DELIVERABLE 5.12

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	Development and description of the traffic noise synthesiser and the included data (sound library, propagation functions)
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0 EXECUTIVE SUMMARY

0.1 OBJECTIVE OF THE DELIVERABLE

The deliverable describes the work performed within work package WP5.12 of the QCity Project. There were two main subjects within this work package. First the development of a software tool, called Traffic Noise Synthesizer (TNS), to auralise the sound resulting of a simulated traffic scenario and second the development of a psychoacoustic metric to evaluate the human perception of the auralised sound. Both parts are the continuation of work performed in earlier stages of QCity.

The TNS is based on the software developed in WP2.3. The result of WP2.3 is a MATLAB tool, which allows for the auralisation of the sounds of the library recorded within WP2.1 and WP2.2. The sound can be filtered to simulate the effect of sound propagation and mitigation measures. Finally a psychoacoustic metric is calculated to evaluate the human perception. The MATLAB tool is a pure sample player. That means, only prerecorded sounds can be played back. It is not possible to generate sounds that have not been measured. Therefore it is not possible to play back sound resulting of pure simulated traffic scenarios. This is the purpose of the TNS developed in WP5.12.

The psychoacoustic metric developed within SP2 is based on a large number of single pass by events including a variety of vehicles (from small passenger cars to trucks) and running conditions (from 30 km/h rolling to full throttle acceleration) The resulting metric is able to predict the human perception with a significantly higher accuracy than the standard dBA value. Although traffic scenarios can be modelled as superposition of single pass by events it is expected that the human perception is strongly influenced by additional effects (e.g. masking). Therefore the psychoacoustic metric developed in SP2 has to be reevaluated and if necessary adapted to cover these effects. This work has been performed in WP5.12 and is described in this deliverable

0.2 STRATEGY USED AND/OR A DESCRIPTION OF THE METHODS (TECHNIQUES) USED WITH THE JUSTIFICATION THEREOF

The tool developed in SP2.3 was written in the programming language MATLAB. MATLAB is widely used for scientific calculation and offers a large library of common available functions and basic tools. This decreases the time for the development of a new application significantly. The major drawback is the increased computation time needed to get the results. The tool developed in WP2.3 is a sample player. The computation time needed for this purpose is not critical. MATLAB was therefore the optimum choice for this purpose. The TNS developed in WP5.12 resynthesises the sound of a large number of vehicles. The computation time needed for this purpose is significantly higher. The main purpose of the TNS is to auralise various traffic scenarios and to simulate the effect of mitigation measures to help communities in the planning process. Time-to-result is therefore an important factor for the success of such a tool.

Therefore the development has been done in the programming language C# based on the library .NET3.0.

The design of listening tests needed for the adaptation of the psychoacoustic metric developed in SP2 was based on the experience within HEAD acoustics and the results of prior studies.

0.3 BACKGROUND INFO AVAILABLE AND THE INNOVATIVE ELEMENTS WHICH WERE DEVELOPED

The result of prior research projects (e.g. HARMONOISE and ROTRANOMO) were calculation tools that allow for the prediction of the noise generated by a given traffic scenario and measured at a specific observer position. The outputs are spectra (third octave in the ROTRANOMO case). These spectra are sufficient to calculate the standard descriptors used in the noise map but are not sufficient for the evaluation of the human perception. For this purpose time signals are needed. The Traffic Noise Synthesiser developed in WP5.12 combines traffic simulations, the third octave spectra calculated by the ROTRANOMO code and prerecorded vehicle sounds to generate the noise of that specific traffic simulation. The result is an auralised time signal. Variations in the traffic flow (e.g. traffic lights or roundabout) or source characteristics (low noise pavement) can be directly perceived by the listener. The psychoacoustic metric developed in WP5.12 allows for the evaluation of the perceived annoyance without the need for listening tests.

0.4 PROBLEMS ENCOUNTERED

The time needed to calculate, auralise and evaluate the sound resulting in a variety of traffic scenarios and/or mitigation measure is important for the applicability of a software tool in the planning process. To minimise this time the development started based on the new programming language CUDA. This language allows for the use of the processor of the latest generation of NVIDIA graphic cards for the calculation. Graphic card are parallel processors with up to 240 single processors. Applications that consist mainly in small and simple parallel calculation steps can be calculated up to 100 times faster than on modern CPU processors. The calculations needed for the resynthesis of traffic sound could be parallelised. In the first phase of the TNS development it was possible to auralise up 16 vehicles in real time. But the developed code is only running on computers that include this specific hardware. Furthermore the software code could not be combined with the various signal processing tools already available within HEAD acoustics. Reprogramming all these tools would have increased the development time, resulting in an isolated solution, whereas the standard HEAD acoustics components are constantly refined.

To make the tool independent of the hardware and to use existing signal processing modules the development of the CUDA code has been stopped and the algorithms have been redeveloped in standard C#. As a result the development was not ready to deliver the synthesised sounds needed for the listening tests in time. Therefore the listening tests were based on prerecorded traffic scenarios and sounds synthesised with the software tool SVEN. SVEN has been developed within the EU project of the same name. It allows for the detailed synthesis of single pass by events based on near field recordings and transfer functions. It is limited on measured running conditions. For the listening test single pass by events have been calculated and then superposed to simulate complete scenarios. The main purpose of the listening tests was to develop a metric capable to predict the human perception of an arbitrary scenario. For this purpose it was important to use sounds covering the whole variety of interesting scenarios. It was not necessary to use the sound of a specific scenario.

After finishing the work on the TNS sounds of typical scenarios have been generated and successfully used to validate the metric.

0.5 PARTNERS INVOLVED AND THEIR CONTRIBUTION

GOOD provided a library of near field recordings of tire/road noises. The sounds were recorded on a chassis dynamometer. Due to various effects (e.g. the curving of the dynamometer surface) these sounds often include orders that are not present in recording performed on a real street. It is therefore difficult to use these sounds directly for the auralisation of exterior noise. Nevertheless the Goodyear sounds are valuable input for an additional research project at HEAD acoustics with the purpose of transforming chassis dynamometers measurement to street recordings that can be used for the TNS software.

The work of KTH is strongly related to the TNS development. The input for the TNS is the traffic simulation performed by KTH. Therefore a common interface between the two tools has been developed. The work will be continued outside the scope of QCity in subsequent research and consulting projects

0.6 CONCLUSIONS

The work package WP5.12 included two different major tasks. The first task was the development of the software tool for the auralisation of simulated traffic scenarios. The second task was the adaptation of the psychoacoustic metric originally developed within SP2 to cover also complex traffic scenarios. Both tasks have been successfully fulfilled.

Due to the delays justified above it was not possible to investigate a wider variety of scenarios within the duration of the QCity project, but the tools are ready now and will be used in subsequent research projects and for consulting projects in cooperation with the partners in QCity.

0.7 RELATION WITH THE OTHER DELIVERABLES (INPUT/OUTPUT/TIMING)

1 DEVELOPMENT OF A SYNTHESIS TOOL TO SIMULATE TRAFFIC NOISE

1.1 INTRODUCTION

The evaluation of traffic noise has been done under many different aspects in the past. Thereby, the main focus was on the sound pressure level produced by the traffic. Different cooperation and institutes are working on sophisticated tools to evaluate traffic noise maps, where the noise is given in broad band levels, octave band levels or even third octave band levels.

To evaluate traffic noise focusing on psychoacoustical aspects sound pressure level values are not sufficient and the time signals have to be taken as the evaluation base. One way to get time signals is the measurement of real traffic situations. Unfortunately, usually the conditions of the traffic flow cannot be controlled. Stochastic environmental influences and varying traffic flow make it difficult to obtain reproducible measurements.

To accomplish systematic evaluations it is necessary to have traffic data changing along certain parameters while other parameters remain constant. This is especially important for listening tests, where the subjective evaluations should be attributed to one changed parameter.

This high flexibility can only be provided by a simulation tool for traffic noise, which synthesizes the complete time signal of traffic scenarios. The synthesized noise can be auralised and used for listening tests.

Within the work package (WP) 5.12 a perception tool for traffic noise has been developed. This is implemented by combining the traffic flow simulation tool of KTH, the level estimation tool RoTraNoMo (see section 1.3.1) and the traffic noise synthesizer (section 1.3). The simulated traffic flow data is supplied to the RoTraNoMo software. This software tool calculates the third octave band levels of the sound radiated by the vehicles included in the traffic scenario. Finally, based on the traffic flow data and the sound pressure levels, the traffic noise synthesizer software calculates the time signal of the respective traffic scenario.

In the following the development of the traffic noise synthesizer tool is described in detail. Prior to the noise simulation a data base has to be created. The analysis and pre-processing needed for that are explained in section 1.2. The methods and functionality of the actual traffic noise synthesis are described in section 1.3. Within section 1.4 the implementation of propagation paths through barriers is described. The auralisation results created with the synthesizer are shown and discussed in 1.5 by means of some examples.

1.2 PRE-PROCESSING AND ANALYSIS (WP 5.12.1 AND 5.12.2)

Before the vehicle sounds can be synthesized a detailed evaluation and analysis of the real sounds have to be carried out. Therefore different measurements have been done (QCity Wp2.1 and WP2.2). As the vehicle sound is radiated from different locations, the corresponding sources were detected and adequate measurement positions were found. From this detailed measurements the characteristic signals have been analysed and pre-processed for the simulation.

On the one hand, measurements provide a very exact representation of vehicle sounds. On the other hand, they are inflexible because the variation of operation modes over time cannot be changed after the recording. This means that measurements can only map real, fixed situations.

A simulation of the vehicle sound provides the flexibility in choosing freely the different operation modes. The traffic noise synthesizer combines the advantages of the measurements with simulation. This is done by creating a data base that stores the measured characteristic signals for the different vehicle types. The simulation application uses these data sets to process the vehicle sound synthesis reproducing the measured signals with the requested flexibility.

In the following the conducted measurements are described. Furthermore, the analysis and pre-processing of the measured data, required for data base inclusion, is explained.

1.2.1 Measurements

For the analysis of the properties that should be stored into the data base it is necessary to carry out specific measurements with the vehicles that are going to be synthesized. The vehicle sound is expected as a composition of the contributions of multiple sub sources (e.g. engine and tire).

The radiated sounds are measured with microphones at near field positions in front of the different sub sources of the vehicle. During the measurements the vehicle has to run through the different operation modes influencing the sound radiation.

1.2.1.1 Power train data acquisition

In the work package 2.2 of the QCity project HAC carried out various measurements to evaluate the source components of vehicles. Within this work many experiences have been collected. These are in particular the detection of the most significant sound sources and the optimal positioning of the microphones in the near field of the sources. Resulting from that the following sources has been measured.

- 6 engine sides in the combustion room
- Air intake
- Exhaust outlet
- 2 Tires (leading / trailing)

The measurements have been carried out on a dynamometer to get reproducible measurements. In the measurements the engine speed, load and gear were varied. In difference to WP 2.2 where only a few operation modes have been measured, here it is imperative to record many different operation modes. This was done by measuring rpm run-ups at constant load and by repeating this for different loads and gears. The following operation modes were measured:

- Engine speed sweep: 750 – 6300 rpm
- Load: 0, 13, 16, 25, 50, 100 percent
- Gear: 2nd , 3rd

Figure 1: The pictures show two examples for the microphone positioning during the measurements. In case of the intake and exhaust sound measurement it was important to supress wind noise with a wind shield foam.

To do the evaluation and for the detection of the operation modes additional microphones and sensors have been used:

- 15 far field microphones
- Engine speed detector
- Dynamometer velocity detector
- Throttle position detector

The evaluation of the measurements had the goal to find a simplified source model of the vehicle. To reduce the complexity of the resulting simulation the number of sub sources representing a vehicle was reduced.

To achieve this reduction the far field signals and near field signals have been compared and evaluated. One aspect in this topic is that the engine signals are influenced by the damping caused by the combustion room in contrast to the exhaust and intake signals. The results of this evaluation are weighting factors for the different measured sources, which were summed up to one engine source.

This summation was not applied to the time signals of the sub sources, but to the analysed data (described in section 1.2.2). As this summation is done in the frequency domain, phase errors are eliminated that would occur when adding the signals in time domain.

1.2.2.1 Tire noise data acquisition

Besides the representative engine source one other source must represent the tire sound. To evaluate the radiated tire sounds, measurements have been carried out by HAC. In addition to that GOOD provided a set of tire noise measurements carried out on a test stand.

The advantages of the test stand measurements are the reproducible conditions. Furthermore, environmental influences of rain and wind on the measurement results can be excluded. The tire noise depends on both, the type of tire and the type of the road surface. On a test stand the different road surfaces can only be simulated in a very limited way. In contrast to it, by means of real road measurements several road surfaces can easily be considered.

The influence of chassis rolls for the measurement of tire noises were discussed in various publications. In general, test stand measurements include modifications of the tire noise caused by the test roll.

In the following the analysis and evaluations are described to reduce this influence.

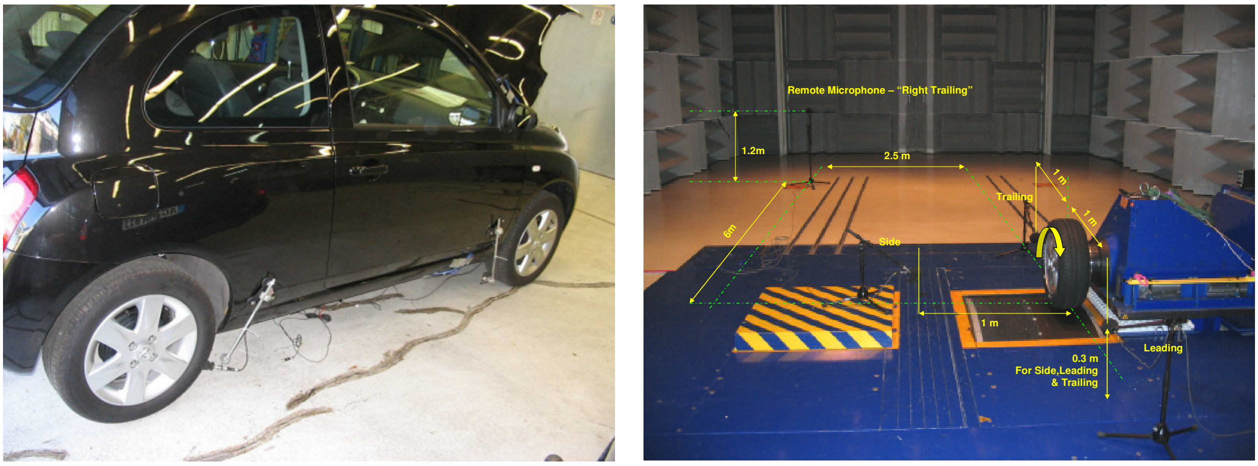


Figure 2: The pictures show set-ups to measure tire noise; left: positioning of the microphones for road measurements; right: set-up for test stand measurements

Tire noise evaluation

Certain effects, that appear when tire sound is measured on a roller test bench, result from the periodicity of the spinning tires and the turning of the test roll. This interaction causes modulations. In Figure 3 (a) a spectrum of a tire noise resulting from road measurements is plotted. Subplot (b) shows a measurement on a test stand. In both cases the sound was recorded with an artificial head at the co-driver position. The vehicle speed / dynamometer speed decreased from 110 km/h to 90 km/h during the measurements. While the spectrum (a) displays a nearly pure noisy frequency content, the spectrum (b) shows dominant harmonic peaks. In case that the frequency distance between these harmonic peaks is small, they can not be easily eliminated by simple notch filtering.

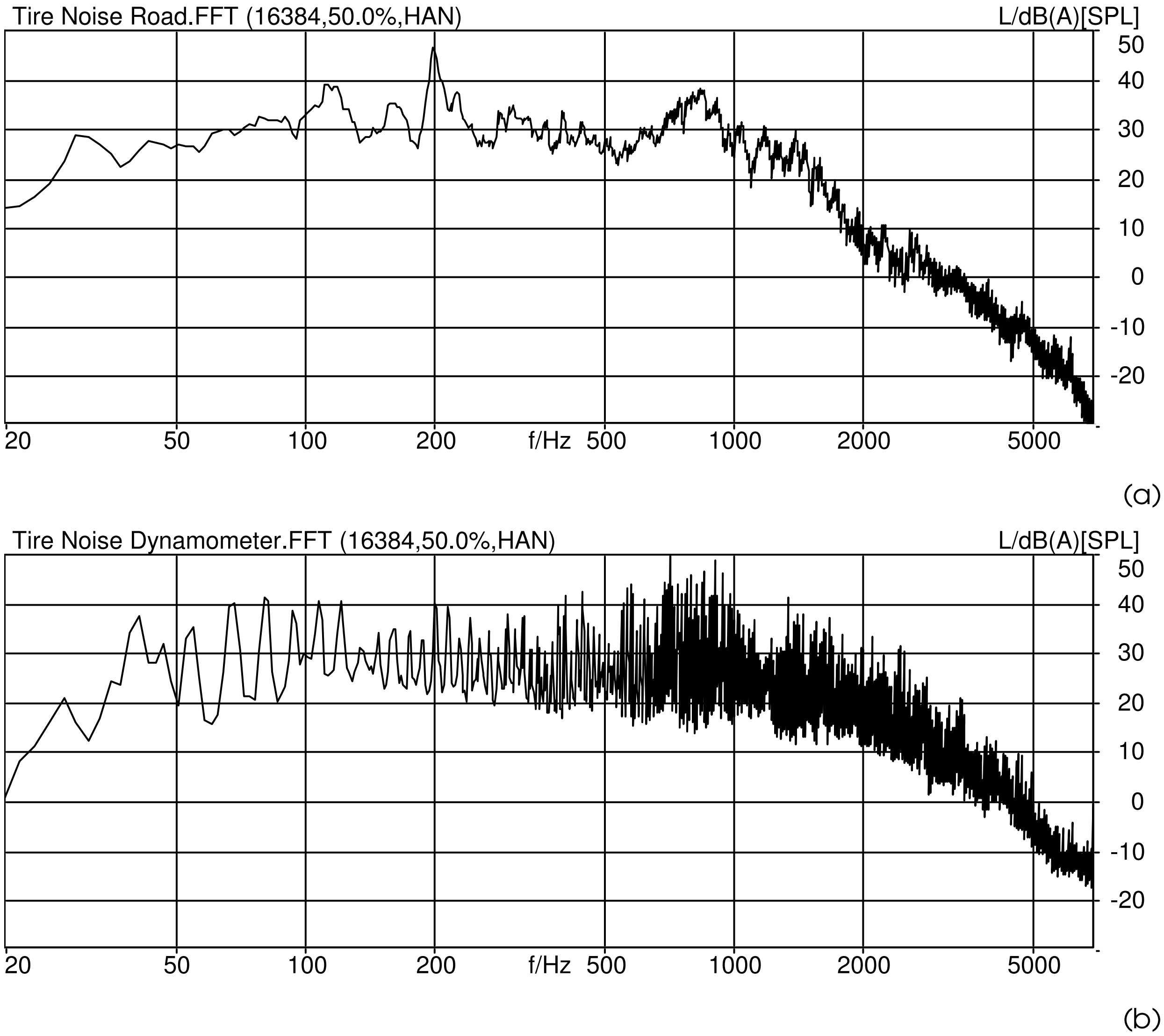


Figure 3: The plots display the frequency spectrum of tire noise measured on road (a) and test stand (b); In (b) the harmonics cause by signal modulations are observable

The above mentioned modulation of the signal is not exactly represented with a FFT analysis, because the time structure of the signal is not shown. A more exact approach for this task is to calculate the modulation spectrum of the signals. This analysis divides the signal in sub bands. Then for each sub band the modulation frequencies are detected and the amplitudes of these modulation frequencies are determined. The resulting plots for the same examples shown above are plotted in Figure 4. In the plot of the road measurement only horizontal lines can be seen, which represent resonances (sub figure (b)). The plot of the test stand measurement (b) displays prominent modulation frequencies, represented by vertical lines.

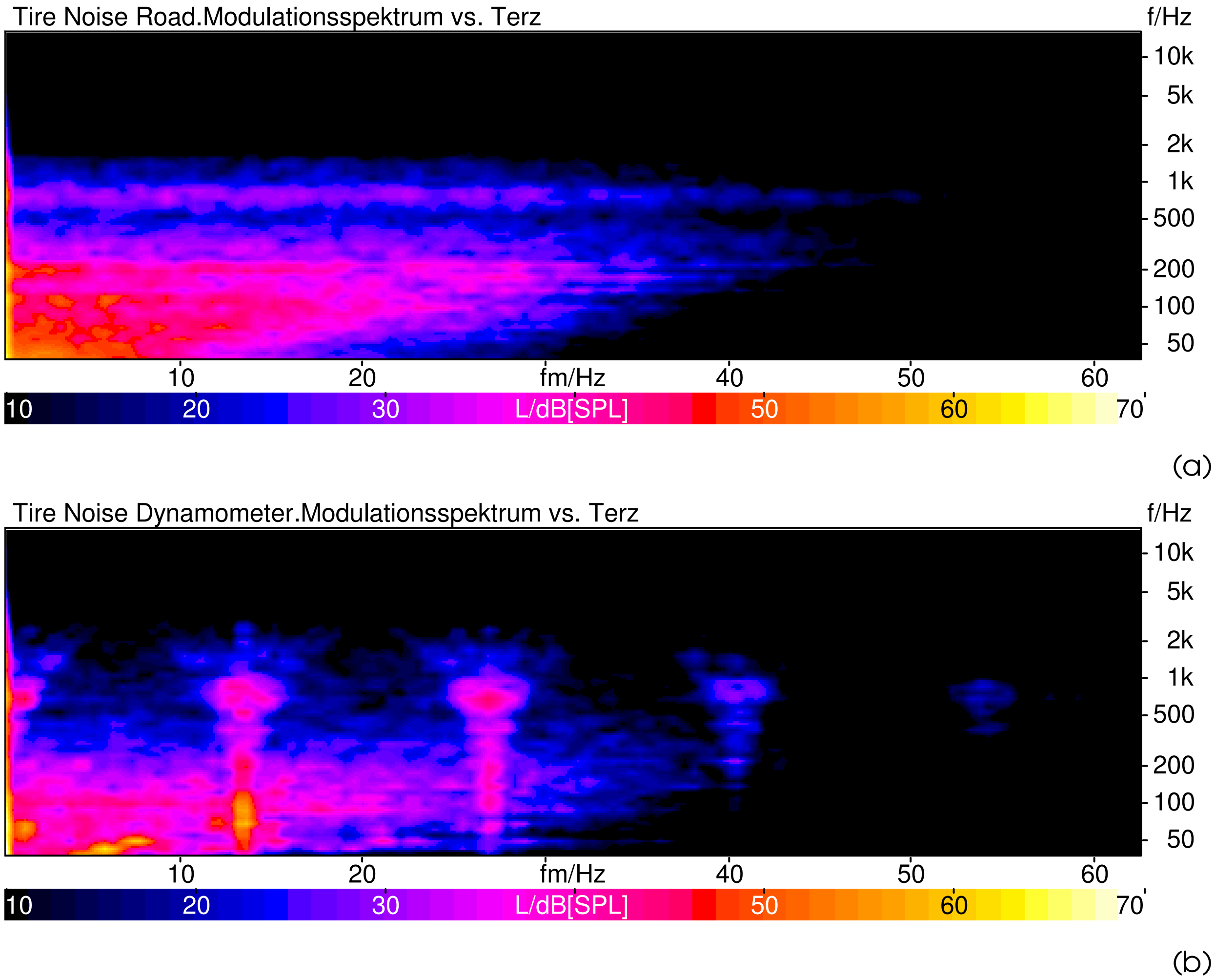


Figure 4: The plots show the modulation spectrum of tire noise measured on road (a) and test stand (b); In (b) the prominent modulation frequencies can be clearly seen (vertical lines)

Using the above described analysis different approaches are applied to reduce the modulation effects. Up to now, the result is not satisfying regarding the generation of natural tire noises. As a consequence the tire noises has been analysed based on road measurements.

1.2.2 Analysis

The analysis as a part of the pre-processing of the measured data has only to be carried out once. Thus, the performance is not of highest priority. In the actual research state the algorithms are implemented in the high level engineering tool Matlab.

As explained in section 1.2.1 the radiation of vehicle sound is considered as a collection of different sources. These source signals are in general complex signals, which result from different physical sound radiation processes. A common approach to split signals into simplified components is to divide it into a harmonic, a transient and a noise part. The benefit of the splitting is that each part itself can be synthesized much more easily.

The traffic noise synthesizer implements the noise and the harmonic (order) synthesis. Transient signals are mainly relevant for the synthesis of idle sounds. The analysis and synthesis of transient signals is part of the current research at HAC and will be included in the future.

Based on the carried out measurements the analysis and extraction of the different signal parts is explained below.

1.2.1.2 Noise analysis

The noise is expected as the residual part of the signal. This means that the noise includes all signal parts that are neither harmonic nor transient.

To analyse the noise signal part the following processing steps have to be considered. The input time signal is divided into blocks and each block is transformed into the frequency domain. Based on this spectrum the noise is estimated. The difficulty of this operation is to separate the harmonic parts of the spectrum from the noise part. An algorithm using a minimum statistics approach produces good results for this task. The calculated output spectrum is then smoothed and stored into the data base.

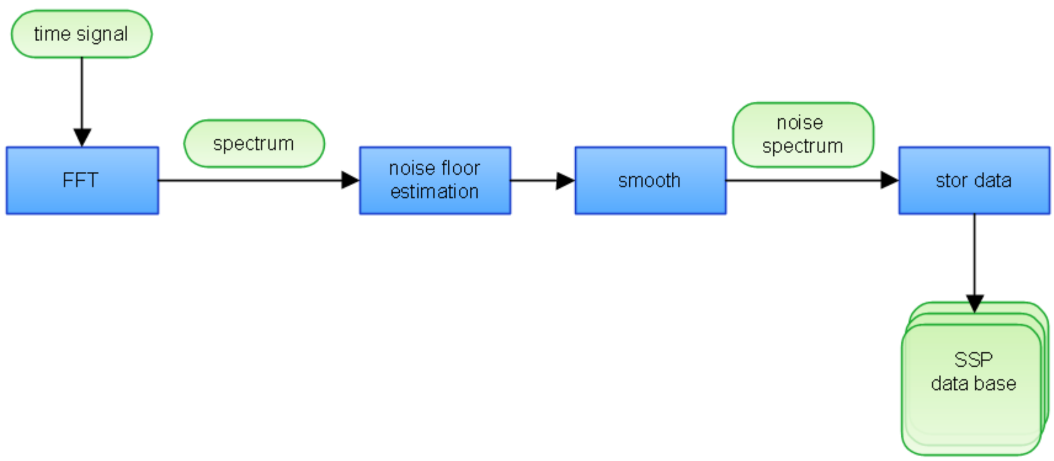


Figure 5: The noise spectra are calculated from the measured time signals. The noise estimation algorithm has to extract the noise part from the harmonic part.

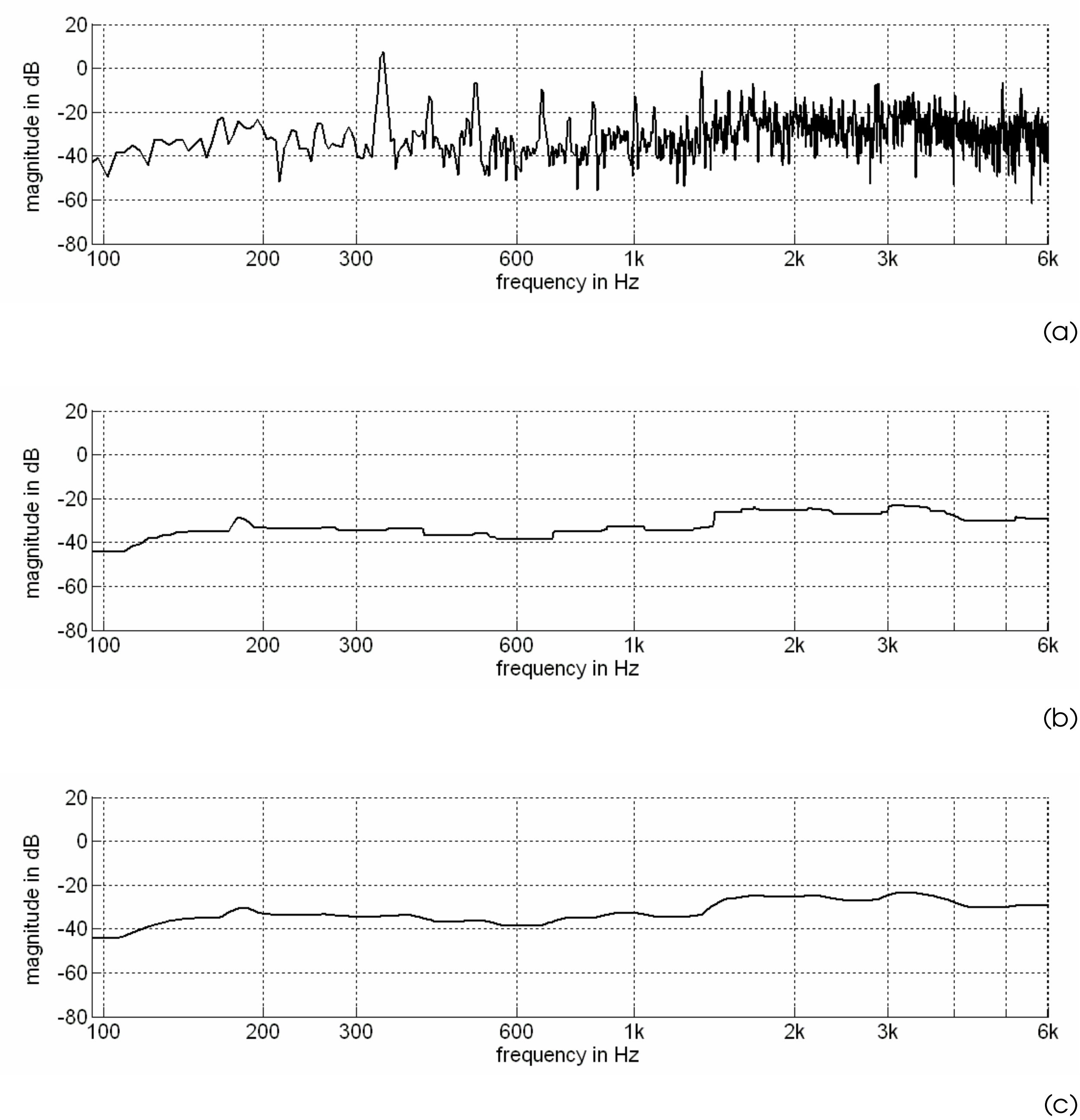


Figure 6: This figure shows the three steps required to calculate the noise spectrum from a signal that contains harmonic parts. Sub figure (a) shows a frequency spectrum of an engine signal recorded at 5000 rpm and 50 percent load. With a minimum statistics approach the noise part of the signal is estimated (b). Finally the spectrum was smoothed (c).

1.2.2.2 Order analysis

All periodic processes cause tonal noise contributions. Due to non linear behaviours the periodic excitation result in harmonic sound signals. In particular this is true for the combustion process of engines.

For the specification of the harmonic part of the signal, it is necessary to obtain the orders' amplitudes of the signal and the fundamental frequency.

The analysis of this signal component is shown in Figure 7. The time signal input is for instance a run-up measurement of a vehicle on a chassis dynamometer. The signal is analyzed in blocks and each block is converted into the frequency domain. With the knowledge of the engine speed the estimation of the harmonic frequencies can be calculated. Within a small frequency band the amplitudes are examined and via a local maximum detection algorithm the actual amplitude of an order is detected and saved. Going through the whole time signal value pairs are created combining the rpm values with the order spectra. These value pairs are finally stored into the data base.

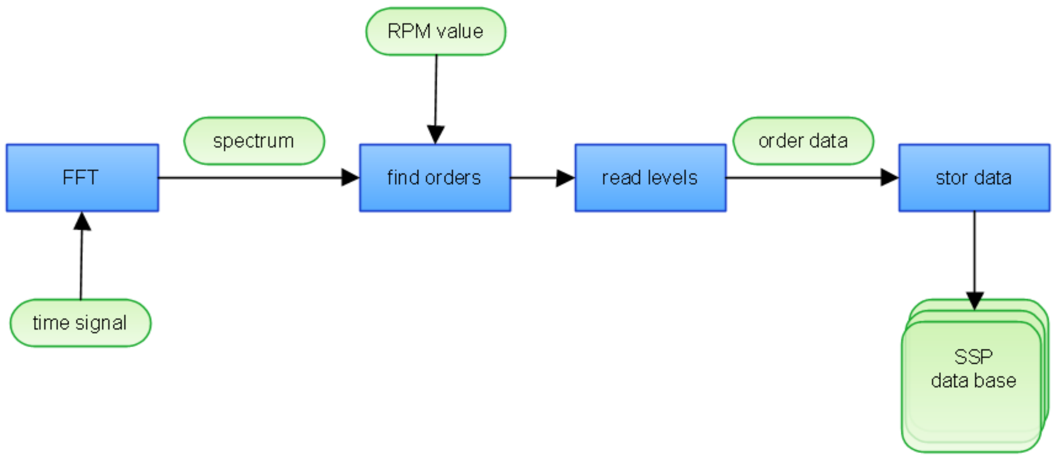


Figure 7: The extraction of the order levels bases on the rpm-values. To achieve a high accuracy an algorithm searches the "best" level values within a frequency range. To reduce data storage the levels are stored as an order spectrum and not as a complete frequency spectrum.

The generation of the above described data including the measurements and the analyses of the different vehicle sounds was the first mile stone for the traffic noise synthesizer. Starting from this the synthesis of the different source signals can be performed. To include the analysed data into the simulation the data need to be quickly recalled during the calculation. To provide this a data base concept was applied.

1.2.3 Data base for vehicle sound properties

The interface between the measurements of the vehicle noise and the simulation is a data base. The data base stores the sound properties, which characterize the acoustic behaviour of the different sources, which should be simulated. Within the traffic noise synthesizer software these property values are noise spectrum data and order levels. The data structure is very flexible; it allows for applying any data type and any source type. For each source the properties must be stored along multiple dimensions, where each dimension represents an operation mode of the physical device radiating the sound. In the following this is described by means of an example.

Sound radiates from the vehicle engine. This sound can for instance be characterized by a frequency spectrum. Depending on the operation mode of the vehicle the engine radiates different sounds, which lead to different spectra. In this example it is assumed that the operation modes differ with the RPM value and the load of the engine. To collect the data for the data base the vehicle has to be measured at a certain range of RPM values and in different load conditions. After the measurement the data must be analyzed to extract the spectra and finally the spectra are stored in the data base.

The described sound property data base can hold data for arbitrary vehicles like gasoline cars, diesel cars, motorcycles or trucks. It is possible to create data sets representing an individual vehicle with its specific characteristics, but it is also possible to include data sets for averaged vehicles representing for example vehicle classes.

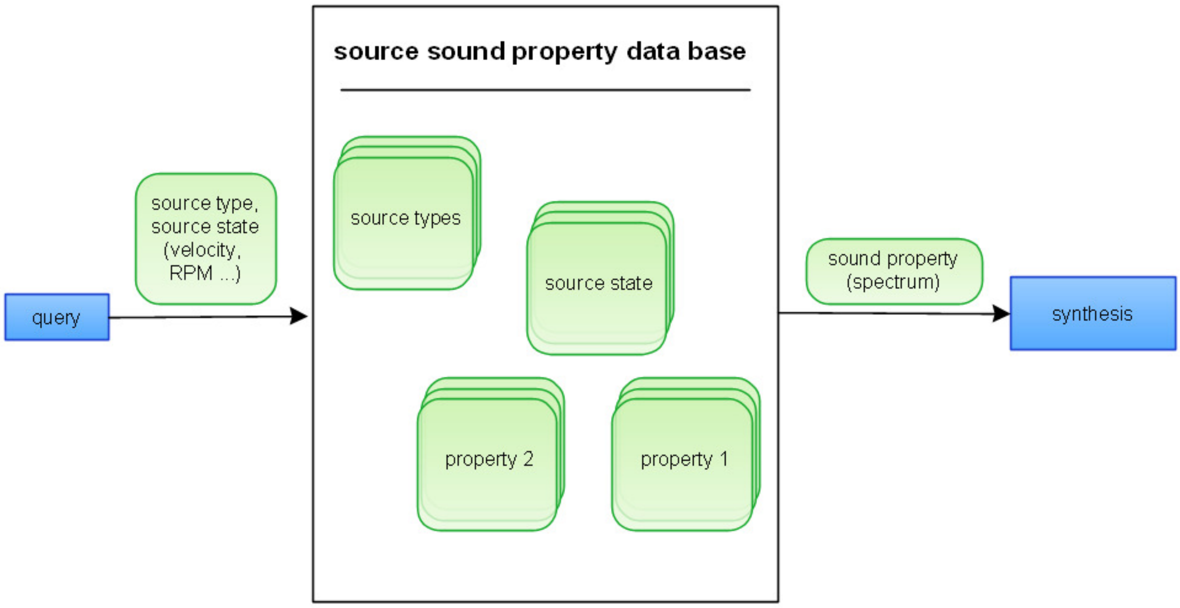


Figure 8: The source sound property data base stores the data used for the source signal synthesis. Data sets have to be included for all interesting operation modes of the vehicles. These data sets can be frequency spectra but also time patterns or any other type of data. During the simulation the sound properties can be accessed directly with no restrictions.

In general, source sounds are completely described by their time signal. To extract the characteristic sound properties of sources the time signal is not flexible enough. Moreover, the time signal needs too many resources for storage.

To find a proper data set for different sources, on the one hand, it is important to reduce the amount of data. On the other hand, it is essential, that the data sets can be easily interpolated between different source conditions. This is of particular importance with respect to the fact that it is not possible to store data sets for all values of source conditions (RPM, velocity, gear, load …), which can occur. This would lead to a huge data base, which would be difficult to handle.

A good compromise between these two requirements is to use the order levels for the harmonic signal parts and a smoothed spectrum for the noise part.

1.3 DEVELOPMENT OF THE TRAFFIC NOISE SYNTHESIZER (WP 5.12.3)

1.3.1 Traffic simulation tool

The traffic noise synthesizer is able to auralise traffic flow data. The traffic data controlling the synthesizer is provided by the KTH. Based on statistic evaluations and analyses KTH has developed a simulation tool that provides the information of arbitrary traffic scenarios.

In addition to the traffic flow data, a second simulation tool generates sound emission information. This was developed in a project, which is explained in the following.

The RoTraNoMo Project

The Road Traffic Noise Model (RoTraNoMo) project was supported by the European Commission`s DG Research (G3RD-CT-2002-00801). One work package of this project was the development of a vehicle noise emission model. This model is implemented in a software program that calculates the noise emission for every second and each vehicle of the traffic simulation model in terms of rolling noise, propulsion noise and total noise as A-weighted levels and third octave band levels.

The noise emissions are calculated using the output data from the traffic flow model developed by the KTH. During the work on WP 5.12.3 KTH supported HAC with input data of these two simulation tools. To link the software tools, a unified traffic data interface is developed. Details are described below.

1.3.1.1 Traffic data interface

The results of the simulations calculated by the RoTraNoMo software include the traffic flow data and the noise emission data as third octave band levels. These data were written into an Excel file including the following data:

- Time
- Position of the vehicle
- Description of the vehicle type
- Velocity of the vehicle
- Type of street surface
- Gear
- Engine speed
- Third octave band levels of the tire noise
- Third octave band levels of the engine noise

These data samples are given second by second for each vehicle moving in the scenario. From the Excel-file the information required for the auralisation is extracted and used within the traffic noise synthesizer.

1.3.2 Source signal synthesis

As mentioned in section 1.2.1 the radiation of the vehicle sound is caused by different sub-sources such as engine sound and tire sound. In section 1.2.2 it is described that the sub-sources signals of the vehicles can be subdivided into two different signal parts, orders and noise. Each signal part is represented by data sets in the sound property data base and each data set is supplied to a synthesizer within the traffic noise synthesizer. According to section 1.2.2.1 the tire sound signal is expected to be only noise. In contrast, the engine signal is treated as a combination of an order and a noise signal part.

1.3.1.2 Order synthesis

The order synthesis bases on the data sets from the sound property data base. The data sets store the amplitudes of the orders and the fundamental frequency.

The calculation of the order signal is based on a sinus calculation in the time domain. For each order frequency a sinus function is calculated and summed up to the complete harmonic signal. The calculation done in the time domain guarantees a continuous signal. This avoids unnatural artefacts in the synthesized signal and provides smooth changes of the fundamental frequencies over time.

The disadvantage of this method is the calculation performance. For each synthesized sample and for each order the sinus function has to be calculated. Thus, it must be decided how many orders necessarily have to be part of the synthesis. As a result from examinations a quantity of 125 orders with a step width of half orders proved to be feasible. This leads to a maximum frequency of 6250 Hz at an engine speed of 3000 rpm. A further step to reduce the quantity of orders is to take only the orders into account, which significantly contribute to the resulting signal. To evaluate this, the amplitudes of the orders are compared to the noise level in the frequency band of the order. If the amplitude is lower than the noise level, the order is not calculated.

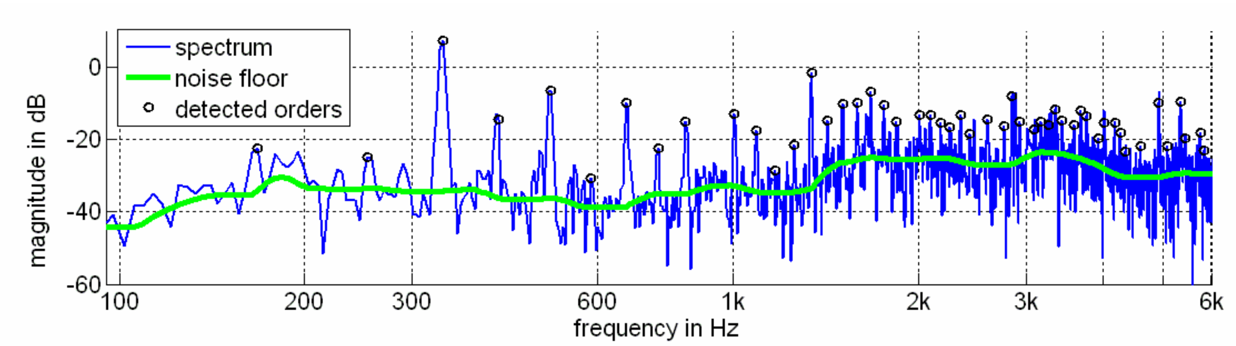


Figure 9: For the detection of the order levels, the previous calculated noise spectrum is used (green line). This is compared to the unprocessed spectrum of the signal (blue line). All frequency lines that are multiples of the fundamental frequency and which have a higher level than the noise level, are considered as relevant orders (black circles).

1.3.2.2 Noise Synthesis

The base for the noise synthesis is a smoothed spectrum. As the noise is expected as purely random the phases are not considered within the synthesis. Initially a random noise with normalized amplitude is generated. This noise is represented by a constant frequency spectrum (white noise). In a next step the white noise has to be filtered to change the constant spectrum into a specific spectrum using data from the data base. This is implemented with a finite impulse response (FIR) filter. As this filtering is a block wise operation a smooth transition is not guaranteed. To assure this the following method is applied. On the one hand, each noise signal block is filtered with the spectrum occurring at the current block. On the other hand, the same signal block is filtered with the spectrum occurring at the next signal block. These two filtered signals are then cross faded to one signal. This double calculation of the signals is necessary for a natural auralisation, but increases the calculation performance.

1.3.3 Sound propagation

After the synthesis of the source signals the signal processing of the sound propagation is a second task for the traffic noise synthesizer. The concept is based on the actual physical situation of traffic scenarios. This means that the signal processing steps follow the physical propagation path of sound.

The propagation in the traffic noise synthesizer is divided into two fields. One includes the influence of propagation that occurs in any scenario; this is the Doppler-Effect and the binaural effect. The second field concerns the propagation paths influenced by barriers. This aspect is described separately in section 1.4.

1.3.1.3 Doppler-Effect

The Doppler-Effect is caused by the finite value of the speed of sound. When sound waves are radiated from a moving source or are received by a moving observer, the perceived sound has a modified frequency. The value of this frequency shift is in relation to the relative speed between source and observer.

The calculation of this modification is well known and simple to evaluate for single frequencies. The challenge is to do this processing for arbitrary broad band signals. From an abstract point of view this calculation "stretches" and "squeezes" the signal. This can be done by resampling algorithms. To achieve a natural sound this resampling has to be done with a high quality, which leads again to a higher calculation load within the simulation.

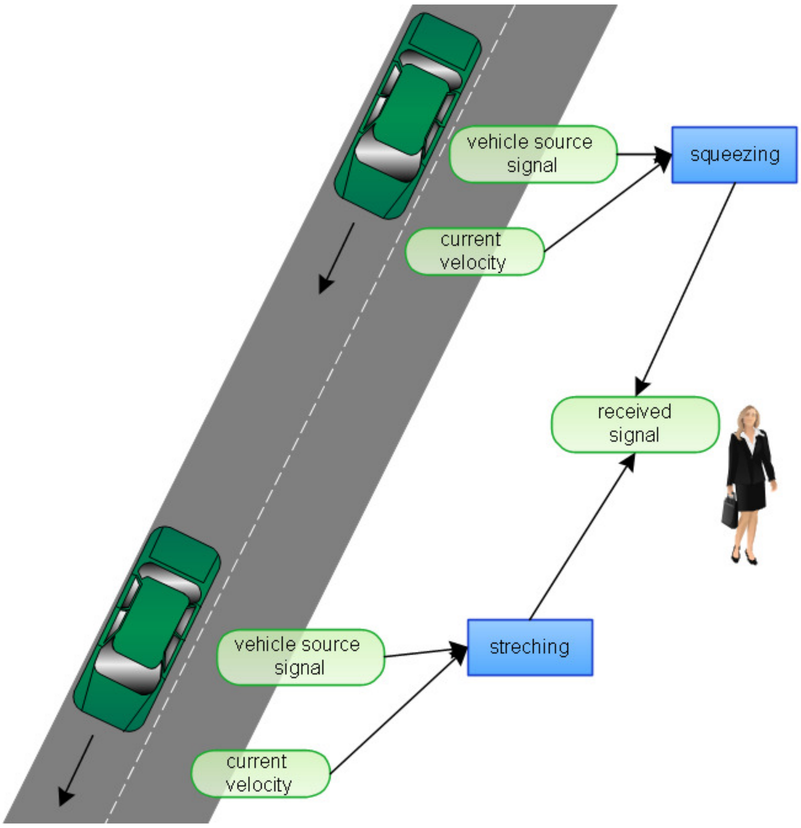


Figure 10: The Doppler-Effect causes a frequency shift of the moving source signals. Approaching vehicles (top) sound higher; this is simulated with a "squeezed" signal. Leaving vehicles (bottom) sound lower; this is simulated by "stretching" the source signals.

1.3.2.3 Binaural filtering

Another propagation effect realized in the traffic noise synthesizer is the binaural filtering of the simulated signals. The perception of directivity within auralisation scenarios can only be realized with a binaural playback. This is obviously essential for the perception of traffic sounds, where the localization of the vehicles plays an important role.

The binaural perception is based on three effects: (a) the interaural time delay, which describes the delay of sound waves arriving at the left and the right ear; (b) the interaural level difference, which is caused by the attenuation of the sound by the head. The third effect is the modification of the sound spectrum (c) by the torso, the head and the pinna of the listener. All these effects can be represented by a dynamic filtering of the received sound signals.

The needed FIR filters for the binaural processing have been recorded related to the different spherical angles defining the incidence direction of the sound wave. These measurements have been done with an artificial head.

During the simulation the direction of sound is calculated and the according filter is loaded and applied to the signal of the different sources.

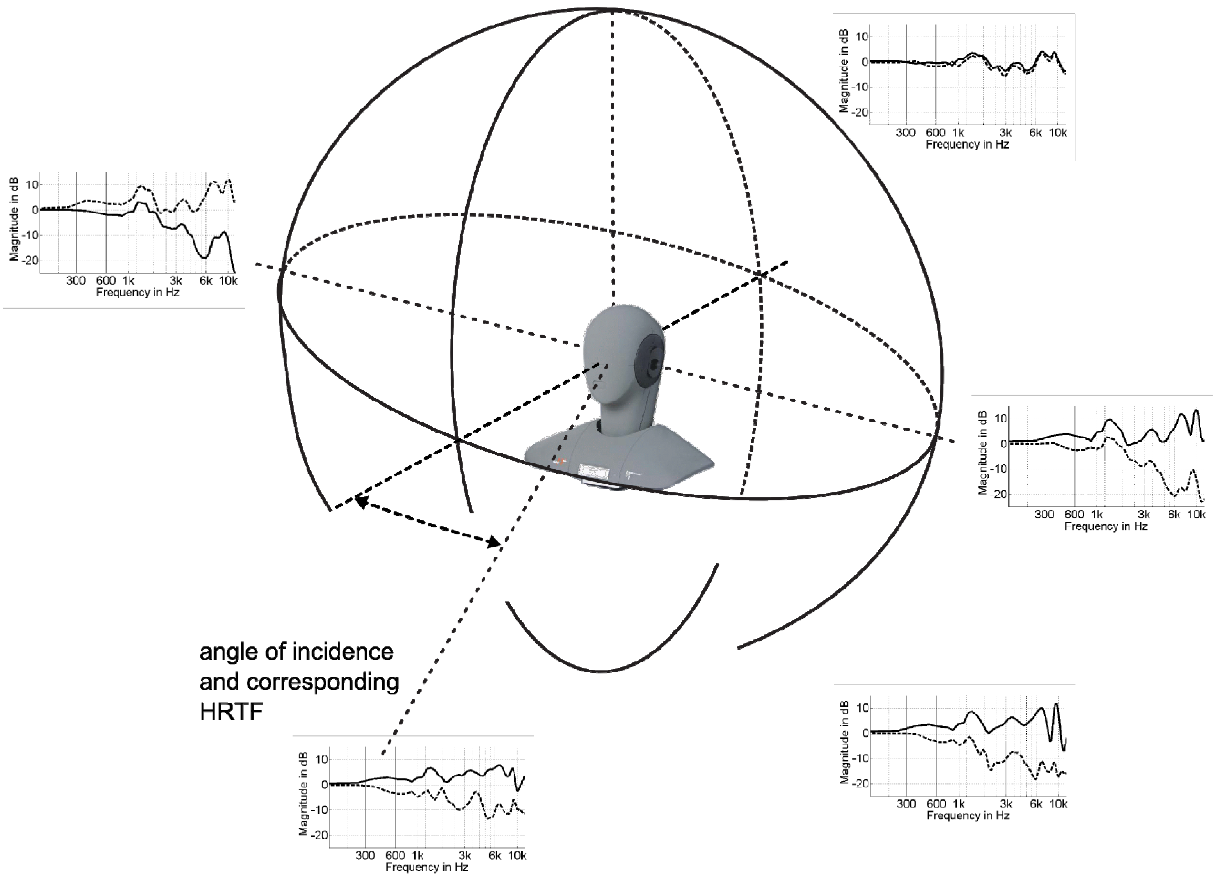


Figure 11: To auralize the spatial location of the different sources a binaural simulation is developed. Each direction of sound incidence is represented with a HRTF (head related transfer function). These are determined with an artificial head. During the calculation of the simulation the corresponding HRTF's are read and applied to the signal.

1.3.4 Software concept

The traffic noise synthesizer software is implemented with the *.Net* based language *C#*. After some preliminary implementations in a high level engineering language (Matlab) and a low level high performance GPU based language (CUDA), HAC decided to use a standard developing language for the following reasons. The integration of existing program modules is easily possible. The chosen language provides software techniques to make sustainable software design with good maintainability. Recently, HAC developed a new signal processing software layer. To have access to that it was also necessary to use C# as programming language.

The software design was developed to provide flexibility to future developments in the field of sound simulations. To implement this, the software is divided into three main parts, the control unit, the source model and the signal processing. A big advantage of this partition is the opportunity to exchange one of these parts. For instance it is easily possible to develop different signal processing networks separately and connect them arbitrarily to the source model. It is obviously also possible to test different source models with the same signal processing network.

1.3.1.4 Moving sources model

With the moving source model arbitrary acoustic scenarios can be described. Each real physical source is represented by a source class within the software. Each source class can again consist of various sub-source classes and so on. In addition, properties can specify the source class in detail, e.g. position, velocity, operation modes. On the on hand, these sources can be abstract and they do not produce any further data. On the other hand, they can be defined as data sources. This means that they read according to their current properties data sets from the source sound property data base and supply them to the signal processing network.

This model structure gives the opportunity to create complex source compositions as well as to cover also simple approaches. Depending on the desired solution it is possible to represent a vehicle with multiple sources specified with various parameters and data sources. But it is also possible to represent a vehicle with just one source with one data source.

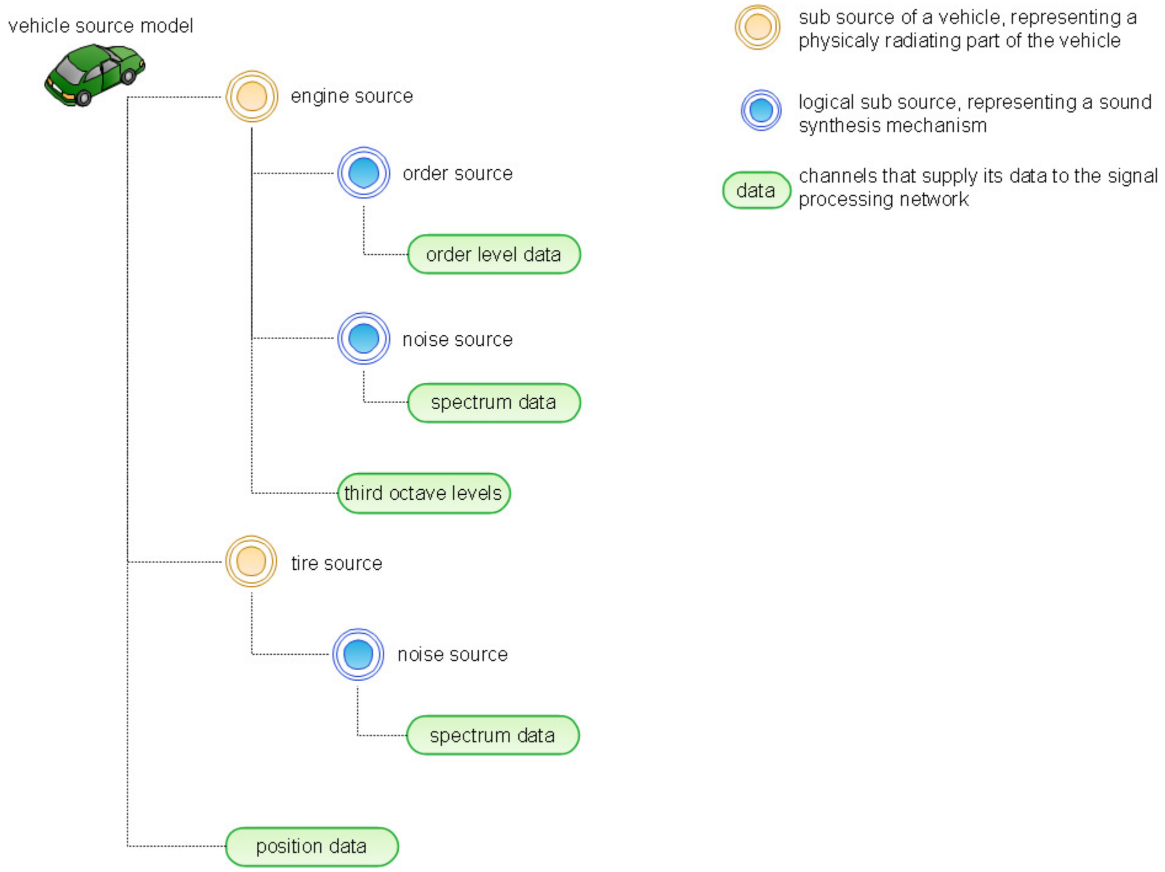


Figure 12: The figure shows an organization map of sources. Like this example different types of vehicles can be designed and configured depending on their complexity of sub-sources and the containing data channels.

1.3.2.4 Controller unit

The controller unit controls the sources within the source model and defines the environmental scenarios. This controller unit can be implemented as a graphical user interface, where all parameters can be adjusted by the user. The controller unit developed within this project has an interface using the output data of the RoTraNoMo simulation software and the traffic flow simulation tool of the KTH.

The task of the controller unit is also the definition of the simulation properties. This has a significant influence on the performance needed to calculate the simulations. A major aspect in this context is the question which vehicles in a complex traffic scenario have to be simulated or not.

Audibility test of vehicles

The data of a traffic flow simulation includes all vehicles within a defined area. This area can have different sizes. If this scenario should be auralised, than an observer position has to be defined. Before the simulation of the vehicle sounds can start, the vehicles that contribute noise to the observer position have to be detected. An audibility test is calculated in relation to the SPL of the vehicles. The exact level contribution of the vehicles at the observer position can only be determined after the actual simulation. As the audibility test should provide an a-priori information, a simplified calculation has been developed to estimate the vehicle level contribution.

Adapted from various vehicle simulations considering the operation modes a simplified formula has been determined. This formula calculates the current level as a function of the engine speed, the vehicle velocity, the vehicle type and the distance between observer and vehicle.

In a second step it has to be decided if the individual vehicles are perceived from the observer or not. This is not only a question of the absolute level of the vehicles but also related to the current cumulative level at the observer position. Depending on masking effects of louder vehicles a maximum distance is calculated to which vehicles must be simulated. This decision criterion is adapted for each calculation time step and so it is guaranteed that all audible vehicles are simulated. On the other hand, vehicles that do not emit a significant contribution are not simulated. This considerably reduces the calculation time.

As mentioned above the controller unit has also the task to integrate the emission levels coming from RoTraNoMo.

Integration of noise emission levels

In contrast to other simulation models, which only offer overall level values, RoTraNoMo is able to give third octave band levels to specify the noise emission of vehicles within the traffic scenarios.

The traffic noise synthesizer has the aim to auralise traffic situations. This implies that a time signal has to be generated. For that third octave band levels cannot be directly used, since there is no time information in the averaged statistic data. The synthesis of the sources' time data is implemented as described in section 1.3.2. For this step the RoTraNoMo data is not essentially needed.

The third octave band levels can be used in two ways within the traffic noise synthesizer. The first possibility is to include the data into the source sound property data base (see section 1.2.3). This can be applied when purely noise sounds like the tire noise are synthesized. For this source type the sound property from the data base is a smoothed spectrum. This can be calculated from the third octave band levels. The extraction of the sound property data sets from the RoTraNoMo data is done by pre-processing. As mentioned the tire noise is related to the velocity of the vehicle, the tire type and the road surface. For each of these differentiations a speed run-up of a single vehicle was simulated by the RoTraNoMo software. These velocity sweeps have been analyzed and stored in the sound property data base. After this pre-processing all possible noises of the specified tire-road combinations can be simulated with the traffic noise synthesizer without the need of additional third octave band information about the tire noise emission.

Source sounds, which do not consist only of a noise contribution, for instance the engine sound, can not be synthesized based on third octave band levels. Source sounds can include harmonic or transient parts. These are not represented by energy values like dB levels. Therefore, another approach has to be chosen. The second possibility to involve the third octave band levels in the traffic noise synthesizer is to use them as a spectral calibration filter.

The source sound is primarily synthesized as described (section 1.3.1.2). To guarantee the exact spectral levels the source signals are applied to the calibration filter. The function of this filter is shown in Figure 13. The spectrum of the synthesized source signal is compared to the retrieved level data from the RoTraNoMo calculation. From that comparison (complex division) an adaptation filter is generated and applied to the source signal by a FIR filter.

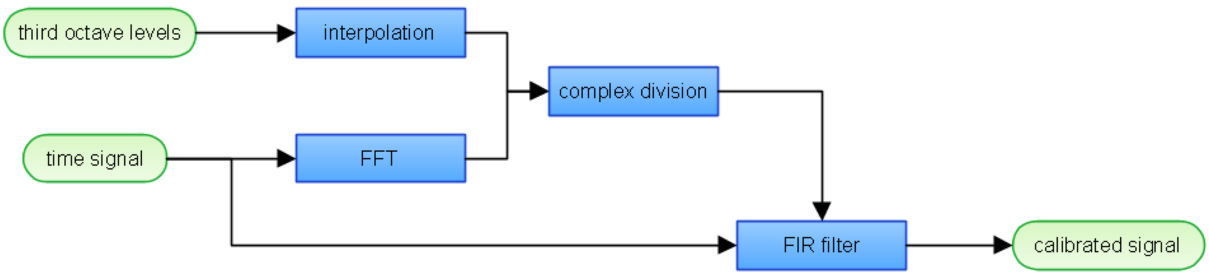


Figure 13: From the spectrum of the source signal and the given third octave band levels a calibration filter is calculated. By applying this filter to the source signal the correct spectrum is achieved.

The third octave band levels calculated by the RoTraNoMo software are based on averaged vehicle signals. In difference to that the vehicle synthesis in the traffic noise synthesizer generates an individual vehicle sound. This leads to incompatibilities between the synthesized vehicle sound and the third octave band levels, in particular related to the frequency range, where the main engine order is present. On the one hand this frequency range has a dominant energy maximum in the synthesized vehicle sound. On the other hand, the third octave band level at this frequency band has a significant lower energy due to the averaging over different vehicles.

When applying the third octave band levels to the synthesized vehicle sound under these circumstances the order levels are significantly reduced. This would lead to a different vehicle sound characteristic.

The traffic noise synthesizer deals with this by providing two different calibration modes. One applies an exact filtering and guarantees the given third octave band levels. With the second mode the calibration is done by the total level over the whole spectrum. This provides the correct level and the original source spectrum, but not the exact third order levels.

Evaluations showed that the third band octave calibration produces a more artificial vehicle sound. It is important that the order amplitudes remain at their original level values to produce an authentic auralisation.

1.3.3.4 Signal processing network

The actual calculation of all simulation steps including the source signal synthesis and the calculation of the propagation is done by a signal processing network. This network interacts with the source model via a well defined interface. This allows to apply different network architectures. The technique of this signal processing network has been developed by HAC for general purposes in the past. Therefore, the software design of the traffic noise synthesizer is connected with established and sustainable software tools at HAC. This guarantees a high flexibility in further progress in the field of traffic noise synthesis.

The signal processing network is an assembly of multiple processing modules that can be handled as plug-ins. The different synthesizers described in section 1.3.2 are examples for these modules. The data exchange between the plug-ins is done by channels. Channels can transport any type of data. This can be for instance a position data channel, including the information of the sources' and observers' movement.

Signal processing networks can be edited, evaluated and plotted using additional development software.

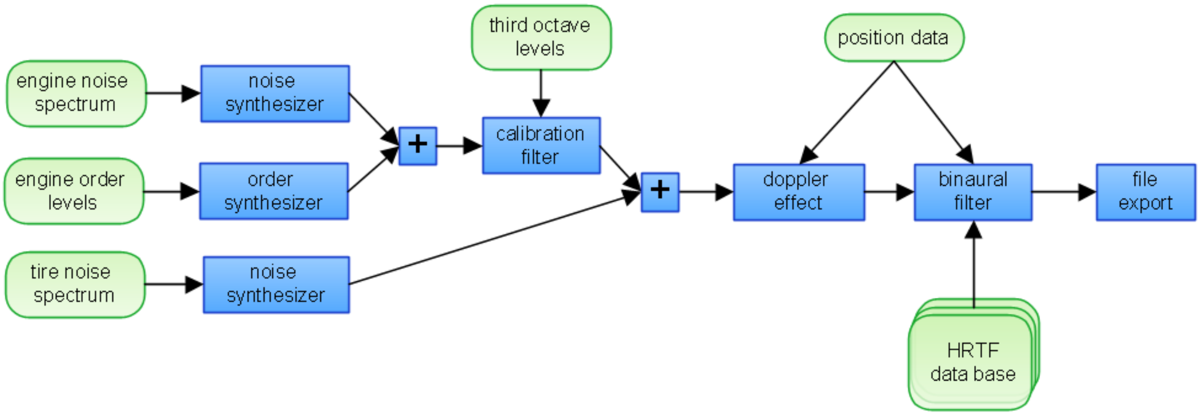


Figure 14: The figure shows an example of a signal processing network. Each node in the diagram is again a small sub-network. With an extra tool these networks can be graphically edited. The green boxes represent the data coming from the source model or the traffic noise application. The blue boxes display calculation nodes and the arrows show the data flow carried by data channels.

1.4 IMPLEMENTATION OF PRPAGATION PATHS (WP 5.12.4)

In many traffic scenarios the sound radiation of the vehicles is not under free field conditions, and thus, the influence of the environmental situation has to be taken into account for sound propagation. In arbitrary traffic situations there are buildings, plant covers, walls and so on. City scenarios with lots of buildings lead to a complex sound field with many reflexions and scattering effects. Simulation effects like these have been extensively examined under the topic of room acoustics. This is not part of the simulations within the traffic noise synthesizer.

The base used for the simulation of sound propagation through environmental barriers is the German industry standard DIN ISO 9613-2. In this standard following propagation effects were described:

- Geometric propagation
- Air damping
- Reflections from the floor
- Damping through barriers
- Damping through plant cover, buildings and industrial areas

Under a signal theoretical view all acoustic effects described in this standard result in a linear filter that can be applied to the source signals. These filters were calculated from attenuation values at the octave middle frequencies defined by the standard.

Within the traffic noise synthesizer the implementation of this effects is done in two steps. In the first step the relevant barriers affecting the source signals are detected in dependence on the position of all sources, the observer position and the scenario map.

This includes the consideration of the type of barriers (wall, forest …), the intersection length and the angle of incidence of the sound. The second step is the calculation of the FIR filters from the geometric information.

In addition to the included propagation path simulation, the traffic noise synthesizer has an interface to import FIR filters as representations of barrier mitigations. This interface defines the position of the barriers and their damping. With this interface mitigation measures, developed and measured in SP4 and SP5, can be imported and used within the traffic noise synthesizer.

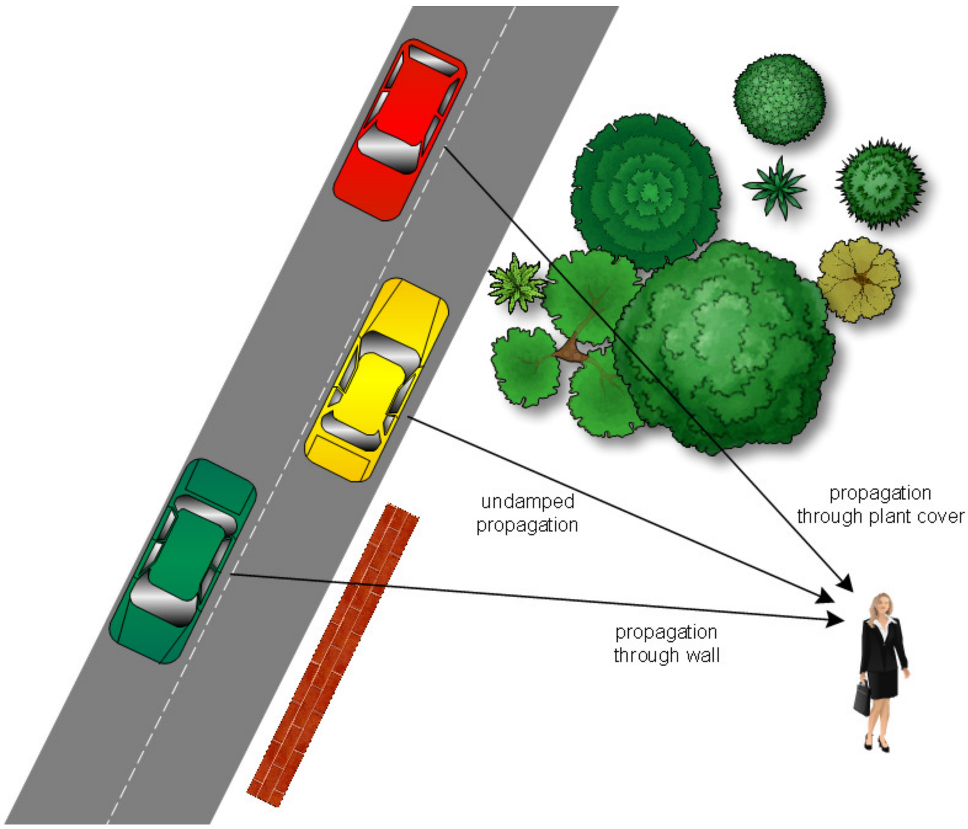


Figure 15: An algorithm checks the intersection of the sound beams with existing barriers. Depending on the type and length of the intersection damping filters are calculated and applied to the source signals.

1.5 AURALISATION (WP 5.12.5)

After the development of the traffic noise synthesizer tool the auralisation results of the software were optimized and evaluated. Different parameters were adapted to achieve a natural and realistic auralisation. These are for instance the calculation update rate or the number of orders taken into account.

The status quo of the traffic noise synthesizer is that arbitrary traffic scenarios can be auralised using the traffic flow data provided by the KTH.

Starting from that the influences of different causes on the acoustic perception can be examined. These are:

- Influence of traffic flow
- Influence of road surfaces
- Influence of mitigation measures.

The evaluation of examples dealing with these influences is currently planned in cooperation with the KTH. These results will be documented in the final report.

In the following some preliminary examples are given to show the opportunities of the synthesis tool.

Examples

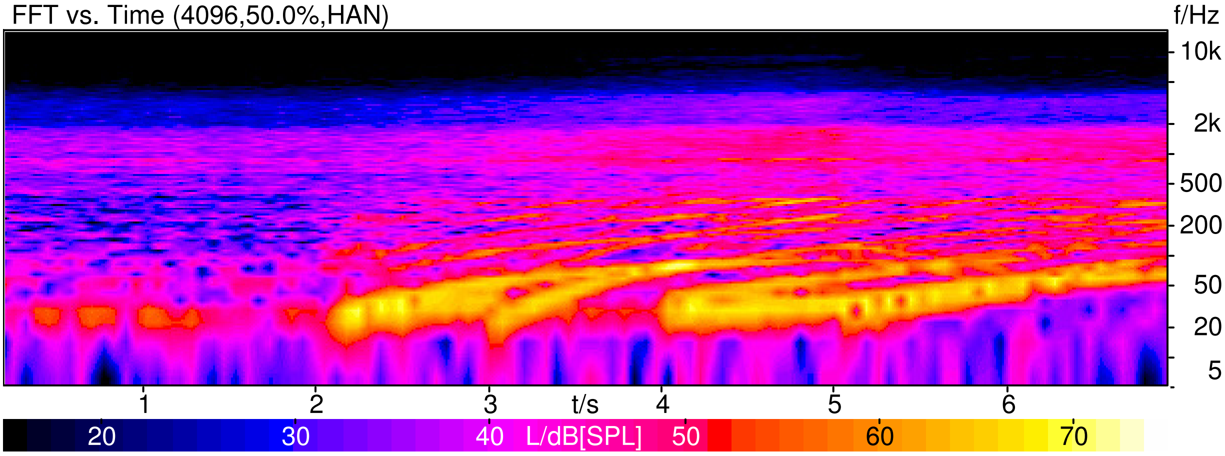


Figure 16: This plot shows an example for a one-lane street with a traffic light turning green situation. At 2 seconds the light turned green and 5 vehicles accelerate.

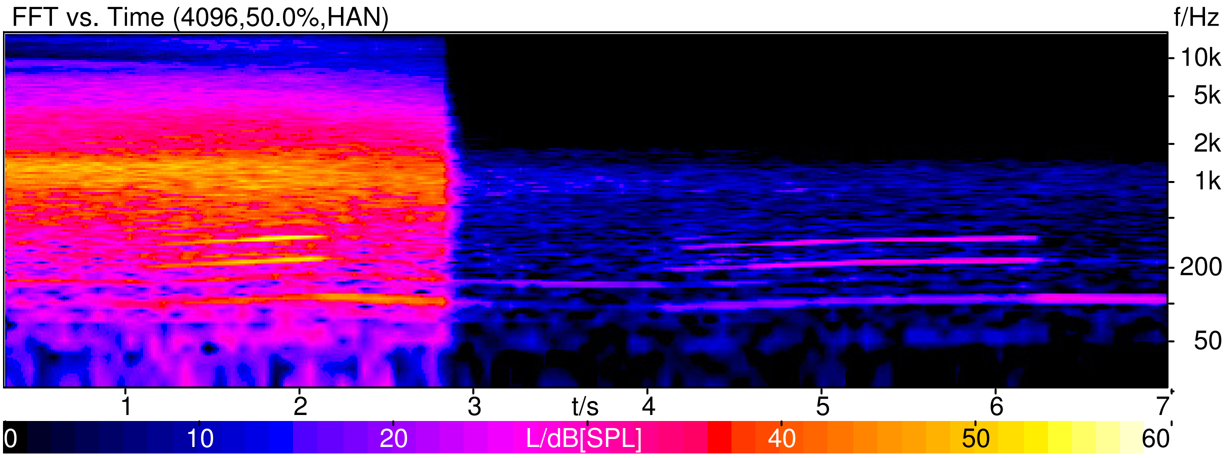


Figure 17: This plot shows the spectrogram of one vehicle passing by in a distance of 30 meters. At the nearest point (2.7 seconds) the vehicle disappears behind a noise protection wall.

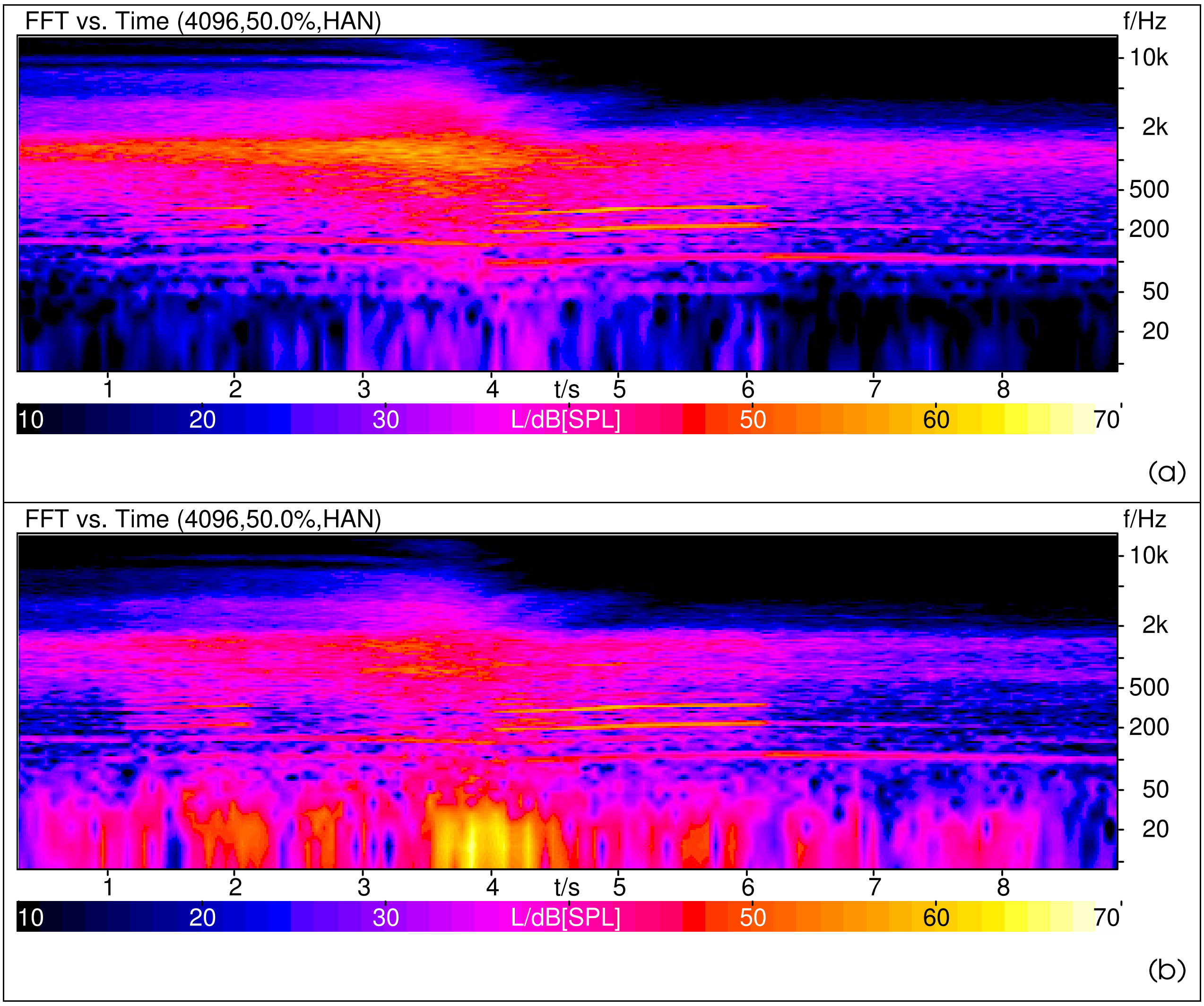


Figure 18: These two plots show the same pass-by situation of one vehicle with identical distance to receiver, velocity and engine parameters. The difference only results from different tire noise simulations. In (a) the tire noise is simulated on the base of RoTraNoMo output data. In (b) the simulation bases on road measurements done by HAC.

1.6 Summary

The section 1 displays the development of a traffic noise auralisation tool in detail. Furthermore, required pre-processing and analyses have been discussed.

The implementation of the simulation tool provides a flexible opportunity to extend the application in different directions. One example for that is the data base concept. Each engine type or tire noise type is represented with one sound property package that can be included into the data base. These packages can result from measurements and analyses as described in sections 1.2.1 and 1.2.2. They can be extracted from other simulation tools like RoTraNoMo (section 1.3.1). Or they can be imported by any other data acquisition, for instance tire measurements done by GOOD.

The simulation scenarios are not limited to special conditions. All vehicles and the observer can move freely in all three dimensions.

The auralisation is controlled by traffic flow data. An interface format has been defined in cooperation with the KTH. With the combination of the traffic flow simulation and the traffic auralisation systematic evaluations of arbitrary traffic situations can be carried out.

2 LISTENING TESTS AND METRIC DEVELOPMENT (WP5.12.6)

2.1 INTRODUCTION

In WP 2.2 single pass-by sounds (mainly passenger cars) were analysed regarding their subjective perception and psychoacoustic characteristics. On the one hand, listening tests were carried out for the psychoacoustic evaluation. On the other hand, different psychoacoustic parameters were calculated for these sounds.

By means of statistical analyses, such as Principal Component Analysis, Cluster Analysis, Regression analyses, similarities between evaluations of the test subjects and the behaviour of few calculated psychoacoustic parameters could be discovered. The acoustical analyses go beyond conventional sound pressure level considerations.

The analyses showed that the most important factor was highly correlated with the Relative Approach analysis. The Relative Approach simulates the adaptation of the human hearing and is able to detect time and/or frequency patterns within the sound the human hearing is very sensitive to. Further important parameters were the 5 % percentile of the loudness (N_5) and the 5 % percentile of the sharpness (S_5). These parameters were included into a metric (evaluation index) representing the evaluation ratings of the subjects. The aim to find a quantitative description for the subjective annoyance effect of pass-by sounds was achieved.

In WP 5.12.6 and WP 5.12.7 the gained knowledge from WP 2.2 mainly described in deliverable 2.8 has to be extended from single pass-by noise evaluations to assessments of complex traffic noise scenarios by means of further listening tests and additional acoustical analyses. Several studies have already shown that complex perception processes are influencing human reactions to traffic noise.[1]

This means in detail that in WP 5.12.6 listening tests have to be carried out for the evaluation of the effect of the superposition of single pass-by noise events on the perception. The tests must consider the variety of potential traffic noise scenarios to adequately investigate for example the influence of sound masking effects or temporal patterns caused by stationary or time-varying noise events on the perception.

Moreover, in WP 5.12.7 the development and implementation of a sound quality metric providing a single value was the main task. This sound quality metric must represent the different subjective evaluations concerning the traffic noise.

Moreover, the need of dB(A)-penalties for increased or decreased annoyance caused by certain traffic-related noise aspects should be proven.

[1] K. Genuit, "Beyond the A-weighted level", Proceedings of Inter-Noise 06, Honolulu, HI, USA, 2006.

2.2 LISTENING TESTS

The realization of listening tests is essential for environmental noise studies in order to get a deeper understanding of human reactions to noise. In the last decades a lot of research work was done to refine tools, methods and procedures in the context of community noise research and noise effects. For the planned tests in this WP existing literature is reviewed and suitable methods for the intended object of investigation are selected. The development of an adequate test design is of high importance with respect to the validity, reliability and generalizability of the derived results. Typical methodical and methodological aspects have to be adequately considered. Bias effects, such as memory, sequence, juror fatigue and contextual effects, etc. must be taken into account and their influence on the test results must be adequately interpreted. The work done in WP 2.2 gives already guidance to adequate test designs. However, the detailed test design must be adapted to the exact object of investigation. Here, for example, the test stimuli length must be increased from a few seconds to much longer durations. A traffic noise sample of only a few seconds does not represent real traffic scenarios very well.

An adequate test procedure is developed and road traffic noise stimuli representing typical traffic noise scenarios are selected for subjective evaluation. By means of the planned listening tests it is expected to collect meaningful subjective evaluation data. An important requirement is that the chosen noise stimuli present traffic noise stimuli close to authentic environmental noises.

A combination of different methods and test procedures can reduce the risk of biases and artefacts through mutual enhancement of the applied methods. Interview techniques as well as noise rating procedures are methodical options in the context of noise perception and assessment.

Another essential aspect concerns the sampling of test persons. The subject population must contain a representative demographic mix – a demographic mixture of different ages, genders, economic status – although several studies observed no major influence of subject demographics on listening test results so far.

2.2.1 Traffic Noise Stimuli for Listening Tests

2.2.1.1 Simulation of the Single Pass-by Sounds and Their Superposition Using the Simulation Technology SVEN

As mentioned above in the Executive Summary due to delays in the development the Traffic Noise Synthesizer was not ready to use for the listening tests. Therefore a single pass-by noise synthesizer developed in the European research project SVEN (Sound Quality of Vehicle Exterior Noise, GROWTH G6RD-CT-1999-00113, 2000-2003) is applied. The simulation technology allows for the synthesis of binaural pass-by sounds of single cars based on near field measurements of the sources and the consideration of transfer functions from source to receiver. The near field input is based on real measurements. The original pass by as well as arbitrary modifications (e.g. filtered sources) can be calculated. The major limitation of SVEN compared with the TNS is that only measured driving condition can be used. In contrast to real measurements no traffic-unrelated noise events can occur and interfere. The different single pass-by noises can be arranged and superposed in any way desired.

To calculate the pass-by noises, SVEN needs component sounds from vehicles (near field recordings) as input data. This means that calibrated time signals are needed, that were recorded as near as possible to the most common sound sources of the respective investigated car, such as tires, engine, intake, exhaust, etc. Additionally, the Source Related Transfer Functions (SRTF) from each microphone position must be determined. These SRTF are processed by SVEN in order to provide direction dependent filtering of the sound sources.
The virtual receiver (the defined immission point) is placed 7.5 metres away from the centre of a 250 metres long virtual road (fig. 19). This distance to road is chosen according to the ISO 362 (Measurement of noise emitted by accelerating road vehicles). Additionally, a second receiver point is defined in a greater distance to the road (25m away from the road) to examine the influence of source distance on perception.

To achieve a realistic soundscape, the simulation technology offers the opportunity to place a virtual sound-reflecting wall with plaster surface on the opposite side of the road. Therefore, the vehicles pass by a L-shaped street geometry.

A total of 7 different vehicles are simulated and binaurally auralized. The selection of vehicles consists of five passenger cars ranging from compact to luxury class, one commercial van and one truck. For the first run of listening tests, two different speeds are simulated for each car: constant passing by at 50 km/h and constant passing by at 30 km/h. The vehicles driving with a speed of 50 km/h mostly drive in 3rd gear.

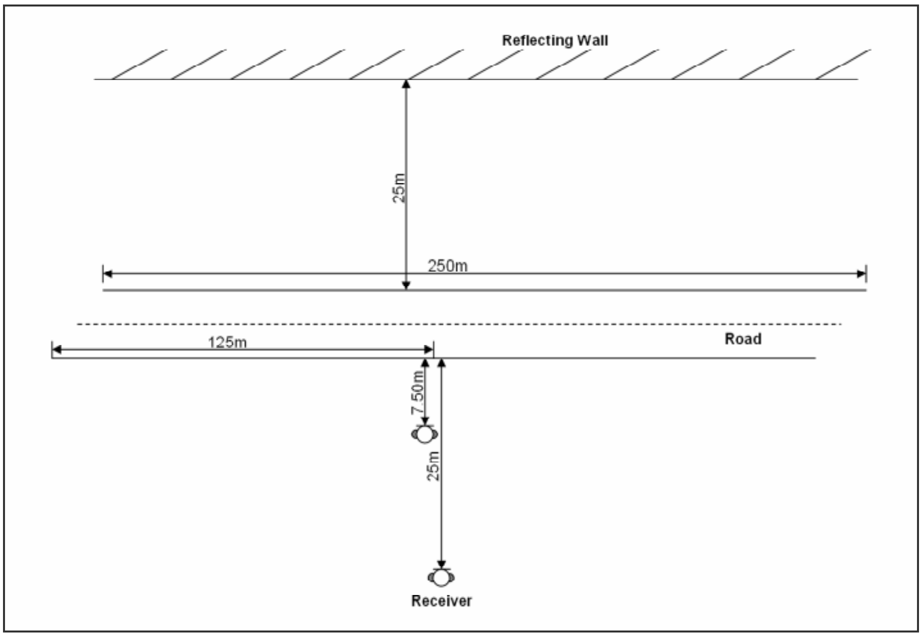


Figure 19: Defined conditions with respect to the generation of single pass-by noises using the simulation technology SVEN

2.2.2.1 Generation of the Traffic Noise Scenarios with Vehicles Driving with Constant Speed

In order to enhance the authenticity of the generated traffic noises the simulated pass-by noise are additionally modified. Hearing exactly the same vehicle pass-by noise without variation in a short time interval irritates the test subjects and biased answers would be the consequence. To obtain some variations, each pass-by sound is randomly equalized with a multi-band linear phase EQ for three times and then a copy of every sound is made. The two identical groups of sounds are pitched apart ±50cents (which makes a total of 100 cents or a semitone) to keep the authenticity at a high level. In this way eight variations of each car are produced.

In the next step, the single pass-by sounds must be specifically arranged to generate different traffic noise scenarios. Before generating different road traffic scenarios, several preliminary considerations have to be made to consider the main research goals of the work task adequately.

Duration of Traffic Noise Stimuli

One important methodical topic is the choice of stimulus duration, which has to be extensively discussed. A meaningful duration has to be determined considering a sufficient duration to allow for an immersion by the test subjects into the specific traffic noise scenario as well as a stimulus duration, which does not cause quick exhaustion and fatigue effects of the test subjects without collecting much data. Both aspects have to be considered in equal measure.

Finally, time periods ranging from 30 seconds to 60 seconds with respect to the traffic noise stimuli are chosen.

To consider potential bias effects caused by the duration of the stimuli, in one sound set, different durations of comparable traffic noise scenarios are used. Here, a 30 seconds traffic noise with a specific time structure and traffic density is virtually prolonged, so that the time structure and traffic density remain constant, only the total duration changed (35s, 40s, 45s). By means of these stimuli the influence of the stimulus duration on the noise assessments can be investigated. The knowledge of that potential effect helps to improve the test design.
However, the listening tests show no significant influence of the stimulus duration on the noise evaluations.

Technical Realisation of Arrangement of Several Single Pass-By Sounds

For arranging the single pass-by sounds, a standard audio/MIDI sequencer is used. Each version of the sounds was converted to a *wav-file* (with maintained level range) and loaded into a sampler instrument in order to trigger them via MIDI sequences. To get each car also driving from opposite direction, the entire group of vehicles is copied and routed to an audio track with the stereo channels switched, because the simulated setting was symmetric.

Since the simulation technology SVEN provides calibrated audio data, strictly no amplification, damping or dynamic processing, such as limiting is used during the whole process with the converted data.

For time intervals with no vehicle pass-by noises, in other words quiet passages, which partially occur, ambient noise is created by means of a band-pass (100 Hz – 400 Hz) filtered pink noise, individually generated for both channels, at a level of 40 dB(A) and is added to the sound files. It is consequently mixed with each generated stimulus, even in case no quiet parts exist in the generated sound file.

Creation of Traffic Noise Scenarios with Vehicles Driving with Constant Speed

Different groups of settings have to be designed to have the opportunity to investigate perception effects caused by certain road traffic-related aspects. Some examples of potential relevant aspects are listed in the following. Does it make a perceptional difference, if a certain amount of cars passes by causing different time patterns? Or does it make a perceptional difference, if the cars come from different directions? Is there a significant change between the evaluations of traffic noise, where vehicles drive with 30 km/h or 50km/h, which cannot be sufficiently explained with the reduced A-weighted time-averaged sound pressure level?

The final set of traffic sounds used for the listening tests can be split into two sub groups: scenarios with temporal uniformly distributed single pass-by noises as well as scenarios where the vehicles pass-by in a clustered way. Few scenarios contain randomly distributed pass-bys and can be seen as a mixture between these two groups.

First group: The traffic scenario consists of a number of passing by cars ranging from 3 to 23, which pass by in similar distance to each other (1 to10 seconds). After the first pre-tests it is found that a slight random variation regarding the temporal distance between the passing by cars is required. Scenarios with constant time distances between the cars lost their authentic impression.

The second group includes the "cluster scenarios", which contain mostly a similar total number of passing by vehicles, but they are differently distributed over time. The time structure is partly irregular, several vehicles pass by at the same moment, whereas in other parts no vehicles pass by at all. These traffic scenarios with clustered passing by vehicles should shed light on the importance of temporal patterns for noise annoyance. Such effects must be adequately considered with respect to traffic control measures.

Each of these two main groups can be divided into the same subgroups: driving with a speed of 50km/h or 30 km/h, and vehicles coming from left or from left and right. (Table 1)

Table 1: Varied noise stimuli (vehicles driving with constant speed)

	Varied parameter	Conditions
1	Speed	50km/h; 30km/h; 30km/h and 50km/h
2	Traffic density (number of vehicles)	3; 5; 6; 7; 8; 9; 11; 13; 14; 18; 23
3	"Distribution" of vehicles	Regular, irregular
4	Driving direction	Right; right and left
5	Stimulus duration	30s; 35s; 40s; 45s

Finally, a total number of 21 sounds are chosen to be evaluated by the test subjects.

2.2.3.1 Traffic Noise Scenarios with Vehicles Driving in Different Conditions

To cover a wide spectrum of scenarios ranging from low to heavy traffic volume and to use real recordings for psychoacoustic evaluation in addition to the sounds synthesised with SVEN several locations were recorded. The figures 20 to 23 show examples of selected locations and measurement spots. The recordings were made on different days without rain and wet street surfaces and on different times of the day to collect different traffic noises as much as possible. The different locations are chosen with respect to a broad variety of traffic volume, traffic compositions, diversity of driving conditions, which are partly forced in the locations through traffic management measures (for example traffic lights leads to permanent stop and start situations). The duration of recordings ranges from 15 to 45 minutes per location.

The recordings were realized with HMS III with wind screen mounted on a tripod and a laptop connected via USB with the artificial head. The used software was the HEAD Audio Recorder. The applied equalization was ID (independent of direction). Here, only the direction-independent resonances of the artificial head are equalized. The ID equalization can be used in almost any type of sound field.

Table 2 shows the different aspects of the locations which were covered in the measurements.

Table 2: Selection of measurement locations

	Location
1	2 track road (30 km/h zone)
2	4 track road uphill (50 km/h zone)
3	2 track crossroads with traffic lights (50 km/h zone)
4	4 track crossroads with traffic lights (50 km/h zone)
5	2 track roundabout (50 km/h zone)

Figure 20: Measurement spot 30 km/h zone with 2 track road (low traffic volume): aerial photography (left)[2], recording of noise with artificial head (right)

[2] All of the displayed aerial photographies are taken from 'http://maps.google.de'.

Figure 21: Measurement spot 2 track roundabout (high traffic volume): aerial photography (left), recording of traffic noise with artificial head (right)

Figure 22: Measurement spot 2 track crossroads with traffic lights (medium traffic volume): aerial photography

Figure 23: Measurement spot 50 km/h zone 2 track (low traffic volume): aerial photography (left), recording of traffic noise with artificial head (right)

2.2.2 Test Procedure

As mentioned before, the test procedure has to adequately reflect the object of investigation: here the perception of traffic noise. For that aim a test procedure has to be developed, which takes into account previous studies and surveys in the scope of environmental noise perception considers their main findings.

Besides the chosen test design, the appropriate noise stimuli have to be selected according to the research issue.

To keep the demands towards the test subjects low, the test procedure is designed in a way, that no specific skills and expert knowledge are needed. The well known method of scoring the perception on a scale facilitates the evaluation task for the test subjects. An important requirement with respect to the test participation is the criterion of sufficient hearing ability. This means that the test subject possesses no more than 20 dB hearing loss at any proved frequency. In case of more than 20 dB hearing loss the test subject is excluded from the test.

Table 3 shows the general structure of the test procedure. The test procedure is carried out with one or more test subjects (group mode) at the same time. Depending on the evaluation behaviour of the test subject a complete test takes 30 to 45 minutes in total. The different steps of the developed test procedure are explained in the following passages more in detail.

Table 3: General structure of the test procedure

	Step
1	Greeting and introduction
2	Audiometry
3	Instruction
4	Execution of listening test
5	Execution of interview

Greeting and Introduction

The test subject or subjects is/are welcomed in a friendly manner to ensure a high level of open-mindedness and intimacy. Nevertheless, the interaction between test supervisor and the test subjects should always be serious and professional to avoid distractions from the focus of the test and to reduce unwanted "demand characteristics"[3].

At the beginning, the motivation and content of the test and of the research project in general are described. Few background information about the EU noise directive 2002/49/EC and the general aim – the improvement of the noise situation in cities – is

[3] « Demand characteristics » describe the tendency of test subjects to change their behaviour because of being in a test situation, e.g. by presenting themselves in a special manner or by giving answers with respect to a imagined test objective.

given by the test supervisor. By showing the positive aim and involving the test subject into it, the motivation of the test subject should be exceedingly high.

Audiometry

The test starts with a special audiometry, called screening, carried out with the HEAD-Audiometer software. The procedure of the audiometry is explained to the subject before the audiometry starts. The subject under test listens to discrete frequencies. The software presents the stimuli with a defined sound pressure level. In the screening mode it is only important whether the test subject hears the stimulus or not. If the subject hears the sound, he/she presses a mouse button. The software changes the frequency and the procedure is repeated. The procedure has to be carried out twice for the left and right ear.

In case the test subject hears every tone played, no hearing loss of 20 dB or more at any frequency exists. In case a test subject has a hearing loss of 20dB or more, the test subject is excluded from the following listening test. Only one test subject must be excluded from the test because of an insufficient hearing ability.

Instruction

After the audiometry the test subjects are instructed about the test procedure and the evaluation task. It is essential that the instruction is always identical and that the test subjects understand all details of the test to achieve valid and reliable results. Questions, which spontaneously arise by the test subjects, should be immediately clarified before the listening test starts. In order to guarantee that the test subjects fully understand the test procedure and the evaluation task, the instructions are given in written form. In addition, the instructions are also given by the experimental leader in an oral form. To reduce the influence of the experimental leader on the evaluation behaviour of the test subjects, the experimental leader is substituted after half of the planned tests.

At first, the written instruction is given to the test subject. The test subject is requested to read carefully. Afterwards, the oral instruction starts. Then the test procedure is discussed in detail step by step. The test subjects are encouraged to ask without hesitation, if questions arise.

Evaluation Task

The instruction with respect to the evaluation task is as follows: "Please, imagine you are sitting in a bus stop and you are experiencing traffic noise. How annoying is the traffic noise?" The annoyance shall then be evaluated on a scale from 1 to 9 for every sound. "1" stands for "not annoying" and "9" for "very annoying".

The hypothetical situation of an open bus stop with vehicles passing by used in the instruction is used to form a common context for all subjects. Their task is to evaluate the traffic noise regarding their annoyance effect in the given context.

A nine-point scale with the German verbal attributes of the Rohrmann scale for intensities is used for the test.(Rohrmann[4], 1978) Figure 24 shows an English translation of the attributes and the question. The test subject has to decide which of the nine categories represents its current perception best. A category scaling is chosen since the test subjects give a numerical value for its perception which can be easily used for continuative statistics.

The software SQuare is used for the creation and execution of the listening tests.

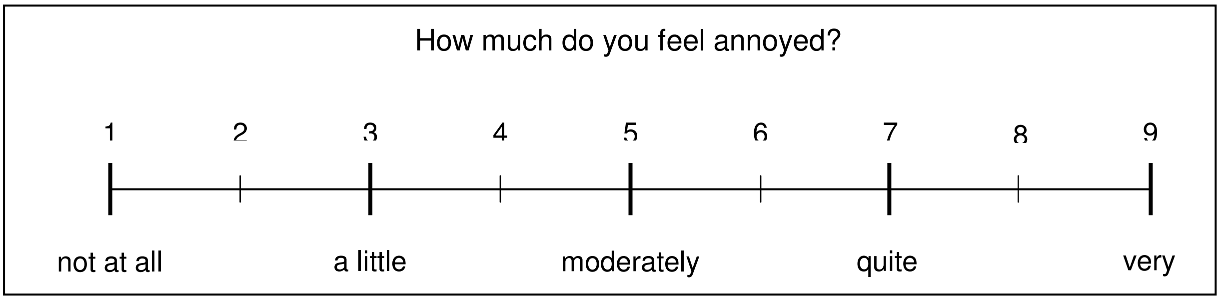


Figure 24: The applied evaluation scale

The advantage of the SQuare software is that the test procedure can be carried out easily and interactively by the test subject on a computer screen using a computer mouse or a touch screen. The results are directly available and can be further processed with descriptive statistics. A new listening studio allows for the execution of tests with up to nine test subjects at the same time. This option is called group mode. In this setup the test subjects make their judgments simultaneously. The test sequence is predefined and can only be changed by the experimental leader, but not by the test subjects. This means that the test subjects hear all the same sounds in an aurally-accurate way at the same time. When all test subjects have made their decisions, the test continues and the next sound is presented.

The traffic sounds are presented in sets. The evaluations method "category test" with a nine-point scale is used. The sounds of one set are presented one after another. After hearing a traffic sound the test subjects give their judgments before the next sound is presented. Figure 25 depicts the computer screen of the SQuare software for the method of category scaling.

To check the consistency of the judgments and the potential influence of sequence effects few stimuli are repeated.

[4] Rohrmann, B. (1978), Empirische Studien zur Entwicklung von Antwortskalen für die wissenschaftliche Forschung, Zeitschrift für Sozialpsychologie, Nr. 9, 222-245

A complete listening test consists of four to five sound sets. The first one usually serves as a training sequence to on the one hand familiarize the test subjects with the evaluation task and on the other hand to present different stimuli to show the range of traffic noises. This facilitates the evaluation task for the subjects; then they typically use a wider range on the scale. The test sequence contains the presentation of three stimuli, which cover the range of different traffic noise. The sounds were selected by a group of three experts.

After the training sequence the test subjects have the possibility to ask further questions, which occurred during their first evaluations.

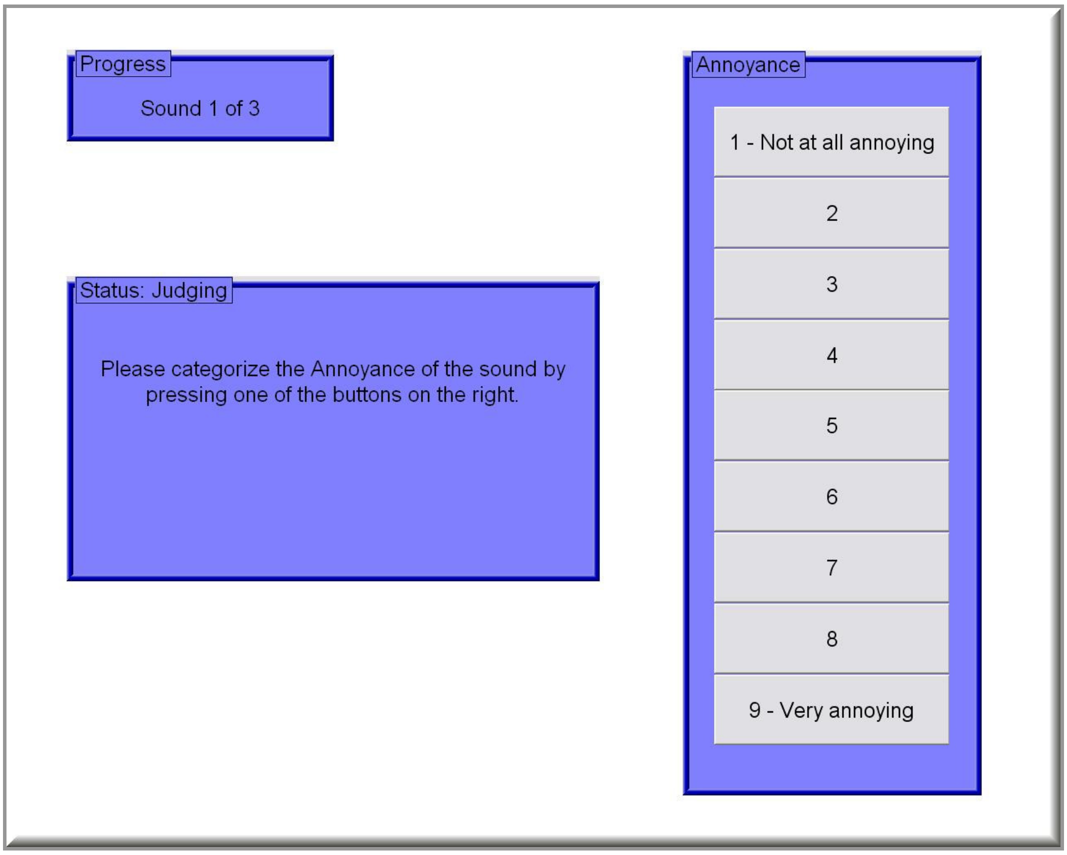


Figure 25: Evaluation screen of HEAD acoustics' SQuare software for the category test with translation text boxes

The order of the noise stimuli is randomly changed to reduce sequence effects. Furthermore, the test subjects are requested to shortly relax between the presentations of the different noise stimuli in order to avoid premature tiredness and fatigue. Between the test sets - a set contains the presentation of 5 to 6 stimuli - a defined break of at least 60 seconds is taken. This given break is intended to on the one hand avoid quick fatigue of the test subjects and on the other hand reduce the risk of sequence effects, because the following evaluations after the break are more unrelated to the preceding noise evaluations.

Of course, there is no time limit for the evaluation decision. However, the test subjects are requested to spontaneously judge the heard sound. Thus, usually no great time is needed by the test subjects to give their judgments.

For compatibility reasons with the previous studies concerning the evaluation of single pass-by noise the evaluation item "annoyance" – in German "gestört/belästigt" (How annoying is the traffic noise?) – as applied in WP 2.2 described in deliverable 2.8 is also used in the listening tests dealing with the assessment of traffic noise.

2.2.1.2 Execution of Listening Tests

The listening tests were carried out in a new equipped listening studio, which is optimized for the execution of laboratory listening tests (fig. 26 and 27). All components, which are not required in the studio room, are removed to an extra, adjacent engineering room to avoid unnecessary noise. For example, this concerns the master-PC, power supplies of the terminal PC and video projector. The air conditioning can be independently controlled. The installation of absorber plates additionally improves the room acoustics. The test supervisor operates the entire test from the master-PC. The test supervisor can immediately give support to the test subjects if any problems occur.

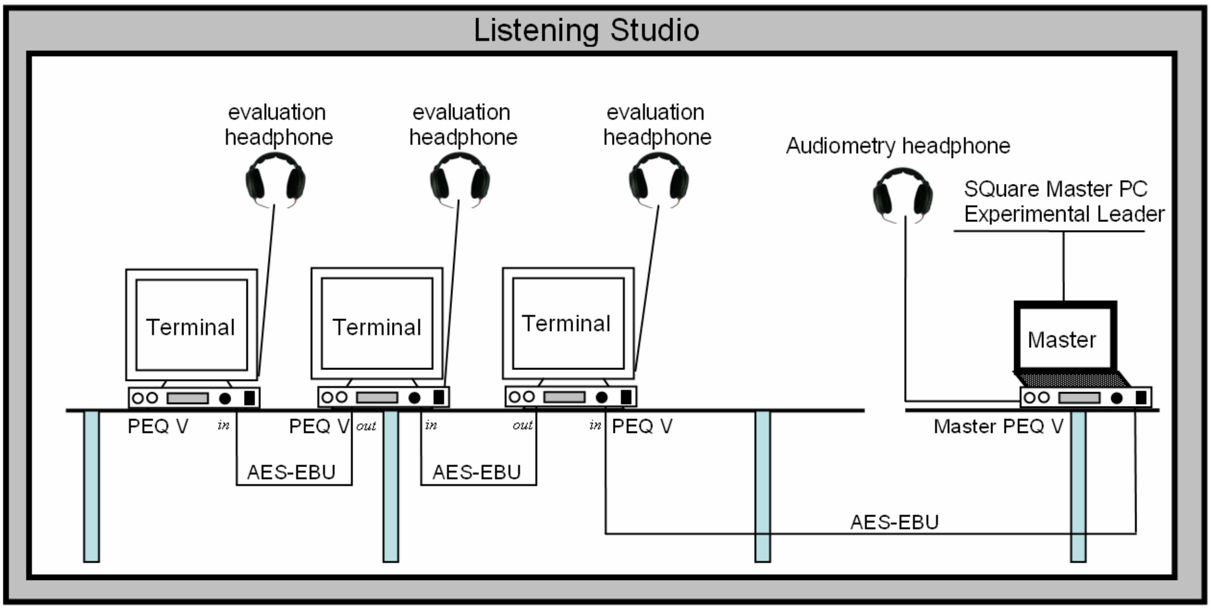


Figure 26: Listening Studio – Simplified setup

The test subjects carry out the listening test as described in the instructions. Mostly, no interference by the test supervisor is necessary during the subjective evaluation; the test supervisor only controls that the breaks between the different sets of judgments are about 60 seconds.

After the evaluation is finished, the experimental leader interviews the test subjects to collect further data. The interviews are carried out with additional experimental leaders, so that one interviewee is asked by one interviewer. Only in few cases a group discussion was carried out.

Only four or less test subjects take part in the listening test at the same time.

Figure 27: Listening room with four test subjects and the tests supervisor

2.2.2.2 Execution of Interview

During the interview the test subjects have the opportunity to express their feelings and thoughts with regard to the test, test procedures, evaluation strategies, etc.

The interviews are recorded for later analysis with a professional handheld solid state recorder (Marantz Model PMD620). In cases of group discussion, at first the test subjects fill out a questionnaire with open questions by themselves and afterwards an open discussion takes place, where comments and remarks can be given by the test subjects (fig. 28). The exact focus of the group discussion is not predetermined, it develops during the discussion. The same applies to the face to face interview with only two persons.

The interview data give insight into the evaluation process of the test subjects and helps identifying relevant acoustical parameters. The answers to the different questions of the interview guide give information about the assumed causes for their judgments and the quality of their ratings.

For example, several test subjects remarked that in particular loud single noise events affect adversely their judgement. In these cases, the time-averaged sound pressure level is not of significance, but rather 5 or 10 percentile sound pressure level values appears to be more important. These comments and remarks are additionally used with respect to the selection of the acoustical analyses and the interpretation of the results.

Test Subject	Date	Time

Interview

What guides your judgments?	
What was your judgment strategy?	
How difficult was the evaluation task?	
Were there any special disturbing noises presented in the listening tests?	
Do you have any comments regarding the listening test?	

Age / Gender	
Are you sensitive to noise?	
How often are you using your car?	

Figure 28: The questionnaire applied in the subsequent interview

2.2.3.2 Evaluation item "Annoyance"

The item "annoyance" is chosen for the evaluation of traffic noise because it is a relevant term in environmental noise research. However, the assessment of annoyance in a laboratory setting has yet to be questioned critically. It is a difference to directly evaluate the annoyance of a sound stimulus, when the evaluation and therefore the sound is within your main focus of attention. In general, things are annoying if they distract you from other activities or focuses. Often in studies the annoyance item is questioned, where the subjects should reflect the noise impact over a long time period such as months or years. The subject memorizes the noise exposure and cumulates the different memorized emotional states to a numerical or verbal value. However, for the development of a noise metric, which directly link acoustical parameters with subjective reactions to noise, a broad database is required with evaluations closely linked to known physical (acoustical) stimuli.

In contrast to it, the memory of an averaged annoyance over a long period of noise is too inaccurate since the noise assessment is also influenced by non-acoustic parameters, which examination were not the focus of the study. Therefore, the direct evaluation of annoyance of noise was necessary to achieve a valid evaluation metric based on psychoacoustic parameters. Here, an important aspect was to choose a context in the instruction, which fits to typical noise exposures in everyday life and is known for all test subjects. The chosen context, you are sitting in a bus stop and you hear different cars passing-by, is a context every test subject is familiar with and which they could relate to the term annoyance. This was verified in some pre-tests, where the plausibility of the given context and the evaluation item annoyance were discussed in detail with the test subjects. After all, there was no negative feedback on the term "annoyance" or on the constructed context. This indicates that the test subjects are able to relate a meaning to the term 'annoyance' regarding the instructed setting.

2.2.4.2 Pre-Tests Results

By means of a small number of test subjects the developed test design and the chosen test stimuli are tested to examine the feasibility of the planned listening tests to determine the test duration and to study the level of tiredness of the subjects after participating in the test.

After the pre-tests the test subjects are extensively interviewed to discover methodical or methodological inconsistencies or conflicts. The duration of the interviews was considerably longer than the intended usual interviews in the "real listening tests" because of the very open character of the interview. The interviews lasted about one hour.

The interviews were recorded with a professional handheld solid state recorder (Marantz Model PMD 620) and were subsequently analyzed by means of repeated listening.

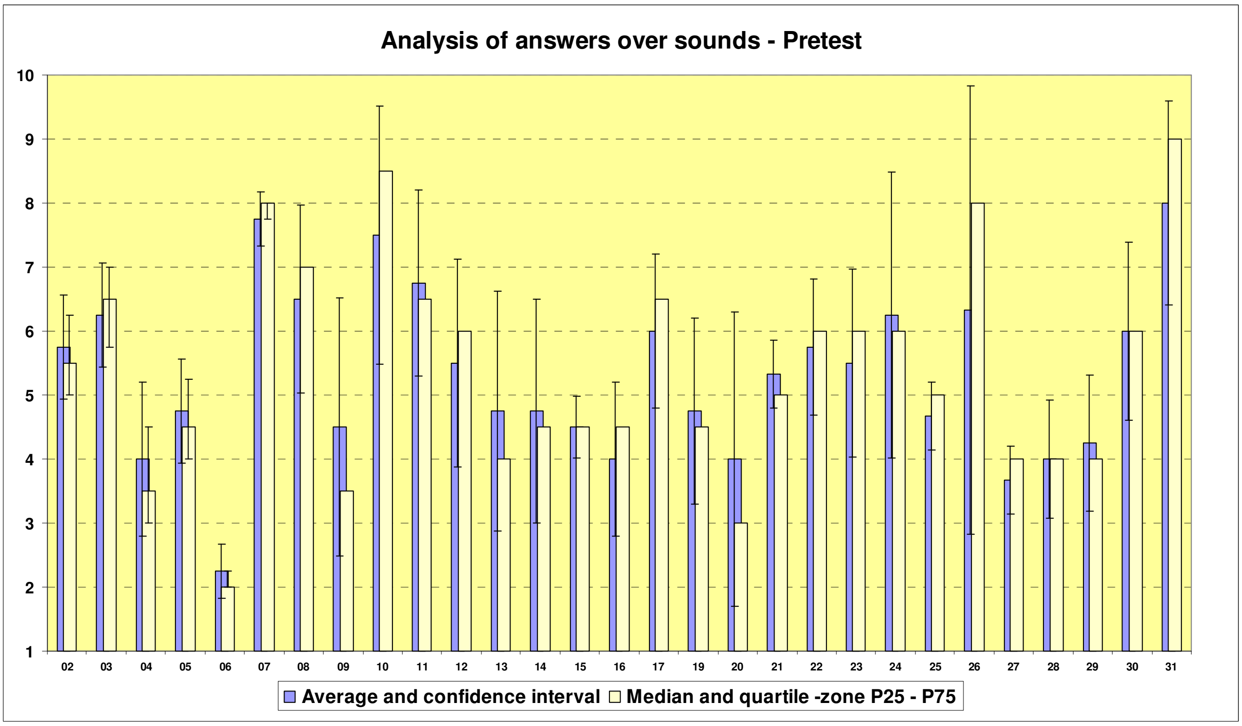


Figure 29: Results of a pretest

All in all, it can be clearly seen that already on the basis of four test subjects clear trends are observable with respect to "not annoying" sounds and "very annoying" sounds. The test subjects obviously have the ability to give category scores regarding the level of noise annoyance. No remarks were given with respect to test-related inconsistencies or too complicated evaluation tasks.

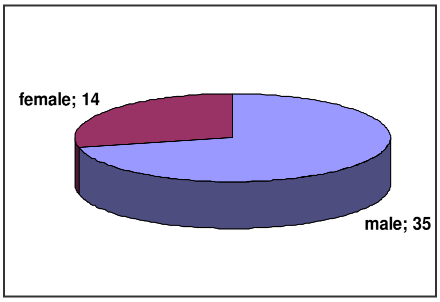
The analyses of the given judgments show that the test subjects sometimes correspond and sometimes strongly disagree. (fig. 29) For example, stimulus "15" was evaluated with grades of 4, 5, 5 and 4 by four test subjects. In contrast to it, e.g. traffic noise "20" was judged with the scores 8, 3, 2 and 3. Here, one test subject identifies a really disturbing aspect of the noise, which the other test subjects do not. This means that simple statistics dealing only with mean judgments and linear regressions cannot capture such different evaluation strategies. Further statistic methods and tools such as Principal Component Analysis (PCA) and cluster analysis have to be applied as well. Moreover, the open-interviews, conducted after the listening tests, can also give information about causes for such evaluation differences.

2.2.3 Composition of the group of test subjects

The test subjects were randomly chosen. The aim is to achieve a representative cross section of the German population. All in all, the clientele is a heterogeneous group, for instance with respect to age, gender, self-reported general sensitivity to noise, frequency of occurrence of car driving and profession.

All in all, 49 different test subjects took part in the different listening tests. Several test subjects participated more than one time in the listening tests. The average age of the test subjects is 34 years. A percentage of 28 % of the test subjects are female, 72 % are male. 98% of the tested subjects passed the audiometry screening test.

The exact group composition concerning age, gender, sensitivity to noise and frequency of occurrence of car driving can be found in the following figures (from fig. 30 to 33)



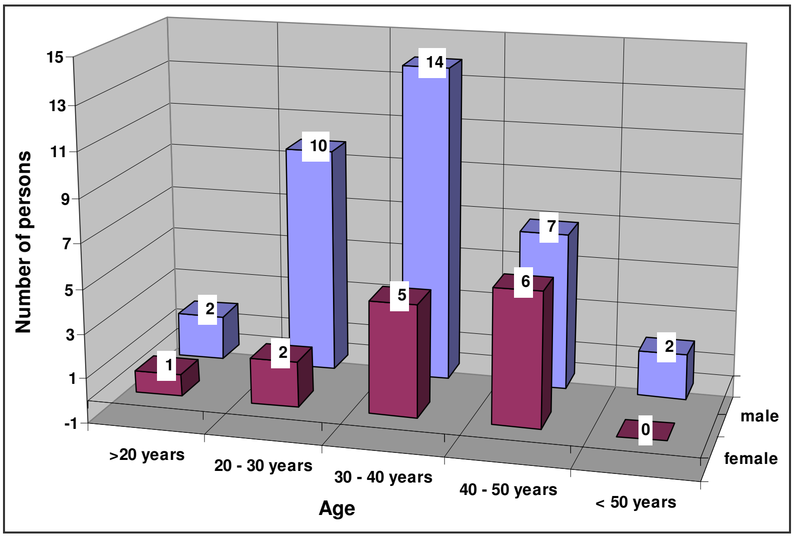


Figure 30: Gender distribution of test subjects in total (left), gender distribution of test subjects according to age classes (right)

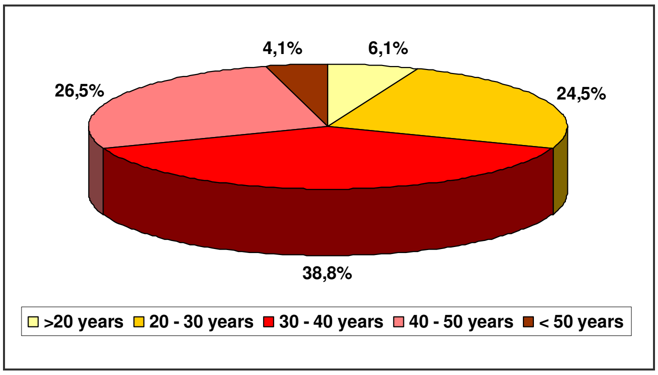


Figure 31: Distribution of test subjects according to age classes in %

As shown in table 4 the sample characteristics with respect to noise sensitivity or regularly driving cars are almost independent from gender. The majority of test subjects (59%) reported no special sensitivity to noise. However, a great deal of subjects stated that they are sensitive to noise (41%). This distribution is preferred, since with respect to the explanatory power of the listening results the consideration of both groups appears to be important. The same applies for the second aspect which is requested. 76% of the test subjects state that they are using their car regularly, whereas only 24 % of the test subjects rarely drive. However, the analyzers found no significant influence of these aspects on the evaluation behaviour of the test subjects.

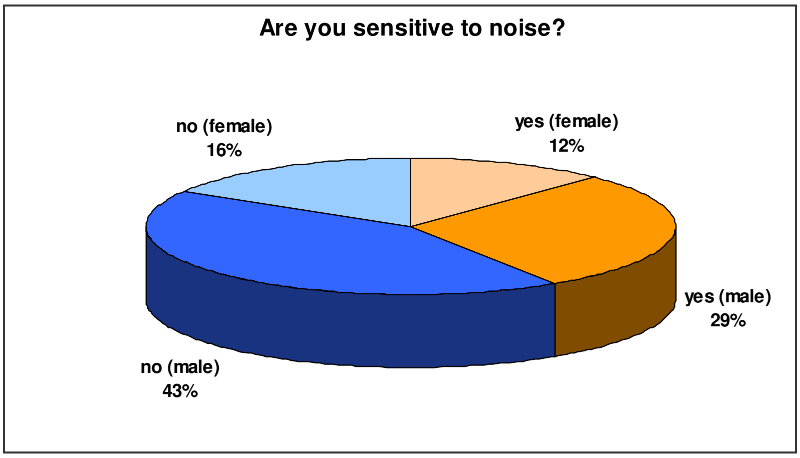


Figure 32: Distribution of self-reported noise sensitivity in %

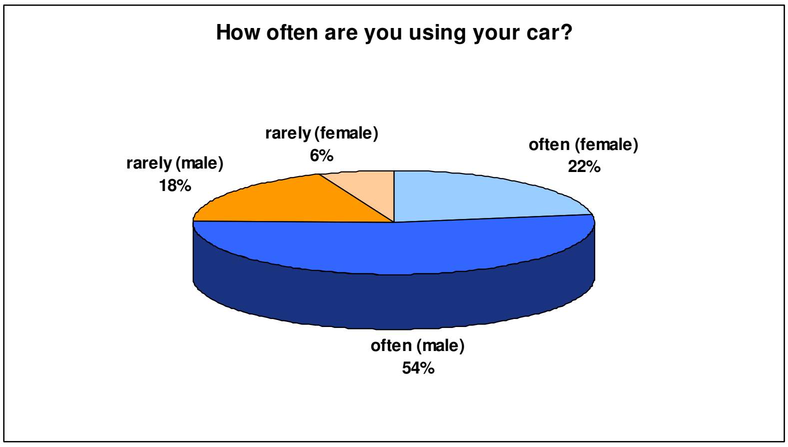


Figure 33: Distribution of frequency of occurrence of car driving in %

Table 4: Answers to questions in interview separated according to gender

Gender	Are you sensitive to noise?		How often are you using your car?	
	yes	no	Often	Rarely
Female	42,8%	57,2%	78,6%	21,4%
Male	40%	60%	74,4%	25,5%

2.3 SOUND ANALYSES

For the objective description of the noise annoyance acoustic parameters have to be found that reflect major perception-related sound properties. The selection of these parameters is based on existing knowledge gained from literature and former research (e.g. WP 2.2) and on the results of the interviews conducted after the different listening tests.

The following acoustical parameters are calculated and considered in subsequent statistical analyses (table 5). Not only average values of the different acoustical parameters are considered, but also diverse percentile values (1, 5, 10, 20, 50, 90, 95) of different (psycho-) acoustical parameters are calculated and considered for further analyses.

In particular, psycho-acoustical parameter are regarded which describe certain sound perception mechanisms. Psycho-acoustical parameters, such as loudness, sharpness, roughness, and fluctuation strength, play an important role with respect to several sensations. As functions of time structure and spectral distribution the parameters lead to results which yield information with greater differentiation than the information generated by the sound pressure alone. In psychometric experiments the connection between several psycho-acoustical parameters and single auditory sensation dimensions is confirmed very well. (Fastl, Zwicker, 2006)[5]. But, with respect to more complex evaluation criteria, such as annoyance, pleasantness or sound quality, the role of the different psychoacoustic parameters is not clarified in detail. However, in numerous studies it was already shown that these parameters, like loudness and sharpness, highly correlate with perceived noise annoyance, particularly with respect to typical environmental noise sources as traffic noise. In the European research project SVEN (Sound Quality of Vehicle Exterior Noise, GROWTH G6RD-CT-1999-00113, 2000-2003) the meaning of these parameters were even shown with respect to the stimulation of certain physiological reactions, which can cause adverse health effects after long-term exposition.

Consequently, the extensive consideration of psychoacoustic parameters is required.

Moreover, several percentile values are calculated to regard the variation of parameter over time as well. Few studies have shown that not in each case the mean value of a physical parameter represents the averaged sensational dimension. The cognitive stimulus integration over time is a complex process. For example with respect to loudness the perceived overall loudness of time-varying noise is represented by 5-percentile loudness (N_5). Prominent and loud noise events dominate the overall loudness sensation and must be emphasized with respect to the physical representation and description. The new DIN standard for the "Calculation of loudness level and loudness from the sound spectrum - Zwicker method - Amendment 1: Calculation of the loudness of time-variant sound the calculation of time-varying loudness (45631/A1)

[5] H. Fastl, E. Zwicker, "Psychoacoustics. Facts and Models", Springer Verlag, Berlin, Heidelberg, New York, 2006

reflects this finding and proposes that N_5 (and not N_{50}) represents the subjectively perceived loudness best. Such potential perception effects are considered by means of the calculation of different percentiles.

Table 5: Selection of analyzed acoustical parameter

Sound pressure level (linear)	Sound pressure Level (A-weighted)	Loudness (DIN 45631/A1)[6]	Sharpness (DIN 45692)[7]
Sharpness (Aures)	Sharpness (Bismarck)	Roughness	Hearing Model Roughness[8]
Fluctuation Strength	Hearing Model Impulsiveness	Tonality	Relative Approach, Time Pattern
Relative Approach, Frequency Pattern	Relative Approach, Time and Frequency Pattern	L_{Amax}, L_{eqA}, L_{eq}, Booming, ΔLoudness, ratios of acoustical parameters (e.g. N5/N50)	

All acoustical parameters are calculated with the commercial analysis software ArtemiS.

The following diagrams show the range and span of the stimuli with respect to certain basic acoustical parameters. It can be clearly seen that the stimuli cover a wide range and vary considerably with respect to the sound pressure level. Figure 34 displays the acoustical parameter L_{Aeq}, L_{A5} and L_{A90}. It can be seen that in some cases the L_{A90} is decisively different to the other parameters due to long periods of quietness (no traffic for several seconds).

Furthermore, figure 35 shows a comparison of the acoustical parameter L_{Aeq} and L_{A50}. It shows that these parameters vary slightly in dependence on the specific time structure of traffic sounds, and are not redundant. Therefore, both acoustical parameters are calculated and analysed.

[6] DIN 45631/A1 (draft): „Calculation of loudness level and loudness from the sound spectrum - Zwicker method - Amendment 1: Calculation of the loudness of time-variant sound".

[7] DIN 45692:2007-04: „Measurement technique for the simulation of the auditory sensation of sharpness ".

[8] R. Sottek, K. Genuit, „Models of signal processing in human hearing, Elsevier, International Journal AEÜ of Electronics and Communications, Int. J. Electron. Commu. (AEÜ) 59 (2005), p.157-165, 2005.

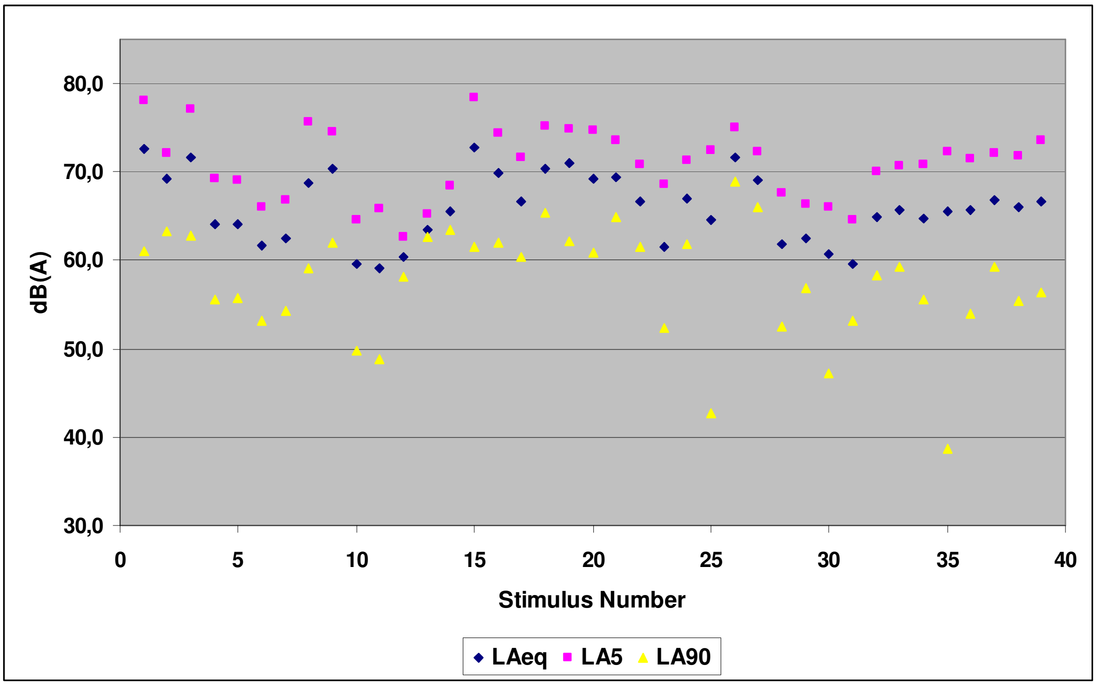


Figure 34: Variation of traffic noise stimuli with respect to LAeq, LA5, LA90

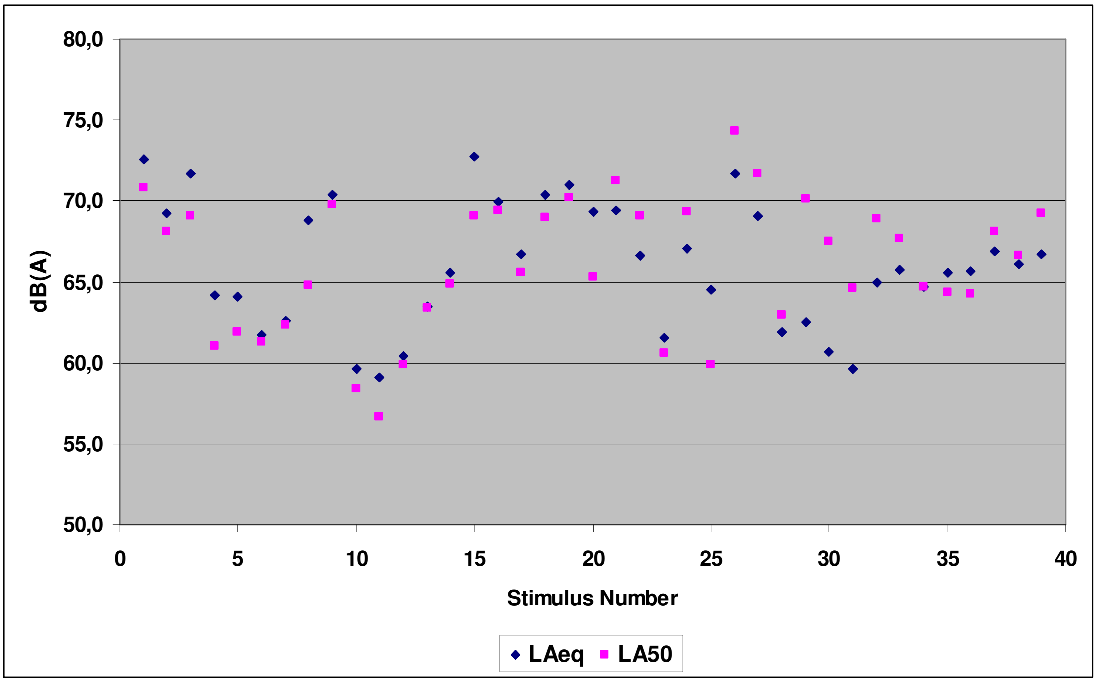


Figure 35: Comparsion of LAeq and LA50 values of traffic noise stimuli

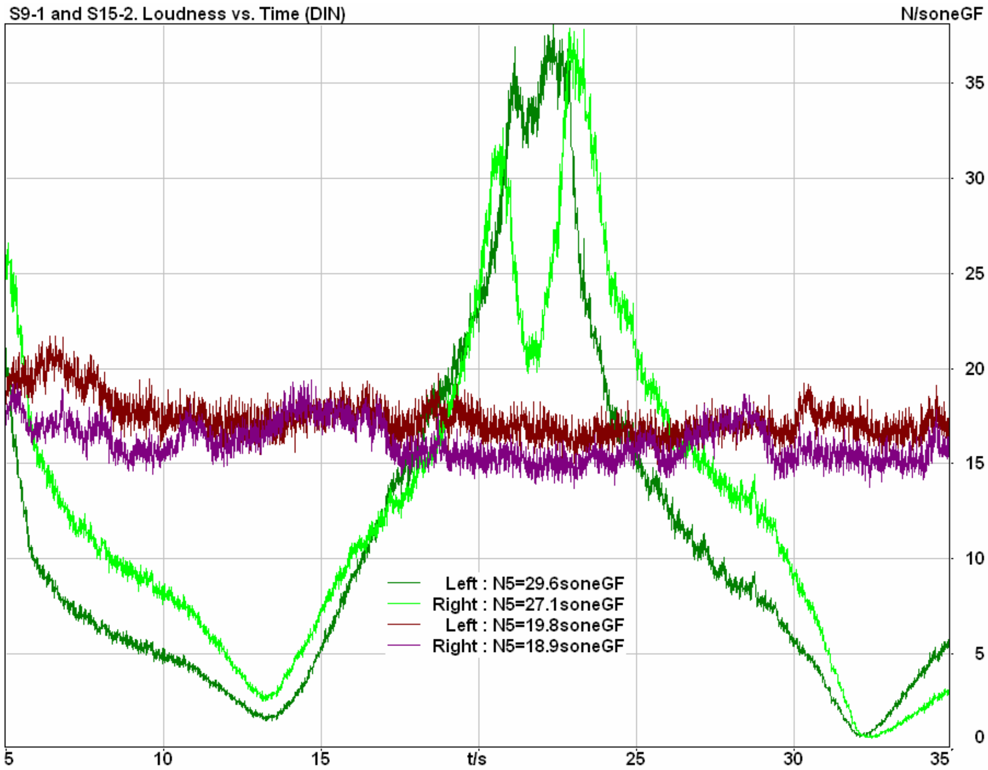


Figure 36: Loudness: Run of loudness over time of two traffic noises and their respective loudness values for both channels

As shown in figure 36 the run of the loudness over time can be different from traffic scenario to traffic scenario. The DIN 45631/A1 defines that the perceived overall loudness of time-varying noise is represented by the N_5-loudness. Obviously, prominent and loud noise events dominate the overall loudness sensation and must be emphasized with respect to the physical representation and description.

The figure above shows complete different runs of the loudness over time, which leads to different N_5-values, although the considered traffic noise stimuli possess comparable L_{Aeq}-values.

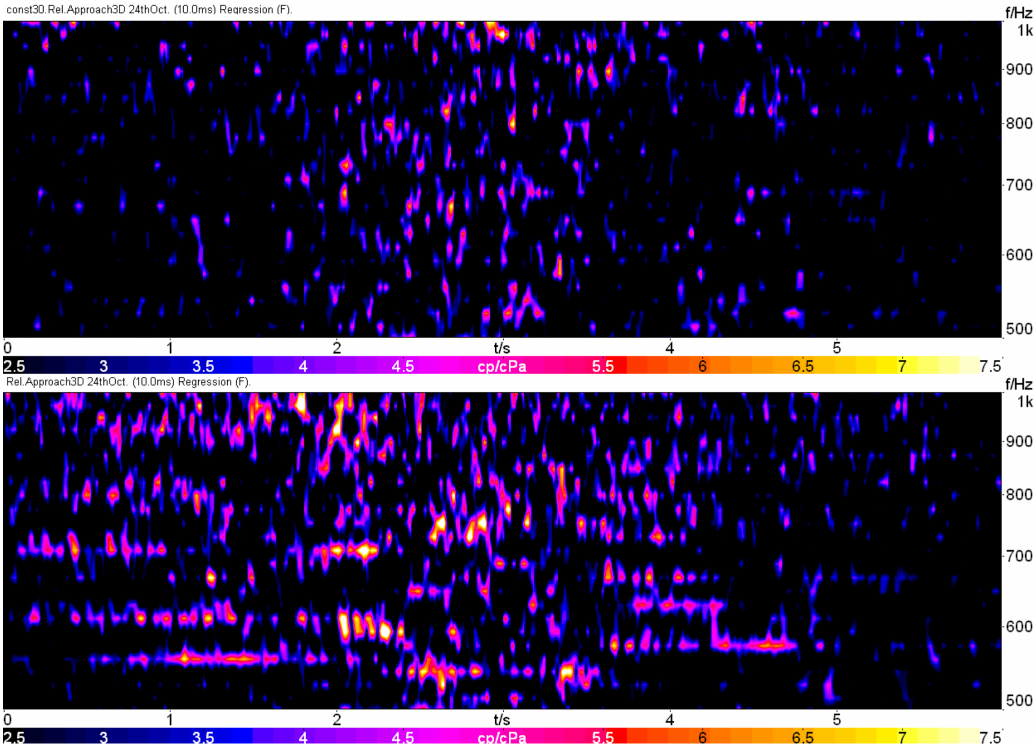


Figure 37: Single pass-by: Relative Approach 3D, Example for a gasoline engine (top) and a diesel engine (bottom)

As found in D2.8, the most frequent answer to the question about sound features influencing the evaluation was "the sound of the engine". Especially the typical sound of a diesel engine was described as very annoying. A strong engine sound is characterized by its dominating engine orders in the low frequency range. The diesel sound has additionally a typical knocking pattern in the mid and high frequency range.

For the detection of these sound properties the analysis Relative Approach (RA) is used. The RA is capable of the detection of tonal components, frequency and time patterns within a sound. The RA was already successfully applied in former investigations about diesel knocking. The human hearing is very sensitive to patterns in the frequency and time domain. Monotonous signals cause a very fast adaptation, whereas permanently changing sounds and sounds with dominant patterns consistently attract attention (and can cause annoyance). The RA separates sound parts with and without pattern and thereby evaluates the contained patterns. An estimated signal – based on the previous values – is constantly compared with the actual signal. High differences are interpreted as dominant patterns. The capability of detecting diesel knocking is illustrated in Figure 37. The picture demonstrates the dissimilarity of gasoline and diesel engine sound on the basis of short-term noise patterns. It is possible to apply the RA only to frequency patterns (RA(f)) or time patterns (RA(t)) or both (RA(f+t)). It is expected that the RA Analysis is of importance concerning the perception of traffic noise as well.

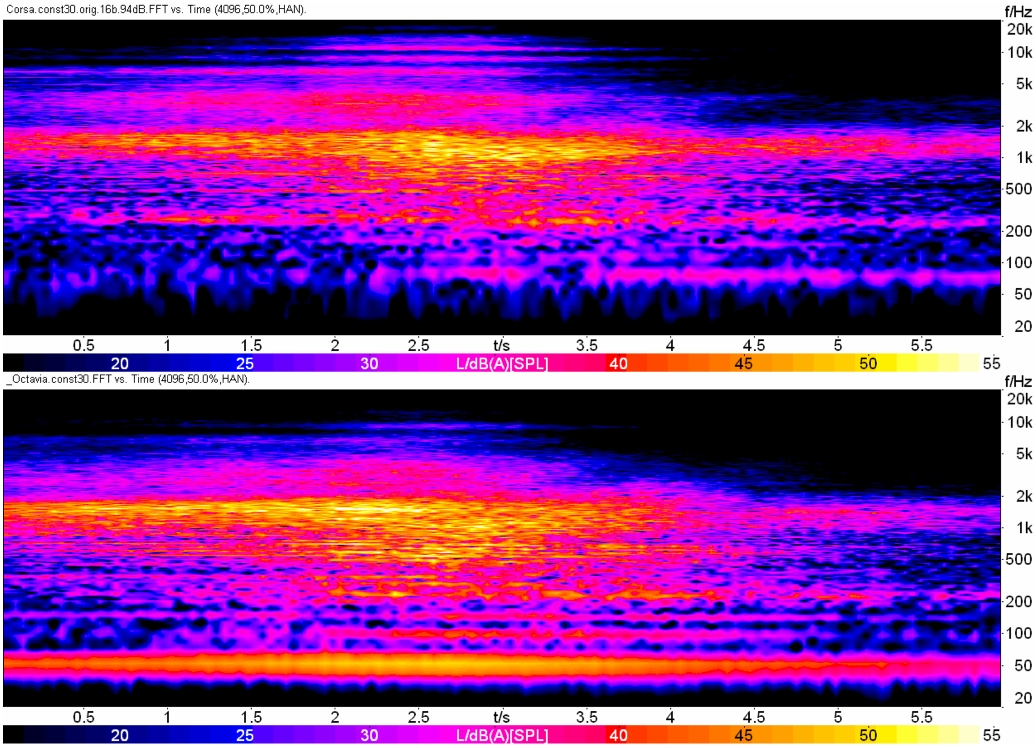


Figure 38: Single pass-by: FFT vs. time. Example for a car with low content (top) and high content (bottom) of low frequencies

Dominant low frequencies emitted by the power train can cause high annoyance. They are described by test subjects as "unpleasant booming noise". Figure 38 shows differences of two single pass-by sounds with respect to the low frequency content. Such differences can be of importance for traffic noise evaluation as well.

Another typical sound feature that can cause annoyance is a high content of high frequencies in the frequency spectrum of a noise, for example caused by high levels of rolling noise. The psycho-acoustic parameter for the assessment of this sound feature is the sharpness. Sharpness is a measure of the high frequency share of a sound. The greater the share of high frequencies the 'sharper' the sound is perceived. The spectral loudness composition is then specifically weighted. Here the DIN 45692 is applied. The sharpness unit is acum. Figure 39 depicts the spectral loudness composition for two traffic noise stimuli used in the listening tests with different sharpness.

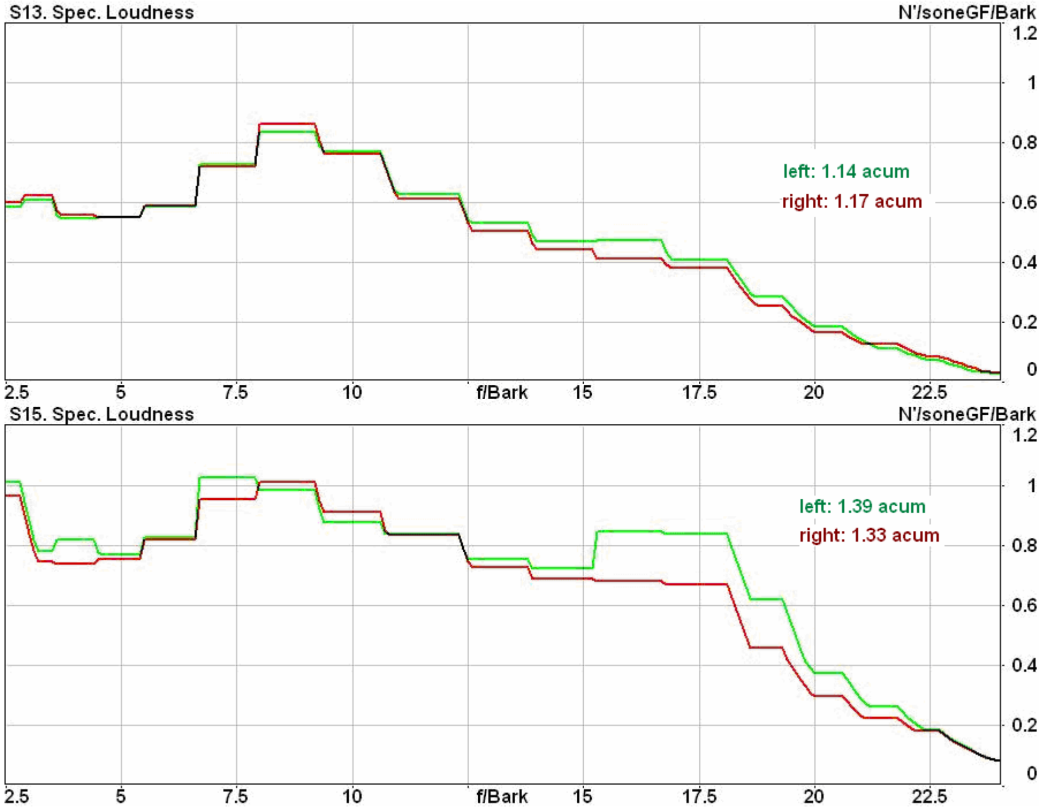


Figure 39: Specific Loudness: Example of two traffic sounds with low content (top) and high content (bottom) of high frequencies and their respective sharpness values (left and right)

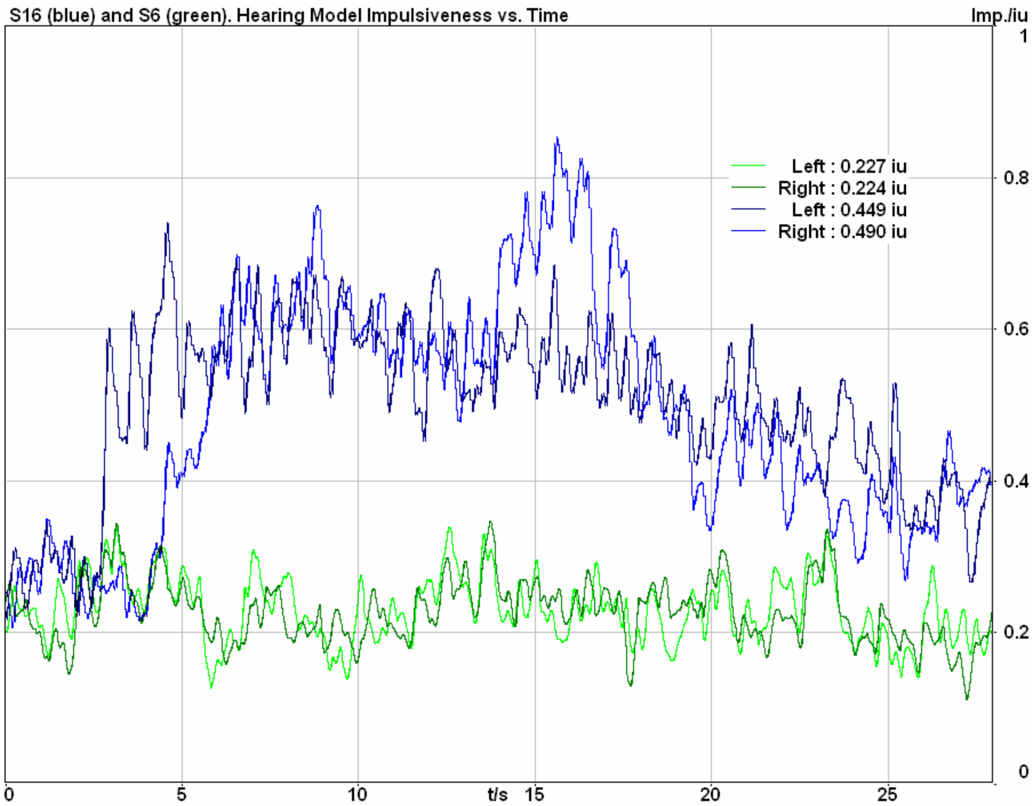


Figure 40: Hearing model impulsiveness: Two traffic noise stimuli and their respective impulsiveness values

As shown in figure 40 with special regard to the acoustical parameter impulsiveness different impulsiveness values of the traffic noise stimuli can be found in the data. The differences result from certain impulsive noise events, which for example can result from the engine of vehicles in idling condition.

The psychoacoustical parameter roughness can also be significant with respect to a perception-adequate evaluation of traffic noise. Figure 41 displays the different roughness of two traffic noise stimuli. The roughness of the first traffic sound (top) is much stronger than the roughness impression of the second stimuli (diagram bottom).

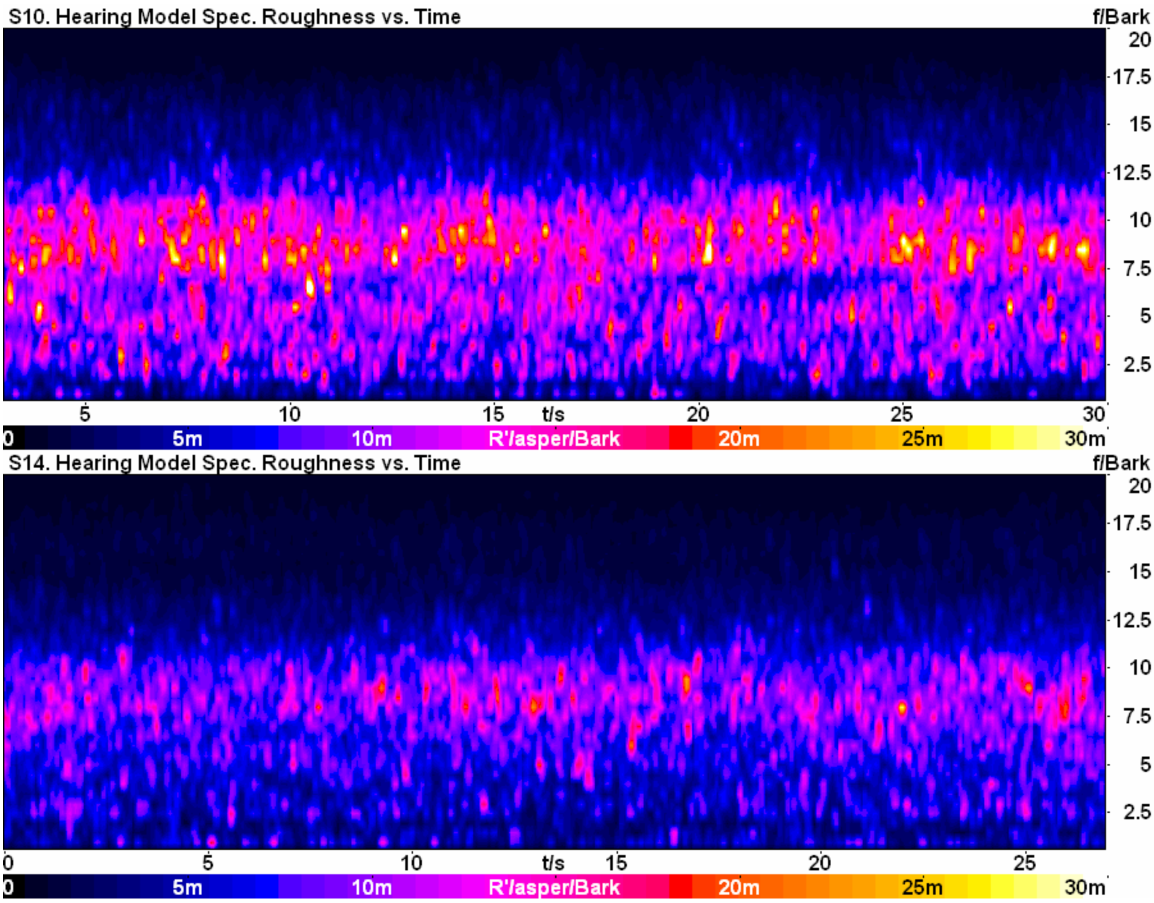


Figure 41: Hearing Model Spec. Roughness: Roughness of two traffic noise stimuli

Another acoustical parameter, which is expected to be of importance, is tonality.

2.3.1 Statistics

2.3.1.1 Statistics of Subjective Evaluations

Some of the known descriptive statistical analyses are applied to analyze the different evaluations given by the test subjects in the listening tests. In figure 42 and 43 it can be seen that the evaluations of the different noise stimuli differ considerably. The worst stimulus was rated with "8" on average, whereas the best stimulus with lowest subjective annoyance level yields assessments around "3". This means that with the selected road traffic noise stimuli a broad sensational range is covered. Typical standard deviations are around "1" (fig. 44)

The exclusion of outliers leads to decreased standard deviations and confidence intervals.

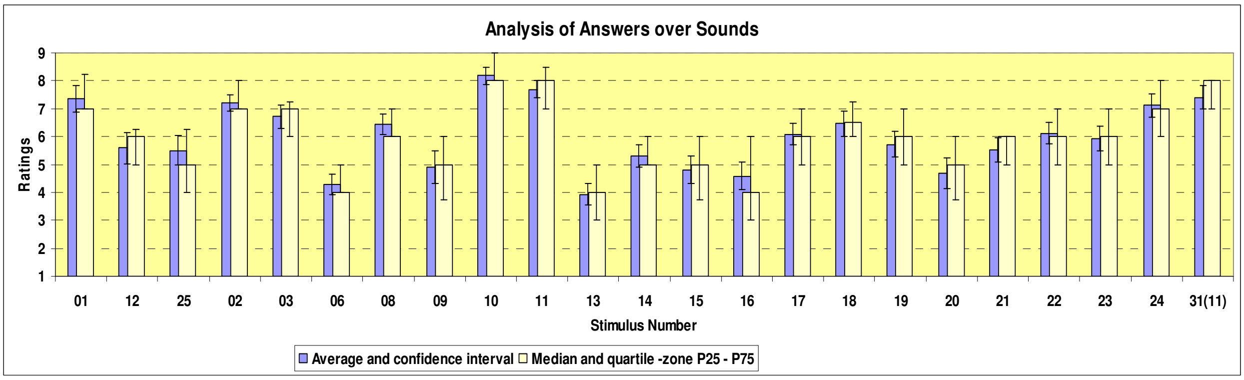


Figure 42: Evaluations of noise stimuli of one test set with average, confidence interval (at 95%), median and quartile (P25, P75) values

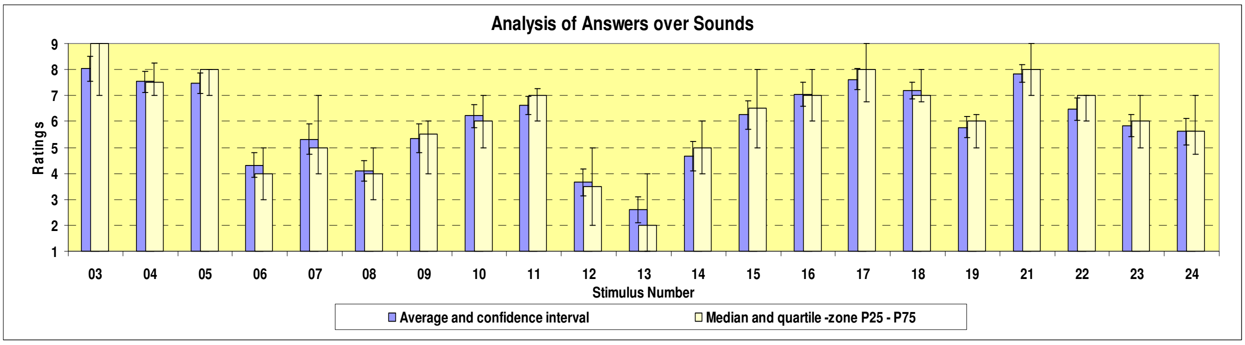


Figure 43: Evaluations of noise stimuli of one test set with average, confidence interval (at 95%), median and quartile (P25, P75) values

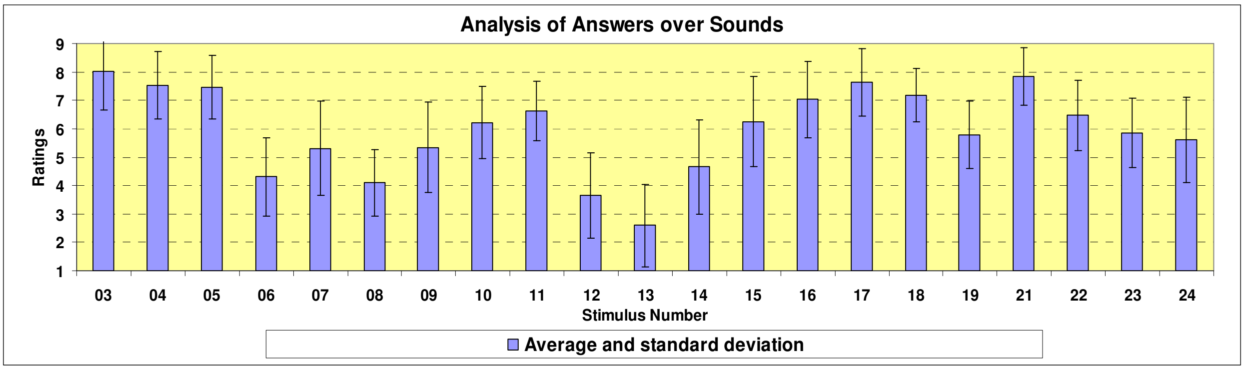


Figure 44: Evaluations of noise stimuli of one test set with average values and standard deviation

Figure 45 shows the averaged ratings of the presented traffic noise stimuli given by males and females. It can be clearly seen that the evaluation tendencies are comparable and seems almost independent from gender. The correlation coefficient between the female and male evaluations amounts "0.956" and the standard deviation is "1.2". This makes clear that no gender-specific evaluation behaviour must be taken into account.

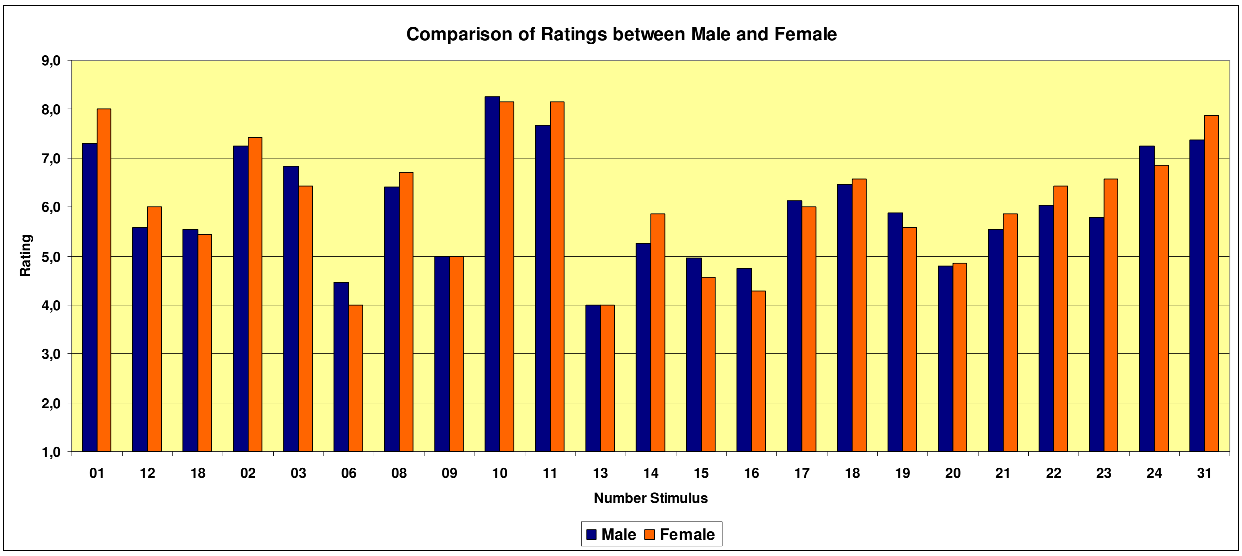


Figure 45: Comparison of evaluations of noise stimuli of one test set between male and female

2.3.2 Analysis of Interview Data

The listening tests, where the test subjects rates the annoyance level of traffic noise on a 9-point scale, are combined with interview methods. After listening and evaluating the noise, the tests subjects have the occasion to explain their feelings towards the stimuli and test procedure in general. Additionally, further personal data is collected. During the interview the test subjects have the opportunity to express their thoughts with regard to the test, test procedures, evaluation strategies, etc.

All in all, the verbal feedback about what aspects influenced the evaluations gives indications on meaningful subjective evaluation parameters. The test subjects mostly describe acoustic and temporal phenomena which they perceive as annoying. For example, frequently used phrases are: "heavy vehicles and buses are really disturbing", "the loudness is important", "loud and prominent single noise events are really disturbing", "accelerating vehicles are most annoying", "acceleration from standing position (at traffic lights) is most disturbing", "speed".

Table 6 shows most frequently phrases assigned to semantic context.

Table 6: Selection of verbal items frequently used in the interview

	Frequently used descriptors
Related to temporal aspects	Frequency of occurrence of pass-bys; constant or time-varying driving conditions, temporal patterns, number of cars passing by, "level of regularity", "quiet periods"
Related to sound properties	Loudness, spectral content, braking noise, frequency, diesel knocking, impulsive events, booming, droning, sharpness, maximum loudness, low frequency content
Related to noise sources in general	Heavy vehicle, motor bike, bus, engine noise, rolling noise
Related to traffic in general	Speed, traffic lights (idling and acceleration), traffic volume, traffic composition
Evaluation strategies	Kind of integration (or averaging) over time, prominent single noise events, regularity vs. irregularity

A broad variety of verbal items are used by the test subjects to describe the reasons for their annoyance judgments. However, some phrases and descriptions are frequently found in the interview data. These comments give valuable information about the sound properties that should be considered during the development of a quantitative description of the annoyance of traffic noise.

Therefore, the qualitative comments have to be translated into acoustic parameters to allow statistical analyses.

2.4 PRINCIPAL COMPONENT ANALYSIS

The principal component analysis (PCA) is applied to the evaluations for each listening test set. It enables the determination of common factors that underlie the single evaluations.

2.4.1 Theory

The evaluation of a sound set with *m* different sounds by *n* different test subjects produces a *n x m* evaluation matrix. The single evaluations of the test subjects differ more or less from one to another. It is now assumed that a few specific common evaluations factors are responsible for the evaluations and their different weighting for each test subject causes the variations between the evaluations[9].

In the first step, the PCA tries to find a set of *m* evaluation values that has the maximum correlation with all the single evaluations of the *n* test subjects. This set of evaluation values owns also the maximum explanation for the variations[10] between the single evaluations of the *n* TI. It represents the first factor, which is characterized by its factor values (here the evaluation values for the sounds) and its factor loading representing the share of explained variation. The second factor is determined using the residual variations. This procedure is repeated until the determined factors together explain the total variation. This point is reached at latest with the factor number *n*.

The percentage of variation explanation and therefore the importance of a factor decreases with every iteration. There are different methods to determine the number of factors produced by a PCA relevant for the respective results. Here the Kaiser-Guttman-Criterion is chosen. This means, that only factors are considered that explain more than an evaluation of a single TI itself; factors with a lower explanation produce no further data reduction. This is mathematically expressed by the requirement of an eigenvalue higher than one for each factor to be considered relevant.

A typical result for a PCA will be the determination of two or three relevant factors that explain more than 80 % of the variations. So the initial *n x m* evaluation matrix is now represented by a *3 x* m factor matrix. That explains also why the PCA is a method for dimensionality reduction. Figure 46 depicts the PCA principle for an example with three relevant factors.

To determine the meaning of the factors the respective factor values can be correlated with other values that stand for certain characteristics (here sound analyses) of the respective sounds. A high correlation between the factors values and a specific

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[9] Example: A psychological test assesses the arithmetic capability as well as the spatial sense of a test subject. The final result of each test subject will base on these two factors and the variations between the results on the different individual capabilities regarding the two factors.

[10] Regarding the example, the total variation between the final results of the test subjects can be explained by their different individual capabilities. If the differences between the individual arithmetic capabilities are the same as the differences between the final results, this factor is explaining the total variation. Hence, the spatial sense has no influence on the differences of the final results; all test subjects perform equally concerning this factor. Typically, one factor is explaining only a certain fraction of the variations (this is a certain correlation between the differences) and the next factor explains a certain fraction of the residual variation and so on.

characteristic indicates that the factor is a good representation for that characteristic. This is the crucial point, where elements of the subjective perception are translated into physical sound analyses.

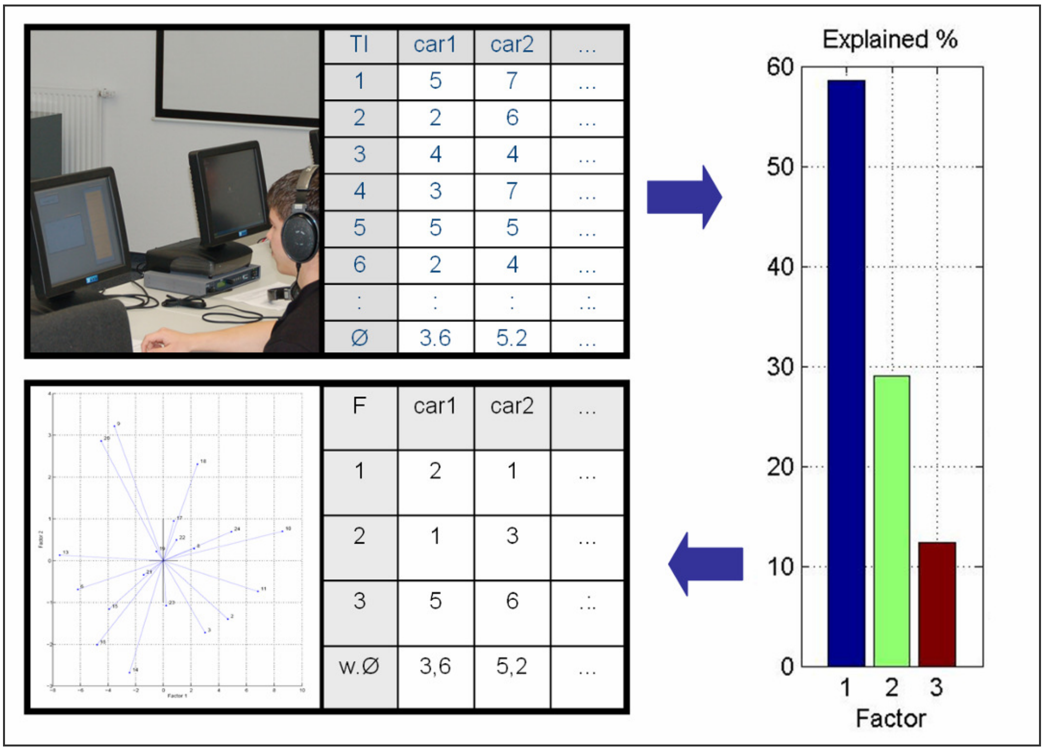

Figure 46: PCA reduces the n x m evaluations matrix by determining the most relevant evaluation factors to a 3 x m factor matrix

2.4.2 Application

The evaluation data is statistically analysed using MATLAB and its statistic toolbox options. A graphic interface was adapted and tested in WP 2.2. This adapted tool allows for – after the selection of a specific sound set – the quick user-defined selection or deselection of certain elements such as test subjects, traffic noise stimulus, psychoacoustical analyses (see Figure 47). Then, the following statistical analyses include only the selected elements.

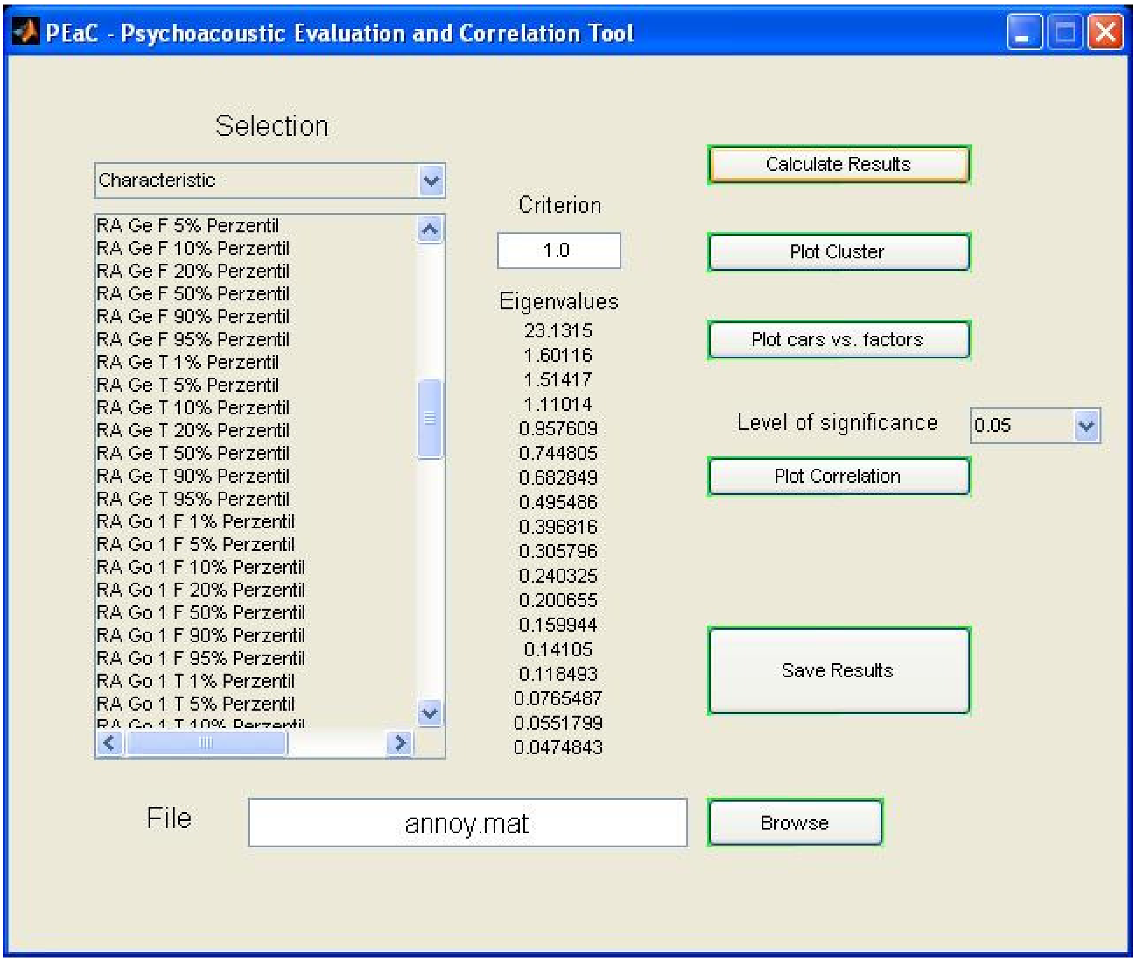

Figure 47: Interface for the statistical analysis of the evaluation data

Within this interface it is possible to define the eigenvalue criterion for the factor selection. As stated above, here a value of 1 is chosen according to the Kaiser-Guttmann-criterion.

Furthermore, cluster analyses for the test subjects or the traffic sounds can be calculated and displayed in diagrams. Thereby, the variations between the evaluations of the test subjects and the sounds can be checked and outliers can be identified. The cluster analyses are performed according to the Ward method and the average linkage method. In figure 48 and 49 examples of these cluster analyses are displayed. Every analysis produces a dendrogram as well as the curve of the increase square error sum with every clustering step.

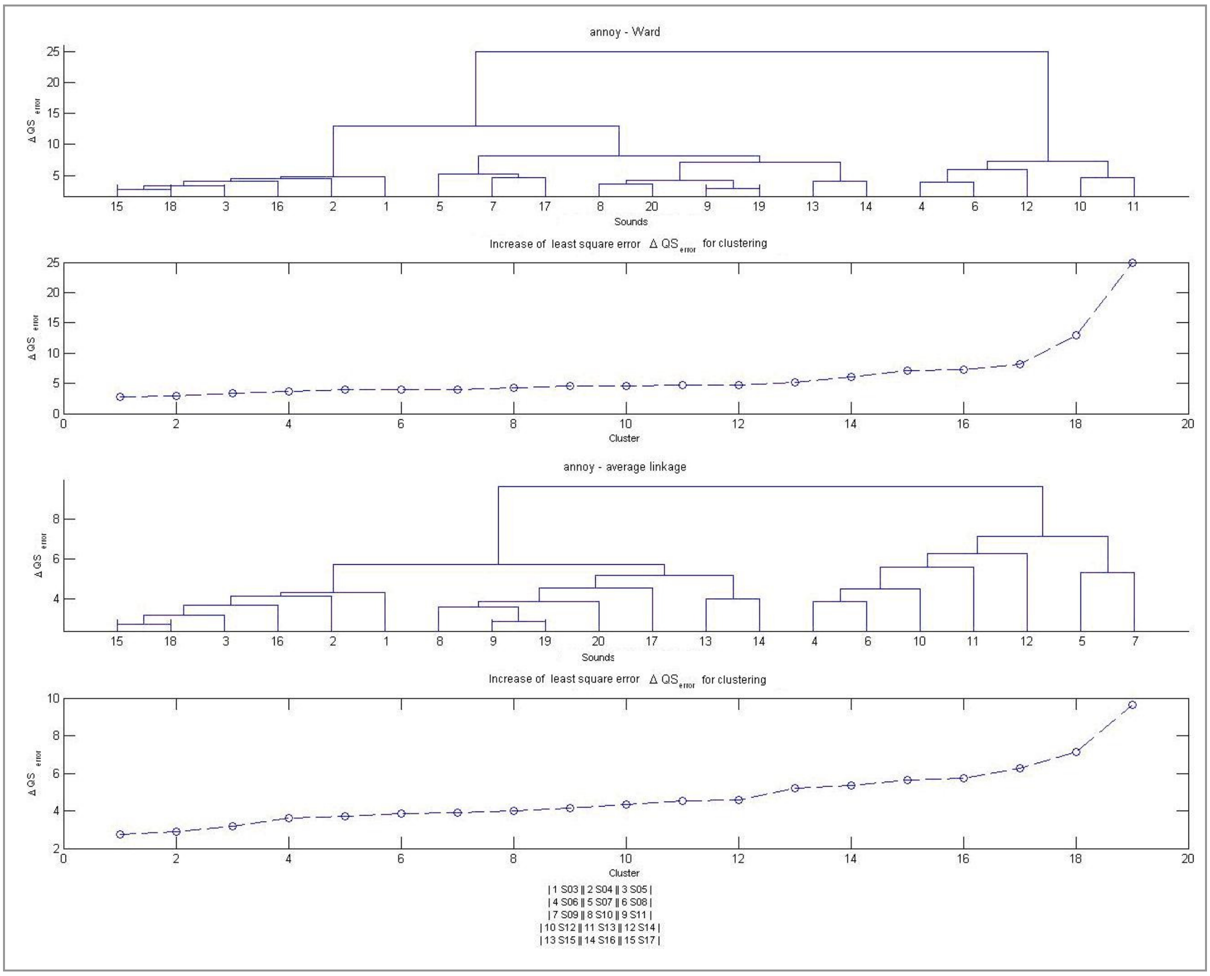

Figure 48: Cluster analyses of the traffic noises using the Ward method (top diagrams) and the average linkage method (bottom diagrams)

By means of the cluster analyses according to Ward and average linkage three test subjects are identified which should be excluded from further statistical analyses. The cluster analyses give indications that the answer behaviour and evaluation strategies of these persons strongly differ compared to the evaluation tendencies of entire test group. The reason for such unrelated differences from few test subjects to the rest of the group can be up to e.g. certain acoustical socialisation aspects (specific acoustic biography) or a general misunderstanding of the evaluation task.

Figure 50 shows the mostly decreased standard deviation caused by the exclusion of only two subjects; this means that the test group is reduced from 32 to 30 subjects. In the other listening test set, where one test subject must be excluded, the same improvement of the standard deviation values is achieved.

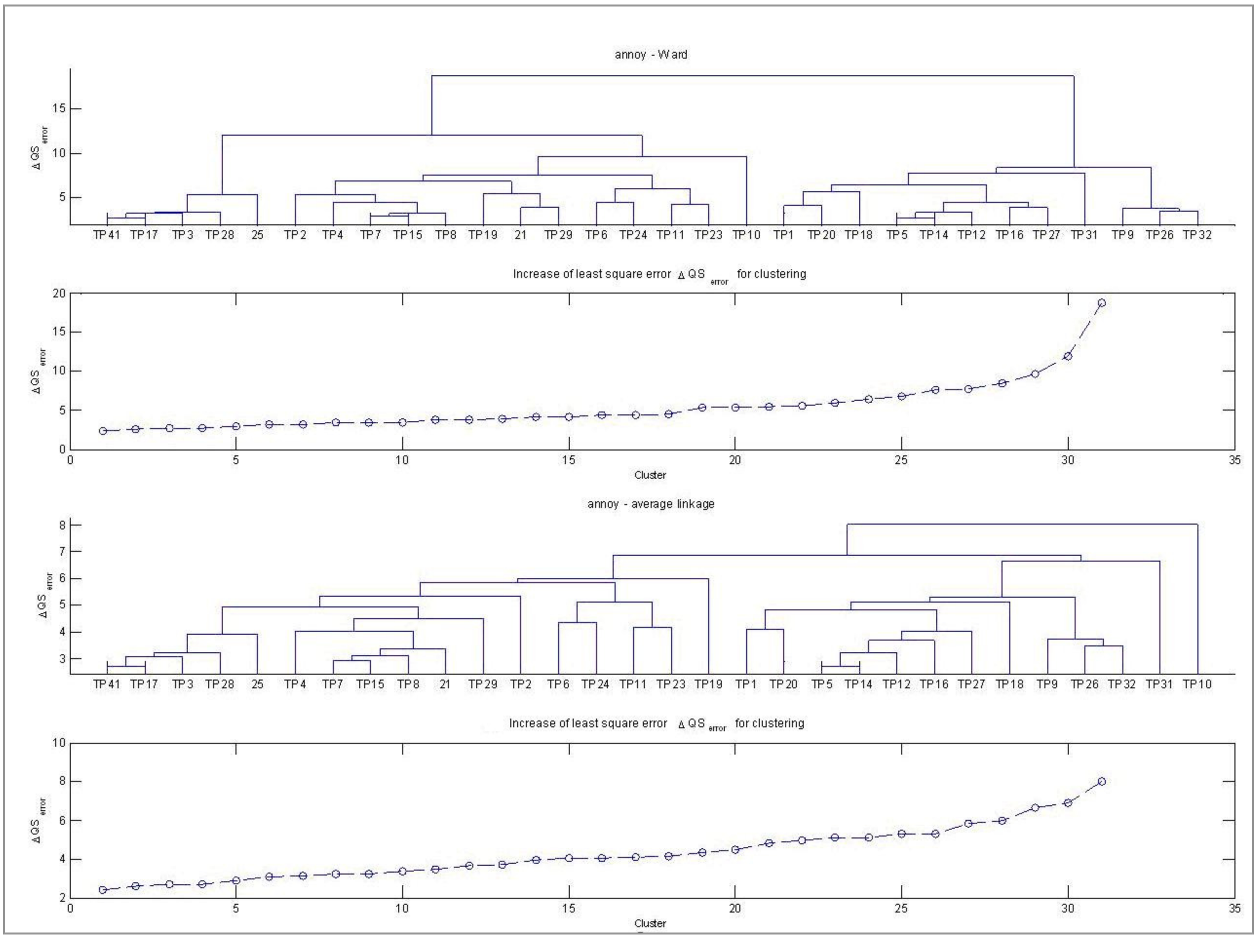

Figure 49: Cluster analyses of the test subjects (TP) using the Ward method (top diagrams) and the average linkage method (bottom diagrams)

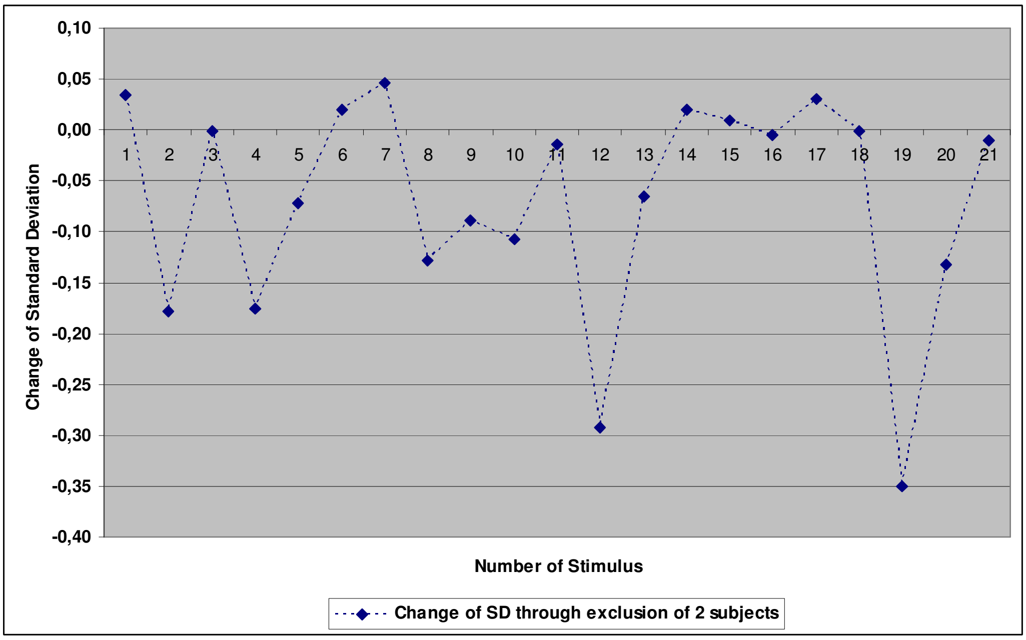

Figure 50: Change of standard deviation by means of the exclusion of 2 subjects for one sound set

It is possible to display the sounds using their new calculated factor values. Such a diagram graphically showing the distribution of the noise stimuli over the factors can support the interpretation of the factors. Figure 51 depicts an example for such a diagram. Here the distributions of the traffic sounds related to factor 1 and 2 (left), to factor 2 and 3 (right top) and related to factor 3 and 4 (right bottom) are displayed. Figure 52 displays the distribution of sounds over the two most important factors. Such diagrams are mainly used for further analyses.

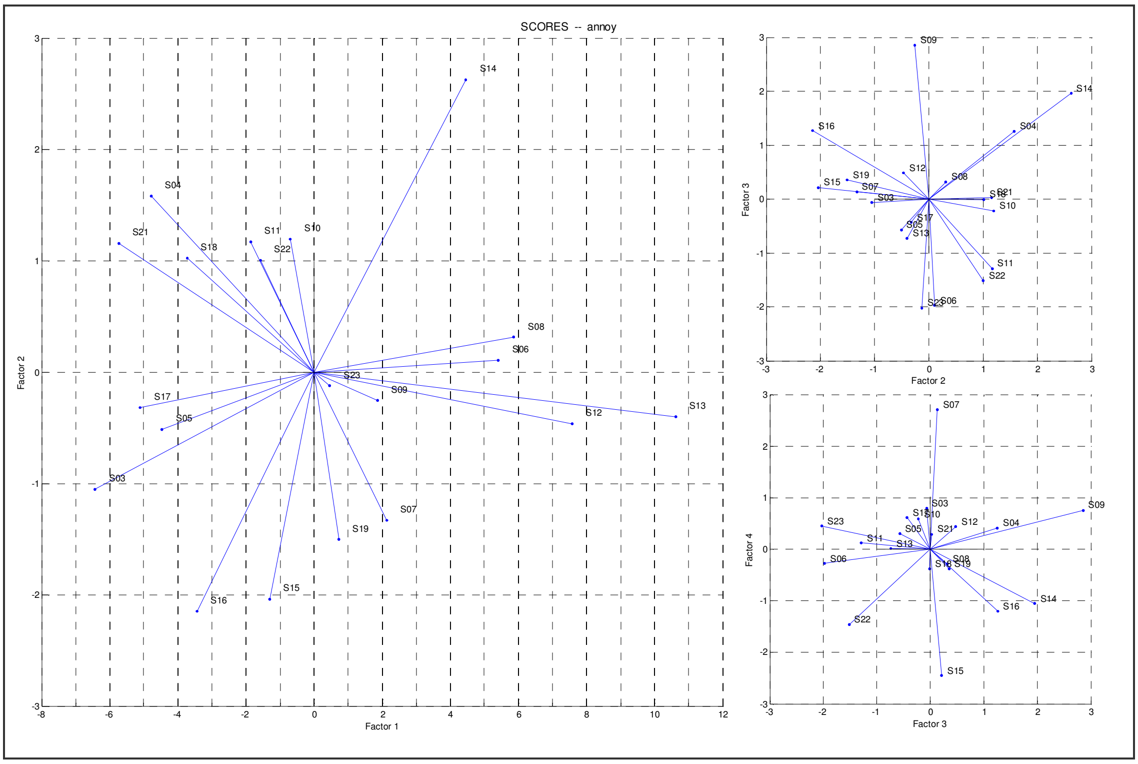

Figure 51: Diagram displaying the distribution of the sounds within the identified factors

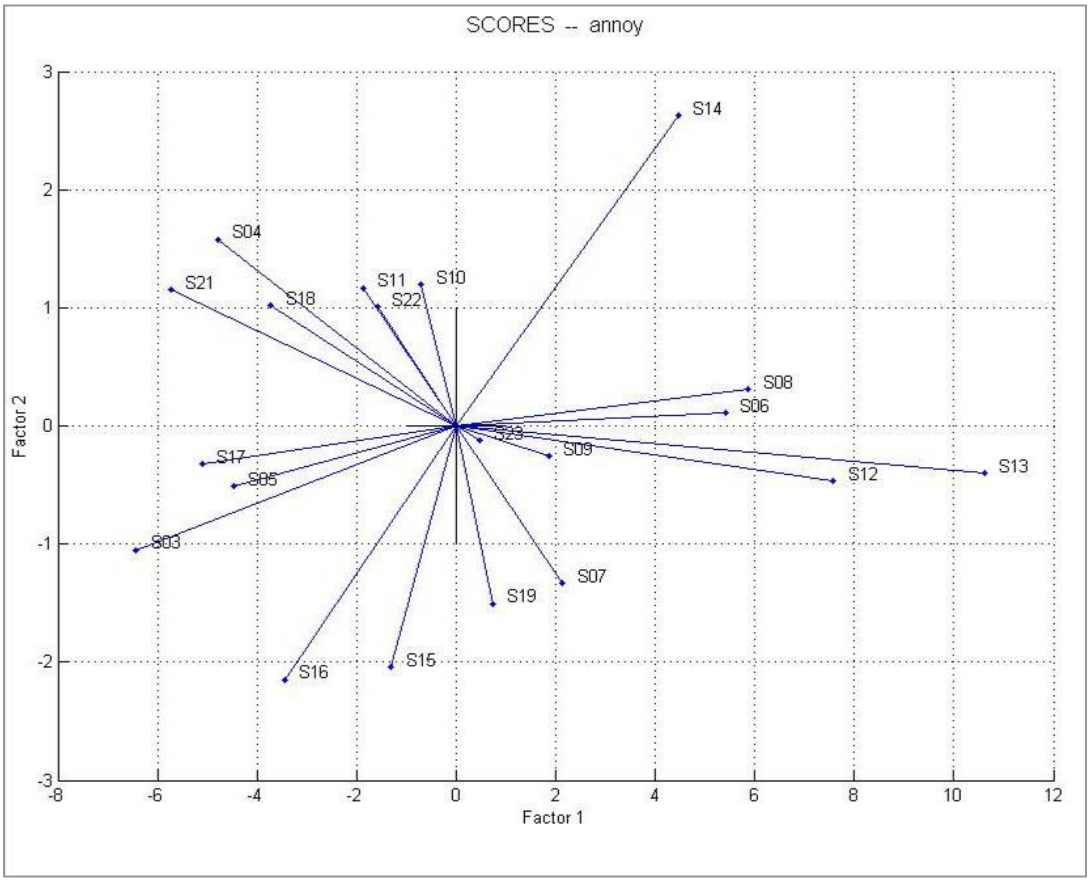

Figure 52: Distribution of the traffic sounds over the first two factors

Finally, linear correlations between the factors (i.e. factor values) and the selected (psycho-) acoustical analyses (i.e. calculated results for the respective sounds) can be calculated and displayed in diagrams. The Pearson correlation coefficient is calculated for every factor complying with the eigenvalue criterion. The values of the correlation coefficient lie between -1 and 1. High absolute values indicate high correlation; the algebraic sign denotes the positive or negative linear relation with the factor values. For the display the desired level of significance can be chosen. Figure 53 depicts an example for a correlation diagram basing on four relevant factors, whereas the factor 1 is the most important factor with a variance explanation of more than 70%. The correlation for factor 1 are the blue columns (right), the ones for factor 2 are the turquoise columns, factor 3 yellow and factor 4 red. Obviously, no selected parameter correlates very well with factor 3.

It can be seen that for this traffic sound set different acoustic parameters highly correlate with factor 1. This is in particular true for traffic sounds containing only cars driving with constant speed. Further analyses are required to identify the actual important acoustical parameters, which reflect the relevant sensational dimensions.

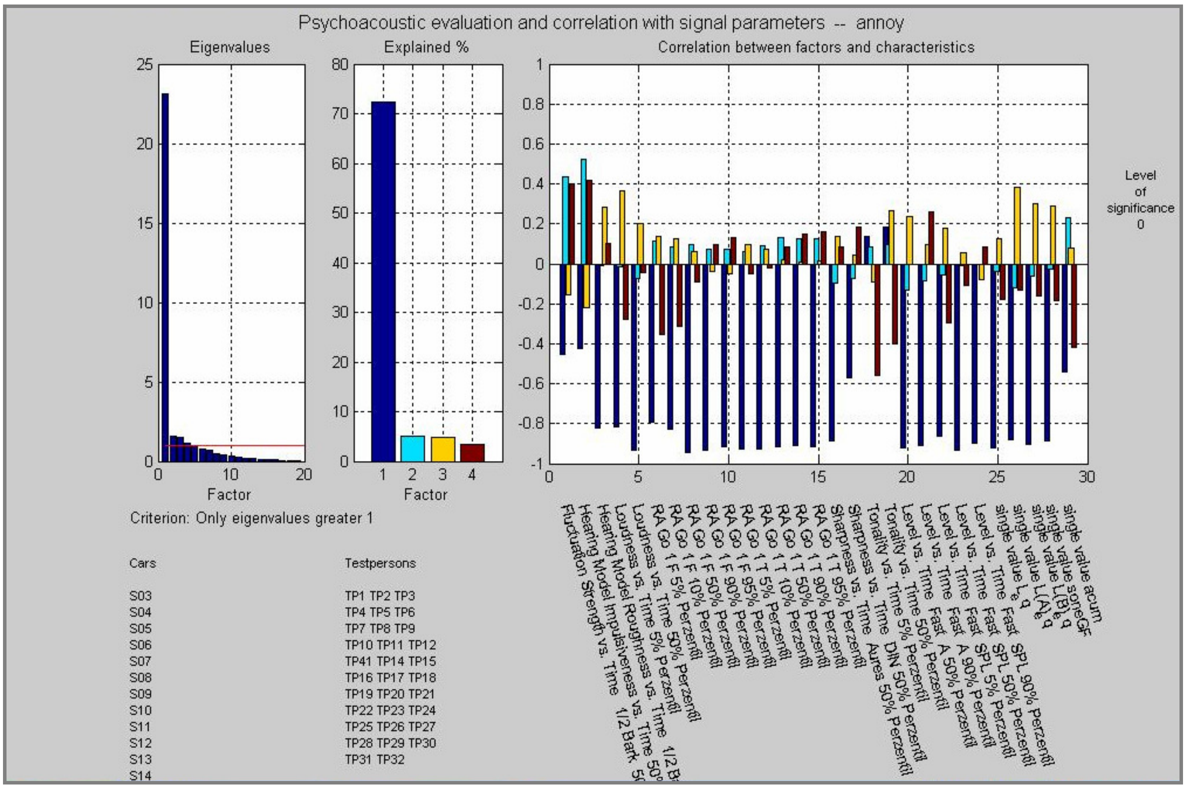

Figure 53: Example for a correlation diagram with four relevant factors

In the following the results of the PCA are analyzed and interpreted to detect the most significant acoustical parameters with respect to the subjective evaluation of traffic noise. Moreover, linear and multiple regression analyses must be used to link physical parameters with subjective responses. All in all, it is aimed to find a metric which allow for the prediction of subjective assessments on the basis of acoustical parameters. Here, it must be investigated whether the usually applied acoustical indicator - the time averaged A-weighted sound pressure level - is sufficient with respect to the estimation of noise annoyance.

2.5 TRAFFIC NOISE EVALUATION INDEX (WP 5.12.7)

2.5.1 Results of the PCA

As mentioned above the results of the PCA and correlation calculations between factors and (psycho-)acoustic analyses describe the evaluation patterns of the test subjects.

The PCA of the different sound sets always produce one dominating factor with an explained variation between 60 % and 80 %. Moreover, three to five more relevant factors are found in the data. However, the explained variation of the higher factors is much lower and amounts about 5% to 8% per factor.

By means of the calculated factor values for example displayed in factor over factor diagrams (fig. 52) the results can be interpreted and first insights can be gained with respect to potential acoustical parameters.

The PCA of the different sound sets depicted in the following figures produce a dominating factor with an explained variation of 65 % and 72% respectively.

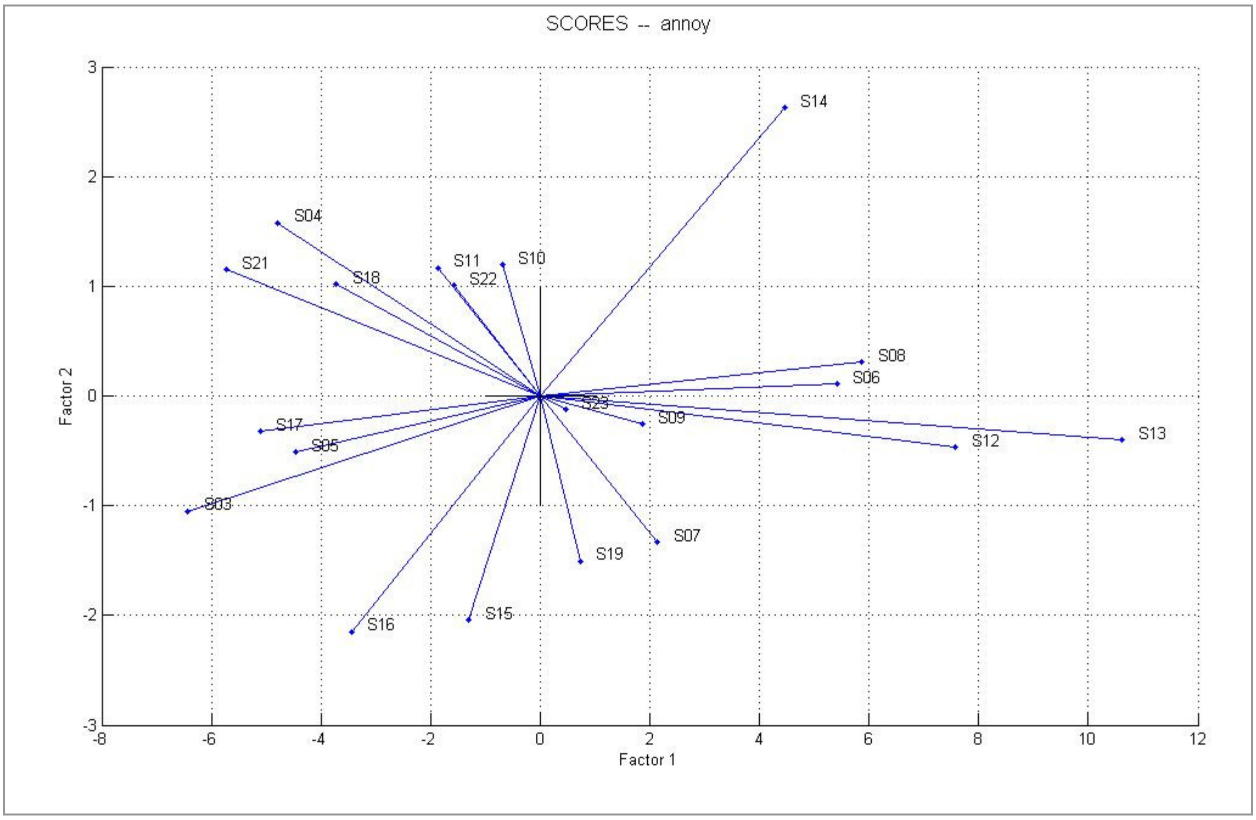

Figure 54: Distribution diagram of a complete sound set with four relevant factors, distributions of the traffic sounds related to factor 1 and 2

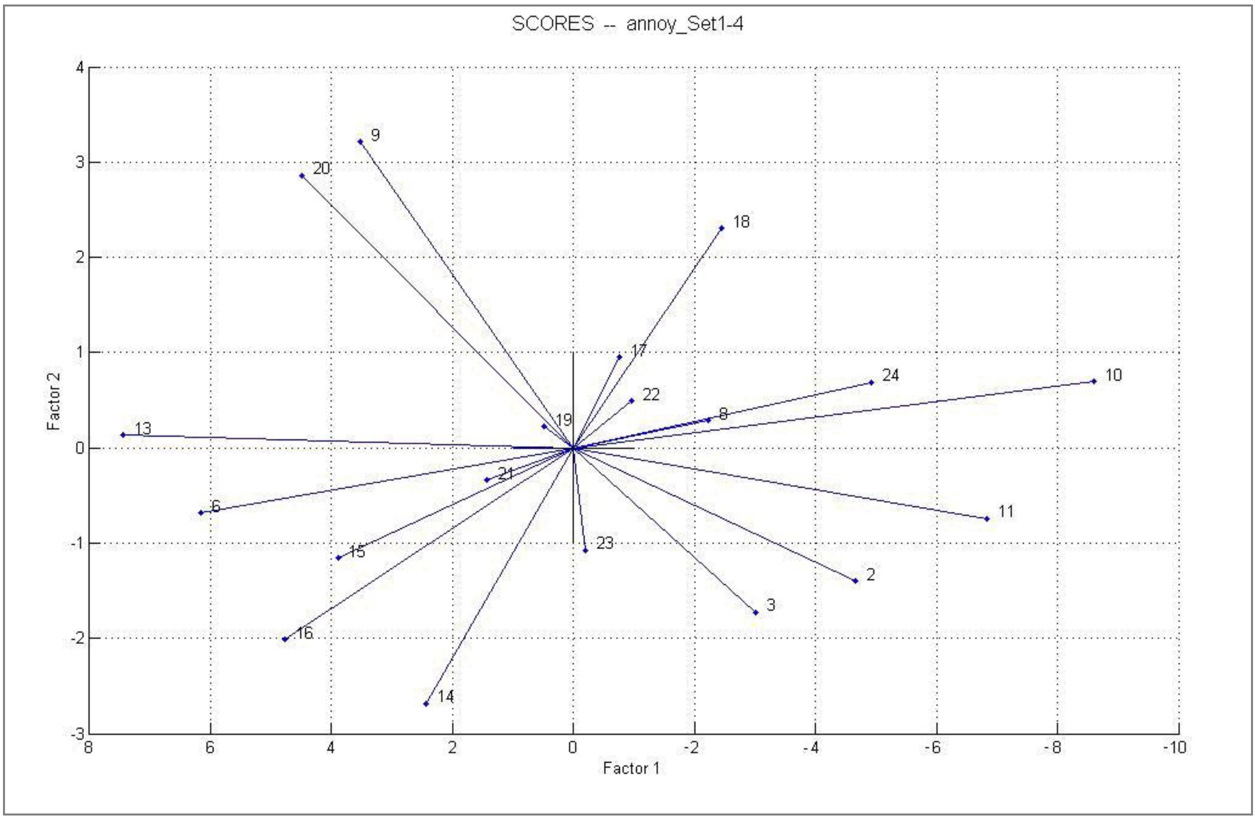

Figure 55: Distribution diagram of complete sound set with six relevant factors, distributions of the traffic sounds related to factor 1 and 2

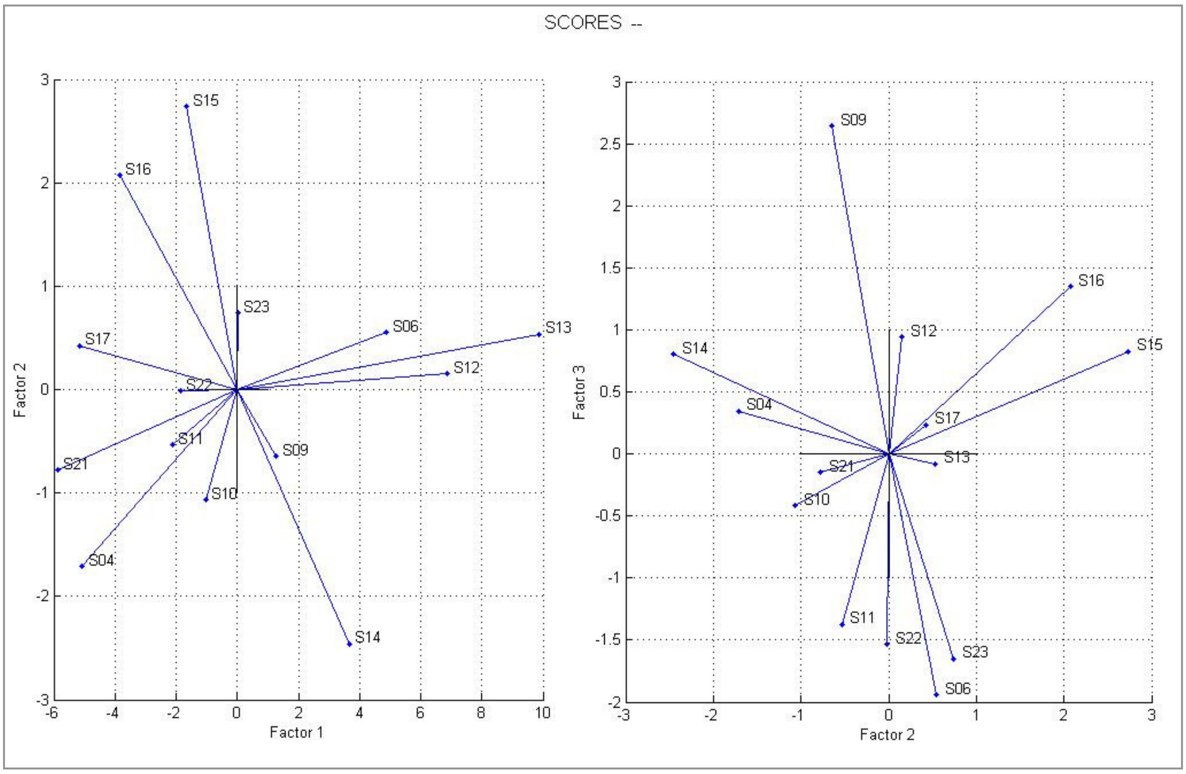

Figure 56: Distribution diagram of a sound subset with four relevant factors, left: distributions of the traffic sounds related to factor 1 and 2; right: distributions of the traffic sounds related to factor 2 and 3

In the following a short example of using the information from the PCA is given. For example, figure 56 shows the distribution of several traffic noises over the first three factors.

It can be observed that stimulus 15 and stimulus 16 are close together in the diagrams and are evaluated as annoying. By means of further listening to these sounds it becomes clear that the sounds contain acoustical similarities and patterns. Heavy vehicles are standing at traffic lights and the idling sound of these vehicles dominates the traffic sound.

Since the first factor is closely connected to loudness or sound pressure level, as the correlation plots with the different factors suggest (fig. 58), it becomes clear that the assessment-influencing sound properties of these sounds are not covered with loudness or sound pressure level. Figure 57 shows the distribution of evaluated sound stimuli related to factor 1, 2 and 3, while in the left diagram the L_{A50}-values of the sounds are also displayed. The general trend is that obviously high factor 1 values correspond with low dB(A)-vales, whereas low factor 1 values apparently stand for higher dB(A)-values. However, few sounds do not follow this principle, as for example S16 and S15. Here, the short-term patterns in the signal caused by the idling vehicles also influence the subjective evaluation and must be considered. This can be done by specific acoustical analysis such as Relative Approach or Impulsiveness. Here, for the detection of these sound properties the analysis Relative Approach (RA) is considered in detail. The Relative Approach is capable of the detection of tonal components, frequency and time patterns within a sound. The Relative Approach was already successfully applied in former investigations about diesel knocking and WP 2.2 described in deliverable 2.8.

This example shows on the one hand the meaning of further factors and on the other hand that simple sound pressure considerations do not adequately reflect the human perception and evaluation of traffic noise.

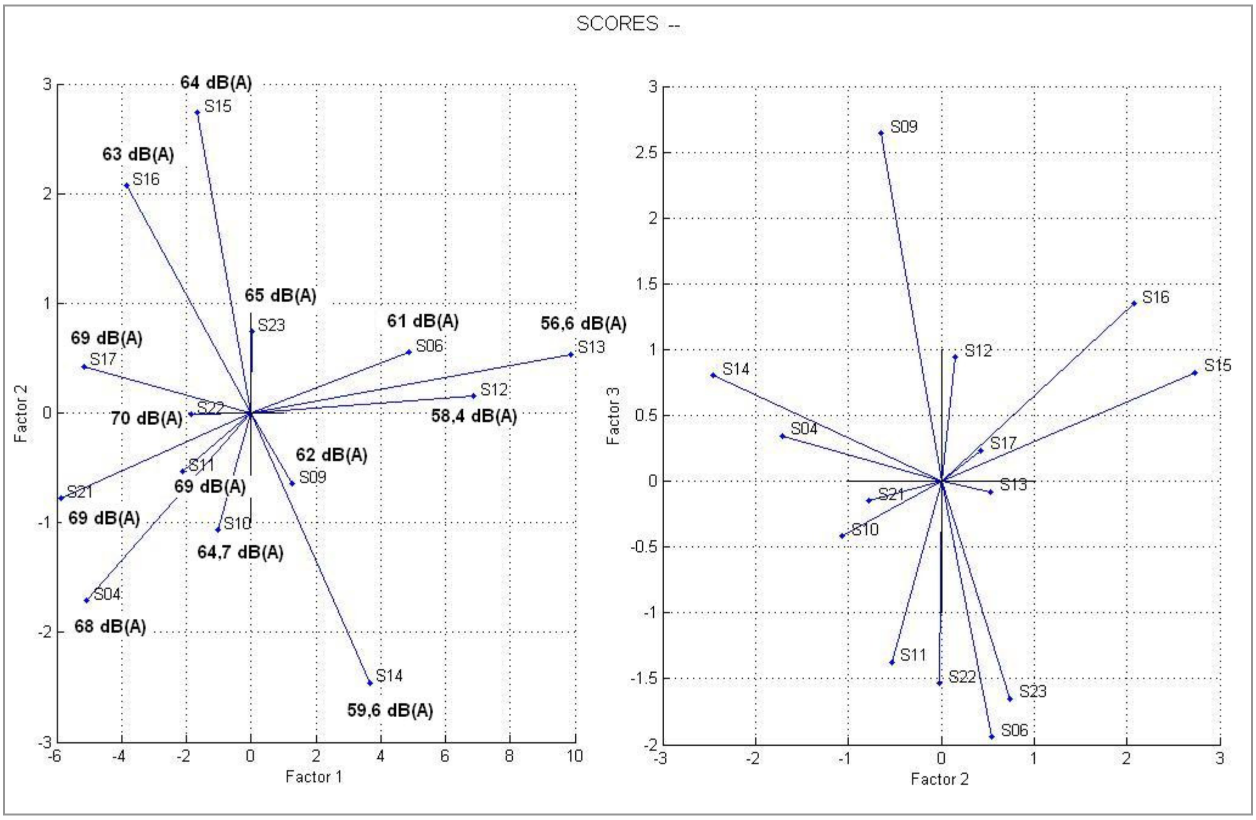

Figure 57: Distribution diagram of a sound subset with four relevant factors, left: distributions of the traffic sounds related to factor 1 and 2; right: distributions of the traffic sounds related to factor 2 and 3

Figure 58 shows the correlation diagram of sound subset mentioned above. It demonstrates on the one hand that highest correlations are not achieved with the L_{Aeq}, but rather with the Relative Approach. Interestingly, factor 2 correlates with the acoustical analysis impulsiveness, which detects also some of the mentioned short-term acoustical patterns.

The detailed investigation of the PCA-results helps to create the evaluation index in a goal-oriented manner considering specific perception-related mechanism adequately.

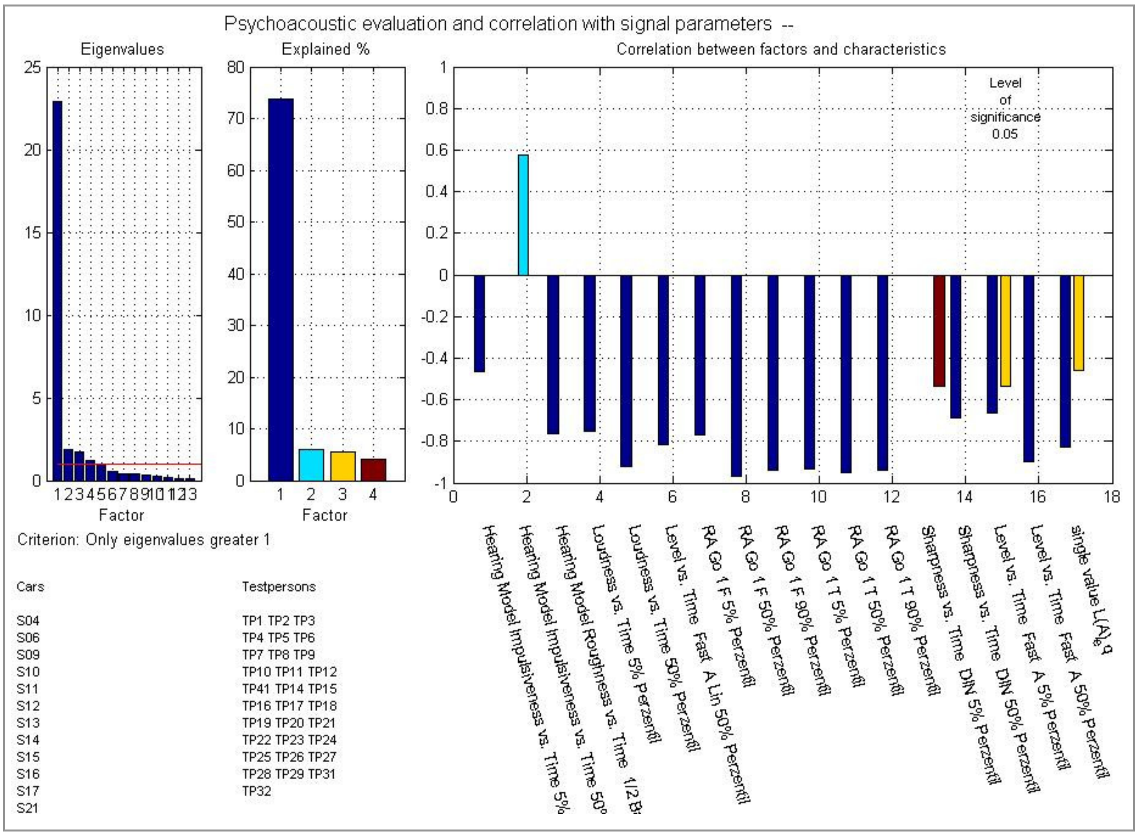

Figure 58: Correlation diagram of sound subset with four relevant factors

The comparison of two traffic sounds with different sound characters should underline the need for further acoustical parameters and indicators besides the L_{Aeq}. The sound stimulus S16 with 65.6 dB(A) (left) and 65.9 dB(A) (right) and S20 with 64.2 dB(A) (left) and 65.9 dB(A) (right) show comparable L_{Aeq}-values. However, the averaged subjective evaluations of these noise stimuli vary considerably. Stimulus S16 was evaluated with a "7.0", whereas the noise S20 gets an average evaluation of "4.7". This is due to other sound properties than the time-averaged sound pressure level. Figure 59 and 60 display the difference with respect to certain acoustical parameters, which are responsible for the different perception resulting in different annoyance judgments. Moreover, the sharpness and roughness values of the stimulus 16, which gets a high annoyance rating, are also higher compared to signal S20.

These differences can help to retrace the different judgments of the traffic noises, although both sounds have the same L_{Aeq}.

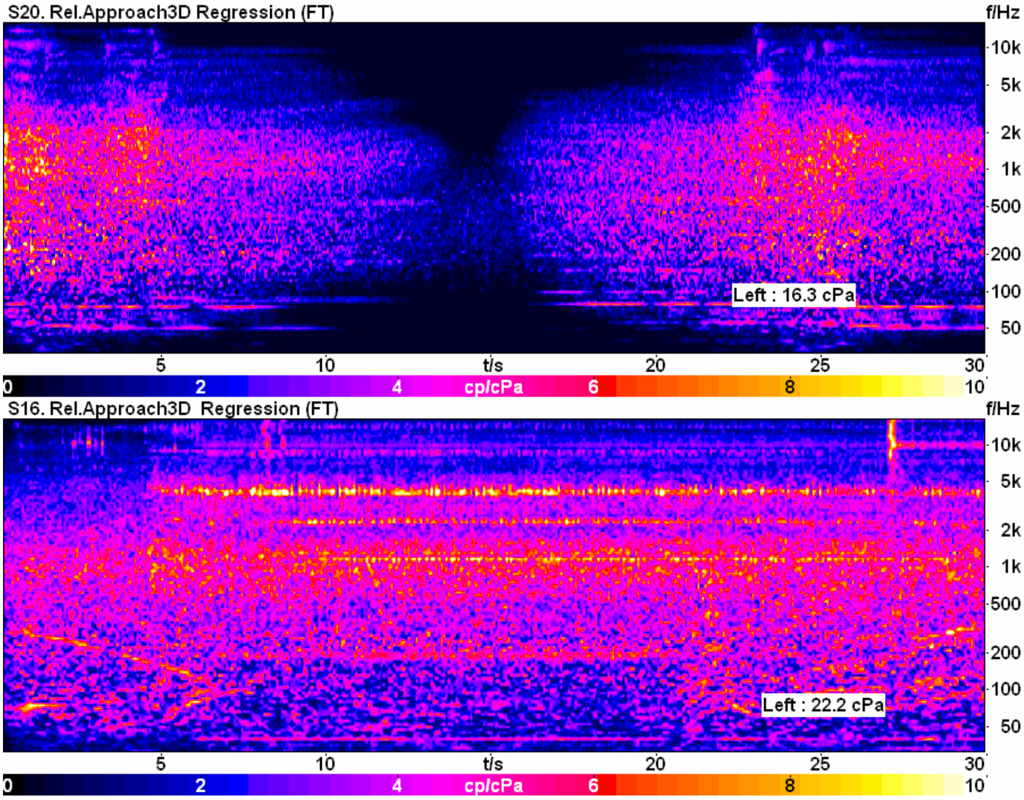

Figure 59: Relative Approach: Analysis of two traffic noises with Relative Approach (TF)(only left channel)

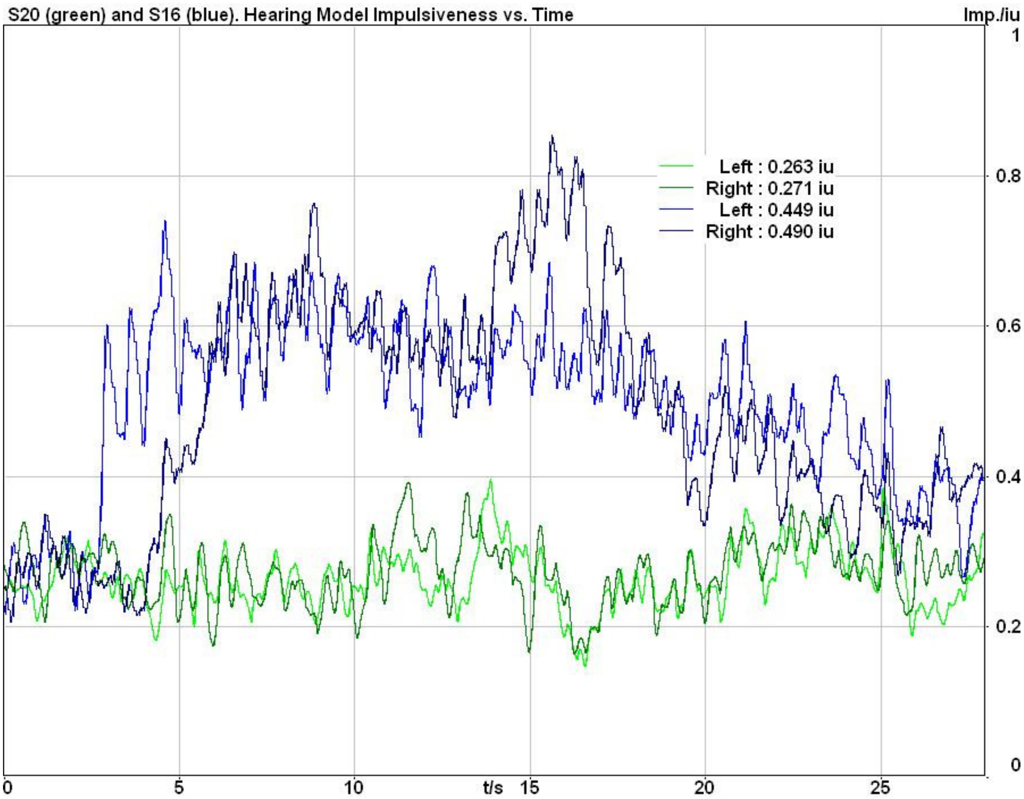

Figure 60: Hearing model impulsiveness: Analysis of two traffic noises with hearing model impulsivenes (left and right channel)

2.5.2 Creation of the Evaluation Index

A first step was to test known annoyance metrics developed in previous studies. For example, Zwicker calculated the "unbiased annoyance"[11] with loudness, sharpness and fluctuation strength. Moreover, Terhardt developed a model for the determination of "Wohlklang"[12] (pleasantness of noise) using loudness, sharpness, roughness and tonality. These metrics show correspondence with the subjective ratings; however, the correlation coefficient was in the range of only "0.7" to "0.8". However, these metrics give valuable information concerning potentially relevant psychoacoustical parameters for noise perception.

Furthermore, the evaluation index, which was developed in D2.8, was also tested with the new data base. The correlation between the different averaged subjective assessments and the calculated values based on the single pass-by Evaluation Index is about "0.7".

Using an adapted version of the previously developed Evaluation Index, where the input parameters are identical (Relative Approach, Loudness, Sharpness) and the weighting factors are adapted to the used stimuli set, the EI works well. By means of that measure the correlation coefficients concerning the link between subjective evaluations and calculated index values increase to "0.9"

However, further parameters turn out to be important regarding noise reaction to traffic noise. Here, using the comments given in the interviews the following parameters were identified as meaningful. The psychoacoustic parameter roughness and the acoustic parameter impulsiveness have to complement the metric.

Using the metric in the test series 1 a correlation coefficient of "0.969" was achieved. Considering only test series 2 an adapted version of the metric yields a correlation of "0.966" (fig. 61 and 63). The standard deviations are "1.15" and "1.48" with maximum deviations from the expected values of "0.58" and "0.74".

In contrast, the correlation between the L_{Aeq} – as the main acoustic descriptor in the context of environmental noise assessment – and the subjective evaluations is lower. By means of the L_{Aeq} values, there is still a good prediction with respect to the given subjective responses to the tested traffic noises. However, there are a lot more predicted values on the basis of the L_{Aeq} , which are outside of the ± 0.5 category hose (fig. 62 and 64). Here, the prediction using the developed evaluation index is considerably better than the L_{Aeq}. Only 15% of the calculated EI-values are out of the ± 0.5 category hose, whereas the A-weighed equivalent sound pressure level predicts over 30% values out of tolerance range. The different values are depicted in table 7. There, it can also be seen that the L_{A50} is better than the L_{Aeq} with respect to correlation, maximum deviation of expected and predicted value and concerning the out of

[11] E. Zwicker, A proposal for defining and calculating the unbiased annoyance, In: Schick, A. et al. (ed.), Contributions to Psychological Acoustics, BIS Verlag, 1991.

[12] E. Terhardt, G. Stoll: Skalierung des Wohlklangs (der sensorischen Konsonanz) von 17 Umweltschallen und Untersuchung der beteiligten Hörparameter. Acustica 48, page 247-253, 1981.

range values. However, in all cases the developed metric gives the best results with respect to the prediction of the subjective evaluations.

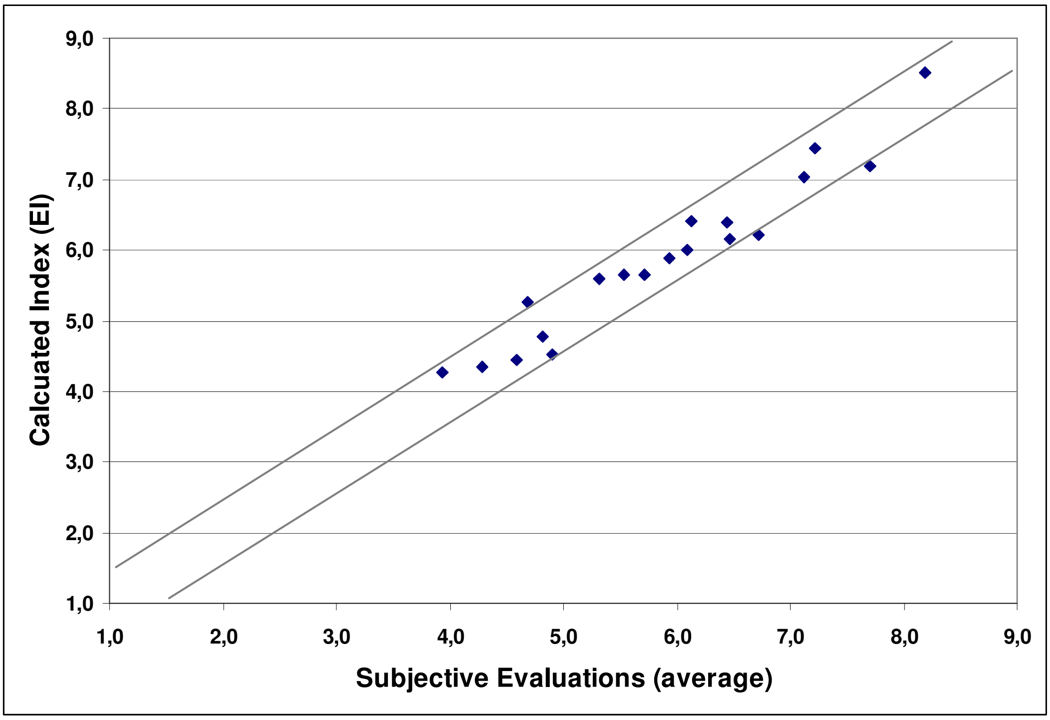

Figure 61: Mapping of the EI-values to the subjective evaluation values of test series 1, diagonals indicating a ± 0.5 category hose

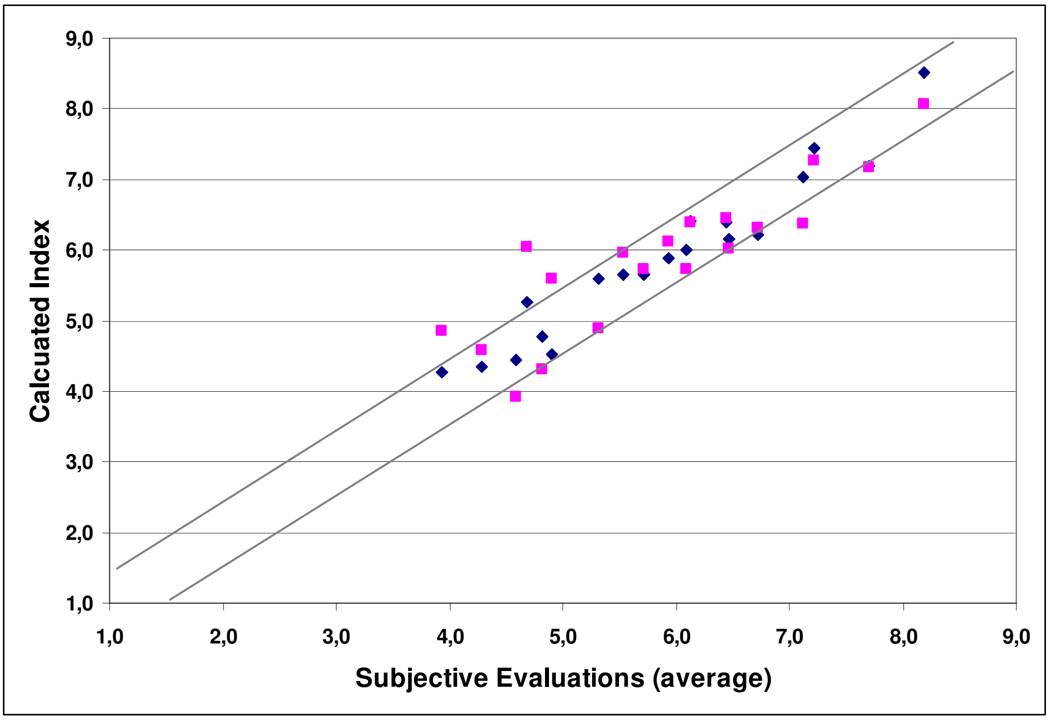

Figure 62: Mapping of the EI-values to the evaluation values of test series 1, diagonals indicating a ± 0.5 category hose; Calculated Index EI (blue) and Calcuated Index L_{Aeq} (pink)

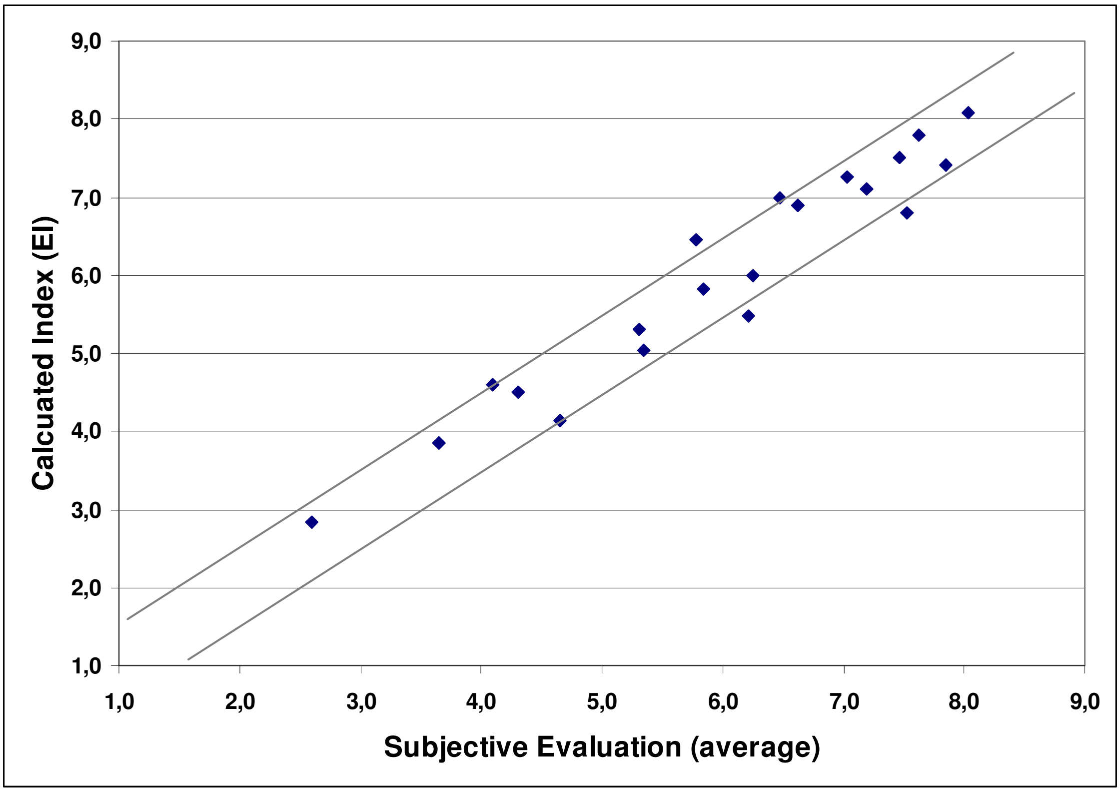

Figure 63: Mapping of the EI-values to the evaluation values of test series 2, diagonals indicating a ± 0.5 category hose

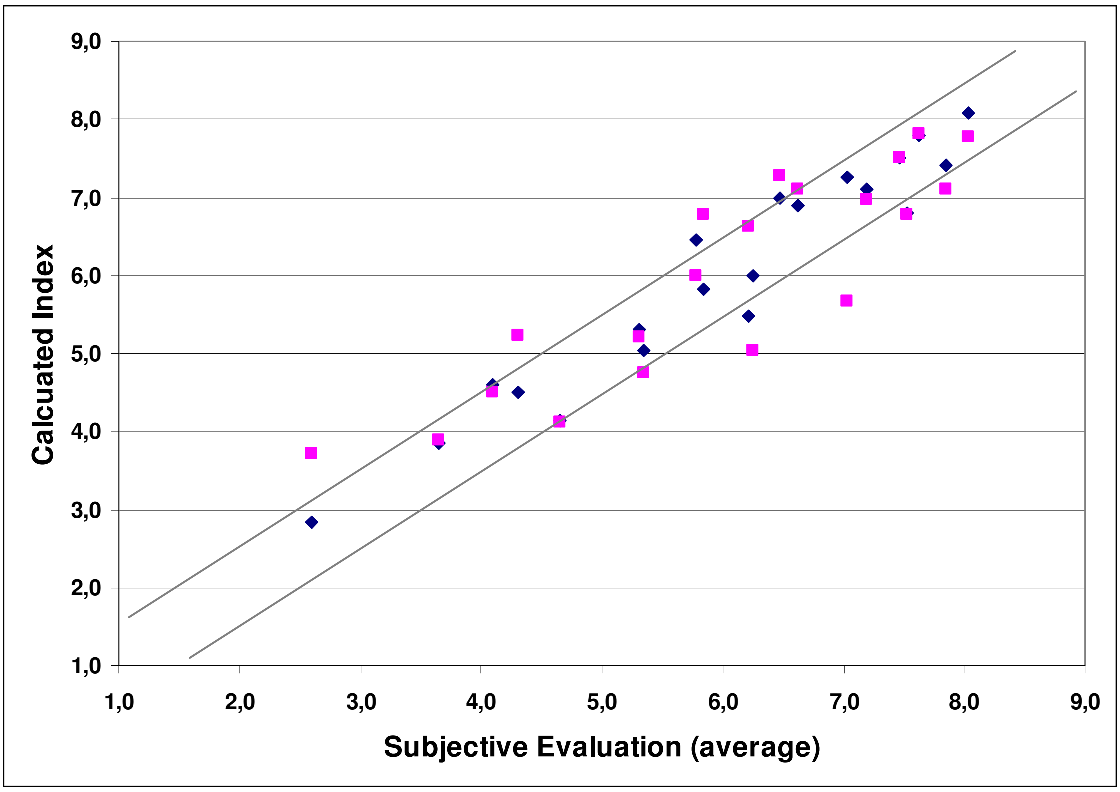

Figure 64: Mapping of the EI-values to the evaluation values of test series 2, diagonals indicating a ± 0.5 category hose; Calculated Index EI (blue) and Calcuated Index L_{Aeq} (pink)

Table 7: Comparison of important descriptive parameters between subjective evaluations and the adapted EI, L_{Aeq}, L_{A50},

Test Series 1/ Calculated Index	Correlation Coefficient (Pearson)	Standard Deviation	Maximum Deviation	I Deviation I > ± 0.5
Adapted Evaluation Index	0.969	1.15	0.58	15.8%
L_{Aeq}	0.879	1.10	1.39	31.5%
L_{A50}	0.938	1.14	0.86	15.8%
Test Series 2				
Adapted Evaluation Index	0.966	1.48	0.74	30%
L_{Aeq}	0.885	1.42	1.36	50%
L_{A50}	0.923	1.45	1.21	35%

Of course, the results of the different test series have to be combined to achieve an Evaluation Index valid for all considered traffic sounds.

By means of multiple regression analyses leading to a refinement of the weighting factors of the relevant acoustical parameters, namely Relative Approach (RA_{50}(FT)), Loudness (N5), Sharpness, Hearing Model Roughness, Hearing Model Impulsiveness, the final Evaluation Index predicting the subjective responses to complex traffic noises is developed.

This equation weights the parameter of Relative Approach and Loudness at a ratio of 4 to 1. The weighting of the two parameters is optimised for maximum correlation with the evaluations of the test subjects. These correlations reach very good values for all tested sound sets. The parameters sharpness (average), Hearing Model Roughness (average) and Hearing Model Impulsiveness (average) have also an influence on the metric.

$$EI_{traffic} \sim RA_{50}\,(FT) + N_5 + S + HMR + HMI$$

The correlation coefficient between the averaged subjective assessments of all traffic noise stimuli and the calculated index values based on the new metric is "0.927". It has to be mentioned that several listening tests are considered and that, of course, the overall connection between the predicted and expected values is a little bit lower than the values of table 7 because of the more heterogeneous data material. For example, different sound stimuli were used in the training sequence of the different listening series. These sounds set a kind of perceptive anchor, which can lead to slightly shifted evaluation ranges from one listening test to another.

However, the results based on the developed evaluation metric (EI) are very promising. Figure 65 depicts the calculated evaluation values over the averaged subjective evaluations. One dot represents the averaged assessment of at least 30 test subjects.

The standard deviation is "1.29". No values differ more than one category from the actual subjective evaluation values with a maximum deviation of only "0.89".

Since the currently used acoustic descriptor for the evaluation of environmental noise is the L_{Aeq} a comparison between the L_{Aeq} and the developed EI is carried out. The L_{Aeq} performs poorer than the EI. The overall correlation is "0.87" the standard deviation "1.27". More than 15% of the values show a difference greater than one category from the actual evaluations. The L_{A50} shows a slightly better correlation with the subjective evaluations than the L_{Aeq}, which is caused by the importance of the time structure obviously better represented by the L_{A50} - at least in the applied laboratory setting. Here, the overall correlation is even "0.89".

In particular, the new Evaluation Index shows more prediction accuracy than for example the L_{Aeq}. For comparability reasons the L_{Aeq}-values are transferred to 9 values with the help of linear regression.

Table 8: Comparison of important descriptive parameters between subjective evaluations and L_{Aeq} and the adapted EI

Test Series 1/ Calculated Index	Correlation Coefficient (Pearson)	Standard Deviation	Maximum Deviation	I Deviation I > ± 0.5	I Deviation I > ± 1.0
Adapted Evaluation Index	0.927	1.29	0.9	30.0%	0.0%
L_{Aeq}	0.875	1.27	1.2	48.7%	15.4%

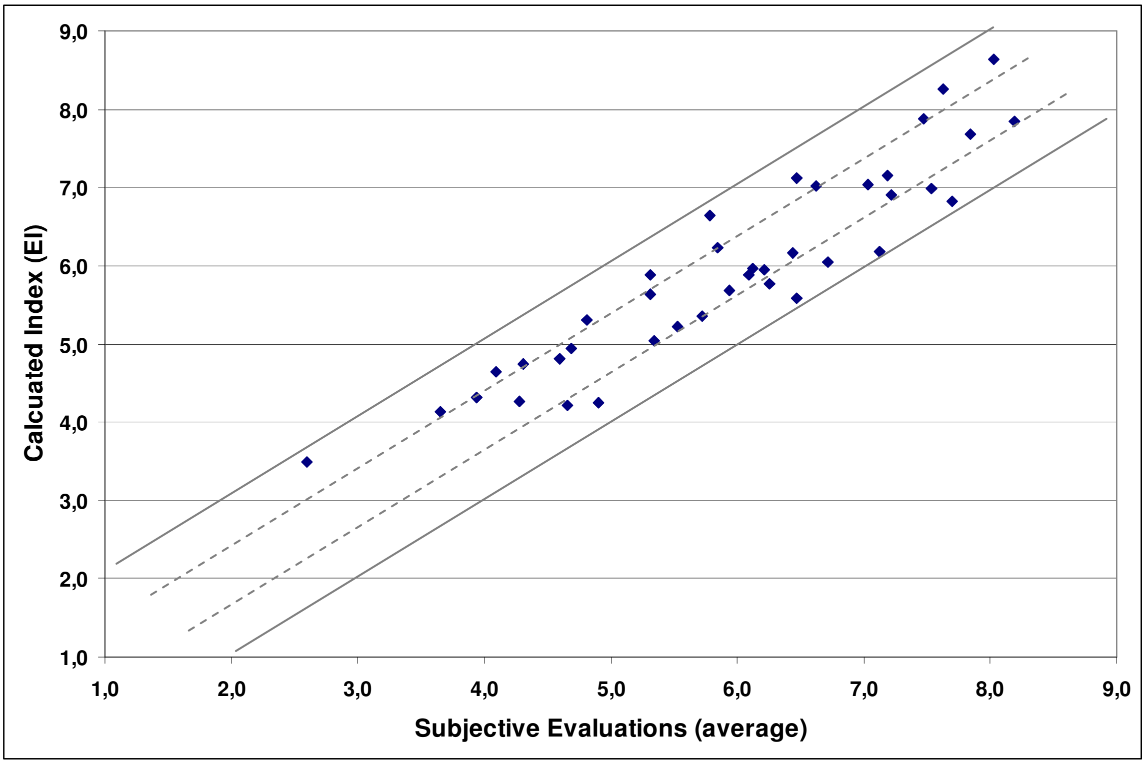

Figure 65: Mapping of the EI-values to all evaluation values, diagonals indicating a ± 0.5 category hose (dots) and a ± 1.0 category hose (solid)

2.5.3 Adaption of the EI to common 10-point scale

The last step is the adaptation of the EI to a common 10-point scale (applied e.g. in the VDI 2563). This procedure follows the principles from D2.8. The specific demands to this scale are:

- 10 point scale from 1 (very annoying) to 10 (not at all annoying)
- no values below 1 or above 10 are necessary

The reasoning for the last point is that if an extremely annoying sound is considered the evaluation of the noise is "unbearable" ("very annoying"). An increase of "unbearable" ("very annoying") makes no sense, it remains "unbearable". The same applies for not annoying sounds that are made quieter. So, the last point ensures that the evaluation index analysis of noise with extreme parameter values (e.g. very loud or very quiet sounds) does not produce values outside the specified range. This risk is given by applying a simple linear relation. It must be mentioned that in the listening tests no non-annoying sounds were used. The sound stimulus with the lowest rating provokes an averaged subjective evaluation of "2.6". This means that more pleasant traffic sounds can result in a lower EI-index.

For the construction of this scale an adaptation function based on an exponential function with a cubic argument is applied upon the current EI formula. Figure 66 depicts the course of the transformation function between the two scales. The actual evaluation values between 1 and 9 are mapped to the linear range of this function.

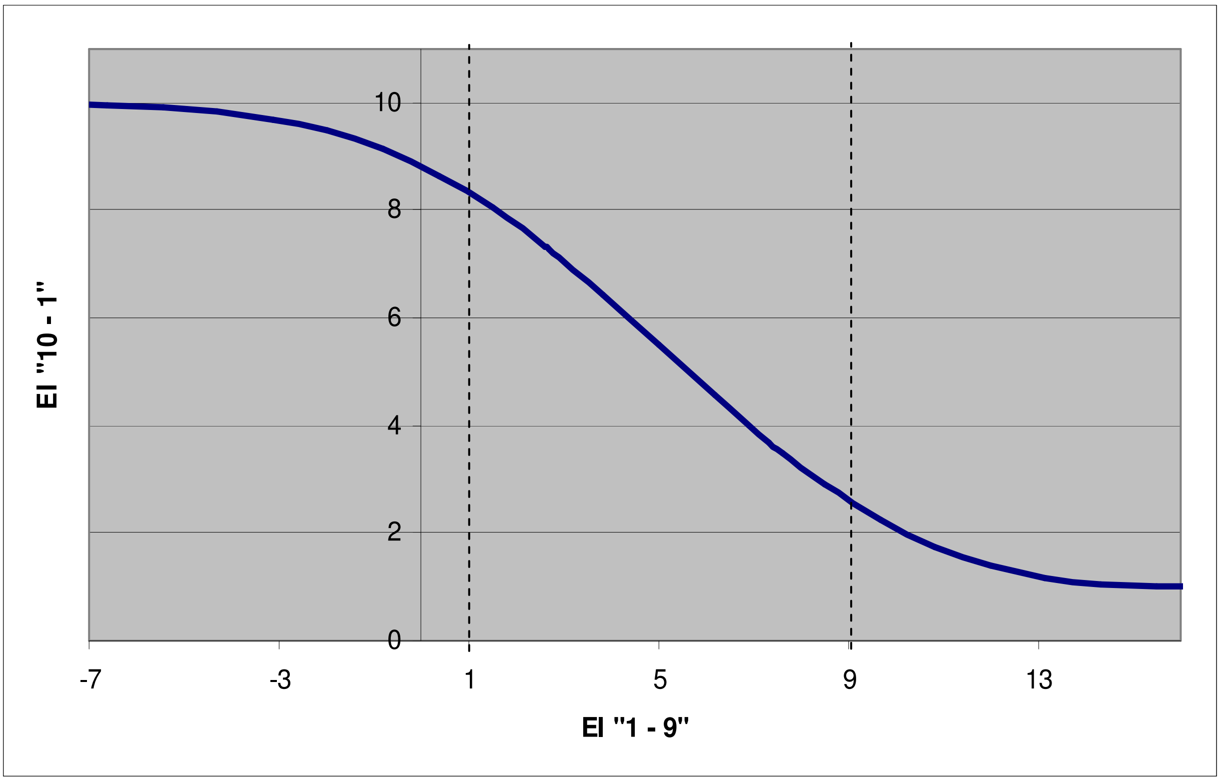

Figure 66: Transformation of the EI scale from "1 – 9" evaluations to "10 – 1" scale

Very annoying sounds that would create EI-values around "9" cannot produce values lower than "1" on the new scale, and the values of very quiet sounds go asymptotically against "10". The transformation has a negligible effect on the quality of the correlation.

The final equation for the Evaluation Index on a 10 to 1 scale is:

$$\boxed{EI_{scaled} = -\left(9 \cdot 2^{\left((0.125 * EI - 1.625)^{3}\right)} + 1\right) + 11}$$

with

$$EI \quad = \quad 1 \quad \text{when} \quad 0.125 * EI - 1.625 \quad > \quad 0.$$

The reasoning for the last boundary condition is to define a threshold. Values above the threshold make no sense, because the value 1 represents already "very annoying".

This equation is implemented into the Traffic Noise Synthesizer, which is available to the partners. It is suitable for real traffic sounds.

It has to be mentioned that the Evaluation Index predicts subjective responses to traffic noise concerning "outdoor noise perception". The metric with respect to the determination of annoyance levels of certain environmental noises cannot be transferred to indoor noise perception and evaluation. If persons are exposed to environmental noise inside a building, they are presumably much more sensitive to noise especially in context of certain activities such as sleeping, relaxing, etc.

2.5.4 General Trends

On the basis of the presented data recommendations for the reduction of noise annoyance can be derived.

In the first listening test series traffic scenarios with vehicles driving with constant speed were considered. It was found that – as expected – with increasing traffic volume the noise annoyance generally increases (fig. 67).

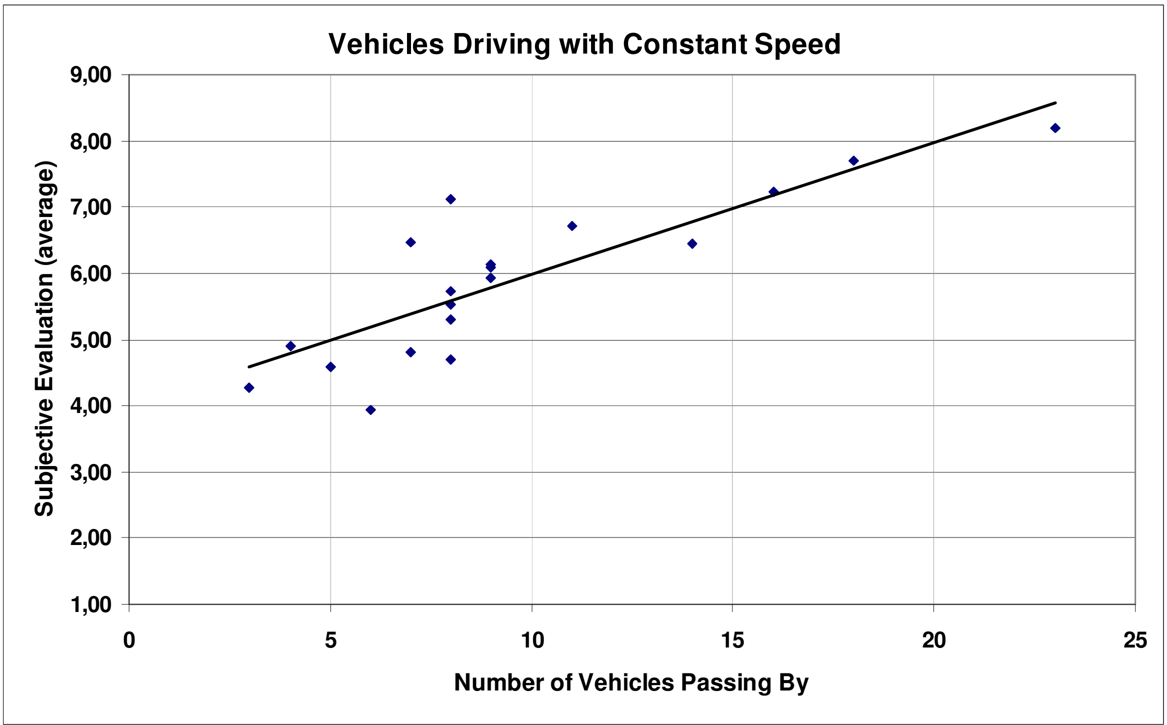

Figure 67: Number of vehicles (driving with constant speed) over subjective evaluations (average)

However, in some cases the evaluations vary although the number of vehicles is constant and of course the L_{Aeq} is almost identical. The reason is that specific sound properties lead to an increase of the annoyance level regardless of the A-weighted time-averaged sound pressure level. This is shown in figure 68, where sounds with comparable traffic volume are investigated more in detail. The differences in the noise evaluations cannot be related to the L_{Aeq}, but rather to the pattern detection algorithm Relative Approach, which quantifies time and spectral patterns. Furthermore, the C-weighted sound pressure level seems to explain the evaluation differences better than the L_{Aeq}. This suggests that low frequency content negatively influences the subjective responses to traffic noise. This example makes clear that in several cases the consideration of the L_{Aeq} is not sufficient.

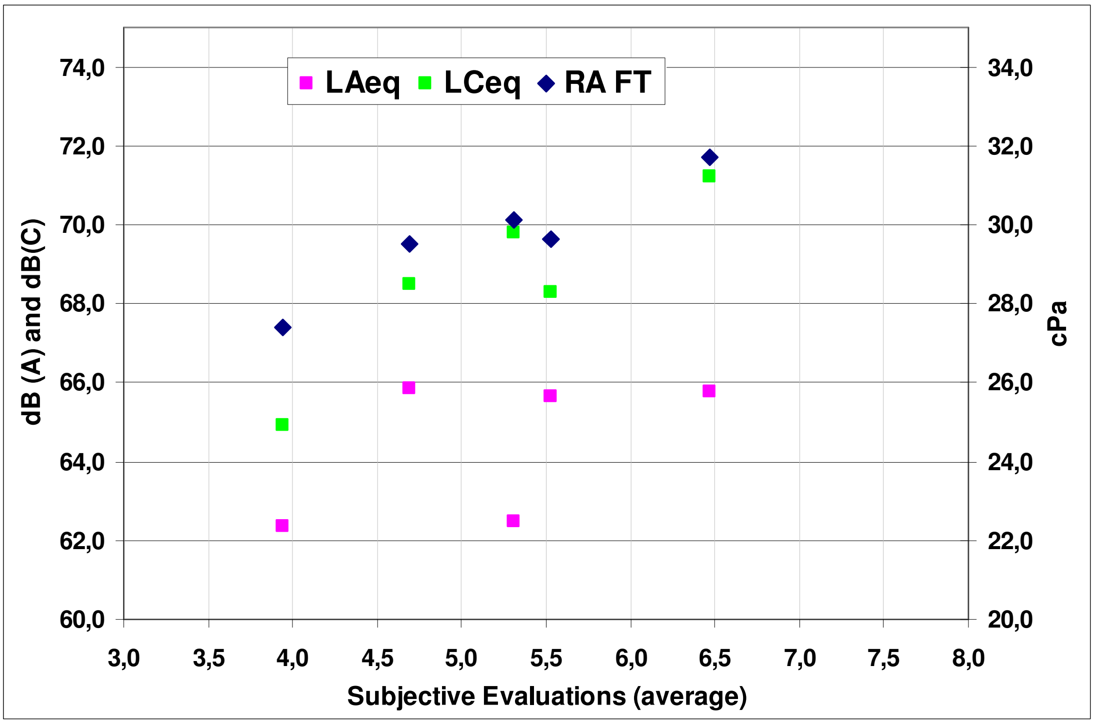

Figure 68: Comparison of evaluated stimuli with constant number of passing by cars related to L_{Aeq}, L_{Ceq}, RA (FT)

Another aspect concerns the occurrence of silent periods. Few traffic noise scenarios contain periods of relative quietness for a period of several seconds. These passages have a positive effect in the used laboratory setting on the subjective evaluation, which the L_{Aeq} does not reflect sufficiently. Here, it seems that the aspect is better covered with the L_{A50}, because this parameter obviously considers the human cognitive integration mechanism in a better way. It has to be mentioned that it appears that several short periods of silence have not the same compensational effect than one longer period of quietness, even the total time of quietness is comparable. However, this effect is not clear yet and has to be investigated further.

Figure 69 and 70 demonstrate the insufficient prediction of subjective annoyance reactions to traffic noise on the basis of L_{Aeq}. If the L_{Aeq} would perfectly match the subjective evaluation of annoyance, than all dots should directly lie on the regression line. However, in a few cases, it can clearly be seen that a bonus or malus must compensate different perception-related phenomena. Obviously, in few cases the L_{Aeq} cannot reflect specific perception effects. Here, as described above psychoacoustics helps to identify the more annoying or less annoying sound properties, which are not covered with the sound pressure level.

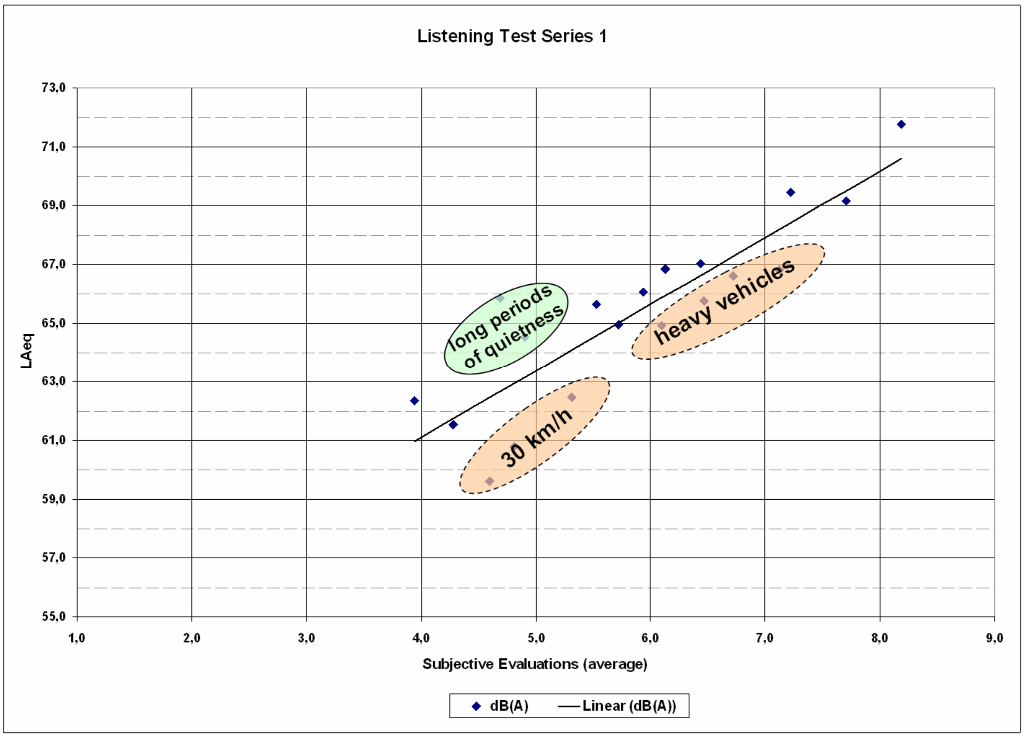

Figure 69: Mapping of the L_{Aeq} values to the evaluation values of test series 1

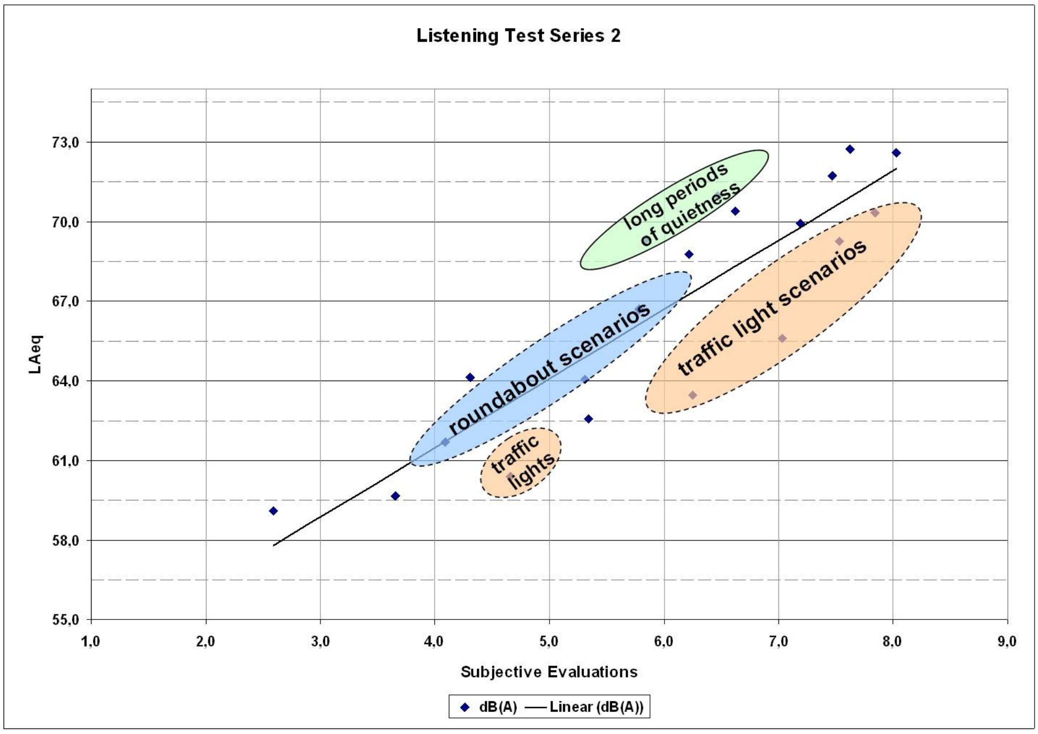

Figure 70: Mapping of the L_{Aeq} values to the evaluation values of test series 2

By means of the following plots few general trends beyond detailed considerations of acoustical parameters can be shown. Due to the PCA calculations the factor 1- values reflects the averaged subjective evaluations. Thus, taking into account that factor 1-values correlate highly with the averaged subjective evaluations, much better than with any acoustical parameter, it can be concluded that certain traffic noise scenarios have in general a positive or negative impact on the judgments.

In figure 71 "semantic clusters" show perceptively connected noises in the perceptive space. The x-axis (factor 1) represents the level of annoyance; from high to low values the annoyance increases (right to left). It can be clearly seen that "traffic lights scenarios" (vehicles decelerate, stop, idle and accelerate) are more annoying than "roundabouts situations", where partly a regular traffic flow is observable. Of course, scenarios with a low traffic volume are at the positive end of the factor 1 scale.

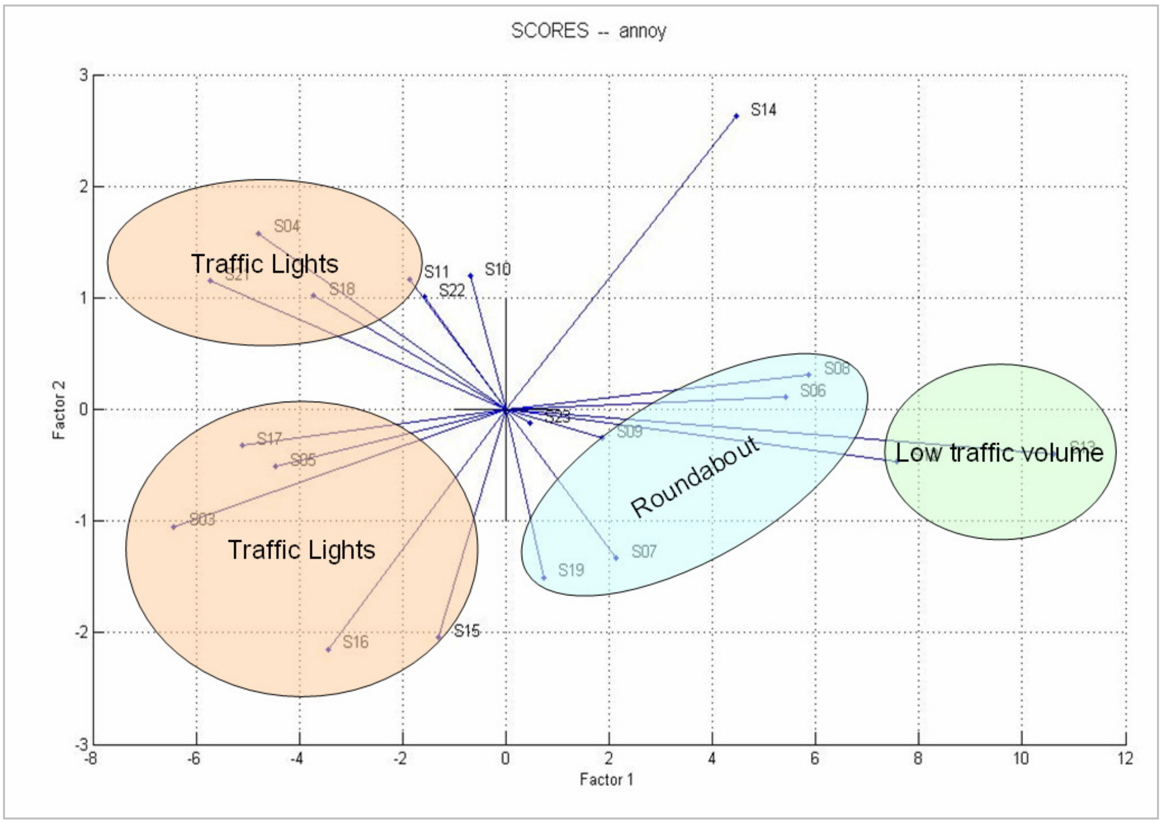

Figure 71: Distribution diagram of a sound subset related to factor 1 and 2

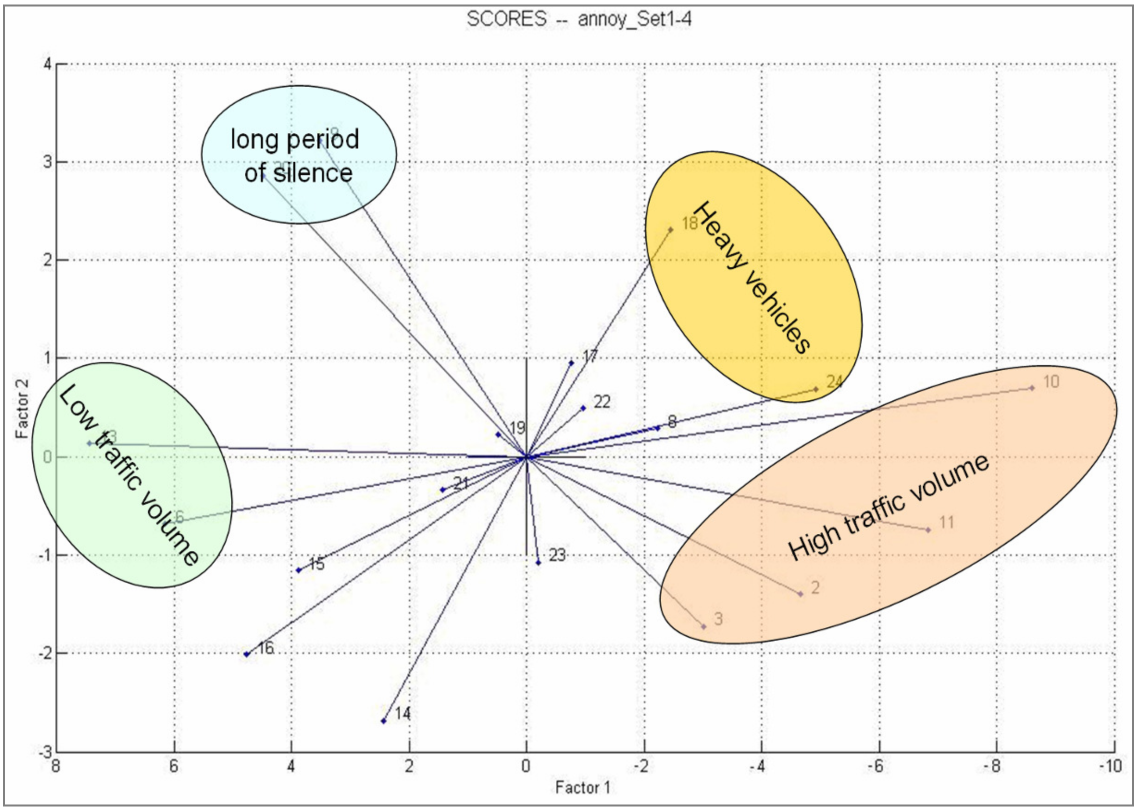

Figure 72: Distribution diagram of a sound subset related to factor 1 and 2

Furthermore, figure 72 shows the distribution of the traffic noise stimuli over the first two factors for a further listening test series. In this diagram general trends can be observed as well. Again, from high to low values (left to right) the annoyance increases. Of course, a high traffic volume leads to high annoyance. However, in case of a traffic composition with for example heavy vehicles high annoyance ratings also result. This cannot sufficiently explained on the basis of the acoustical descriptor L_{Aeq}, it is due to specific sound properties in the pass-by noise.

In contrast to it, the occurrence of longer periods of silence considerably decreases the annoyance judgments. In these cases the L_{Aeq}-values does not represent this psychological effect very well. This psychological effect was explicitly reported by the interviewed test subjects.

It was also discovered that traffic noise, where vehicles drive with a constant speed of 30km/h, is better evaluated than traffic noises, where vehicles drive with 50km/h. However, the decrease of the annoyance was lower than could have been expected from the decrease of L_{Aeq}. Here, a penalty of 1 to 3 dB could be justified.

Of course, the different phenomena, which were observed in laboratory tests under stable boundary conditions for guaranteeing reproducibility, must be confirmed in reality, where lots of unstable conditions are typically present. Reactions and responses to traffic noise in reality can slightly vary to the laboratory results presented here.

2.5.5 Bonus / Malus

On the basis of the different listening tests the need of dB(A)-equivalents for the increased or decreased annoyance caused by certain traffic-related noise aspects was studied. The analysis of these listening tests with respect to the derivation of a dB(A)-related bonus and malus turns out to be difficult.

However, few phenomena were observed, where the introduction of penalties is recommended.

It turns out in the interviews that "ear-catching", prominent noise sources (e.g. occurrence of heavy vehicles and/or motorbikes) provoke strong emotional reactions to noise leading to increased annoyance. Here, a penalty up to 3dB appears meaningful, because the increased sound pressure level does not completely cover this phenomenon. The cause for the increased annoyance results from several psychoacoustic aspects in the sound signals, such as tonal components, impulsive noise, short-time patterns, which were considered in the developed evaluation metric.

Furthermore, it seems reasonable to carry penalties for traffic lights as already defined in few regulations; the penalty can range up to 3dB in dependence of traffic volume and distance of "receiver to road". In contrast to it, roundabout traffic situations perform better with respect to the subjective evaluation even in case of comparable L_{Aeq}-values. Nevertheless, the detailed analysis of the roundabout traffic situations shows that no bonus should be given.

Another sensational phenomenon, which was observed in the conducted tests, concerns the response to long periods of silence in the evaluated traffic noise stimuli. Few noise stimuli contain sequences of silence, where rarely traffic noise was audible. It appears that this influences the judgments in a positive way. Here, the introduction of a bonus is possible, but that requires further tests.

Furthermore, as expected it was observed in the tests that traffic noise, where vehicles drive with a constant speed of 30km/h, are better evaluated than traffic noises, where vehicles drive with 50km/h. However, the decrease of the annoyance was lower than the reduced L_{Aeq} indicates. Here, a penalty of 1 to 3 dB could be justified.

It is reasonable to perform further investigations concerning potential bonus/malus before suggesting general penalties in legislation.

2.5.6 Use of the Traffic Noise Synthesizer for Noise Evaluation

On the basis of the developed TNS tool specific traffic scenarios can be auralised and evaluated. In this context, the developed metric EI gives indications with respect to the expected noise annoyance. The efficiency of specific measures and actions, which are intended to reduce noise annoyance, can be evaluated before taken.

After finishing the work on the TNS, sounds of typical traffic scenarios have been generated by means of the developed TNS and successfully used to validate the metric. For it, several traffic noise signals were generated by means of the traffic noise synthesizer. The input for the TNS was traffic simulation data. The simulated traffic scenarios differ in traffic density, driving behaviour of drivers (moderate, more aggressive) and in the street geometry (e.g. single street, roundabout, intersection). The diverse traffic simulations were performed by KTH.

The scenarios and respective sounds were auralized, evaluated with the Evaluation Index and the different results considering their explanatory power, plausibility and validity judged by experts.

All in all, considerable sensational differences were audible, which result in different judgments of the investigated traffic noises. These judgments were collected on the basis of expert listening tests and compared with the calculated values on the basis of the Evaluation Index. The calculated Evaluation Index values of the generated traffic noise stimuli and some further acoustical parameters are shown in table 9.

Table 9: Simulated traffic scenarios which were auralized with the TNS; calculation of L_{Aeq} and evaluation index (EI_{scaled})

	Short description	$L_{Aeq\ /\ Left}$ dB(A)	$L_{Aeq\ /\ Right}$ dB(A)	EI_{scaled}
1	Street, 50km/h, low traffic volume, aggressive driving behavior, Standard road surface	67.3	66.3	4.5
2	Street, 50km/h, high traffic volume, moderate driving behavior Standard road surface	66.7	66.6	5.2
3	Street, 50km/h, high traffic volume, aggressive driving behavior Standard road surface	70.0	69.6	3.5
4	Street, 50km/h, low traffic volume, moderate driving behavior Standard road surface	64.9	64.0	5.5
5	Street, 50km/h, low traffic volume, Standard road surface	68.5	68.4	4.25
6	Street, 50km/h, low traffic volume, "OPA" road surface	65.3	65.2	5.16
7	Street, 50km/h, low traffic volume, single wall (5m) Standard road surface	57.2	57.2	7.11
8	Street, 50km/h, low traffic volume, double wall (5m) Standard road surface	48.6	48.6	8.33

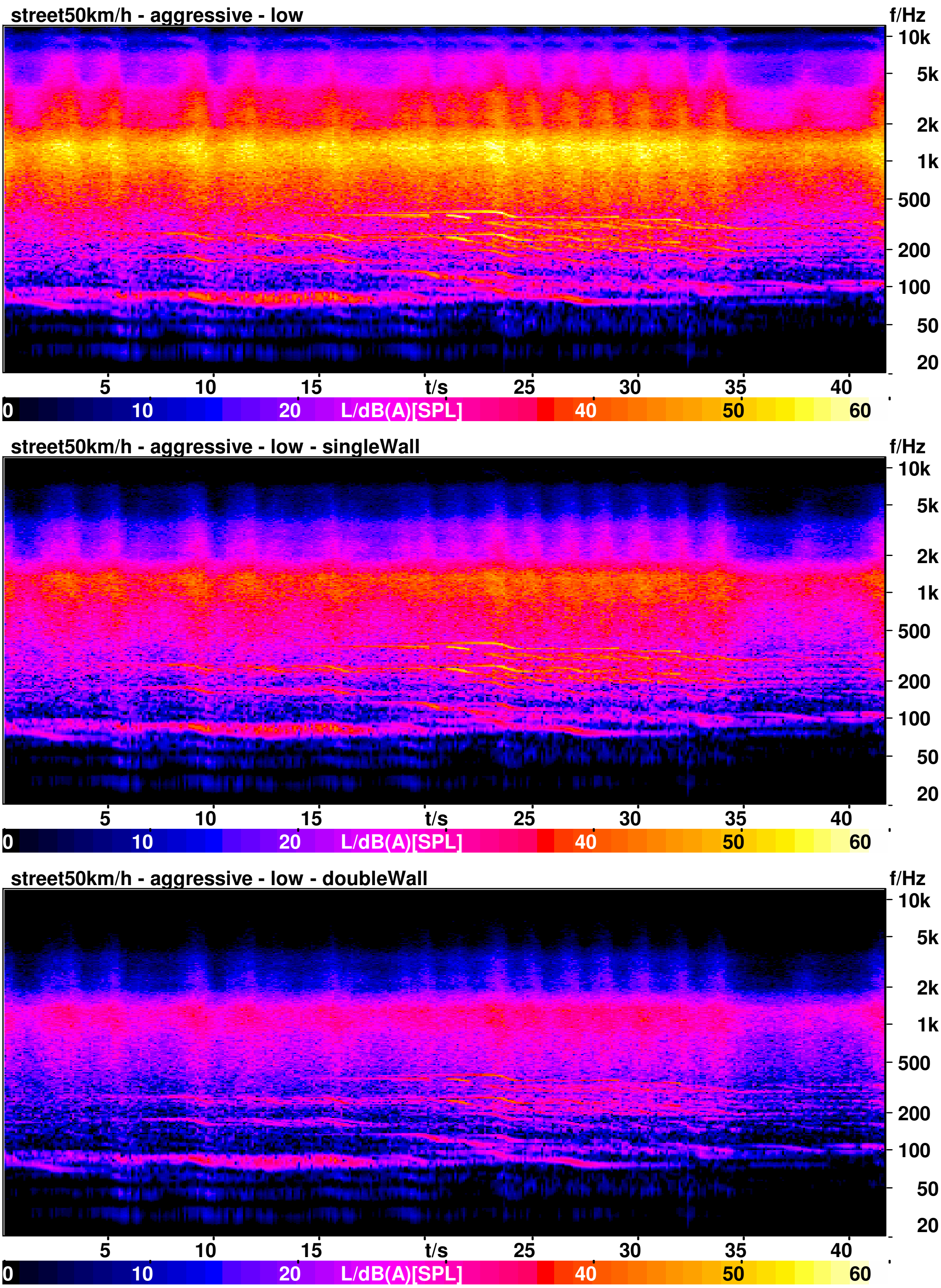

Figure 73: Auralised traffic scenarios: Noise of single street with low traffic volume (top) compared to noise of same street with virtual implementation of noise mitigation measures (single wall – middle, double wall – bottom)

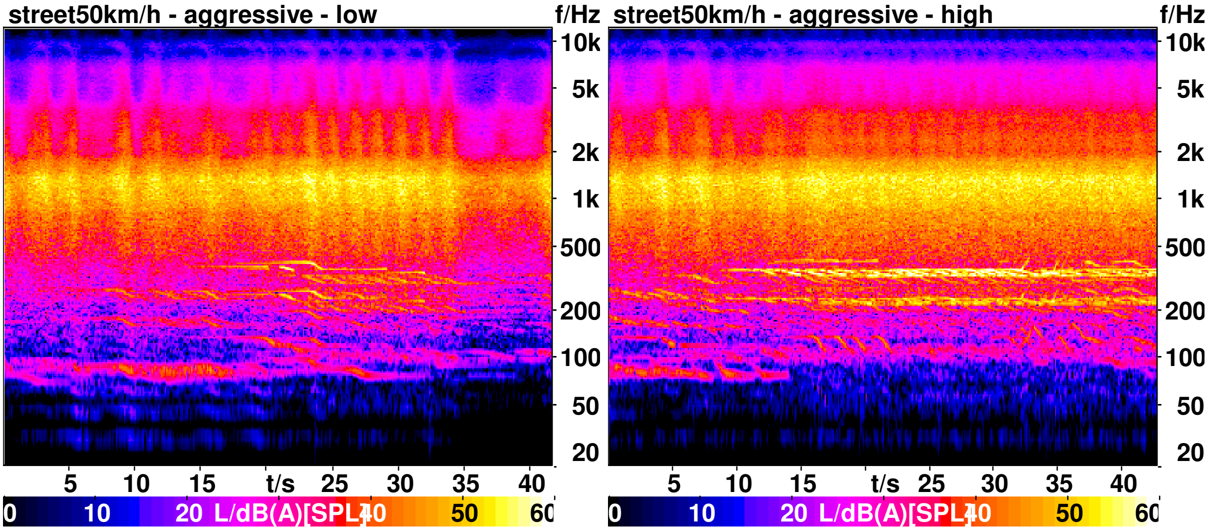

Figure 74: Auralised traffic scenarios: Noise of single street with low traffic volume (left) compared to Noise of single street with high traffic volume (right)

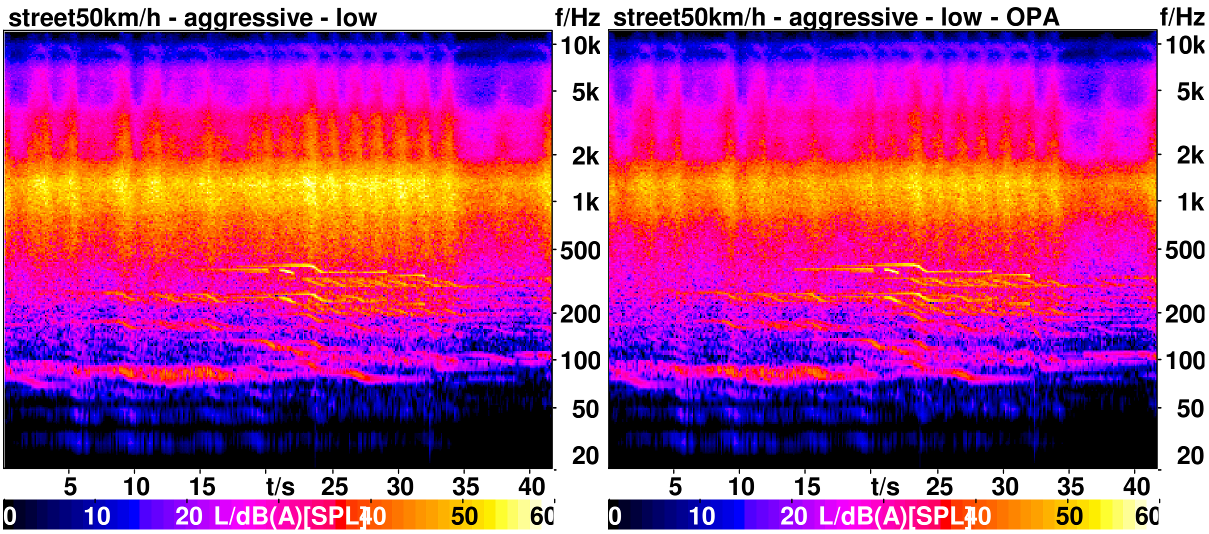

Figure 75: Auralised traffic scenarios: Noise of single street with low traffic volume (left) compared to same street with low noise pavement (right)

On the one hand, the different observed cases show the gained flexibility concerning the generation of (virtual) traffic scenarios and their resulting noise using the TNS. Furthermore, it demonstrates the possibilities with respect to the identification of most efficient noise mitigation measures and actions, which can be virtually experienced. This efficiency can be assessed not only on the basis of a dB(A)-reduction, but also on the basis of listening (personal experience) and the reduction of the Evaluation index, which considers further hearing-related parameter besides the L_{Aeq}. This means that decisions for or against specific noise mitigation measures can be well grounded.

Furthermore, the examples show the benefit of the Evaluation Index, which gives quick indications with respect to the expected subjective response to the different traffic noises. In particular, in the cases with comparable A-weighted sound pressure levels the Evaluation Index shows a much better differentiation than the L_{Aeq}. Therefore, it provides further information, which can be used for urban planning and the detection of promising actions against noise annoyance.

In Conclusion: The combination of traffic noise synthesizer TNS and Evaluation Index EI can substitute costly measurements and extensive listening tests and allows for the listening to environmental noise of certain traffic scenarios including the consideration of noise protection measures, which are not implemented in reality so far. Thus, it could be a helpful planning tool, which enables urban planners to consider the aspect of noise annoyance right from the beginning.

3 CONCLUSION

Different sound stimuli based on recordings of real traffic noise and synthesized sounds were analysed regarding their perception and psychoacoustic characteristics.

The aim was to find a quantitative description for their subjective annoyance effect and a dB(A)-equivalent for the different annoyance effect. The Evaluation Index initially developed for the assessment of single pass-by noise in D2.8 should be tested for complex traffic noises with lots of superposing single pass-by noises.

On the one hand, extensive listening tests were carried out for psychoacoustic evaluation. Thereby, traffic noise was evaluated by test subjects regarding its annoyance. Furthermore, the test subjects were interviewed by the experimental leader to explore the causes and reasons for their judgments. On the other hand, diverse (psycho-)acoustic parameters were calculated for the traffic sounds. The selection of the psychoacoustic parameters was carried out with respect to psychoacoustic measures commonly applied when analysing the perception of vehicle noise. Furthermore, the different comments given by the interviewed test subjects were used to select psychoacoustic parameters, which could be of importance for perception and evaluation of traffic noise. All in all, more than 50 acoustical parameters were considered.

To systematically analyze the data, besides descriptive statistics a principal component analysis (PCA) was applied to the subjective ratings achieved in listening tests. Hereby, similarities between the single evaluations of the test subjects could be discovered and common factors influencing the evaluations were determined. By means of comparisons and correlation analyses of the detected factors with the calculated psychoacoustic parameters it was possible to identify parameters that represent the evaluation factors.

The most important factor was highly correlated with the Relative Approach analysis (RA_{50} (FT)), which detects and quantifies audible temporal and spectral patterns in a signal. There, the RA simulates the adaptivity of the human hearing. The human hearing is very sensitive to patterns and irregularities in sounds. This hearing-related acoustical parameter considers a lot of sound aspects, which were frequently mentioned in the interviews. Sound aspects such as "characteristic diesel knocking", "unpleasant howling sounds", "rumbling of motorbikes", "obtrusive sounds caused by heavy vehicles" etc. are covered very well by this parameter. The second important parameter was the 5 % percentile of the loudness N_5, which covers the perceived overall loudness of time-variant noise. This relation is already described in the DIN 45631/A1 (2008).

In addition, the consideration of the psychoacoustic parameter Sharpness (average) meets the sensational effect of unpleasantness in case of sharp environmental noise. This link is already described in the DIN 45692 (2007).

Further relevant parameters were the Impulsiveness (HMI average) and Roughness (HMR average). The impulsiveness and roughness are calculated on the basis of a hearing model[13] developed by Sottek.

The gained equation for the evaluation index EI representing the evaluation ratings of the test subjects was fitted to a 1 (not at all annoying) to 10 (very annoying) scale:

The final equation for the Evaluation Index on a 10 to 1 scale is:

$$EI_{scaled} = -\left(9 \cdot 2^{\left((0.125 * EI - 1.625)^3\right)} + 1\right) + 11$$

with

$$EI = 1 \quad \text{when} \quad 0.125 * EI - 1.625 > 0.$$

Apart from the development of the Evaluation Index the conducted research allows for some recommendations with respect to potential penalties that could be applied in noise regulation. The detected penalties are required because in few noise situations it seems that the measured/calculated L_{Aeq} does not represent the subjective reaction to that kind of traffic noise sufficiently.

For example, noise near traffic lights provokes reactions to noise, which are slightly underestimated by the L_{Aeq} (malus up to 3dB). Roundabout traffic situations perform better concerning the subjective evaluation even in case of comparable L_{Aeq}.

A specific traffic composition causes also stronger reactions to noise than expected on the base of L_{Aeq} – values. This concerns noise sources like heavy vehicles, scooters, motorbikes, buses. Here, a malus up to 3dB is possible depending on the traffic composition. Furthermore, it was observed in the tests that traffic noise, where vehicles drive with a constant speed of 30km/h, are better evaluated than traffic noises, where vehicles drive with 50km/h. However, the decrease of the annoyance was lower than the reduced L_{Aeq} indicates. Here, a penalty of 1 to 3 dB could be justified. Further investigations concerning potential bonus/malus values should be carried out before suggesting general penalties in noise legislation.

[13] R. Sottek - Modelle zur Signalverarbeitung im menschlichen Gehör. Dissertation, RWTH Aachen, Germany, 1993.

By means of the developed traffic noise synthesiser TNS it is now possible to test elaborately diverse traffic scenarios considering different traffic management measures and different traffic compositions. As shown in some case studies the traffic noise synthesiser allows for the detailed examination of certain traffic scenarios and therefore can help to identify the most promising noise mitigation measures with respect to costs and annoyance decrease. This means that the perceptive efficiency of noise protection measures can be determined. Thus, it can be an efficient tool for town planning and urban development.

However, it must be mentioned that the findings and results of the listening tests carried out in WP 5.12 are valid for noise evaluations given in laboratory to certain traffic configurations. The developed psychoacoustic metric EI gives detailed indications concerning the expected annoyance level caused by certain traffic noises. In further investigations new approaches with respect to decreased artificiality of listening test situations should be developed and applied to determine for example indoor noise annoyance.

4 OUTLOOK

4.1 TNS

The variety of vehicle types is very limited in the current state of development. In the next steps analyses will be carried out to add more vehicle types such as diesel cars, vans, trucks, motorcycles.

Related to diesel and motorcycle sounds transient noise parts will be more important. To represent this within the simulation the analysis and the synthesizer must be extended to transient noise. This will be part of future research.

Using standard desktop PC (dual core, 2GHz) scenarios with 2 to 4 vehicles can be calculated in real time. In reality it is possible to hear up to 30 vehicles at the same time. It is intended to simulate at least this amount of vehicles in real-time.

4.2 Evaluation Index

The results of the listening tests and the derived Evaluation Index are very promising with respect to effective noise protection. This could be a big step forward in the direction of a successful and comprehensive noise protection in the EU. The methods and tools described above go partially beyond the current methods in the context of community noise research.

By means of the developed traffic noise synthesiser it is now possible to examine diverse traffic scenarios considering potential traffic management measures to prove the perceptive efficiency of specific noise protection measures.

All in all, to guarantee a noticeable decrease of noise annoyance and to achieve a sustainable development, it appears reasonable to perform further target-oriented investigations concerning the introduction of perception-oriented penalties and regarding the application of an evaluation index and psychoacoustics for advanced traffic noise evaluation.