). Both are based on the model introduced by Zwicker and Fastl [118]. Here the sound is split up in bark bands or third octave bands and the specific loudness is first calculated for the individual bands before summing them up. The specific loudness depends on the level in the band, and the centre frequency of the band.

Roughness is a perception of sounds that describes fast envelope fluctuations. It occurs for amplitude and/or frequency modulations of signals with modulation frequencies between 15 and 300 Hz. The unit of roughness is asper. One asper is defined as a 1 kHz tone with 100% modulation at 70 Hz modulation frequency and at a level of 60 dB.

Roughness depends on the level of the sound and increases with increasing level. There are some calculation models. Most are based on the model by Aures [5]. Here the signal is split up into overlapping bands. For each band the modulation frequencies are estimated and used to estimate the partial roughness. Out of these the total roughness can be estimated.

Fluctuation Strength is a perception of slow envelope fluctuations in sounds [101]. It occurs for amplitude and/or frequency modulations of signals with modulation frequencies between 1 and 20 Hz.

The unit of fluctuation strength is vacil. It is defined by a 1 kHz tone with 100% modulation at 4 Hz modulation frequency and at a level of 60 dB having a roughness of 1 asper.

Sharpness is defined in the ISO [27] as "*that aspect of timbre that is related to the spectral envelope of sounds*". It gives a description of the relative amount of high frequency components in the sound. Sounds with a high sharpness are described as high pitched, sharp or bright.

Sharpness mainly depends on the spectral content and the centre frequency of the sound (for narrow band sounds). The unit is acum; 1 acum being the sharpness of a narrow band noise with a centre frequency of 1 kHz (920 Hz - 1080 Hz) and a level of 60 dB.

A more objective method of analysing the effects behind sharpness is to perform a frequency analysis. For this, different methods has been derived by Aures [6] and Bismarck [108]. Both methods derive the sharpness from the specific loudness, the loudness and the frequency in Bark.

Pitch is defined in the ANSI [3] as "*that attribute of auditory sensation in terms of which sound can be ordered on a scale from low to high*". Pitch relates to the repetition rate of the waveform of a sound. For pure tones (sinusoid) it corresponds to the frequency and for complex tones to the fundamental frequency. The unit of pitch is mel. It is defined by a 1 kHz with 40 dB above hearing threshold producing a pitch of 1000 mel.

2.4.2 Emotional measures

Emotional measures try to capture the subjective experience of a feeling (emotion) and describe them in a commonly understandable way.

The emotional space has two main dimensions: valence (pleasantness) and arousal (activation) as discussed by Barrett [7] or Bradley [17]. These two dimensions are pan-cultural. The concept is, that all other emotions can be expressed by combinations of valence and arousal. Russell [92] uses these two parameters to define the core affect as the primitive, universal and ubiquitous base of emotions.

Pleasantness There are different theories using pleasantness. It is used both as a psychoacoustic measure and as an emotional measure. In the emotional theory pleasantness or valence is one of the dimensions in measuring emotions. It ranks from negative valence or unpleasant to positive valence or pleasant.

As a psychoacoustic measure, there are approaches to find other parameters that form the perception of pleasantness. One suggested model for this, is the sensory pleasantness suggested by Zwicker and Fastl [118]. They describe the pleasantness as an emotional response to a sound that is influenced by elementary auditory sensations and the relationship of the listener to the sound. Their model is based on the basic auditory sensations of loudness, roughness, sharpness and tonality.

Activation or arousal is the second basic dimension in measuring emotions [7]. It is ranked from low or passive to high or active.

Activation describes how strong the reaction to a stimuli is, and how much the human body and brain react to it. A high activation is often coupled with a high heart rate and increased blood pressure, whereas a low activation means that the body is relaxed [8]. Activation is the key reaction to attention and alertness.

Stress is a combination of valence and arousal. It is seen as a relationship between a person and the environment that is appraised by the person as exceeding thir own resources and there by endangering their well-being [66]. This means that it is a emotional reaction to a stimulation that indicates health risks by this stimuli. It can be measured by self-report or by measuring hormones like cortisol. It has been found that stress is an emotional reaction with generally high activation and low pleasantness, as can be seen in studies by, for example, Russell [93]. Stress has been utilized to deepen the focus on negative valence and arousal combinations further in measures of emotional responses in the first attached paper.

All the previous measures have been utilized in the present studies. For complementation, annoyance will be discussed as well, even though it has not been utilized in the presented studies, due to a strong overlap with pleasantness, stress and activation.

Annoyance is a term often used in sound quality evaluations. It is related to activation (arousal) and inverse to pleasantness.

In the WHO guidelines for community noise [14], annoyance is one of the criteria used, and is defined as a feeling of displeasure associated with any agent or condition.

The annoyance of sounds is strongly effected by the loudness of the sound [13] but there are other parameters involved as well. It is closely related to other negative responses like anger, displeasure, exhaustion, and stress-related symptoms [119]. Öhrström [119] recommends annoyance as one of the parameters to be used to indicate health effects by noise.

A mathematical approach to calculate the psychoacoustic annoyance has been derived by Fastl and Zwicker in their book [118]. They calculate the psychoacoustic annoyance of a sound out of the loudness, the roughness, the fluctuation strength and the sharpness.

Chapter 3

Methodology

3.1 Psychoacoustic methodology and statistics

In the following, the utilized testing methods and the important statistical methods for this study are introduced.

Two testing methods were chosen for this study: the semantic differential and the paired comparison. Both methods are capable of providing answers to the posted questions with a reasonable amount of time and effort. They are described in detail in the following section.

Listening tests were conducted following both methods. The results of those tests were analysed by different statistical methods. Additionally to the mean values and the standard deviations, the method ANOVA (ANalysis Of VAriance) was chosen to test the statistical reliability of the test results. The different ANOVA methods utilized in this studies are described in more detail below.

3.1.1 Semantic differential

The semantic differential was introduced first by Osgood in 1957 [28]. It was developed as a scaling instrument for the measurement of meaning [79]. Thus it can be used as a method to investigate the connotative meaning and the affective qualities of random objects or words [28].
The evaluation of an object is made by either metaphoric relations or by emotional relations to the object and not by a rating of the object itself [17].

The semantic differential is defined as a set of several semantic scales [79]. Each scale is defined by a bipolar combination of adjectives. Examples for these polar adjectives could be “smooth–rough” or “loud–silent”. The universal semantic differential introduced by Osgood [79] is one available method, but it is common to use semantic differentials that are adopted to suit the question at hand.

It is most common to use bipolar pairs of adjectives, but there is also the possibility to create an artificial bipolar scale by using one adjective and a scale, for example from “agree” to “disagree” [28]. This method is called categorical scaling test. This method has been used in the presented studies.

For the semantic differential the scale for a single attribute is divided into steps. Different lengths of scale are possible, but the most common has seven steps [79]. This arises from the fact that shorter scales have too poor a resolution for most questions, whereas longer scales are harder to handle for the participants. The space in between the steps is assumed to be equidistant. A scale in seven steps has been used in the presented studies.

For perceptual acoustics, semantic differentials are often used to characterize sounds. There are different kinds of semantic differentials known for this. In the car industry, semantic differentials are, for example, used to analyse the sound and vibration impression of cars in different driving situations.

If more than one object is tested with the same semantic differential, the resulting profiles can be tested for their similarity with the help of correlation analysis [28].

3.1.2 Paired comparison

A paired comparison test can be used to define a ranking order of test objects under a chosen attribute. For this, the different objects, for example sounds, are compared pair wise. For each single comparison the test subject is asked to choose one of the two objects e.g. the louder of the two. This method had been introduced by Thurstone in 1927 [102].

The results are collected in a matrix of predominance, where each object is compared with all others. For each object the matrix contains how often it had been preferred over the other objects and can be used to create a ranking of the objects.

The disadvantage with paired comparison tests is that they can be very time consuming [28]. The amount of pairs to test can be calculated using the formula $\binom{n}{2} = \frac{n \cdot (n-1)}{2}$,where n is the number of objects to test. Another problem of the paired comparison is, that the information gained only describes the order of the tested objects for the tested attribute, but neither the distance between them nor the overall validity of the attribute for the tested objects [28]. There are methods to include this information in paired comparison tests, like multi-dimensional scaling or Thurston scaling. These methods are more demanding for the participants.

To analyse the perception of rolling noise, a paired comparison test was utilized in a pre-study. In this study the participants were asked to rank the signals in pairs of two for different attributes, to order the signals on an ordinal scale.

Due to time limitations the test has only been made for the attributes ”pleasant”, ”loud” and ”rough”. Each participant repeated the experiment 2 times, and the order of the signals was randomized for each repetition. The question was: ”Which signal is more pleasant/loud/rough?, with Signal A and Signal B to choose from.

The results correspond well with the results of the first semantic differential, that had been made with the same signals and participants. Due to the fact that the results did not show a far better consistency or resolution, but need a longer experiment time, the decision was made to focus on the semantic differential as the method for the performed studies.

3.1.3 ANOVA

ANOVA was developed by Fisher [30] and is an acronym for analysis of variance. It is a statistical test for differences between or among groups of measurement values.

ANOVA as most other statistic theories is based on the idea that the collected data of repeated measurements of any kind are random samples from a normal (Gaussian) distribution. The distribution can therefore be characterized by its mean value and variance. If the sample size is big enough, i.e. if the measurement has been repeated often enough, the mean values and variance of the measurement are equal to the mean value and variance of the underlying distribution. Different statistical tests, like the Student t-test and ANOVA have been developed to test whether groups of values derive from the same distribution. Where the t-test only allows to test for two groups, the ANOVA allows multiple groups by comparing group and overall variances to statistical tables. The test is made on the null-hypothesis that there is no difference or variance between the tested groups.

Different versions of the ANOVA with different underlying statistics have been developed for various relations between the test groups. A main difference is if the tested relation lies within the test group (within design), or is between different groups (between design). The one-factor analysis can only test effects between designs, whereas the repeated measure ANOVA can even test within design effects.

A one-factor-ANOVA tests the effect of an “independent variable” on a “depending variable” [16]. The dependent variable is normally a measurement result or set of test subject responses. The independent variable is part of the test design, e.g. the sound files that are evaluated. The ANOVA can be used to test if the variance in the results can be explained by the change of the independent variable. It is possible to test more than one independent variable on one depending variable in, for example, a two-factorial- or n-factorial-ANOVA.

The repeated measure ANOVA provides a method to analyse variances in data-sets where a limited number of test subjects are tested multiple times. It allows detection of not only influences of independent variables between the test subjects, but also in between different responses from the same test subjects

.

An ANOVA calculates the mean squares for the different degrees of freedom in the data set. The ratio between the mean squares is then evaluated using the F-Test. The variance between the data sets in the variable is compared to the variance within the data sets in the variable. The results of such a test are commonly presented depending on the degrees of freedom, as $F(df, d_{error}) = XX$. df gives the degrees of freedom of the independent variable and d_{error} gives the degrees of freedom of the rest of the data-set. Error is used in this context to name unexplained variations in the collected observations.

For easier interpretation, the probability p is calculated as well. It calculates the probability of the null-hypothesis being correct. Commonly the null hypothesis is that the data sets belongs to the same population. Common levels used to decide whether to accept or dismiss the null-hypothesis are significance levels of 1% or 5%. If the p value is below the chosen significance level the null hypothesis is dismissed, meaning that the data differs on the tested variable.

The probability is only a measure of an existing difference, not about the size of the difference. If more information is desired about the amount of difference, the effect size can be calculated. There are several different methods to calculate an effect size. Generally, the higher the effect size is, the stronger the tested effect. The method used in this thesis is called eta-square (η^2). It tests the amount of variance that is explained by the underlying model.

3.2 Used road surfaces and tyres

The used road surfaces and tyres in this study are based on documented data from the SPERoN Database. This database contains sets of documented data from measurements in Sperenberg [63].

Three tyres and three roads were chosen for the validation of the auralization of pass-by signals.

3.2.1 Road surfaces

In figure 3.1 the pass-by levels of a set of measurements in the SPERoN Database can be seen. The three road surfaces that were chosen for the simulation are marked. They cover most of the level differences of the road surfaces.

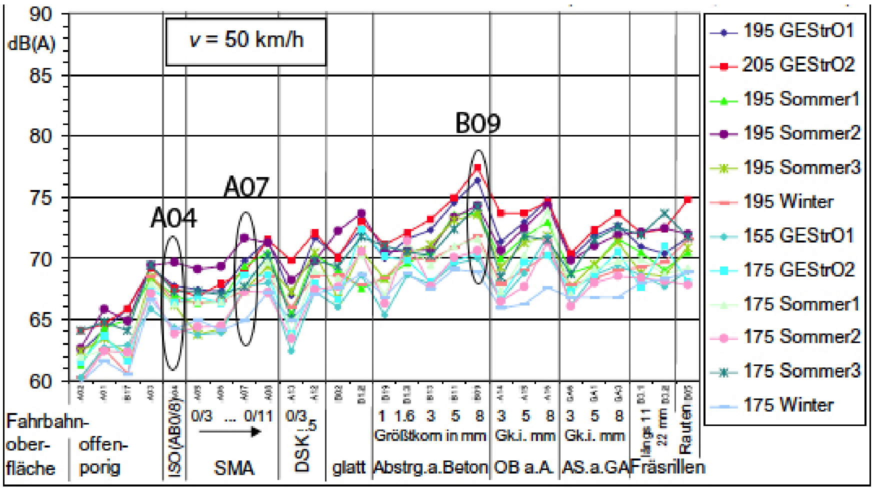


Figure 3.1: The pass-by levels in dB(A) are given for all tyres that were tested in Sperenberg and are displayed over the different road surfaces [9]

Road surface A is an asphalt concrete surface 0/8 produced according to the regulations defined in ISO 10844 [50], and called A04 in the Database. This surface is used for testing of vehicles in Europe. A picture of the surface can be seen in figure 3.2. The grain size used is up to 8mm.

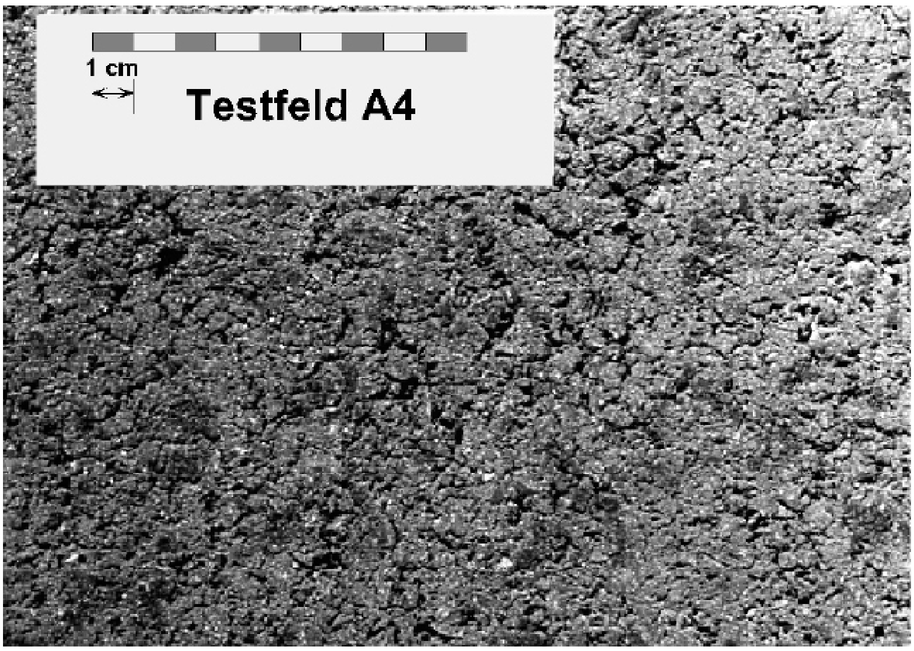


Figure 3.2: Picture of the road surface A (A04) [9]

Road surface B is a stone-mastic asphalt 0/8, called A07 in the Database. The main grain size is 5mm to 8 mm. It is a common road surface. It was produced and treated in the same way as it would be for public roads. A picture of the surface can be seen in figure 3.3.

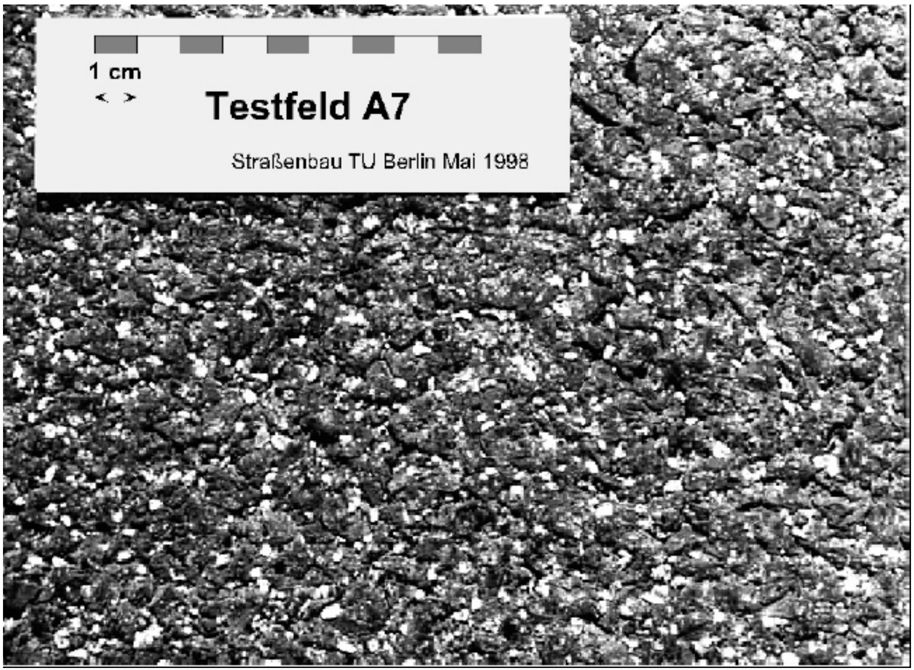


Figure 3.3: Picture of the road surface B (A07) [9]

Road surface C is a concrete surface covered with synthetic resin and gravel, called B09 in the Database. The concrete surface was polished. Then the synthetic resin was applied and gritted with gravel with sizes from 5 mm to 8 mm. A picture of the surface can be seen in figure 3.3.

All three surfaces contain mainly gravel of the same size (5 - 8 mm), but differ in the mix of materials and the production methods.

3.2.2 Tyres

From the same data set three tyres were chosen for the simulations and validations. The chosen tyres are marked in the full data set in figure 3.5. All the used tyres are conventional tyres that were or are on the market.

The first and the second used tyre were attached to a Mercedes C280 whereas the third tire was attached to a VW Polo.

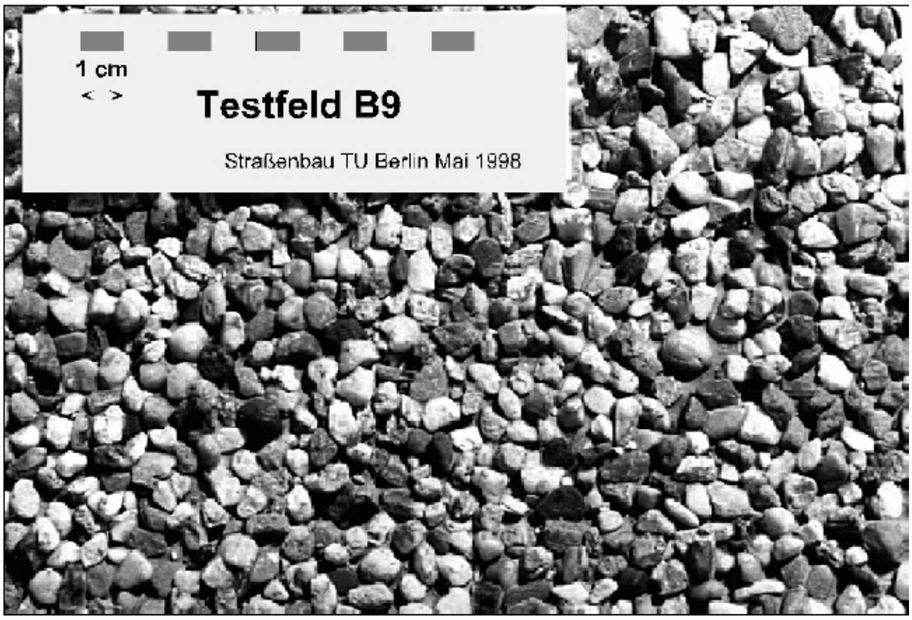


Figure 3.4: Picture of the road surface C (B09) [9]

The first tyre (DB3) is one of the most silent tyres from the available set as can be seen in figure 3.5 and the third tyre (VW3) is one of the loudest tyres in the data set. The second tyre (DB4) is more in the middle and less varying in the sound levels, depending on the road surface.

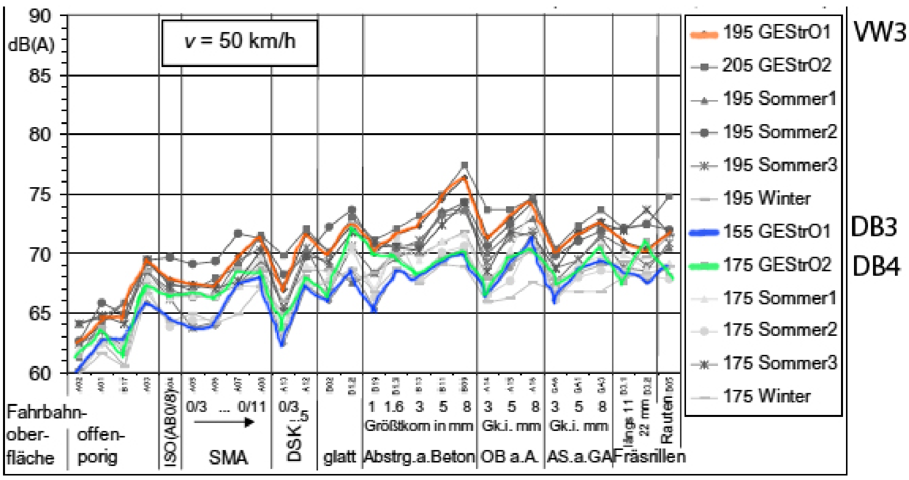


Figure 3.5: The pass-by levels in dB(A) are given for all tyres that were tested in Sperenberg and are displayed over the different road surfaces [9]

The first tyre (DB3) is a tyre by Continental: SportContact CH90 (1995/65-R15

90H), the second tyre (DB4) is a Pirelli tyre P600 (205/60-R15 91V) and the third tyre (VW3) is a tyre by Michelin: MXT (155/70-R13 75T), In figure 3.6 to figure figure 3.8 the profiles of the three tyres can be seen.

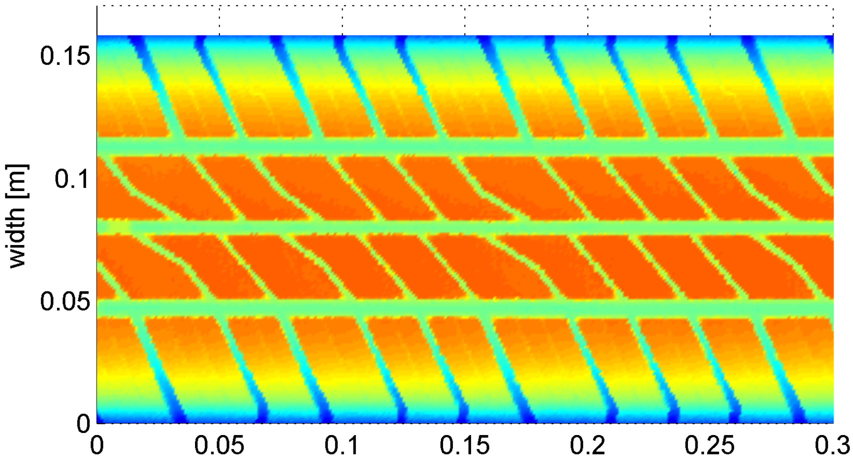


Figure 3.6: Profile of tyre 1 (DB3)

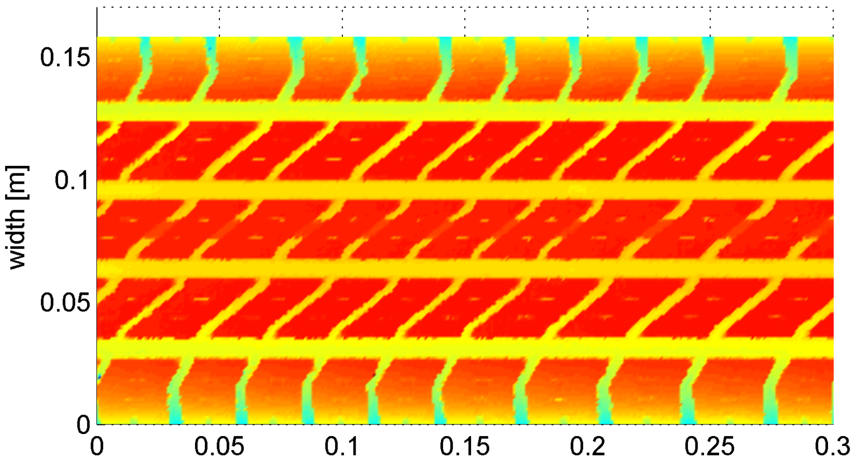


Figure 3.7: Profile of tyre 2 (DB4)

For both cars, tyre pressure and weight were adjusted according to ISO 13325, with some variation in the tyre pressure. There were variations between the recommendations by the car manufacturer and the ISO. The pressures recommended by the manufacturer were chosen over the ISO. For the VW Polo the load estimated by ISO would have led to a total weight at the limit of the total accepted weight for the car. Thus the load was reduced to a reasonable amount. The used pressures and loads are given in table 3.1.

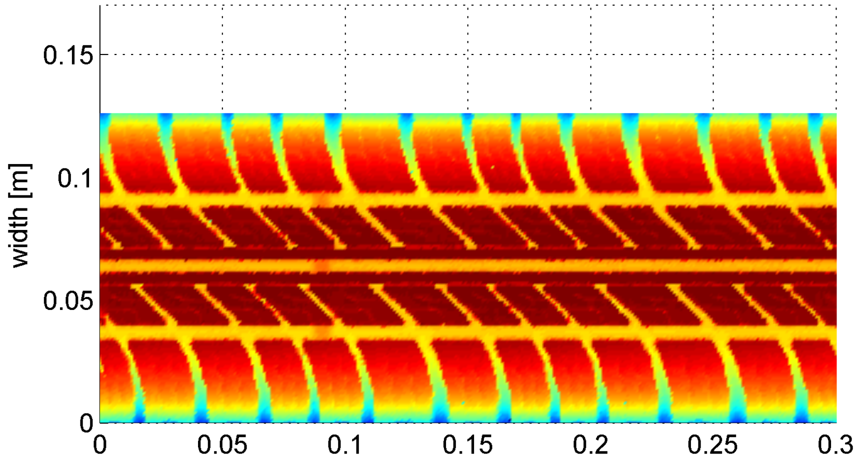


Figure 3.8: Profile of tyre 3 (VW3)

Car	Car 1 (DB3, DB4)	Car 2 (VW3)
total load	1620 kg +80 kg	1060 kg +100 kg
load rear	800 kg + 80kg	400 kg + 100kg
load front	860kg	680kg
pressure rear	2.3 bar	2.1 bar
pressure front	2.1 bar	2.1 bar

Table 3.1: Loads and tyre pressures of the two test cars. The loads are given as the basic weight and driver plus the weight added to achieve a fitting load index

The combination of the three tyres and three roads will lead to a set of nine pass-by signals covering all combinations. In the following the roads will be marked by the letters A, B, C where A is A04, B is A07 and C is B09. The tyres will be marked by the numbers 1 to 3 were 1 is DB3, 2 is DB4 and 3 is VW3.

Chapter 4

Auralization of pass-by signals

In this thesis and in the first paper, an auralization technique is introduced to make simulated tyre/road noise audible. To do this a new combination of two existing models is utilized. Tyre/road noise, that was simulated in SPERoN [63] is made audible by combining SPERoN with an auralization software developed for the so-called Listen Demonstrator [85]. The models used in this approach are described in the following.

4.1 Models

4.1.1 SPERoN

SPERoN is the acronym for Statistical Physical Explanation of Rolling Noise. It is a model to estimate the controlled pass-by sound level in third octave band spectra emitted by a passenger car for a certain tyre/road combination. For this estimation the model needs information about the tyre and road. The SPERoN model has been developed and improved in a set of research projects such as "Silent Road Traffic Noise 1-3" by the German Federal Highway Institute [35].

SPERoN is the combination of a physical model, that calculates contact forces for the tyre road contact, with a statistical model, that relates these contact forces to measured pass-by levels. The physical model can further be separated into two parts: a tyre model and a contact model. The interaction of the three sub-models and their needed input and output is depicted in figure 4.1

The tyre model has been developed by Kropp ([56] and [57]). The tyre model simplifies the tyre structure by projecting the tyre on a plane. This can be seen in figure 4.2. The resulting plate is characterized by different properties of the tyre. These properties are the tyre geometry, the elasticity, the bending stiffnesses for the different directions, the pre-tension due to the inflation pressure and loss factors for different movements. To compensate for the neglected round shape of the tyre, the elastic foundation parameters are varied for different modes. Validations with

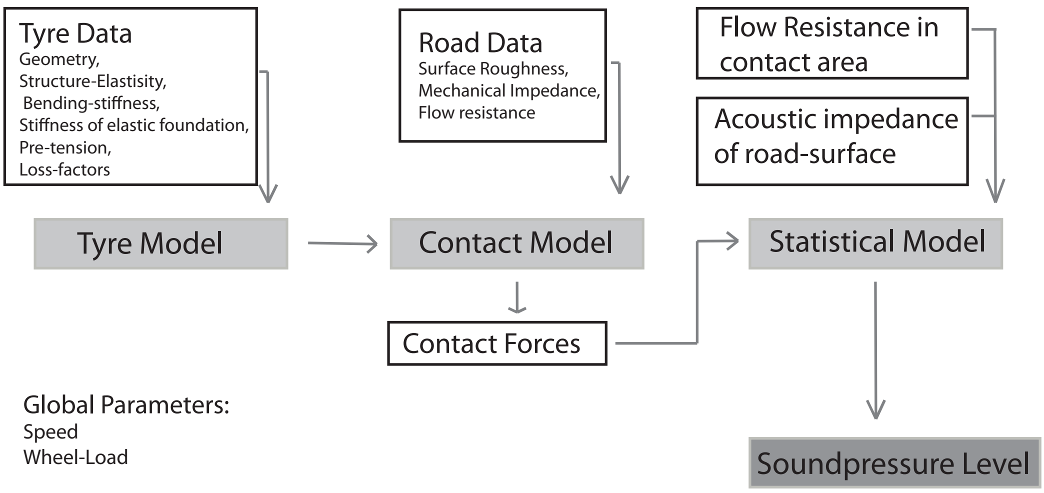


Figure 4.1: Illustration of the SPERoN model with the three sub-models and their needed input and output

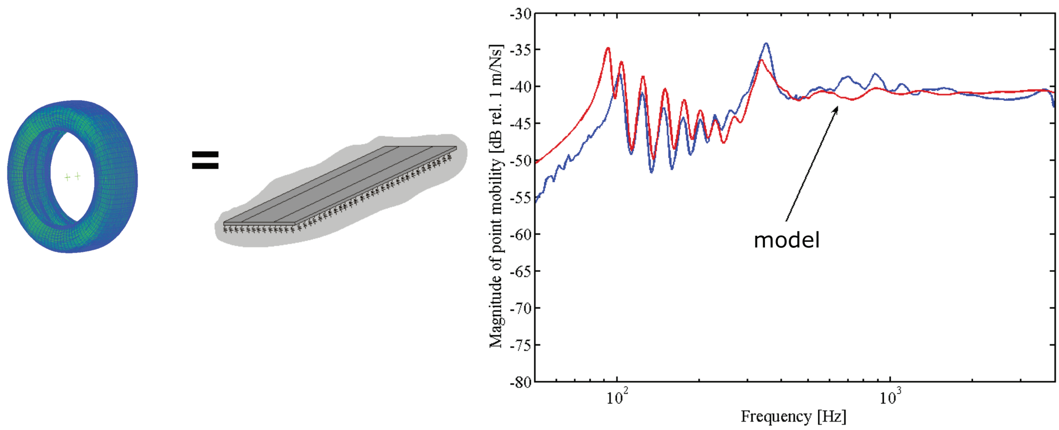


Figure 4.2: Illustration of the tyre modelled as an orthotropic plate, and an example of a resulting vibration-response from modelled tyre and a measurement (the excitement was radial in the middle) [56]

measured vibrations on tyres showed a good agreement with the tyre model [60] as can be seen on the right side in figure 4.2. The difference in the figure for the first resonance is related to the fact that the tyre in the measurement was freely suspended whereas the model had a fixed rim.

The next phase in the SPERoN model is the contact model. This model needs information from the tyre model, as well as the roughness and the flow resistance of the road surface. As a contact model, a version of the "Chalmers tyre/road interaction" model [62] and [103] is used. In this model the 3-d structure of the tyre as well as the one of the road is reduced to a two-dimensional problem by transferring the roughness of the road surface and the tyre profile into a contact stiffness depending on the intrusion of the road into the tyre surface. For the tyre, this is achieved by dividing the tyre into contact segments. For each of these segments the possible contact is compared to that of a tyre without profile. The relative surface in contact is then used to estimate the stiffness of the segment and the stiffness of a tyre without profile. To transfer the roughness of the road into stiffness parameters the contact between tyre and road can be described by a set of springs. The more the tyre presses onto the road, the more springs get in contact and compress. This concept is depicted in figure 4.3. This leads to a non-linear stiffness function. The stiffness parameters for road and tyre structure can than be used to calculate the contact forces for the rolling tyre on the road surface. For this a non linear algorithm is needed. The resulting total contact force is time varying and is handed over to the statistical model in the form of a third octave band spectra.

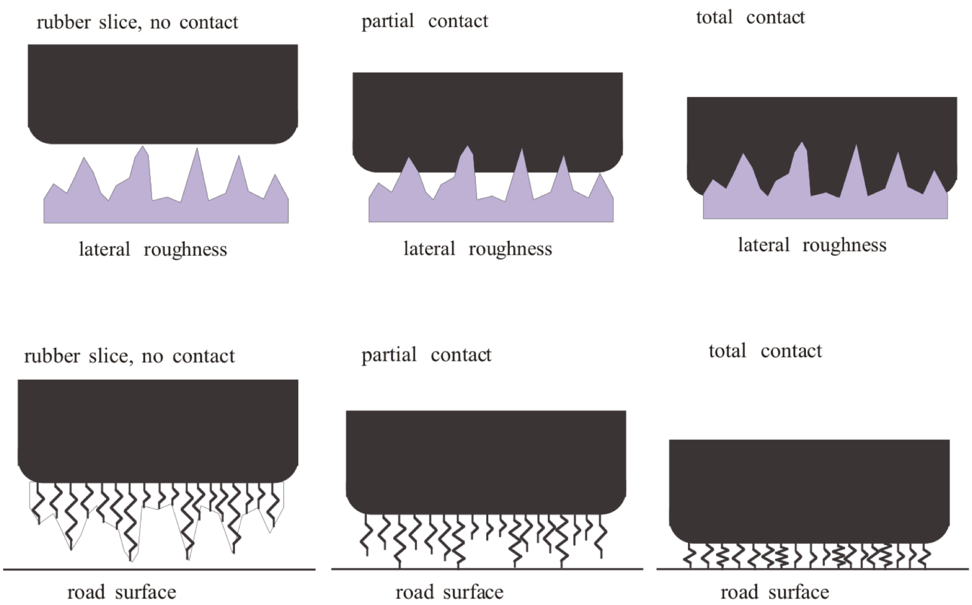


Figure 4.3: Illustration of the contact model; the contact is described in the form of springs. The closer the contact between rubber and road, the more contact with the springs and, following this, the greater the compression [114]

The last stage of the SPERoN model is the statistical model. This model is based on a documented set of measurements in Sperenberg [63], the SPERoN Database. These measurements are controlled pass-by measurements for a variety of tyre/road combinations. The spectra from the measurements are related to the contact forces by a set of physical relations. For this, four sound generation mechanisms are considered: sound radiation due to vibrations in the tyre, sound radiation due to airflow related processes, sound radiation by cavity modes inside the tyre and aerodynamic processes around the tyre and vehicle that contribute to the sound radiation. These mechanisms are related to a set of parameters: the surface texture, the flow resistance in the tyre/road contact area, the vibration properties of the tyre, the stiffness of the contact patch, the tyre profile, the size of the tyre, the load and the rolling speed. [9]. Utilizing these parameters the four radiation mechanisms can be estimated and summed up to the levels of a pass-by. This can be seen for one example in figure 4.4. A validation between estimated sound spectra by SPERoN and measured sound spectra has been made for different cases and demonstrates the high quality of the model [59].

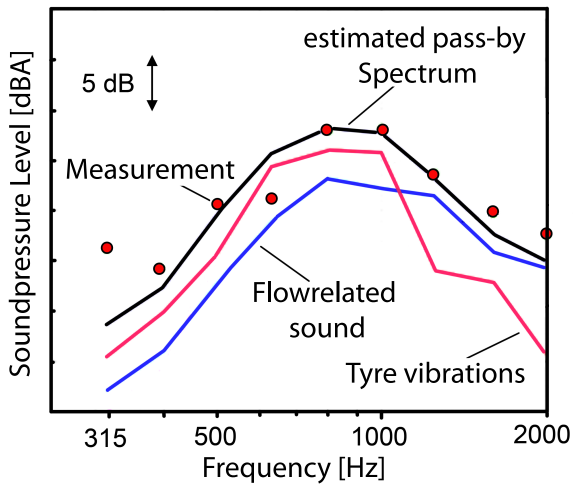


Figure 4.4: Measured third octave-band spectrum of a controlled pass-by at 50km/h on a rough street in comparison to the calculation by SPERoN [114]

4.1.2 Auralization tool

The auralization approach used in this study is based on the Listen Demonstrator [85]. The main objective of that project had been to develop a demonstration software for simulation and auralization of the acoustic environment in urban areas [82]. The tool should enable city planners and stakeholders such as politicians to better understand sound environments in the planning stage [70]. The tool is based on noise mapping methods described in the Harmonoise methods ([112], [106] and [75]) and the Nord2000 methods ([84] and [51]). The concept of the demonstrator was to separate the source signal and the radiation and propagation effects. For this both sound source models and models of the sound propagation were implemented in the demonstrator.

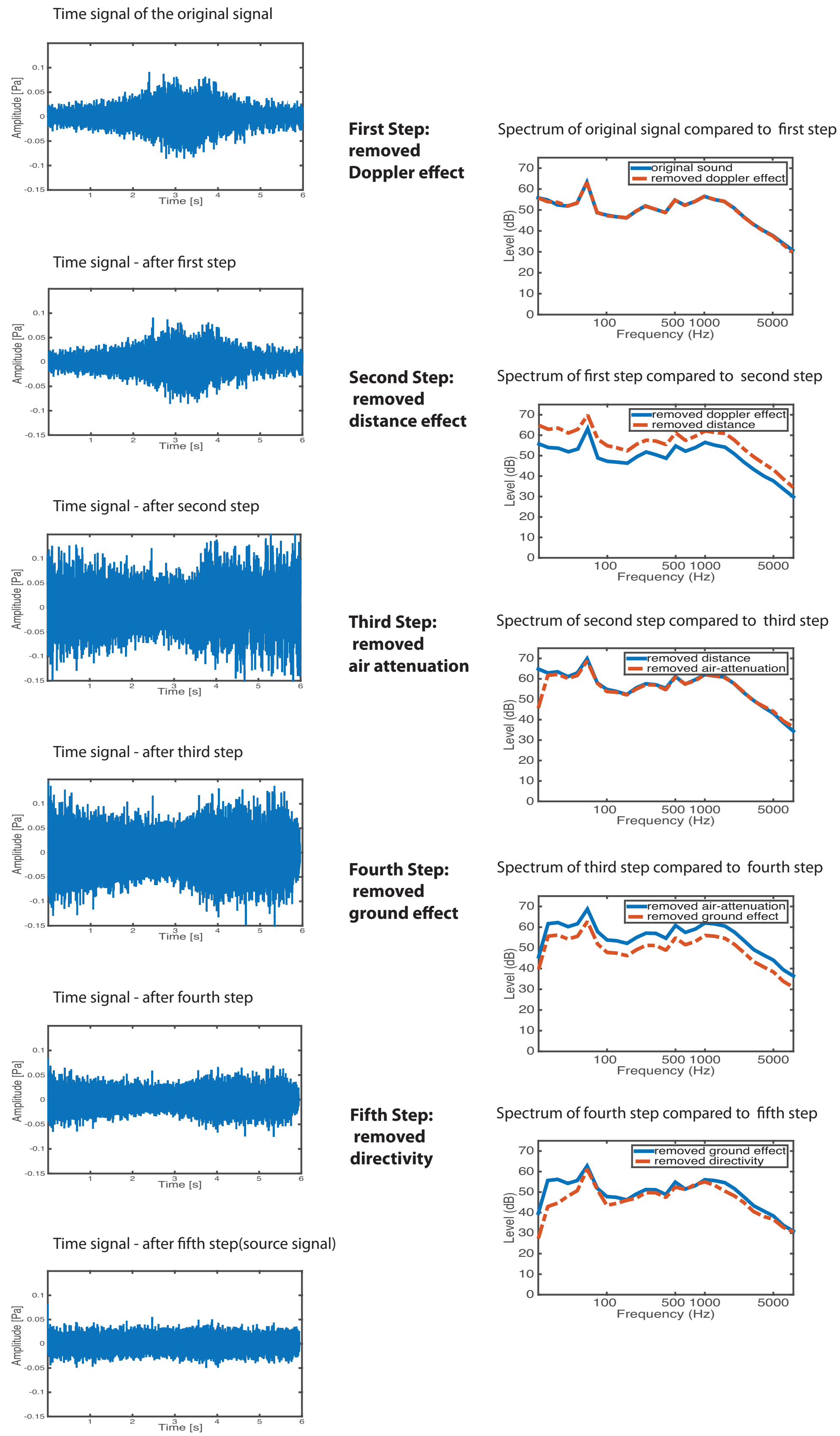


Figure 4.5: The concept of the auralization process from a mono recording to a source signal. Illustration of the changes of the signal both in time and frequency domain

The part of the Listen Demonstrator that has been applied in this study is based on an approach by Forssén [32]. The starting point was a recorded monaural pass-by signal of a car with defined parameters like speed, tyre specifications and road specifications. Applying the inverse propagation effects to that signal, a stationary signal is obtained that can be considered as the source signal. The different stages of this process are illustrated in figure 4.5. First the frequency shifts due to the Doppler effect are removed (first step in the figure). Then the effect of the varying distance is removed. This can be seen in the second step in the figure as a quite constant level increase over frequency, and in the time domain the early and late times are increased in level in relation to the middle. The third step is to remove the effect of air attenuation. As can be seen in the figure, this mainly affects the low frequencies. The fourth step is to remove the ground reflections. This leads to a decrease in level for all frequencies and mainly the early and late times. As a last step the influence of the directivity is removed, leaving a very steady time signal as our source signal. This source-signal is separated in two therms. One therm characterizes the propulsion related sound sources like the engine, air intake, air exhaust etc. (figure 4.6, red line), and the other source therm characterizes the tyre/road noise (figure 4.6, blue line). Both therms can be modified to create new driving scenarios with differing speeds, road surfaces and tyres. To re-create new pass-by signals, all propagation effects are added back to the source signals. To go back from third octave band data to a full spectrum, each band is filled with noise having the same total level as the corresponding third octave band.

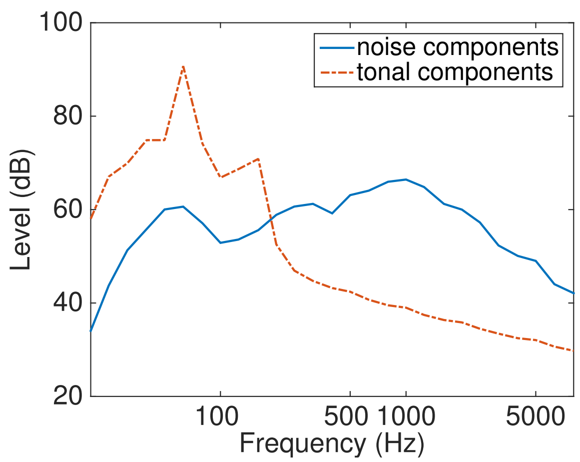


Figure 4.6: The two parts of the source signal: the noisy part is related to tyre/road noise (blue) and the tonal part is related to the engine etc. (red)

4.1.3 Combined model

To combine SPERoN and the Listen Demonstrator the source component in the Listen Demonstrator that is related to the tyre/road noise is modified. This data is given in third octave bands. Those octave band values are now modified according to the Sound pressure levels estimated by SPERoN.

The values in SPERoN are calculated for the third octave bands from 350 Hz to 2000 Hz. They are adjusted to match the format in the Listen Demonstrator. For all bands where a value from SPERoN (350 Hz to 2000 Hz) exists, this adjusted value is used. For the lower and higher frequency bands the original values in the Listen Demonstrator are kept. With this approach, the source term in the Listen Demonstrator, that is mainly related to the tyre noise, can be shaped by the spectra estimated in SPERoN and synthesized back into a pass-by signal. This is illustrated in figure 4.8 for the nine tyre-road combinations that were introduced earlier.

The combined auralization process is depicted in the sketch in Figure 4.7.

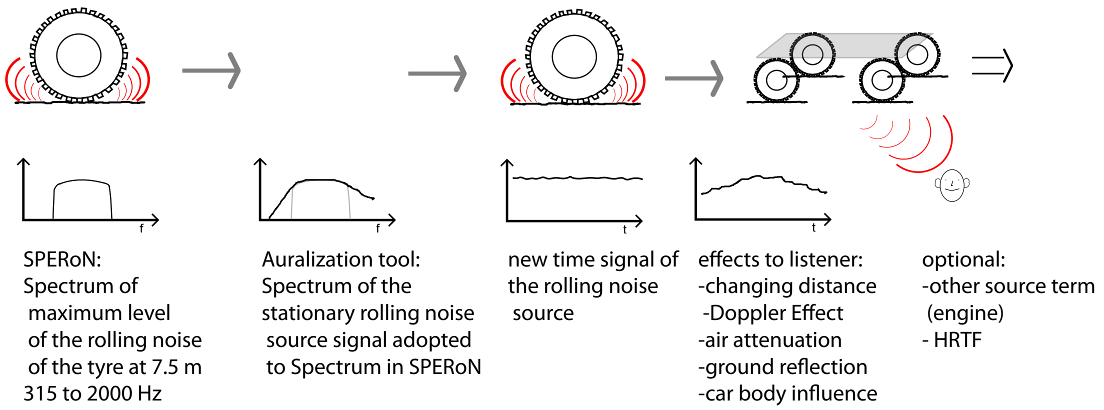


Figure 4.7: Illustration of the Auralization Process: SPERoN estimates the rolling noise spectrum out of basic properties of tyre and road; The source terms in the auralization are compared with the calibrated spectrum and fitted to the new source; propagation effects are added to the source term and a pass-by signal is generated for such desired conditions as Distance, Speed, Surrounding

For different tyre/road combinations (described in Chapter 3.2) the SPERoN model was used to calculate the sound pressure levels in the third octave bands from the contact between tyre and road. These levels have than been transferred in the described way to the Listen Demonstrator, and pass-by sounds for the cases have been generated. These signals were used in a listening test to validate the combined model.

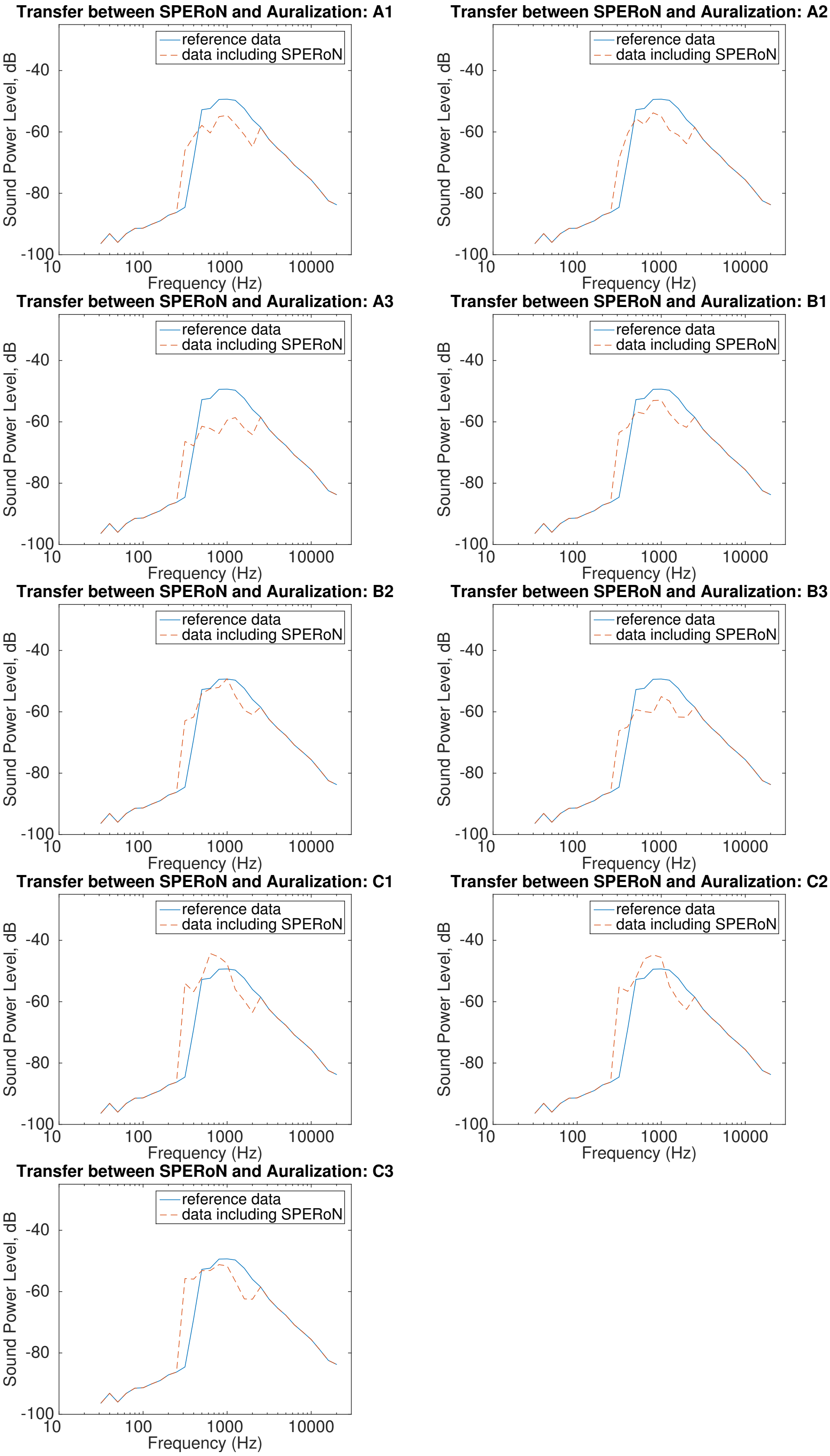
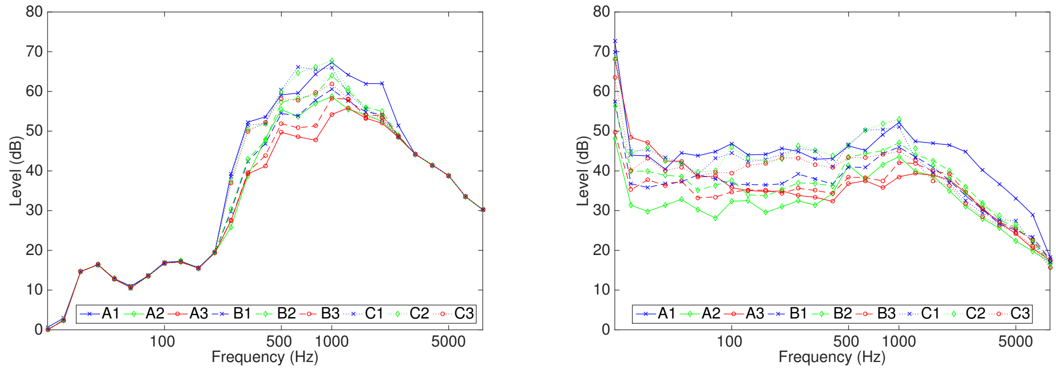


Figure 4.8: Source data in the auralization before and after the adaptation to SPERoN for the nine applied tyre-road combinations



(a) auralized sounds (b) recorded sounds (uncalibrated)

Figure 4.9: Spectrum in third octave bands of the nine recorded and simulated (by the extended Auralization model) pass-by sounds

4.2 Validation

4.2.1 Listening Test

The model was tested for the three different road surfaces and for the three different tyres presented in the previous section.

In total, two listening tests have been conducted to validate the combined model. The listening tests were designed as a seven-step categorical scaling test. The participants were asked to rate the signal due to their impression of pleasantness, sharpness, loudness, and roughness. In the first listening test they were also asked to rate fluctuation strength. In the second listening test fluctuation strength was replaced by pitch. For each signal and each attribute the participants were asked to rate on a scale from 1 to 7 as to how much they agree that the attribute describes the sound.

The first listening test was conducted containing only simulated sounds; whereas the second listening test contained only recorded sounds. The spectra of the used nine simulated sounds in third octave bands can be seen in figure 4.9a and the spectra of the used nine recorded sounds can be seen in figure 4.9b.

In the first listening test, the signals were presented via loudspeaker in a sound-insulated room furnished as a lecture room. The participants were listening in groups of maximum three participants at a time and receiving the questions on paper. Only simulated signals (total of nine) were presented. 14 participants (7 male, 7 female) participated in the listening test (age: $mean = 28$ years, $s.d. = 5.1$ years). The experiment was repeated two times and the order of the signals and questions was randomized.

The second listening test was conducted in a soundproof and neutral room. The test was set up on a computer and the sounds were presented via open headphones (Sennheiser HD 650). The relative relation between the levels of the signals was adjusted according to the data set of the recordings. However the signals were not played back at the exact measured levels, but the playback level for the listening test was adjusted in a way that all sounds stayed in a comfortable range for the participants. The focus of the experiment was not on the absolute values, but on the relative differences. Both signals and questions were presented in randomized orders, with different orders for each participant and each repetition to minimize order and learning effects. Each trial contained one signal and one question. A training on the signals and the rating was included in the experiment. The experiment was repeated two times. In total 18 participants (9 male, 9 female) participated in the listening test (age: $mean = 26$ years, $s.d. = 3.3$ years).

4.3 Results and discussion

The results of the listening test with the simulated signals and the results of the listening test with the recorded signals will first be investigated separately, and then compared to validate the simulation.

4.3.1 Simulated Signals

In the first experiment only the simulated signals were presented to the listener. In Figure 4.10 the mean value with standard deviation of all participants can be seen. The responses are plotted for the different tyre/road combinations. The different colours indicate the different perceptual attributes.

One can see that the pleasantness seems to be approximately inverse to the other percepts. That is why it is plotted inversely in Figure 4.11. The difference in perception between the different tyre/road combinations is small, compared to the standard deviation of the responses.

In addition the different percepts vary similarly for the different signals. That might be due to the effects of sound generation for rolling noise. This becomes clear in Figure 4.11 where the standard deviations had been removed.

Tests were made to see if the signals differ significantly for each percept with an ANOVA, to validate the importance of the high standard deviation. The results for the F-test will be given together with the degrees of freedom. Additionally the probability (p-value) for accepting the null-hypotheses will be given. The meaning of these values is described in chapter 3.1.3. The results gave significant differences between the signals for all percepts except fluctuation strength (pleasantness: $F(8, 117) = 3.13; p < 0.01$, sharpness: $F(8, 117) = 5.72; p < 0.01$, loudness:

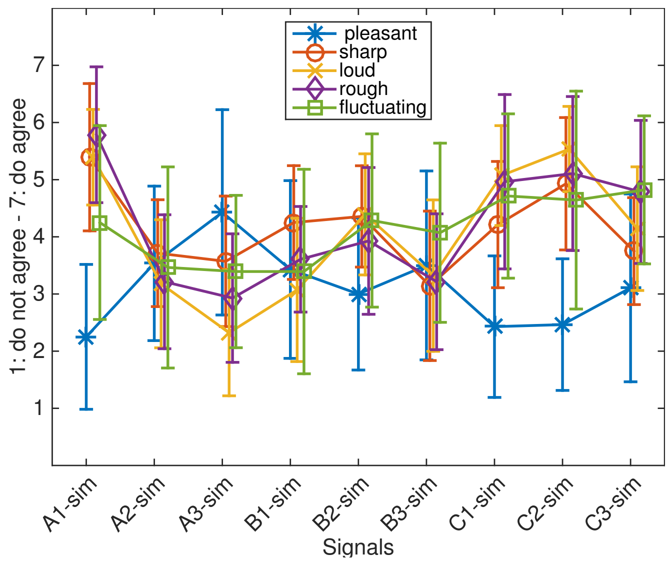


Figure 4.10: Results for simulated signals. Mean values and standard deviations of the responses of all participants are plotted for all tyre/road combinations and for the different percepts (colours)

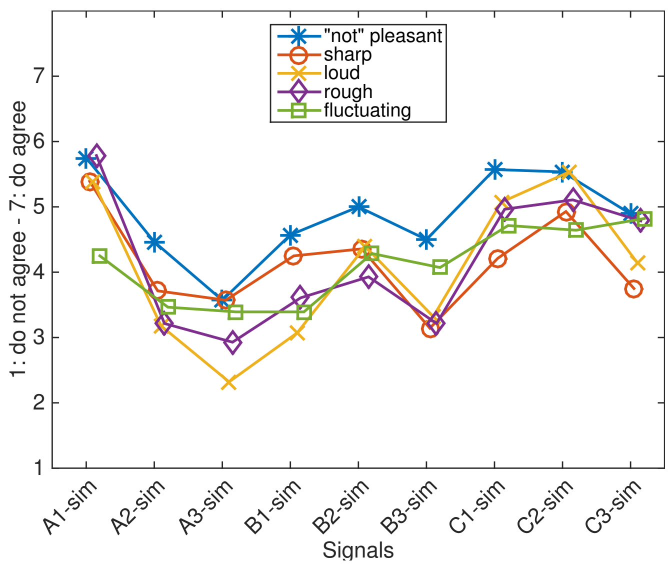


Figure 4.11: Results for simulated signals. Mean values of the responses of all participants are plotted for all tyre/road combinations and for the different percepts (colours). The responses for pleasantness have been inverted for easier comparison

$F(8, 117) = 16.23; p < 0.01$, roughness: $F(8, 117) = 9.5; p < 0.01$, fluctuation strength: $F(8, 117) = 1.81; p = 0.081$) The results of the ANOVA indicate that the data is interpretable.

Because the perception of fluctuation strength gives no significant difference in variations, and it is only rated around the middle of the scale, it was decided to remove it from the experiment. It seems to have a rather low meaning for these types of signals.

4.3.2 Recorded Signals

In the second experiment the recorded signals have been presented to a set of listeners. In Figure 4.12 the mean value with standard deviation of all participants is presented. The responses are plotted for the different tyre/road combinations. The different colours indicate the different perceptual attributes.

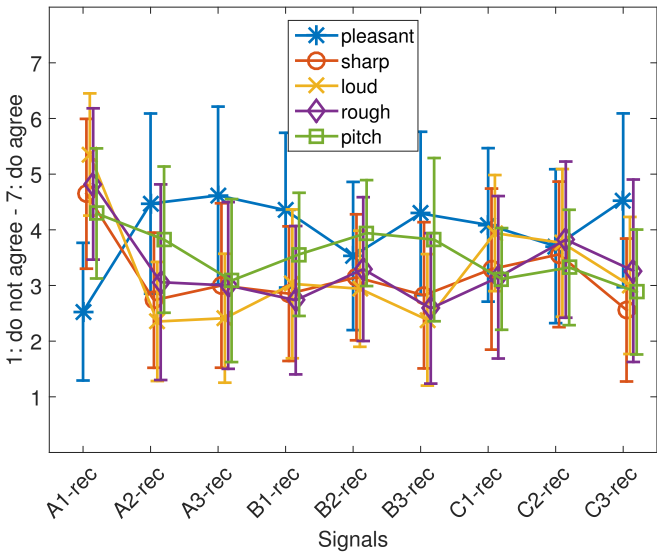


Figure 4.12: Results for recorded signals. Mean values and standard deviations of the responses of all participants are plotted for all tyre/road combinations and for the different percepts (colours)

Due to the high standard deviation tests were made to see if the signals differ significantly for each percept with an ANOVA test. The results for the F-test will be given together with the degrees of freedom. Additionally the probability (p-value) for accepting the null-hypotheses will be given. The meaning of these values is described in chapter 3.1.3. The results indicated significant differences between the signals for all percepts (pleasantness: $F(8, 297) = 7.26; p < 0.01$, sharpness: $F(8, 297) = 7.86; p < 0.01$, loudness: $F(8, 297) = 23.69; p < 0.01$, roughness: $F(8, 297) = 7.15; p < 0.01$, pitch: $F(8, 297) = 5.29; p < 0.01$).
The results look similar to those of the simulated signals. The results seem somewhat compressed. This might be due to the presence of two simulated signals that were included in the listening test, but excluded from the evaluation. They were perceived to be stronger than the recorded signals. The comparison between the

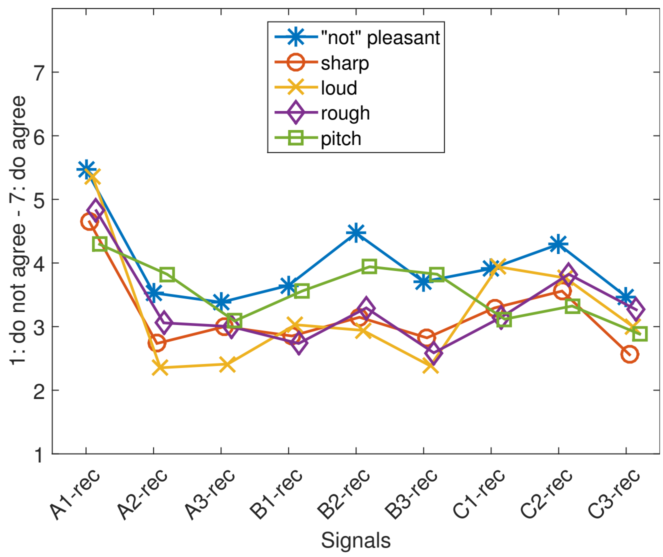


Figure 4.13: Results for recorded signals. Mean values of the responses of all participants are plotted for all tyre/road combinations and for the different percepts (colours). The responses for pleasantness hve been inverted for easier comparison.

recorded signals to these simulated signals will not be considered here due to some uncertainties in calibration between simulated and recorded signals.

4.3.3 Comparison of the models

In the following the results from the listening tests for the recorded and simulated signals are compared in more detail for each percept. For all four cases the absolute distance between the curves has no meaning, due to different sets of listeners being used and different methods in the experimental set up.

For inverse *pleasantness*, the mean responses of the simulated and the recorded signals are plotted over the different tyre/road combinations in figure 4.14. A correlation analysis between the signals has been carried out. The resulting correlation coefficient is $R = 0.73$. This leads to a probability of $P = 0.026$ that the null-hypothesis of no correlation between the signals is true. Thus, the null-hypothesis is dismissed and the responses for the simulated signals correlate with those for the recorded signals at the 5% significance level.

Looking closer at the result one can see that the highest and lowest responses fall on the same tyre/road combination. However there are changes in the order of the combinations in between. But those changes only occur between responses that are very close to each other.

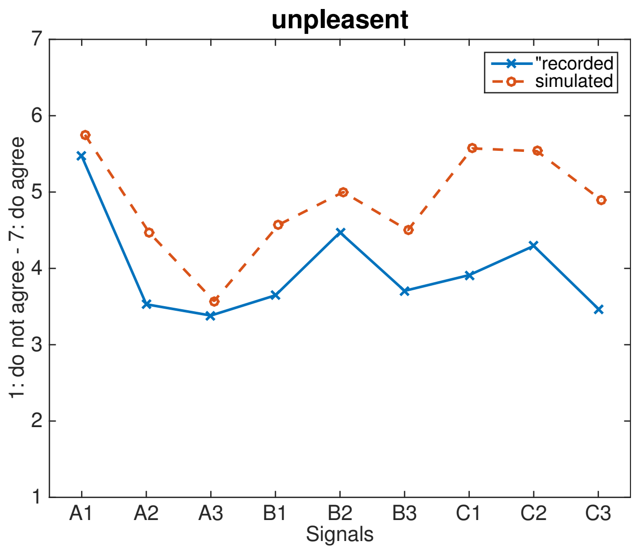


Figure 4.14: Comparison between the responses for simulated and recorded responses for the perception of inverse *pleasantness*.

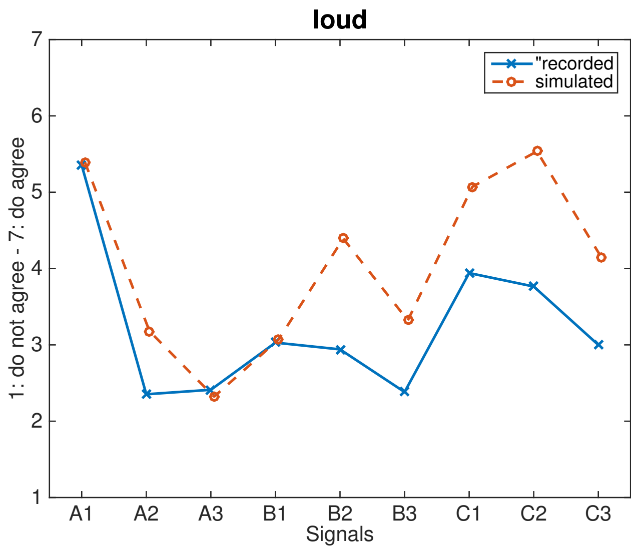


Figure 4.15: Comparison between the responses for simulated and recorded responses for the perception of *loudness*.

For *loudness* the mean responses of the simulated and the recorded signals are plotted over the different tyre/road combinations in figure 4.15. A correlation analysis between the signals has been carried out. The resulting correlation coefficient is $R = 0.81$ with a probability of $P = 0.01$. This means that the responses for simulated signals correlate with those for the recorded signals at the 1% significance level. Looking closer at the result one can see that there are changes in the order of the tyre/road combinations from high to low response. These changes occur between responses that do not significantly differ from each other.

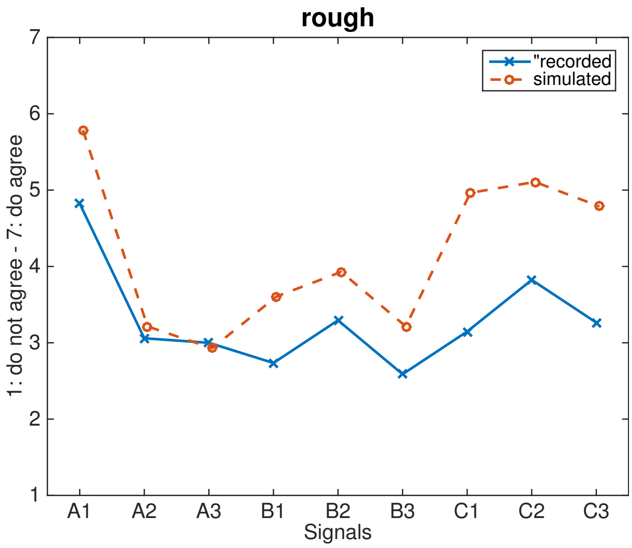


Figure 4.16: Comparison between the responses for simulated and recorded responses for the perception of *roughness*.

For *roughness* the mean responses of the simulated and the recorded signals are plotted over the different tyre/road combinations in figure 4.16. A correlation analysis between the signals has been carried out. The resulting correlation coefficient is$R = 0.81$ with a probability of $P = 0.01$. This means that the responses for simulated signals correlate with those for the recorded signals at the 1% significance level. Looking closer at the result one can see that the highest two responses fall on the same tyre/road combinations. However there are changes in the order of the combinations for the lower responses. These changes only occur between responses that do not significantly differ from each other.

For *sharpness* the mean responses of the simulated and the recorded signals are plotted over the different tyre/road combinations in figure 4.17. A correlation analysis between the signals has been carried out. The resulting correlation coefficient is $R = 0.81$ with a probability of $P = 0.01$. This means that the responses for simulated signals correlate with those for the recorded signals at the 1% significance level. Looking closer at the result one can see that the highest two responses fall on the same tyre/road combinations. However there are changes in the order of the combinations for the lower responses. These changes only occur between responses that do not significantly differ from each other.

In general one can see good correlations between the recorded signals and the signals simulated by the combined auralization tool. However when looking at the order

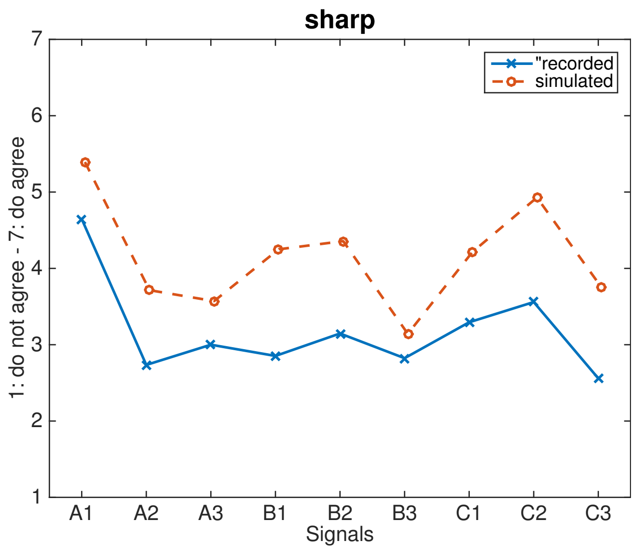


Figure 4.17: Comparison between the responses for simulated and recorded responses for the perception of *sharpness* .

of the signals from high agreement to the rated percept to low agreement, one notices that the orders differ for all percepts at several positions between recorded and simulated signals. These changes in order occur mainly in-between signals that are very close to each other in the responses.

Although the auralization based on the SPERoN model is working fairly well, there is still need for improvement. The main problem with the used simulation is, that SPERoN is not analysing frequencies below 315 Hz and those frequencies were assumed to decay linear to the lower frequencies. In the recordings the very low frequencies are partly influenced by aerodynamic noise around the vehicle. This noise term is not taken into account in the simulations. However, frequencies below 315 can play an important part in the perception of sound and have an influence on different percepts like loudness, roughness and pleasantness. This problem will be discussed further in the next chapter.

Another aspect could be the missing consideration of tonal components. The spectral information is transferred from SPERoN to the auralization tool in 1/3-octave bands. This leads to a strong suppression of tonal components. If present, tonal components have a strong effect on the perception as has been shown in various research ([99], [11] and [25]).

By including these effects one could improve the simulation significantly and gain a even better estimate of the tyre/road noise. This can than be used to test tyres in different traffic situations.

Chapter 5

Extended Auralization

5.1 Adding low frequency content

A method to combine SPERoN and the Listen Demonstrator into a powerful auralization tool has been introduced in chapter 4. A problem with this auralization tool is, that the used simulations in SPERoN do not deliver values below 315 Hz. Spectral comparison of the auralized pass-by signal with recordings shows that the signals differ strongly in the low frequency range (figure 5.1) and that the levels are generally too low. Even if the low frequencies are mainly related to the wind noise we can not neglect them, since they are included in the recordings and in every real situation and have an impact on the perception.

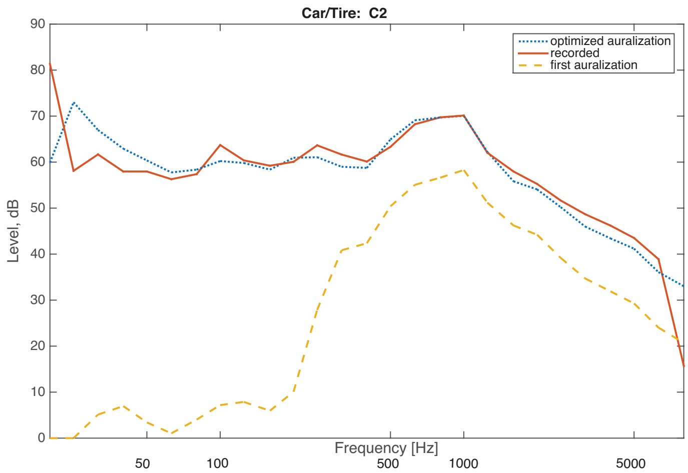


Figure 5.1: Comparison for the smoothed spectra of the recorded signal, the basic auralized signal (without level calibration) and the signal by the extended auralization including a level calibration

To adapt the simulated signals in the auralization process better to the recorded signals, the transfer of information between SPERoN and the Listen demonstrator was changed. Instead of replacing the values from 350 Hz to 2000 Hz with the information from SPERoN and leaving the other octave bands as they were, the data in both models is fitted better with one another. The process of the extended auralization is depicted in figure 5.2.

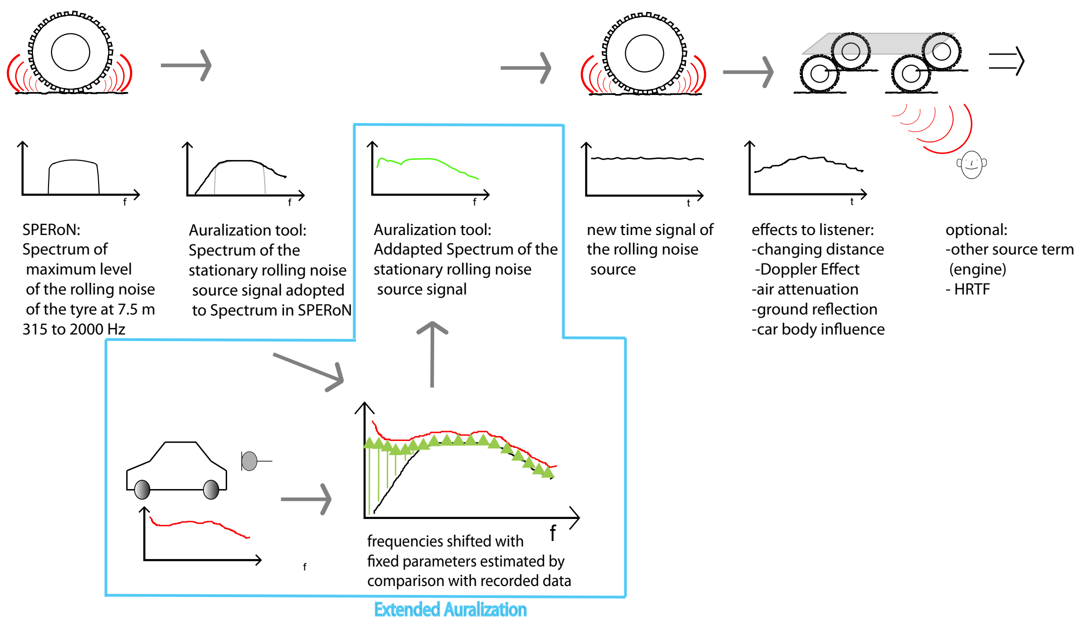


Figure 5.2: Illustration of the extended Auralization Process: SPERoN estimates the rolling noise spectrum from the basic properties of tyre and road;
new: in a comparison with measured pass-by sounds the rolling noise spectrum estimated by SPERoN is adjusted accordingly; The source term in the auralization is compared with the shifted spectrum and fitted to the new source;
propagation effects are added to the source term and a pass-by signal is generated for desired conditions such as Distance, Speed and Surrounding

The signal was divided in different frequency regions for the transfer. For the frequencies below 315 Hz the levels are based on the last value from SPERoN. From there values are decreased until 125 Hz. Then the values are raised to achieve a fitting auralization for the low frequencies. The values from SPERoN were used up to 2000 Hz. For the higher frequency bands the levels from the source data were used, but with a corresponding calibration factor to match the levels in SPERoN. The transfer between SPERoN and the source data in the Listen Demonstrator can be seen in figure 5.3 both for the first auralization method and the extended method for the tyre/road combination C2. The other cases were comparable.

The changes in the transfer of the sound pressure level values from SPERoN to the Listen Demonstrator led to a higher agreement of the spectra of the auralized and

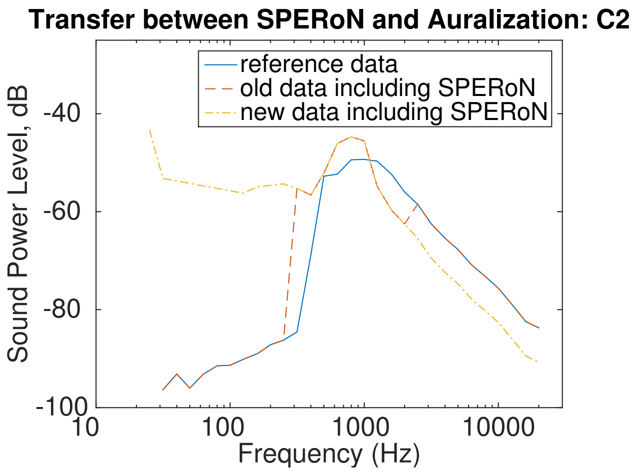


Figure 5.3: Source data in the Auralization before and after the adaptation to SPERoN and with the extended model for case C2.

the recorded signals. In figure 5.1 one pass-by situation is chosen to exemplify the differences in the spectrum of the generated signal to the recording. The spectrum of the first auralization is given in red, the spectrum of the recording is in green and the new auralization is in blue. It can be seen that the auralization with the new calibration factors is very similar to the recording, where as the earlier differs, especially for the low frequencies.

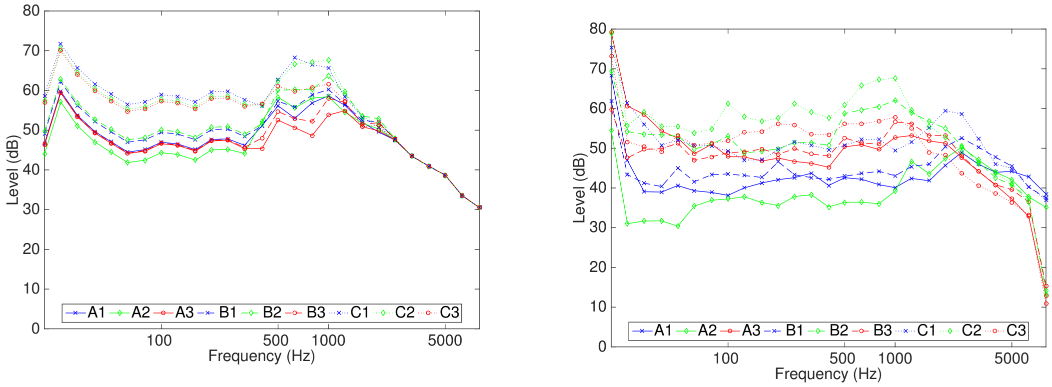
The extended auralization method was then used to create a new set of pass-by sounds, that were evaluated in a listening test in comparison with the recorded pass-by sounds.

5.1.1 Listening Test

To validate the extended auralization, a listening test has been performed. For this listening test, both recorded and auralized signals have been used at a speed of 50 km/h. For both cases nine tyre/road combinations have been used. These were the same combinations as in the previous experiment (three roads: A-C and three tyres: 1-3 as described in chapter 3.2).

The recorded signals were calibrated on their maximum sound pressure level (L_{AFmax}). The simulated signals were generated as described above. The spectra of the resulting nine simulated sounds in third octave bands can be seen in figure 5.4a and the spectra of the resulting nine recorded sounds can be seen in figure 5.4b

The listening test was performed as a categorical scaling test, and the language was Swedish.



(a) simulated sounds by the extended auralization

(b) recorded and calibrated sounds

Figure 5.4: Spectrum in third octave bands of the nine recorded and simulated (by the extended Auralization model) pass-by sounds

The used statements were: The sound is pleasant/ sharp/ loud/ rough. The response scale was in seven steps and the limits were marked as "do not agree" / "agree".

The listening test was performed in a soundproof and neutral room. The test was set up on a computer base and the sounds were presented via Sennheiser HD 650 headphones (calibrated via a HEAD dummy head). Both signals and questions were presented randomized. A single presentation contained one signal and one question. In total 18 participants were evaluated.

5.1.2 Results and comparison

To be able to compare how similarly recorded and auralized signals are perceived, the results are shown together for each psychoacoustic variable in figure 5.5. It can be seen that the ratings became both closer and more similar in variations between the signals, than for the previous auralization (figure 4.14 to figure 4.17). This can be partly explained by the calibration of the recorded signals (Chapter 3.1.1).

To investigate only the effects of the extended auralization, a correlation analysis has been made. In table 5.1 the corresponding correlations can be seen. According to these, there is a correlation for the judgements of inverse pleasantness at the 5% limit, and for loudness and roughness at the 1% limit. So for those, both auralized and recorded signal are perceived as being the same. For sharpness the rating of the auralized signal and the recorded signal is not correlating at the 5% limit.
In table 5.1 the correlation values for the earlier auralization are given as well. With the new auralization method the correlations increased for pleasantness, loudness and roughness. But they decreased for sharpness. It has to be considered though,

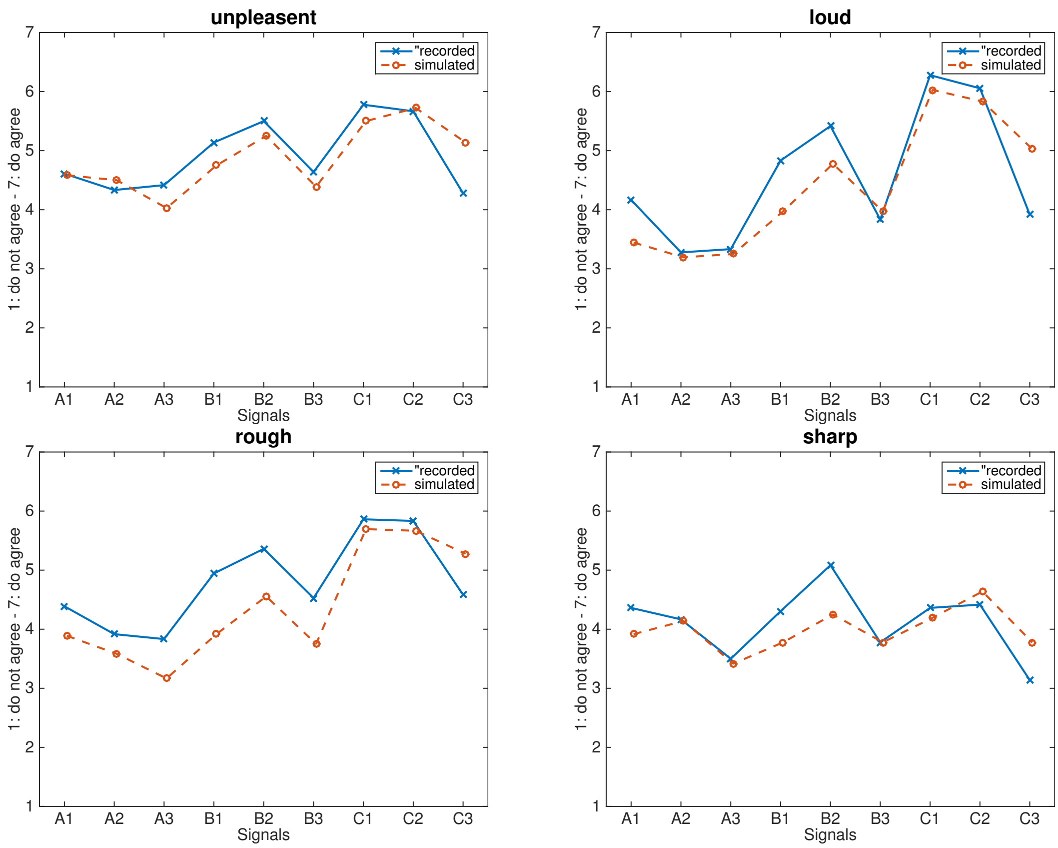


Figure 5.5: Comparison between the responses in the listening tests between recorded and auralized signals (adopted for $f < 315$ Hz) for the psychoacoustic variables "pleasant", "rough", "loud" and "sharp"

	pleasant	sharp	loud	rough
R_{opt}	0.769	0.658	0.86	0.843
P_{opt}	0.015	0.054	0.003	0.004
R_{alt}	0.729	0.852	0.813	0.811
P_{alt}	0.026	0.004	0.008	0.008

Table 5.1: Table of the correlation coefficients between simulated and recorded signals for the old and the extended auralization

that sharpness was rated as very neutral and in neither of the two auralization methods did it correlate between recordings and simulation. Increasing the low frequencies might have increased the suppression of this percept, since it depends on the relative amount of high frequencies.

Investigations in the form of listening tests showed that a good agreement can be reached for the simulated signals compared to recordings under the same conditions. The agreement is best with an extra inclusion of the low frequencies. The analysis of the listening tests showed, that the auralization is improved by the extension. Recordings and simulations are perceived as being very similar. Thus the simulation method can be used instead of recordings and it can be expected that the simulated acoustic situation will represent the real situation well.

5.2 Investigation of tonal components

A weakness of the used auralization approach is, that the signal is treated in third octave bands. By this, the fine resolution of the signal cannot be investigated, and effects by tonal components are lost. This can lead to an incorrect hearing impression and thus to a wrong perception of the signal. It is possible to include tonal components in the auralization. For this they need to be detected and included with the correct strength. To further investigate the effect by considering tonal components, the signals used in the previous experiments were analysed for their tonal content.

In SPERoN the sound pressure level is only available in third octave bands. But it is possible to look at the full spectrum of the calculated contact forces. These are linear related to the sound pressure levels, so they can be used to detect the tonal components and their relative strength in the simulated data.

If there are tonal components in a signal, the energy in the third octave band can be separated in a part belonging to the noise and a part belonging to the tonal component. Both can then be treated separately in the auralization and recombined into the full signal.

For each simulated signal an analysis of the tonal components has to be made. For the signals used in the previous experiments within only the pass-by situation A3, a tonal component could be detected. This can be seen in figure 5.6. Compared to the general fluctuation of the noise, this tonal component is not very distinct, giving it only a small amount of the energy in the surrounding third octave band.

Peaks in the spectrum have to be very distinct to be interpreted as tonal components, due to the fact that the auralization reacts very sensitively to shifting energy

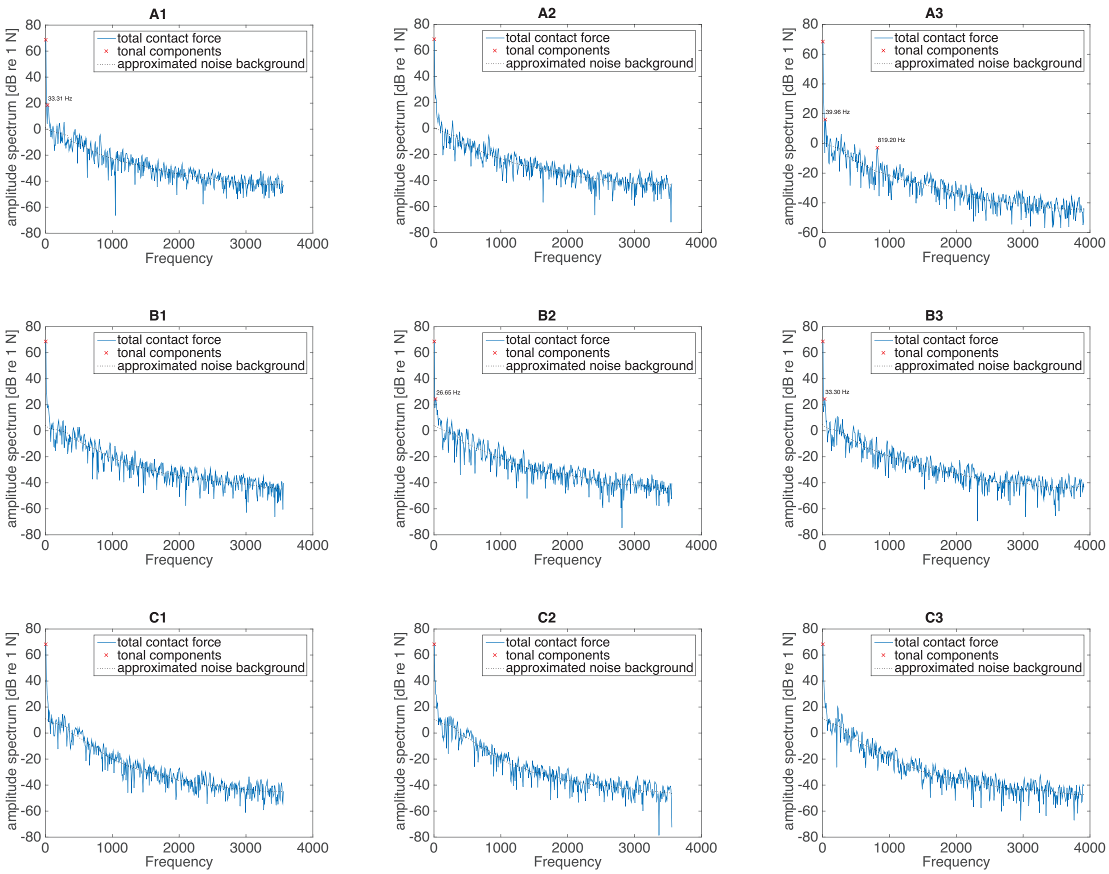


Figure 5.6: Spectra of the contact forces in SPERoN of the nine tyre road combinations used in the auralization

from the noise in the third octave band to a tonal component. Only the very strong tonal components improve the hearing impression when included. The tonal components tend to dominate the signal even if they are implemented with low energy content.

Since there were no distinct tonal components found in the signals used in the previous studies, no additional listening test to evaluate the effect of including tonal components could be done.

There was another data set available, containing rolling sounds that were designed to be more tonal. These sounds were generated in the Leistra3 project to investigate special tyre patterns designed by Stalter [100]. In some of the sounds simulated in SPERoN, distinct tonal components were detected, as can be seen in figure 5.7.

In this set of sounds, there are three sounds with strong tonal components. Sound S1 has two tonal components, one at 693 Hz and one at 1386 Hz. Sound S4 con-

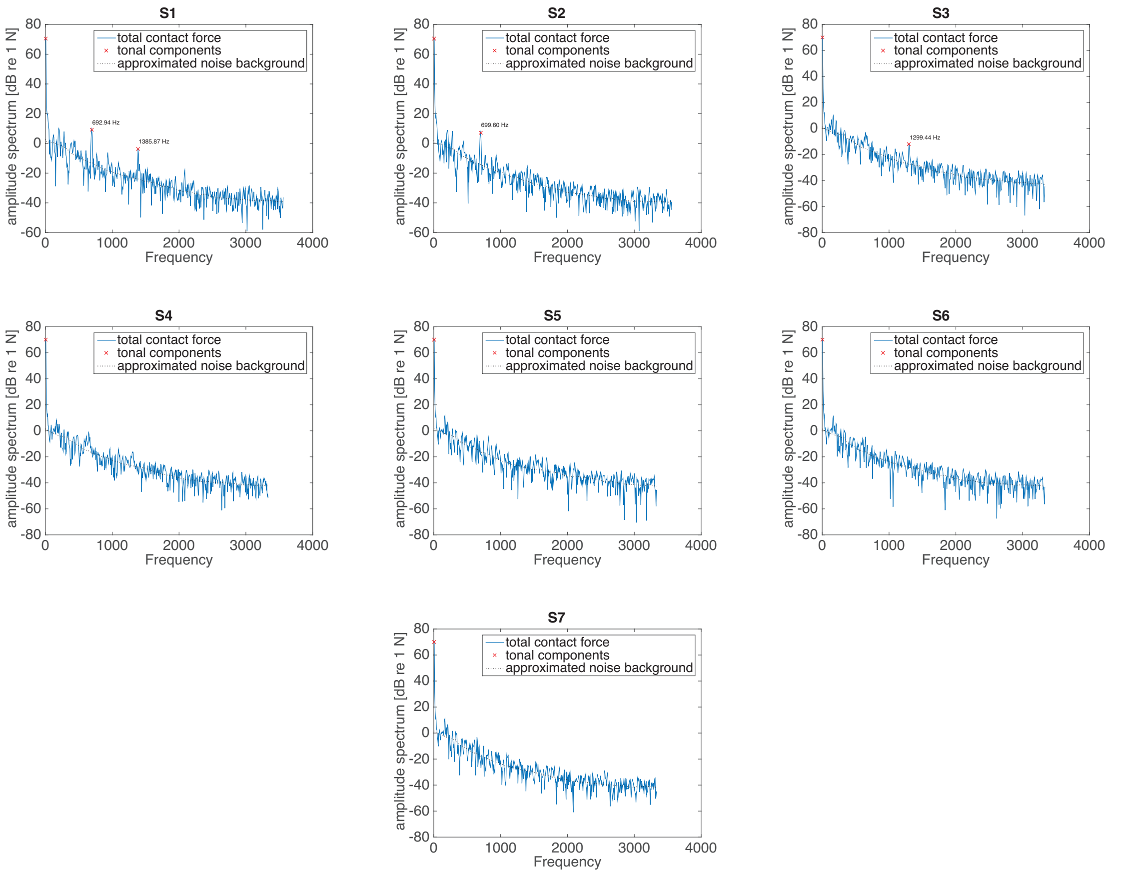


Figure 5.7: Spectra of the contact forces in SPERoN of 5 specially designed sounds by Stalter [100] in the Leistra3 Project

tains one tonal component at 699 Hz and sound S2 one at 1299 Hz. The hearing impression seems to improve for these sounds if adding the tonal component. It was not possible to perform an experiment to validate this impression, due to missing recordings under the exact same conditions. The tyres used for the recordings and the tyre data available for simulation was not the same.

In conclusion it can be said that “normal” pass-by situations do not seem to have tonal components that are strong enough to be considered in the auralization separately. For special situations there is a possibility of including tonal components, but this has to be treated with care.

Chapter 6

Perception of rolling noise

The aim of the second paper and this chapter is to evaluate how changes to the tyre or roads could affect the perceptual responses to the rolling noise. Is it possible to measure the differences in the perception of rolling noise? And is it possible to separate between the influence of the sound due to tyre and road on the perception? To investigate these questions a parametric study was designed using the three tyres and three roads described in chapter 3.2 to simulate rolling noise of a driving car. This study was part of the same listening test that was also used to validate the extended auralization tool in chapter 5.1.1. The listening test performed to validate the first version of the auralization tool (chapter 4) had also been conducted as a pre-study, investigating the nine signals by psychoacoustic means to find a set of fitting psychoacoustic parameters.

6.1 Pre-Study

To determine which psychoacoustic parameters might be useful to characterize tyre/road noise, a pre-study using a smaller set of participants was conducted. It is one of the two studies used in chapter 4.2.1 to validate the auralization tool. In the pre-study the participants were asked to rate the 9 pass-by signals based on the tyres and roads described in chapter 3.2 and at a speed of 50 km/h by a set of psychoacoustic parameters. The psychoacoustic parameters were chosen based on the psychoacoustic annoyance defined by Zwicker and Fastl in [118]. The chosen parameters were pleasantness, loudness, roughness, fluctuation strength and sharpness. The results of the pre-study showed that fluctuation strength was not fitted to describe the used car pass-by sounds. The most prominent fluctuation in level is due to the passing by of the car and that might be interpreted more as information about the sound source than as fluctuation strength. It is also the same for all cars, since all sounds were simulated at the same speed (50 km/h). For all other psychoacoustic parameters the participants appeared to be able to differ between the rolling noises. These were therefore included in the main experiment. The statistical analysis of the pre-study further indicated that it is possible to differ between the influence of the street and of the tyre as regards the perception of the tyre noise. The analyses also indicated that there is an interaction between the influence of the tyre and the influence of the road on the perception.

Interviews with the participants indicated that the pitch of the sound is not perceived as being the same for the different pass-by signals. This led to the decision to include pitch as another psychoacoustic parameter in the main experiment. Due to the promising results in the pre-study, the decision was made to extend the evaluation of the emotional response to the sounds. For this as an addition to pleasantness, activation was included. This was done to be able to locate the sounds in the two main emotional dimensions of valence and activation [93]. Additional stress was added as a perceptual attribute, since it is related to high activation and negative valence and to negative health effects [46]. The emotional response was extended to be able to investigate if there are any particular physical aspects that are connected to higher activation and negative valence, and thus potential negative health effects. For the main experiment a total of seven attributes were tested in the listening test: pleasantness, loudness, roughness, sharpness, pitch, stress and activation. The utilized psychoacoustic parameters were chosen to characterize the emotional response to the signals and to find psychoacoustic parameters that describe the sound characteristics of rolling noise. Models for calculation exist for some of the utilized psychoacoustic parameters (loudness, roughness, sharpness).

Based on the pre-study the hypothesis is made that physical differences between tyres and between roads affect the perceptual responses to rolling noise both for psychoacoustic and emotional parameters. Further, the hypothesis is that the influence by the street and the road on the perception can be separated and that tyre and road interact in their influence on the perception.

6.2 Method

To investigate the hypothesis that tyre noise can be differentiated by the perception, a listening test was designed using nine different car pass-by sounds. The sounds were all synthetic monaural car-pass-by signals, generated by the method described in chapter 4 and chapter 5. The sound pressure levels estimated by the SPERoN prediction tool for the 9 sounds are given in table 6.1.

Signal	A1	A2	A3	B1	B2	B3	C1	C2	C3
L_{tot}, dB	67.43	67.24	65.94	68.45	68.68	66.71	68.90	69.29	67.24
$L_{tot,A}, dBA$	67.04	66.91	65.59	67.95	68.19	66.31	68.22	68.60	66.59

Table 6.1: Levels of the nine used Signals in dB and dB(A) estimated by the SPERoN prediction model

Signal	A1	A2	A3	B1	B2	B3	C1	C2	C3
loudness [sone]	34.7	34.9	31.1	37.5	41.4	33.8	52.5	52.2	44.5
roughness [asper]	3.36	3.36	3.09	3.49	3.75	3.32	4.13	4.16	3.75
sharpness [acum]	2.61	2.62	2.69	2.57	2.55	2.65	2.38	2.41	2.43
f. strength [vacil]	0.29	0.29	0.29	0.30	0.31	0.28	0.38	0.36	0.39

Table 6.2: Calculated psychoacoustic parameters for the nine signals, using Artemis from Head acoustics

To characterize the 9 signals utilized in this study, they were analysed with Artemis from HEAD Acoustics [1] and the maximum values for the psychoacoustic parameters loudness, roughness, sharpness and fluctuation strength were calculated (Table 6.2). In a study on just noticeable differences (JND) for different psychoacoustic parameters using refrigerator noise [117], the found JND were for loudness 0.5 sone, for sharpness 0.08 acum, for roughness 0.04 asper and for fluctuation strength 0.012 vacil. Using these as a reference to evaluate the calculated psychoacoustic parameters for the nine sounds in this study, it can be expected in an experiment that the signals will be perceived differently in loudness and roughness for both tyre and road variations. For sharpness it should be possible to differentiate between some signals. The variations between roads seem to have more effect than the variations between tyres. Fluctuation strength only has a few variations stronger than the JND.

Apart from one signal (C3) the calculated values for loudness follow the order from more silent to louder as expected from the levels of the signals (table 6.1).

6.2.1 Listening Test Design

To determine whether the participants could differentiate between the different tyres and roads on their acoustic and emotional parameters a seven-step categorical scaling test was utilized (the same as used in the study described in chapter 5.1.1). For each signal and each attribute the participants were asked to rate on a scale from 1 to 7 how much they agreed that the attribute described the sound. The emotional responses were tested with the sentences: The sound is ”pleasant” / ”stressful” / ”activating”. For the psychoacoustic response the test sentences were: The sound is ”sharp” / ”loud” / ”rough” / ”dark/bright ”. The listening test was conducted in a soundproof and neutral room. The test was set up on a computer and the sounds were presented via open headphones (Sennheiser HD 650). The relative relation between the levels of the recorded signals was adjusted according to the data set of the recordings. The simulations were adjusted to match the same relative levels. However the signals were not played back at a level matching the original measurements, but the playback level for the listening test was adjusted in such a way that all sounds stayed within a comfortable range for the participants. The focus of the experiment was not on the absolute values, but on the relative differences. Both signals and questions were presented randomized with different orders for each participant and each repetition to minimize order and learning effects.

Each trial contained one signal and one question. In total the session had 63 trials. Before the experiment the participants conducted a practice session to familiarize themselves with both the sounds and the attributes. The main session was repeated twice. In total 18 participants (9 male, 9 female) participated in the listening test (mean age = 26 years, s.d. = 3.3 years).

6.3 Results

The results of this listening test were analysed with a repeated measure ANOVA (ANalysis Of VAriance) to be able to statistically validate the results and to be able to investigate effects by embedded parameters lsuch as tyres and roads. This method also allows measuring the interaction of embedded parameters. The results confirmed the hypothesis that tyre noise can be differentiated by its perception, and they further indicate that it is possible to differ between streets and tyres in the perception of rolling noise.

In figure 6.1 the mean values of the responses of the participants for the nine signals are displayed over the emotional and psychoacoustic parameters. It can be seen that there are differences in the responses for the different rolling noise cases. The results are compared to the calculated sound pressure levels and to the calculated psychoacoustic parameters and are analysed statistically.

Comparing the results for loudness (figure 6.1) with the estimated sound pressure levels (table 6.1) one can see similarities, but the loudest signal from Figure 6.1 (C1) has only the second highest sound pressure level in dB or dB(A). This is even stronger for the least loud signals. A2 and A3 are rated the same in loudness, but the level of A2 is about 1.2 dB higher, and there are signals on levels inbetween them that are rated higher in loudness. A2 and A3 have the same level of 67,24 dB and only half a dB difference in dB(A) but they were rated very differently in loudness.

Comparing the results from the listening tests (figure 6.1) with the values calculated in Artemis by HEAD acoustics (table 6.2), one can see that the results for loudness lead to similar ranking in both methods. Only the signals A2 and B3 change more than 2 places between the 2 methods. For roughness the basic order remains similar for the two methods. There are only changes in order between signals that are rated closely to each other. For sharpness, the orders differ completely. This can be due to the fact that they are all very similar and almost not differentiable at all. These findings can be confirmed by plotting the experimental results over the calculated results for each parameter (figure 6.2).

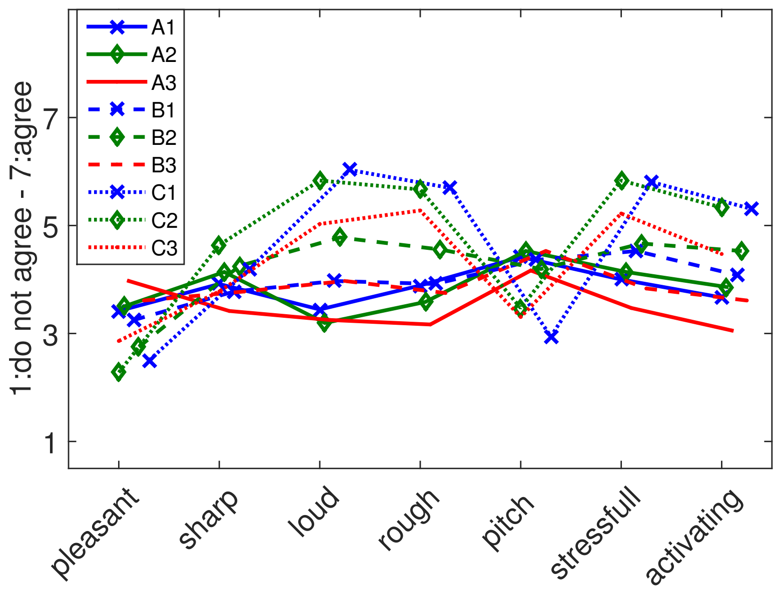


Figure 6.1: The results of the listening test are displayed: the means of the nine different tested sounds are shown for the tested percepts. The lines are marked corresponding to the different streets (A:solid, B:dashed and C:dotted line) and the different tyres (1:blue, 2:green and 3:red). The judgement ranges from 1: no participant agreed to 7: all participants agreed that the precept is describing the sound; for pitch the range was 1: dark to 7: bright

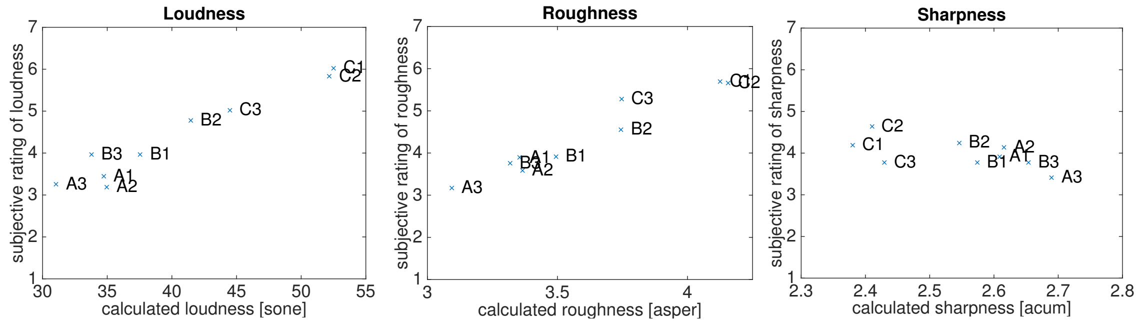


Figure 6.2: Comparison between the results from the listening tests and calculations for the nine signals for loudness, roughness and sharpness

To analyse if significant differences in the perception of the nine signals can be found, a one-factorial analysis had been done for the responses of each psychoacoustic and emotional parameter. For each analysis the results for the F-test will be given together with the degrees of freedom. Additionally the probability (p-value) for accepting the null-hypotheses will be given, and the effect size. The meaning of those values is described in chapter 3.1.3.

The results for the one factor analysis revealed that only sharpness could not be differentiated between the different signals. Pleasantness is significant with $F(8, 153) = 3,61; p < 0.001$ and an effect size of $\eta_p^2 = 0.16$, stress is significant with $F(8, 153) = 7,91; p < 0.001$ and an effect size of $\eta_p^2 = 0.29$ and activation is significant with $F(8, 153) = 7,30; p < 0.001$ and an effect size of $\eta_p^2 = 0.28$.

All emotional responses show significant differences in the perception of the nine signals and all show medium effects.

The results for the psychoacoustic parameters show that sharpness is not significant with $F(8, 153) = 1,45; p = 0.18$ and an effect size of $\eta_p^2 = 0.07$, loudness is significant with $F(8, 153) = 21,89; p < 0.001$ and an effect size of $\eta_p^2 = 0.53$, roughness is significant with $F(8, 153) = 10,31; p < 0.001$ and an effect size of $\eta_p^2 = 0.35$ and pitch is significant with $F(8, 153) = 3,86; p < 0.001$ and an effect size of $\eta_p^2 = 0.17$.

For the psychoacoustic parameters, loudness, roughness and pitch show significant differences in the perception of the nine signals, but pitch only has a minor effect. Loudness and roughness show a large effect. Sharpness has no significant difference in the perception of the nine signals and no effect either. This shows that the hypothesis of a difference in perception of rolling noise is true.

Further, the results in figure 6.1 indicate that the different street surfaces (solid, dashed and dotted line) modulate the responses. The road C (dotted) is rated for all tyres as the least pleasant, the darkest sounding, and the loudest, roughest and most stressful. The difference between the other 2 roads is not as big, but road A (solid) is rated more pleasant, less loud, rough, stressful and activating than road B (dashed). For the tyres the third one (red) is the most pleasant on all roads. It is also the least rough, stressful and activating. The first tyre (blue) and the second tyre (green) are very similar in their perception and change order on the different streets for most psychoacoustic parameters.

For all the psychoacoustic parameters that showed significant results in the one factor ANOVA, a multivariate ANOVA has been made, to analyse the effects within the signal parameters road ($F_{road} = F_r/F(r)$) and tyre ($F_{tyre} = F_t/F(t)$) and their interaction.

For the emotional parameters the results are significant both for the road and the tyre and the effects are medium to large. There was no significant result for the interaction between road and tyre for the emotional responses. The effect of the roads was significant for pleasantness with $F_{road}(2, 34) = 5.92; p < 0,01$ and an effect size of $\eta_p^2 = 0.26$, for activation with $F_{road}(2, 34) = 17.02; p < 0,001$ and $\eta_p^2 = 0.5$ and for stress with $F_{road}(2, 34) = 36.05; p < 0.001$ and $\eta_p^2 = 0.7$. The effect of the tyres was significant for pleasantness with $F_{tyre}(2, 34) = 12.22; p < 0.001$ and an effect size of $\eta_p^2 = 0.42$, for activation with $F_{tyre}(2, 34) = 18.68; p < 0.001$

and $\eta_p^2 = 0.52$ and for stress with $F_{tyre}(2, 34) = 17.71; p < 0.001$ and $\eta_p^2 = 0.5$. The interactions between tyre and road were not significant (pleasantness with $F_{road} \times F_{tyre}(4, 68) = 1.6; p = n.s.$, activation with $F_{road} \times F_{tyre}(4, 68) = 0.71; p = n.s.$ and stress with $F_{road} \times F_{tyre}(4, 68) = 0.12; p = n.s.$).

For the psychoacoustic parameters, loudness and roughness show the strongest effects. There are significant main effects of both road and tyre on the perception. The effect is large for the road and medium for the tyre. Pitch gives a significant difference only for the road with a minor effect, but no significant result for the tyre. The interaction is significant for loudness and for pitch, but not for roughness. The effect of the roads was significant for loudness with $F_{road}(2, 34) = 51.21; p < 0.001$ and an effect size of $\eta_p^2 = 0.75$, for roughness with $F_{road}(2, 34) = 39.12; p < 0.001$ and $\eta_p^2 = 0.7$ and for pitch with $F_{road}(2, 34) = 5.2; p < 0.05$ and $\eta_p^2 = 0.23$. The effect of the tyres was significant for loudness with $F_{tyre}(2, 34) = 11.71; p < 0.001$ and an effect size of $\eta_p^2 = 0.41$, for roughness with $F_{tyre}(2, 34) = 8.97; p < 0.001$ $\eta_p^2 = 0.35$. But not for pitch ($F_{tyre}(2, 34) = 0.72; p = n.s.$ and $\eta_p^2 = 0.04$). The interactions between tyre and road was significant for loudness: $F_{road} \times F_{tyre}(4, 68) = 7.41; p < 0.001$ and for pitch: $F_{road} \times F_{tyre}(4, 68) = 3.06; p < 0.05$ but not for roughness: $F_{road} \times F_{tyre}(4, 68) = 2.03; p = n.s.$.

6.4 Discussion

The results confirm the hypothesis that tyre noise can be differentiated by the perception. This is valid both for the emotional psychoacoustic parameters of pleasantness, stress and activation and for the psychoacoustic parameters of loudness, roughness and pitch. Only in the perception of sharpness were the used signals not rated as significantly different.

The experiment also indicates it is possible to distinguish between the influence of the tyres and the roads on the resulting rolling noise. Our experiment was evaluated using a multivariate ANOVA to analyse the influence of tyre and road. For the emotional responses the effects for the tyres and for the roads are significant and have a medium to large effect size. For the psychoacoustic parameters, the responses show significant effects for the road as an influencing parameter for loudness, roughness and pitch with large effect size for loudness and roughness and a medium effect size for pitch. For the perception of the tyre the response differed significantly for loudness and roughness with medium effect sizes, but not for pitch. In general the effect sizes indicate a higher difference in the perception of the roads than for the tyres. This can also be seen in figure 6.1.

The analysis of the interaction between the perception of the tyre and the road showed no interaction for pleasantness, stress, activation, and roughness but for loudness and pitch, whereas the pre-study indicated an interaction for all tested psychoacoustic parameters. One reason could be that the used signals in the pre-study were based on an older version of the auralization tool. Thus the signals in both studies were not exactly the same. This difference has to be further investigated. It would be helpful to know if the effects of the tyre and of the road on the rolling noise are independent from each other or interacting in the perception.

For loudness and roughness the spread in the rating of the signals was largest and also showed the highest effect sizes. That leads to the assumption that they are suited to characterize rolling noise. Pitch and sharpness seem to be of less importance due to their lower effect sizes. Stress and activation show a large variance and are thus of importance to the signals. Pleasantness showed a smaller effect size and the spread in the ratings was smaller than for the other emotional parameters. One reason can be that the sound in general was not seen as pleasant over all. This limits the scale to half. It could be better to test annoyance instead in further experiments and to focus more on that aspect of the perceptual space.

When comparing listening test results for loudness with the calculated sound pressure levels of the signals, it can be concluded that the levels do not indicate properly how strongly all signals will be perceived. This is also valid when applying A-weighting.

The calculation models in Artemis led to good agreement with the experiment for loudness and roughness. For sharpness no agreement between model and experiment could be found.

The performed experiment improves the understanding of the perception of rolling noise. It indicates that rolling noise evokes psychoacoustic and emotional responses in a measurable range. This study confirms that a distinction can be made between the contribution of the road and the tyre on the perceptual rating of tyre/road noise. The emotional responses have primary effects on all tested parameters (pleasantness, activation and stress) for the tested sounds. The psychoacoustic parameters of loudness and roughness are of main importance to the perception of rolling noise and have the largest effects. In relation to these, pitch and sharpness show a much smaller effect on the perception of the tested signals.

Any final conclusion about the interaction of both could not be drawn due to contradicting results. An interaction between the effects by road and tyre could only be shown for loudness and pitch,and not for the other tested parameters, as the pre-experiment suggested.

6.5 Interaction of psychoacoustic parameters

Another matter that could be followed up with the performed listening tests was to investigate the interaction of the psychoacoustic parameters with the emotional parameters. Which parameters influence the perception of pleasantness, stress and activation the most and do they interact with each other? To follow up on that question a correlation analysis between the parameters has been made.

	sharp	loud	rough	pitch	stress	activation
pleasant	-0.81^{**}	-0.93^{***}	-0.95^{***}	0.75^{*}	-0.96^{***}	-0.98^{***}
sharp		0.64	0.67	-0.35	0.71^{*}	0.81^{**}
loud			0.97^{***}	-0.87^{**}	0.94^{***}	0.94^{***}
rough				-0.89^{**}	0.97^{***}	0.95^{***}
pitch					-0.86^{**}	-0.78^{*}
stress						0.98^{***}

Table 6.3: Analysis of the correlation between the different percepts over the mean value responses of the participants for the different sounds. The displayed values are the **R** values for each cross-correlation. $*$ marks the correlations at 5% limit, $**$ marks correlations at the 1% limit and $* * *$ marks correlations at the 0.1% limit

The results are given in table 6.3. Pleasantness is inverse to all attributes but pitch. The emotional responses pleasantness, stress and activation correlate with each other, as expected for the investigated type of sounds. Both pleasantness and activation correlate with roughness, loudness and sharpness, but not with pitch on a 1% limit. Stress correlates with roughness, loudness and pitch, but not with sharpness on a 1% limit.

Due to the fact that there is no significant difference in the ratings of sharpness (chapter 6.3), even though sharpness correlates with activation and pleasantness at the limit of 1%, it cannot be interpreted as a parameter that influences the emotional reaction to the tested signals. This leaves loudness and roughness as the main parameters that influence both pleasantness and activation. Stress is additionally affected by the pitch of the sound.

Chapter 7

Conclusion

The first aim of this thesis was to create a tool that makes simulated tyre/road noise audible. An auralization method has been introduced, tested and further developed. This resulted in an auralization tool that creates pass-by sounds of passenger cars that are perceived comparably with recordings. For this auralization method, a combination of the SPERoN prediction model [59] with the Auralization tool developed by Forssén [32] is utilized.

In the resulting auralization tool the basic characteristics of the signal are estimated by the SPERoN model. In the simulation process the SPERoN model specifies tyre and road types and provides source characteristics in the form of third octave band spectra to the auralization model. For this, it requires detailed information about the road surfaces (measured roughness, flow resistance), the tyres (mechanical properties and profile), driving speeds and load (i.e. weight of the vehicles). Underlying measurements are included in an extensive database [9], which was created in the Sperenberg project.

The spectrum delivered by SPERoN is then used in the auralization approach based on the Listen Demonstrator, which was developed by Forssén [32] in the Listen Project. The source therm that characterizes the tyre/road noise from the reference signal in the auralization is reshaped by the third octave band spectra calculated by SPERoN. To create new pass-by signals according to the source parameters defined in SPERoN, propagation effects are applied to the source signal to create the final signal at a defined receiver position. The considered propagation effects are directivity, ground reflections, air attenuation, distance effect and Doppler effect.

The auralization tool has been validated with the help of listening tests. These showed that the simulated signals are perceived as being very similar compared to recordings under the same conditions. One limitation in the auralization was given by the lower frequency limit in SPERoN. It is not possible to simulate for frequencies below 315 Hz. Noise in these lower frequency bands is mainly related to wind noise. It cannot be excluded in recordings and thus might have an effect in comparisons between recorded and simulated sounds. A method had been included in the auralization tool to consider those frequencies and to improve the data transer between the two tools. Comparisons with recordings showed that the agreement between simulations and recordings is made best with this extra consideration of the low frequencies.

A further point of investigation was the question of how to treat tonal components. Since the transfer of information about the signal between SPERoN and the auralization is made in third octave bands, information about tonal components could be lost. The implemented auralization method allows seperate consideration of tonal components. The findings were however, that the auralization is very sensitive to the tonal components and tends to overestimate them and that the investigated pass-by sounds did not contain tonal components strong enough to be included. For special situations there is the possibility of including tonal components, but this has to be treated with care.

The second aim in this thesis was to use synthesized pass-by sounds to investigate and verify the perception of rolling noise. The question was if tyre noise can be differentiated by the perception. The performed listening tests and analysis showed that this is valid, both for the emotional psychoacoustic parameters of pleasantness, stress and activation and for the psychoacoustic psychoacoustic parameters of loudness, roughness and pitch. Only in the perception of sharpness were the used signals not rated significantly different. Fluctuation strength was dismissed as a parameter in most of the performed studies. Both calculations and the experiment indicated that the analysed signals showed no significant variance in fluctuation strength.

The performed studies further indicate it is possible to differ between roads and between tyres in the perception of rolling noise. Statistical analysis to investigate the influence of tyre and road on the perception of rolling noise shows significant effects of both road and tyre on most of the tested parameters. For the emotional responses the effects for the tyres and the roads are significant and have a medium to large effect size. For the psychoacoustic parameters, the responses show significant effects for the road as an influencing parameter on loudness, roughness and pitch. For the perception of the tyre the response differed significantly for loudness and roughness, but not for pitch. In general the effect sizes indicate a higher difference in the perception of roads than for tyres.

The effects of tyre and road on the perception of rolling noise interaction can not be answered with the performed studies. Results were partly contradictory. The statistical analysis of the interaction between the perception of the tyre and the road showed no interaction for pleasantness, stress, activation, and roughness but for loudness and pitch, where as the pre-study indicated an interaction for all tested psychoacoustic parameters.

Furthermore, interaction between the utilized psychoacoustic parameters has been analysed. Pleasantness is inverse to most tested attributes, as expected. The emotional responses of pleasantness, stress and activation correlate with each other, as expected for the investigated type of sounds. Due to the fact that there is no significant difference in the ratings of sharpness, even though sharpness correlates with activation and pleasantness at the limit of 1%, it cannot be interpreted as a parameter that influences the emotional reaction to the tested signals. This leaves loudness and roughness as the main parameters that influence both pleasantness and activation. Stress is additionally affected by the pitch of the sound.

To summarize, the performed experiments clearly indicate that variations in rolling noise evoke a variety of psychoacoustic and emotional responses in a measurable range and thus confirm the hypothesis behind this work. This study further confirms that the perception of rolling noise can differentiate between effects in the signals from the road and the tyre. Thus from the viewpoint of perception of rolling noise both tyre and road contribute to the noise experience.

Chapter 8

Future work

In the previous chapters a method has been introduced and validated to auralize tyre/road noise. This method offers a possibility to auralize car pass-by sounds under very controlled conditions. Possible parameters under control are distance, speed, type of tyre, type of engine, street surface and presence of a noise barrier. This full control of the car pass-by sounds can be used to realize more complex acoustic traffic situations, by combining the seperate signals into a desired sound. Single auralized pass-by sounds can be combined to the sound of a street or several streets. With this method there is full control of the traffic volume, the traffic flow, variances in speed and the types of cars and their numbers. The sounds for the streets can be created for different distances to the listener and in different directions. The last step is to combine different streets into a complex sound impression.

Up to now, listening tests about traffic sounds were mainly based on sets of recorded signals representing specific situations. With the introduced method, acoustic impressions of different traffic situations can be produced as very controlled, reproducible and variable in all relevant parameters.

Future studies should focus on using the presented tool for an elaborate study of the perceptual space of a car in background noise. With the tool at hand it will be possible to separate individual parameters that influence the perception and to study their impact on the perception. Possible parameters are the geometry between different streets, the traffic flow both in amount and regularity, and the type of vehicles involved. It would be of interest to investigate how changes in the different parameters affect the reaction time of a listener to the test car.

Another interesting question is if there are differences in the perception or reaction time comparing different noise reduction methods, such as a noise barrier, a longer distance or a level reduction of the original source. All methods should have the same overall level, but with slightly varying spectra.

Another interesting field where the presented method could be used, is the conflict between too silent and too noisy cars. With this method an extreme case of a silent car (only tyre and wind noise, no engine) can be compared with cars with a combustion engine or additional tonal components representing an electric engine or warning sounds. Using these different cars as test cars and combining them with background traffic noise in different circumstances, it might be possible to gain a better understanding of influences on vehicle detection and of possible solutions.

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