MASTER THESIS

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering at the University of Applied Sciences Technikum Wien – Degree Program Intelligent transport systems

Sound module for interactive transport simulators

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Prague, 30. November 2015

FACHHOCHSCHULE TECHNIKUM WIEN

CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF TRANSPORTATION SCIENCES
INTELLIGENT TRANSPORT SYSTEMS

DIPLOMA THESIS

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Abstract [EN]

Author: Bc. Matúš Lorinc

Title: Sound module for interactive transport simulators

University: Czech Technical University in Prague, Faculty of Transportation Sciences
University of Applied Sciences Technikum Wien

Date: 2. 11. 2015

Abstract: This master thesis concerns the sound analysis and the sound simulation for driving simulator as the most overlooked aspect for a car drive simulation. When driving a real car sounds of engine, tires, brakes and sounds from surroundings (e.g. ambulance sirens wailing) are very important for perception and sequent driver’s reaction. It helps him to avoid an accident, change a gear or for instance slow down. Methods for sound generation and different approaches of simulated sound reproduction are described in this thesis. Main contribution of this work is a complex sound model created for the closest imitation of real sounds of car, which might be used in a static car simulator.

Keywords: sound, simulation, car simulator

Abstrakt [CZ]

Autor: Bc. Matúš Lorinc

Název práce: Zvukový modul pro interaktivní dopravní simulátory

Vysoká škola: České Vysoké Učení Technické v Praze, Fakulta Dopravní

University of Applied Sciences Technikum Wien

Datum: 2. 11. 2015

Abstrakt: Tato diplomová práce se zabývá analýzou zvuku a zvukové simulace na automobilovém trenažéru, která je nejvíce přehlížený aspekt pro simulaci jízdy automobilu. Při jízdě skutečného automobilu jsou zvuky motorů, pneumatik, brzd a zvuky z okolí (např. houkání sirén ambulance) velmi důležité pro vnímání a následní reakci řidiče. To mu pomáhá, aby zabránil nehodě, změnil zařazenou rychlost nebo například zpomalil. Metody pro generování zvuku a různý přístupy k simulované reprodukci zvuku jsou popsány v této práci, pro co nejvěrnější napodobení skutečných zvuků vozu, které by mohli být použity pro automobilový simulátor.

Klíčová slova: zvuk, simulace, simulátor jízdy

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1 Preface

One of the most overlooked aspects of driving simulation is sound. Audio waves affect speed judgment, urgency, operator performance, alertness, and fatigue. As we drive, we use many audio queues for making decisions, such as using the pitch of the engine sound to decide to change gears. In a simulation out of place, inaccurate sounds can also distract a participant and negatively affect results. Sound plays an important role in the realm of driving. Wind and engine noise contribute to fatigue in drivers who have been driving for many hours. Sirens and horns grab our attention away from the task at hand. Traffic noise can also affect a driver's state of being and decision-making. Tires squealing are indicators that the car is being pushed towards its handling limits. When developing a realistic driving simulator, a three-dimensional sound environment also needs to be modeled.

A major goal in driving simulation is to immerse the driver into a meaningful virtual world. The success of this immersion depends on the realism of many sensations, including 3D sound. It is preferred to render 3D sound using loudspeakers instead of headphones because drivers do not wear headphones in real vehicles. Different methods to render 3D sound using loudspeakers include crosstalk cancellation, stereo-dipole methods, and surround sound will be mentioned.

2 Introduction

The main subject of this master thesis is sound analysis continuing to creation of a new module for simulating a car drive in a car simulator. For deeper understanding of this topic I tried to illustrate some difference between sound and noise in chapter three. As you find out later, the issue around sound and noise definition is more related to personal judgment of the person than precise ranges of physical values. Eight parameters of sound are described in subchapters of the chapter three which shows the meaning, formulations and relations between them. Those basic parameters are necessary to know for full understanding of the sound power, intensity, sound pressure level and sound sources. Which in this thesis are loudspeakers used for reproduction of a car noise for a driver in a simulator.

Very important topic related to sound reception by observer is a combination of more sound sources. There is still more than one source of sound (e.g. engine, transmission, brakes, aerodynamic sounds, disturbing noises from surroundings etc.) which are observed in real car. Therefore it is needed to understand assembling of sounds and noises.

Chapter four is devoted to vehicle simulators. Firstly main purpose of them is explained for better understanding the different types of simulators and their usage in practice. Commercial software HEAD 3D sound simulation system H3S and its architecture is described to show how can the simulator reproduce the sound of car. The most fundamental part of chapter four is devoted to the simulator in Czech Technical University in Prague (CTU). For this simulator the whole module of simulated sound was proposed, designed and in the end produced.

As the thesis continues to the chapter six, seven and eight, the biggest part of sound analysis, recording and module creation is described for coming into the conclusion, to sum up created research and points for next improvements in the field of sound simulation.

3 Sound and noise

Sound is such a common part of ordinary life that we rarely appreciate all of its functions. It provides charming experiences such as singing of birds or for example listening to music. Sound enables spoken communication and it can warn us in dangerous situations (e.g. siren sound). Sound perception permits also to evaluate a quality and diagnose a system - a red sign on a crossroad, chattering valves of a car, a squeaking wheel etc.

Yet, too often various sounds in our surroundings, annoys us. Numerous of them are unpleasant or unwanted. These sounds are called noises. However it's hard to find an edge between sound and noise, as it do not depends only on the quality of sound, but mostly on personal attitude towards received sound. For instance the type of music delightful for some people could be regarded as noise for others. Loudness is very important measure for decision making between sound and noise, too. For instance scratch on a blackboard or creaking doors can be as annoying as loud shouting or thunder. The judgement of loudness will also be dependent on the time of the day (e.g. higher noise level tolerated during day time than at night). In summary it can be said that:

- **Noise** is an excessive or unwanted sound which potentially results in annoyance and/or hearing loss (can be from occupational and/or non-occupational sources)
- **Sound** is a pressure variation (wave) that travels through air and is detected by the human ear [1]

Sound can also harm and destroy. A sonic boom can smash windows or move objects from their positions. However the most unfortunate case is when sound damages the mechanism designed to receive it - the human ear.

3.1 Physics of sound

Sound can spread through compressible media, for example, air, water and solids as longitudinal waves furthermore as a transverse waves in solids. It cannot travel through a vacuum. Sound waves are generated by a sound source, such as a tuning fork or vibrating diaphragm of a stereo speaker. The sound source makes vibrations in the surrounding medium. As the source keeps on vibrating the medium, the vibrations spreads from the source at the speed of sound, thus forming the sound wave. At a fixed distance from the source, the pressure, velocity, and displacement of the medium vary in time. At an instant in time, the pressure, velocity, and displacement vary in space. Note that the particles of the medium do not travel with the sound wave. This is obvious for a solid, and the same is true for liquids and gases (that is, vibrations of particles in the gas or liquid transport vibrations, while the average position of the particles over time does not change). During propagation, waves can be reflected, refracted, or attenuated by the medium. [2]

3.2 Parameters of sound

Parameters of sound are the different categories by which we break down and define sound. It is necessary to list these categories to fully understand them, and understand the relationships between them.

3.2.1 Frequency

Frequency is the quantity of completed cycles every second, measured in Hertz [Hz]. We hear frequency as pitch. More cycles per second, then higher pitch of sound (the higher frequency, the higher pitch). Humans can discern sounds approximately between 20 -20 000 Hertz [20 kHz]. Related terms to frequency are:

- Cycle - an entire sound wave
- Period [s]- time to complete one cycle
- Second [s] - an unit of a time
- Hertz [Hz] – cycles per second
- compression - the section in a wave cycle where the wave is pushing out against the next molecules (Figure 1)
- rarefaction - the opposite of compression; the section in a wave cycle where the wave is pulling back away from the next molecules

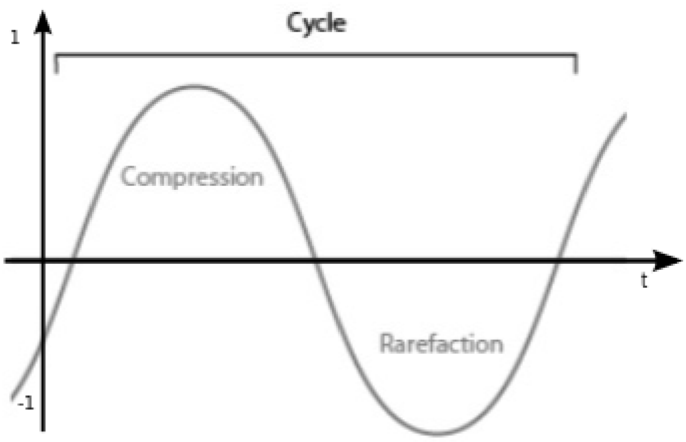

Figure 1: Example of a sine wave with compression and rarefaction

3.2.2 Amplitude

Amplitude is the height of a wave, measured in Decibels [dB]. We hear it as loudness. Example for amplitude in sine wave is shown in Figure 2.

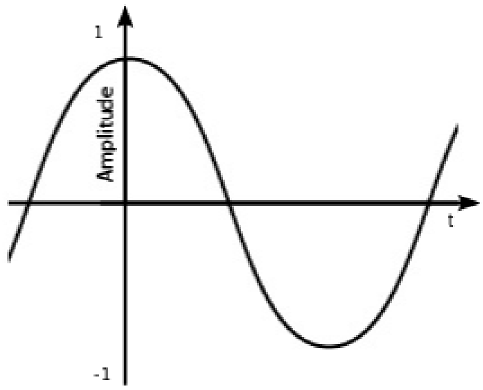

Figure 2: Amplitude of a sine sound wave

3.2.3 Wavelength

Wavelength shown in Figure 3 is the length of a wave, measured in meters [m].

$$\lambda = \frac{v}{f} \quad [\mathrm{m}]$$

Where v is called the phase speed (magnitude of the phase velocity) of the wave and f is the wave's frequency. In a dispersive medium, the phase speed itself depends upon the frequency of the wave, making the relationship between wavelength and frequency nonlinear. Higher frequency, shorter wavelength. [2]

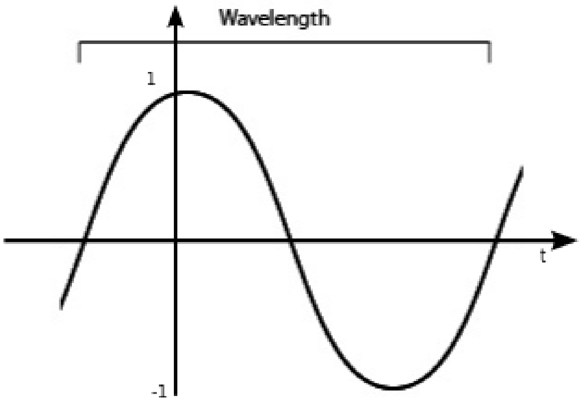

Figure 3: Wavelength of sine sound wave

3.2.4 Speed of sound

The speed of sound depends on medium which the sound waves pass through. Speed of sound in gases depends also on their temperature. For example in 20 °C air at sea level, the speed of sound is approximately 343 m/s [1 230 km/h] using the formula:

$$v = (331 + 0.6\,T) \quad [m.s^{-1}, °C]$$

Where T is the temperature in degrees Celsius.

In fresh water, also at 20 °C, the speed of sound is approximately 1482 m/s [5 335 km/h]. In steel, the speed of sound is about 5,960 m/s [21 456 km/h]. The speed of sound is also slightly sensitive to the sound amplitude, which means that there are non-linear propagation effects, such as the production of harmonics and mixed tones not present in the original sound.

3.2.5 Waveshape

Waveshape is real shape of the wave. Types of different waveshape are: sine waves, which are pure tones – they have no harmonics[1]. Triangle or square waves which both have only odd harmonics, however the different levels of their harmonics distinguish them from each other. Sawtooth waves have both odd and even harmonics. It is uniquecombination of the harmonics and the fundamental that gives a sound its timbre.

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[1] Harmonics – integer multiple of a fundamental frequency. i.e. if the fundamental frequency is f, the harmonics have frequencies 2f, 3f, 4f, . . . etc. The harmonics have the property that they are all periodic at the fundamental frequency, therefore the sum of harmonics is also periodic at that frequency.

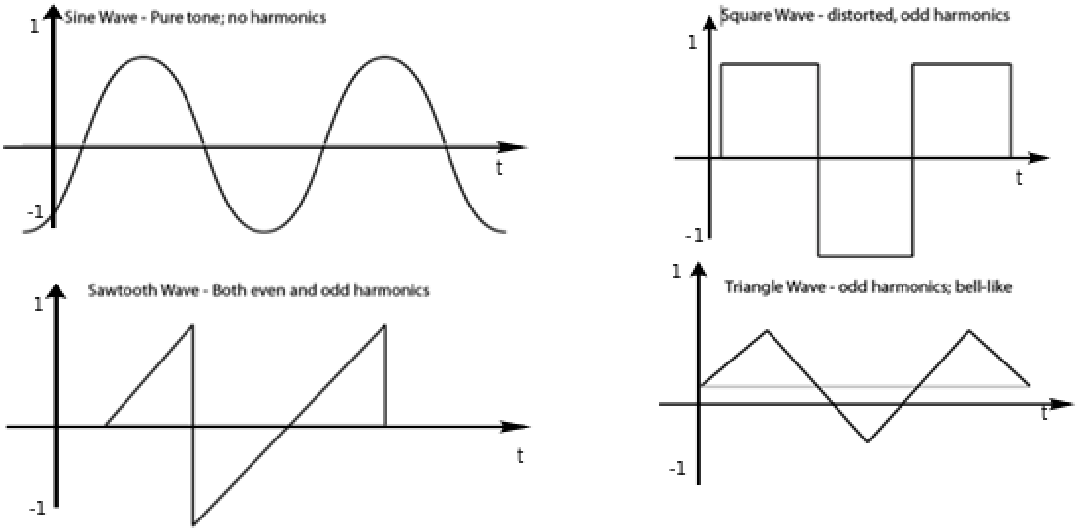


Figure 4: Waveshapes and harmonics of different sound waves

3.2.6 Envelope

The envelope is a combination of amplitude and wavelength. It is very important for determining a sound's timbre. Sound is described by individual parts of envelope:

- Attack – how a sound starts after the sound source begins to vibrate
- Decay – initial dying off coming in sequence right after attack
- Sustain – when sound remains relatively constant
- Release – time period when a sound fades out

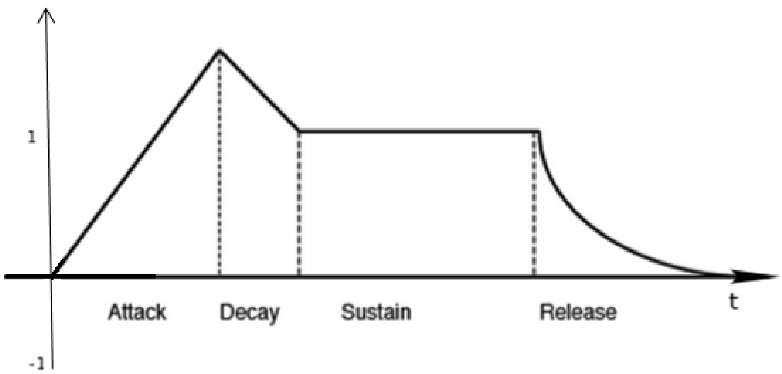


Figure 5: Types of envelope

3.2.7 Timbre

Timbre is also termed as tone color or tone quality. It is the quality of a musical note, sound or tone that distinguishes different types of sound production. For example voices, musical instruments, string instruments or percussion instruments. The physical attributes of sound that determine the perception of timbre are spectrum and envelope.

It can be said that timbre is the thing that makes a specific musical sound unique in relation to another, even if they have the same pitch and loudness. (i.e. it is the difference between a piano and a guitar playing the same note at the same loudness). Experienced musicians are able to recognize diverse instruments of the same type based on their varied timbres, even if those instruments are playing notes at the same pitch and loudness.

3.2.8 Phase

Phase is the time relation between two waves. This affects timbre, frequency, and amplitude of the sound.

In-Phase – the waves are working together; (compression and rarefaction occur in both waves at the same time.) This increases the amplitude. If two waves are totally in-phase, then amplitude is increased by 3 dB. (See chapter 3.5.1)

Out-of-Phase – the waves are working against each other (compression is occurring in one wave while rarefaction is occurring in the other. If the waves are totally out of phase (180°), there will be extreme cancellation. (Figure 6)

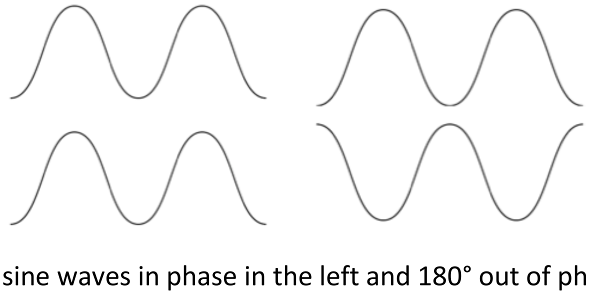
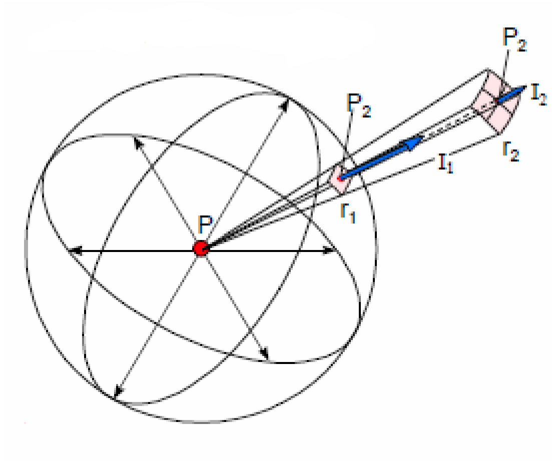


Figure 6: Two sine waves in phase in the left and 180° out of phase in the right

3.3 Sound power, intensity and pressure

Sound intensity or acoustic intensity is defined as the sound power per unit area. The SI unit of sound intensity is the watt per square meter [W/m2]. When sound is produced by a sound source with a sound power, P, a transfer of energy from the source to the adjacent air molecules takes place. This energy is transferred to outlying molecules. Thus the energy spreads away from the source rather like ripples on a pond. The rate at which this power flows in a particular direction through a particular area is called the sound intensity, I. The energy passing a particular point in the area around the source will give rise to a sound pressure, p, at that point. ρ is the density of air, c is the speed of sound. The Sound Intensity vector, I, describes the amount and direction of flow of acoustic energy at a given position as shown in Figure 7. [3]



$$I = \frac{P}{4\pi r^2} = \frac{p^2}{\rho c}$$

Power: P [W]

Intensity: I [$J.s^{-1}.m^{-2}$] = $W.m^{-2}$

Pressure: p [Pa = $N.m^{-2}$]

Figure 7: Sound intensity vector I [4]

Sound pressure and sound intensity can be measured directly by suitable instrumentation. Sound power can be calculated from measured values of sound intensity levels or sound pressure and the knowledge of the area over which measurements were taken. The main use for sound power is for noise rating of various machines etc. The sound intensity is used for locating and rating of sound (noise) sources. The most important measure for evaluation of the harmfulness and annoyance of noise sources is sound pressure.

3.4 Sound pressure level

The acoustic pressure vibrations are superimposed on the surrounding static air pressure which has a value of 10^5 Pascal. If we compare it with the static air pressure variations changes in audible sound pressure are very small from 20 µPa (20.10^{-6} Pa) to 100 Pa. Where 10 µPa is the quietest sound that can be heard by a person and it is called the threshold of hearing. Sound pressure around 100 Pa is so loud that it causes pain to an average person and therefore it is called the threshold of pain. The ratio between these two thresholds is too big. Therefore measurement of sound pressure in Pascals would lead to the use of enormous numbers (Figure 8). Also ears responds logarithmically not linearly to the stimulus of sound pressure change. For these reasons acoustic parameters are expressed as a logarithmic ratio of the measured value to a reference value. The logarithmic ratio is called decibel [dB].

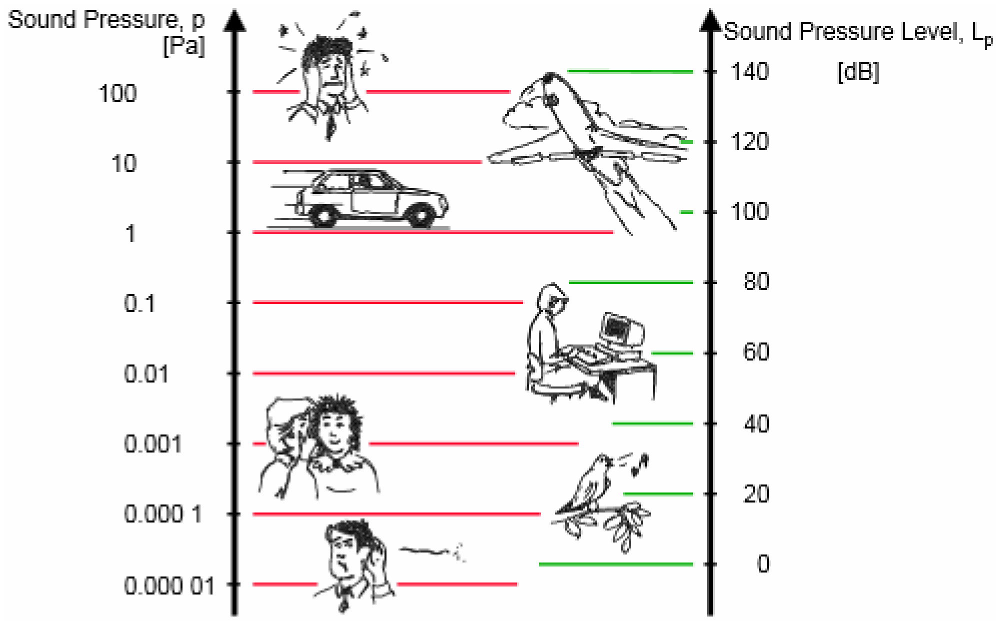


Figure 8: Range of sound pressure levels in Pascals and decibels [4]

The sound pressure level L_p is defined as:

$$Lp = 20.\log\left\{\frac{p}{p_0}\right\}[dB, Pa, Pa]$$

Where p is measured in Pa, p_0 is the standardized reference level of 20 µPa (threshold of hearing) in air and of 1 µPa in water. Without a specified sound pressure, a value expressed in decibels cannot represent a sound pressure level. As shown in Table 1 an increase of 5 dB in pressure is noticeable difference, but for instance change of 10 dB leads to a sound twice as loud.

Change in Sound Level (dB)	Change in Perceived Loudness
3	Just perceptible
5	Noticeable difference
10	Twice (or 1/2) as loud
15	Large change
20	Four times (or 1/4) as loud

Table 1: Perception of decibels [db]

3.5 Sound sources

As mentioned before a sound source used for example in chapter 3.3 is called a point source. For this type of source is important to know that the sound pressure drops to half of its value when the distance to the source is doubled. The change corresponds to 6 dB drop in a sound pressure.

Other type of sound source is the line source. This source is very well known in simulations of tunnels or roads with high traffic flow. The sound pressure in this case drops approximately by 3dB for a doubling of distance from the source. It is caused by sound spreading out from the source as a wavefront in a direction perpendicular to the line source (Figure 9).

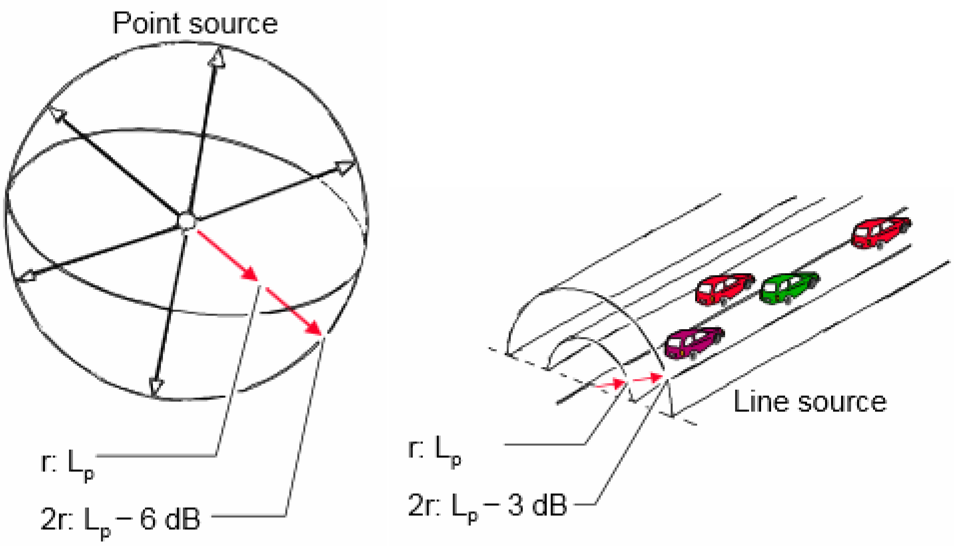


Figure 9: Point source and line source of a sound [4]

Sound energy cannot always radiate freely from the source. When sound radiates in closed areas reaches the surface for example walls, floor or ceiling, some energy will be reflected and some absorbed a transmitted through the surfaces.

In a room where are set mostly hard reflecting surfaces will energy be reflected and diffuse field with sound energy. Such a room is called reverberation room. In a room with highly absorbent surfaces will energy be absorbed by the surfaces and sound energy will spread away from the source as if it was in a free field. Such a room is called an anechoic room shown in Figure 10.

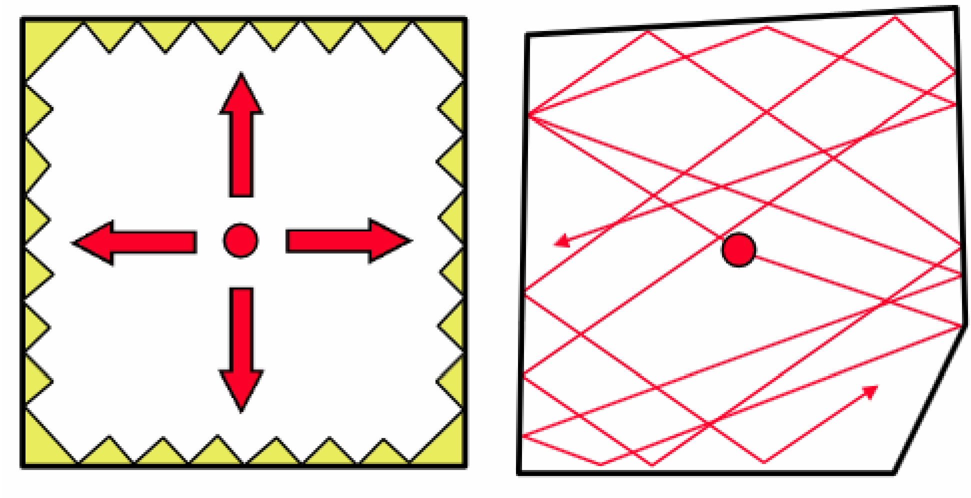


Figure 10: Anechoic and reverberant inclosed areas [4]

Practically speaking, the majority of sound measurements and recordings are made in rooms that are neither anechoic nor reverberant. This makes it is hard to locate the right measuring position where sound should be measured or recorded. Therefore the area for the recording of a sound source (e.g. a car engine) is divided into four different fields (Figure 11):

- Near field – is the zone near to the machine where the sound pressure level may vary significantly with a small change in position. The area extends to a distance less than the lowest frequency wavelength. Measurement of sound pressure should be avoided in this region.

- Far field – contains two other fields, free field and reverberant field

- Free field – sound behaves in this area as if the sound source was in open air environment without any reflecting surfaces to interfere with its propagation. The sound level in this area drops by 6 dB when doubling the distance from the source.

* Reverberant field – reflections from walls in this field might be as strong as initial sound from the machine (e.g. a car engine).

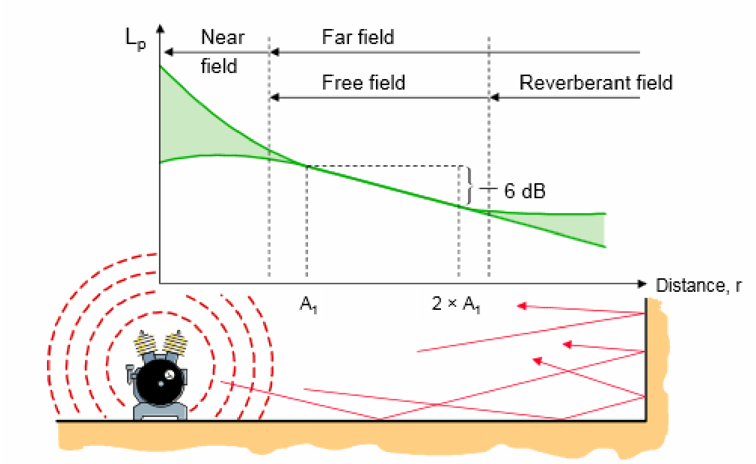


Figure 11: Sound field for sound measurements and recordings [4]

For simulation of a car going through the tunnel it is very important to mention that the pressure L_p close to a reflecting surface is mirrored and should be considered as two pressure levels with the same magnitude and phase (see chapter 3.2.8). Therefore the sound pressure close to the surface L will be:

$$L = L_p + 6\ dB$$

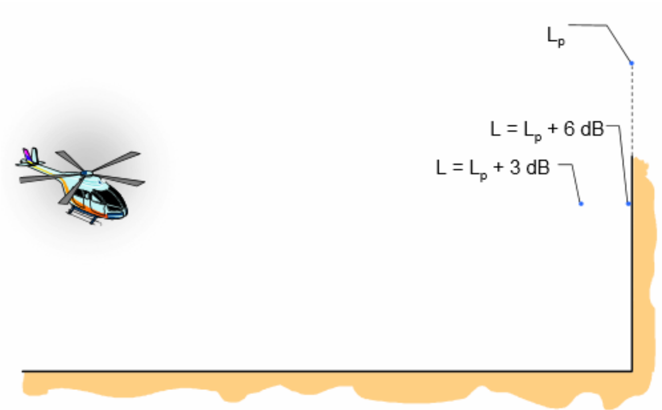


Figure 12: Sound pressure increase at walls [4]

3.5.1 Two or more sound sources

In real conditions it is very rare to have only one source of sound. When is simulated a car drive various sounds have to be considered. The most important sounds are: sounds of tires, engine, aerodynamic sounds, passing by cars and a couple of different other noises from the surroundings of the car.

When two sound sources radiate the sound energy, they both contribute to increasing sound pressure level at a position of an observer. If it's the same amount of energy and a distance from sources to the observer is the same then the sound intensity at that point is twice as high as when only one source is radiating (Figure 13). As intensity is proportional to the pressure squared, doubling the intensity results in an increase in the sound pressure of $\sqrt{2}$ corresponding to 3 dB.

$$L_{p1} + L_{p2} = X + 3dB$$

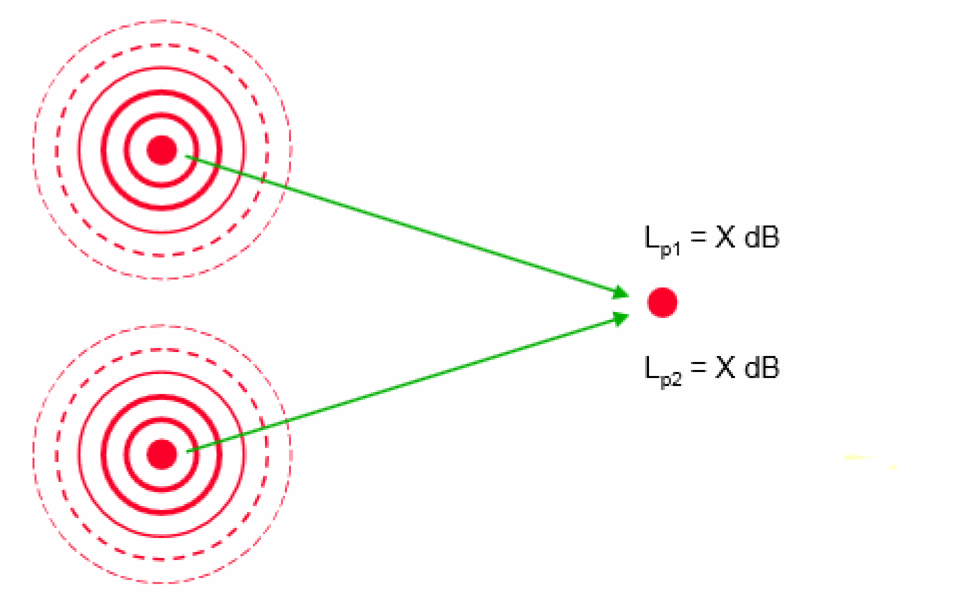


Figure 13: Sound pressure from two the same radiating sources [4]

3.6 Perception of sound sources and modeling possibilities

Human ear is very precise and perfect sense for determining the direction of incoming sound. Man is quite capable to accurately estimate the sound source in terms of direction and distance.

In a lot of papers from this field was introduced a concept called "Head Related Transfer Function", for short HRTF, sometimes translated also as "transfer function of the head" [5]. This function expresses the transmission of sound from the environment to the human eardrum. Unlike most acoustic measurements, which are considered that the receiver of a sound (e.g. small microphone) will have little influence on the acoustic field, we have to consider the impact of the head and shoulders on the acoustic field for the study of human hearing, which includes a variety of phenomena. Above all, it is a diffraction of sound on ears, head and shoulder. Very important is also influence upon transfer function of the ear canal and eardrum. The transfer function of the head depends on the rotation angle of the head compared to the incoming sound, and also frequencies for right and left ear are different. HRTF is a function of the elevation ϕ, the azimuth υ and the frequency f, as shown in Figure 14. It is also different for each ear.

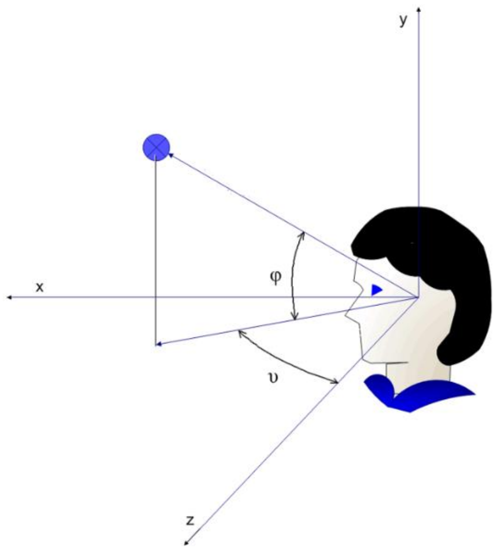


Figure 14: HRTF as a function of azimuth, elevation and frequency

HRTF is a very complicated function of these variables and it cannot be expressed analytically. Moreover it's individual for every human, mainly due to the unique shape of the pinna and ear canal.

Practical measurements of HRTF is performed on a physical model of the human head, in the literature sometimes referred to "dummy head" or "Head and Torso Simulator (HATS)", which dimensions and acoustic properties are standardized.

The head transfer function can thus be used to add information about the position of any sound source. HRTF transformation into the frequency plane, for example using FFT, we get HRIR or "Head Related Impulse Response", also translated as impulse response of the head. If we then perform a convolution of HRIR with incoming sound, we get the sound transferred to the eardrum. A convolution can be performed in real time such as the signal processor or from recorded data for example in environment of Matlab Mathworks.

The advantage of using HRTF modeling directional audio information in the simulator is very good accuracy and fidelity, but the disadvantage is the need to use headphones in combination with the head rotation sensor. Headphones are required for direct transmission of sound into the ear. When using speakers, the effect is almost completely lost. The head rotation sensor is needed to capture elevation and azimuth for the calculation of HRTF, respectively HRIR. During rotation of the head relative to the direction of incoming sound the HRTF is changing and therefore it is necessary to scan these variables.

It is possible to apply this principle for example through the programming environment SLAB, designed by laboratories NASA, which has recently been released for public use, including source codes.

3.6.1 Multiple speakers modeling

Besides the use of HRTF for modeling a directional audio information system, it can be also used for multiple speakers mounted around the listener.

If the direction of the sound source corresponds to the real location of the speaker with respect to the audience, it is possible to achieve a precise localization of the source. This principle is necessary to adjust in the terms of the potential number of speakers. In practice 4,5, 6,7 or 8 speakers are used (Figure 15).

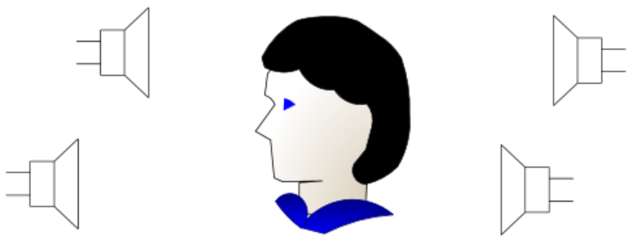
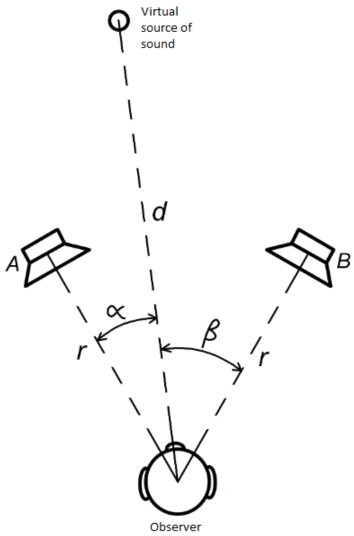


Figure 15: System of HRTF use with four sound speakers around the observer

For audio sources, which are not exactly in the direction where the speaker is mounted a combination of those closest to the respective distribution of performance is used. The distribution of power between the speakers shown in Figure 16 is calculated by the following equations:



$$A = \frac{r}{d}\cos\left(\frac{\pi\alpha}{2\beta}\right)$$

$$B = \frac{r}{d}\sin\left(\frac{\pi\alpha}{2\beta}\right)$$

Figure 16: Distribution of power between speakers for virtual source of sound [6]

The human ear has less directional resolution in the vertical than the horizontal direction. Loudspeakers most often are mounted around the listener in the horizontal direction. Another reason for such placement is the fact that most of the sound sources in surroundings of man are disposed around - few sources located above and below the listener. Vertical spatial information in such sources for this model is usually lost, but it's not critical in most cases.

Another disadvantage of the formation of spatial information using the multiple loudspeakers is the inability to locate sound sources, which are closer than the physical distance of speakers from the observer. However, in the sound simulation for a car, are such sources not expected. Therefore, this phenomenon should not apply.

However, the key advantage of such a system (Figure 15) is a good overall impression of the sound produced combined with a significantly greater environmental friendliness. It is not necessary for the driver in the simulator to wear headphones over his ears, which could lead to less driving comfort, especially on “long trips”. Another interesting thing to look at is the fact that potential drivers in a simulator are often used to this kind of sound production because it is used for example in theaters and in consumer electronics. It is therefore a benefit to use a similar principle to achieve subjectively natural sound without the obligation to give the driver time for adaptation to a completely new virtual environment.

3.6.2 Crosstalk cancellation

Another method to create spatial information is the method of suppressing crosstalk (crosstalk cancellation). This method uses stereo speakers and works on the principle that sounds coming from the left loudspeaker to the observer’s right ear are cancelled and vice versa. Speakers are from the perspective of the listener located 30 ° - 60 ° apart. The stereo-dipole method (dipole-stereo playback) is similar to the crosstalk cancellation. The difference between those methods is in the position of the loudspeakers, which are separated by only 5 ° -10 ° for stereo dipole. It is recommended to add HRTF functions for both methods. According to Blommer [7] these methods are not suitable for acoustic system simulators, because for their proper functionality they need the exact location of the listener's head. They have a small, so called sweet-spot, i.e. the place for optimal hearing.

4 Vehicle simulators

Driving a vehicle requires that a lot of different tasks have to be fulfilled in order to drive the vehicle on a particular trajectory or take it to the desired place. It is necessary to have information regarding the different states of the vehicle. This information is acquired by human sensors and merged together in order to analyze the current driving conditions and come up with appropriate decisions. By collecting of informational feedback from several different sources it is possible to create an acceptable illusion of a vehicle driving in a virtual environment.

4.1 Different types of vehicle simulators

Currently, driving simulators are increasingly used in the automotive industry and for research of driver behavior. Generally they can be divided into two groups according to the purpose for which they are intended:

- Simulators for non-acoustic applications - ride comfort
- Simulators for acoustic measurements (Noise, vibration, and harshness (NVH) simulators) - noise suppressant treatment, realistic car drive

Simulators for non-acoustic application are commonly used in automakers development centers and research institutes for testing in traffic (effect of fatigue, alcohol, effect of the control elements on the driving and many others).

Simulators for acoustic purposes - NVH simulators are used primarily for the development of new cars in an automobile factory. They contribute to the reduction of time and cost of development of new models by simulating the sound and vibration “speech” of cars and helping to reduce the number of prototypes. Simulators generally operate in different modes:

- Mode without driver intervention (Non-interactive driving mode) – Simulators are used to test specific situations or manifestations of the car. They are able to generate all the manifestations of driving a vehicle, but without a possibility for changes by the driver, thus enabling 100% repeatability tests.

- Interactive mode, free control (Free-driving mode) - simulators that allow simulation of driving. Their purpose is to be as close as possible to actual conditions in the vehicle. Such simulators have to properly respond to the driver interactions and controls. They differ from each other according to the complexity and type.

One of the first types of CTU simulation device used a common PC steering wheel with two pedals with a sequential gear shifter (or automatic shifting was applied). Now a special three pedal system (including a possibility of involvement of the clutch if required) is used and an H-pattern gear shifter. The realistic three-dimensional cockpit lets the driver to immerse him into the projected scene. Figure 17 shows CTU's very first approach to the driving simulation technology. The experimenting driver uses a big TV screen and common game steering wheel and pedals.

Figure 17: First type of vehicle simulator in CTU

The next type of simulator is based on fixed platforms, which do not have any mechanical movement. The dynamic and inertial effects are absent and no motion reproduction technique is used. The movement sensation is only induced by the convection brought by visual feedback shown in Figure 18. These simulators are made of a vehicle cabin, and besides the visual projection they are also sometimes equipped with an audio rendering system, along haptic feedback (effort feedback on the steering wheel, vibrating seat, etc.), which creates a more realistic driving environment.

Figure 18: Fixed-based simulator in CTU

The most advanced and the highest cost simulators are sometimes called "pod-simulators". They are located on moving platforms that allow simulation of the mechanical action on the driver during driving. At present time, probably the most advanced simulator is Toyota’s driving simulator at Higashifuji Technical Center, Japan, shown in Figure 19. [12]

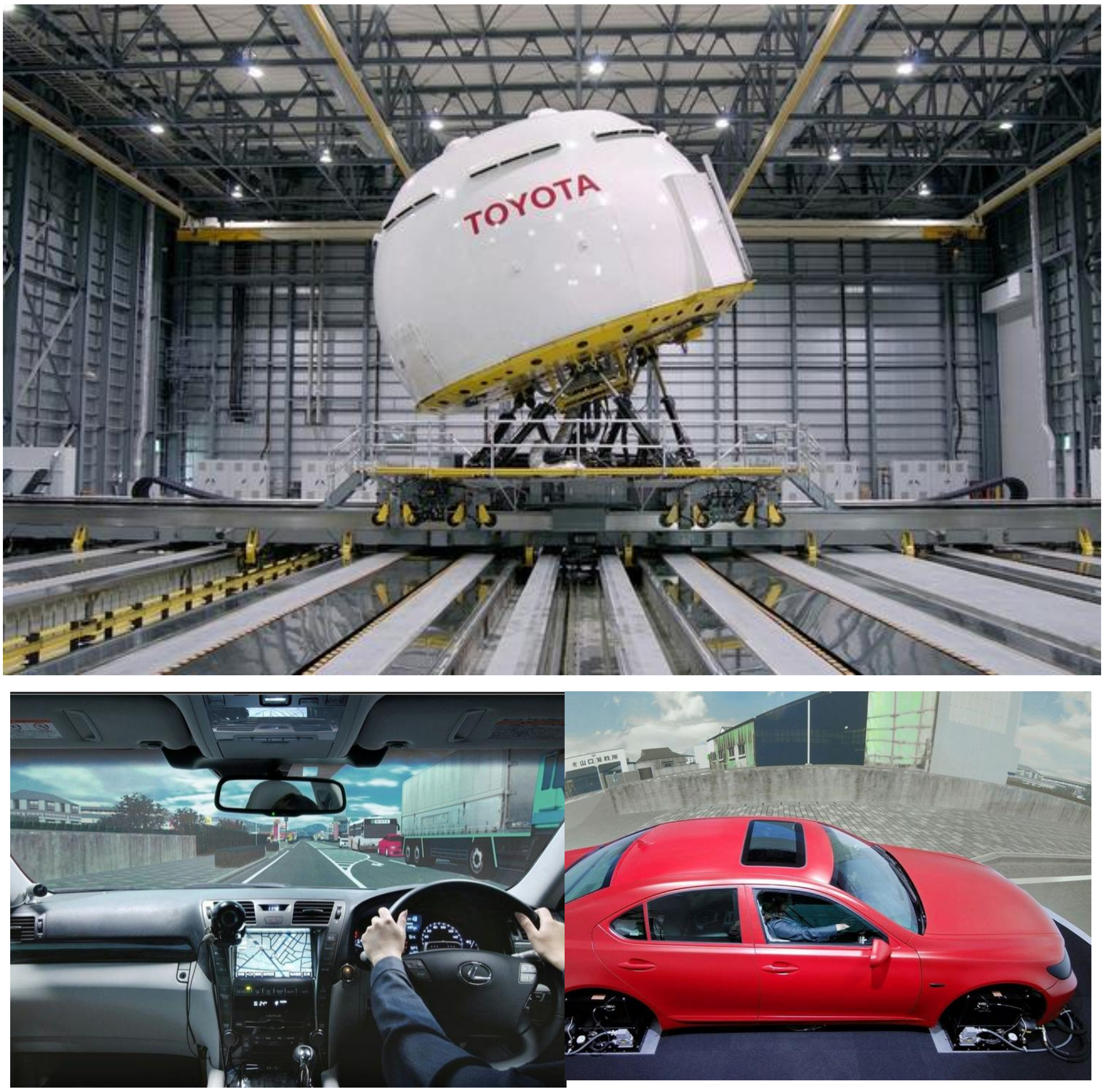


Figure 19: Toyota’s driving simulator at Higashifuji Technical Center, Japan [12]

4.2 Acoustic system for simulators

Details about the technologies used in the acoustic systems of individual simulators are usually not published. In this chapter, I would like to summarize available information about the acoustic systems for different simulators.

4.2.1 HEAD 3D Sound Simulation System

The HEAD 3D Sound Simulation System H3S is a software for the interactive playback and simulation (airborne sound and vibrations) of vehicle interior noise. H3S adapts sounds and vibrations to the individual “driving situation” and reacts in real-time to changes in speed, Revolutions per minute (RPM, throttle position, etc. During the simulation, H3S allows the interactive replacement of engines, other components and much more. Modifications are working immediately and allow a realistic prediction of the effects.

4.2.2 Architecture

A soundscape created by H3S consists, for example, of the following individual sound components: engine with gearbox, tires and brakes, wind and background noise as well as operating control elements and indicators. The sounds of oncoming and overtaking vehicles are created via binaural synthesis. For quickly “moving” sounds, the Doppler effect is simulated, too. The driving dynamics model in the H3S Control module polls the operating controls of the vehicle and controls the actual H3S sound system. The “user interface”consists of ignition switch, accelerator pedal, brake pedal and gearshift lever as well as the dashboard instruments of the vehicle. The user can choose between conventional and automatic transmission. Via the H3S Control module, it is also possible to control customer-specific extensions, for example the simulation and virtual replacement of turn signal units or windscreen wiper models.

During the simulation, H3S plays the pre-recorded sound segments depending on the vehicle state. An innovative synthesis algorithm allows H3S to react to changes of the driving situation in real time. Furthermore periodically repeating sound patterns during constant driving situations are avoided (Figure 20).

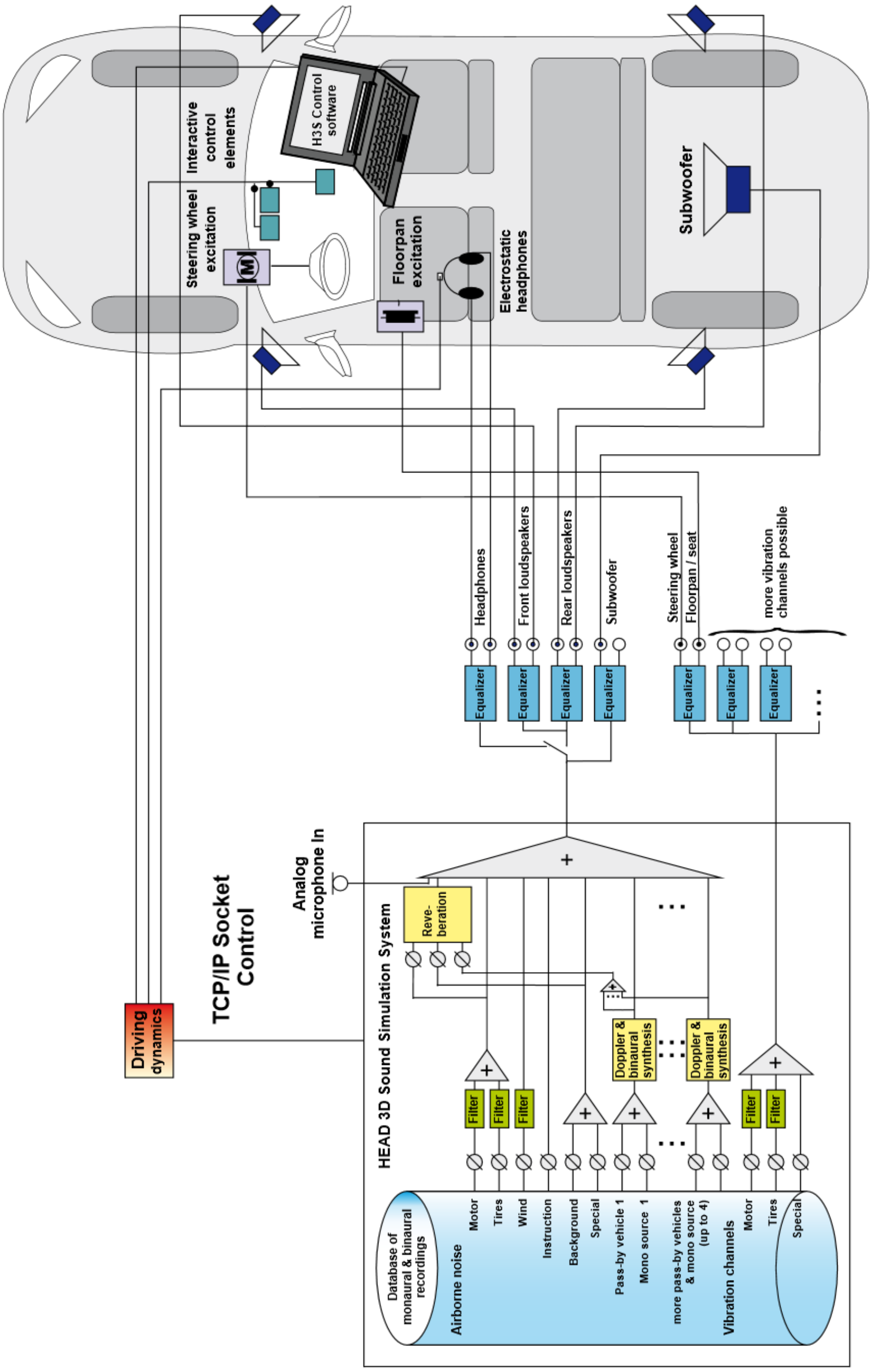


Figure 20: Head acustics architecture [11]

5 Vehicle simulator in CTU

The vehicle simulator in the joint laboratory of system reliability in Czech Technical University, Faculty of Transportation Sciences is a simulator of a so called, compact type. It consists of a chassis and a cabin of Škoda Superb. Screening is carried out from two projectors onto a screen in front of the driver. The physical model of the vehicle, as well as a graphical rendering and sound simulation is performed on a single computer. This configuration had limits arising from the computing power of the computer. Also, it was not possible to further expand the screen due to the number of outputs from a single computer to projectors. For these reasons, it was necessary to change the architecture of the simulator to distributed simulation. The distribution of computing tasks requires efficient and robust communication system. The CEDSS communication system, which is used for this simulation is described in Section 5.2.

5.1 Simulator structure

The structure of the simulator in a simplified form is shown on Figure 21. The car simulator consists of three basic modules:

- The synchronization module (MS) provides a common time base for measurements performed on a simulator.

- The module of physical model and rendering virtual scenes (MFM) evaluates the physical model of a virtual environment and is responsible for its rendering to the screen. It has a form of an application running on a powerful computer.

- The acoustic module (AM) assesses the state of the simulator and a surrounding environment and generates a soundstage for the simulator through a computer sound card and multichannel loudspeakers.

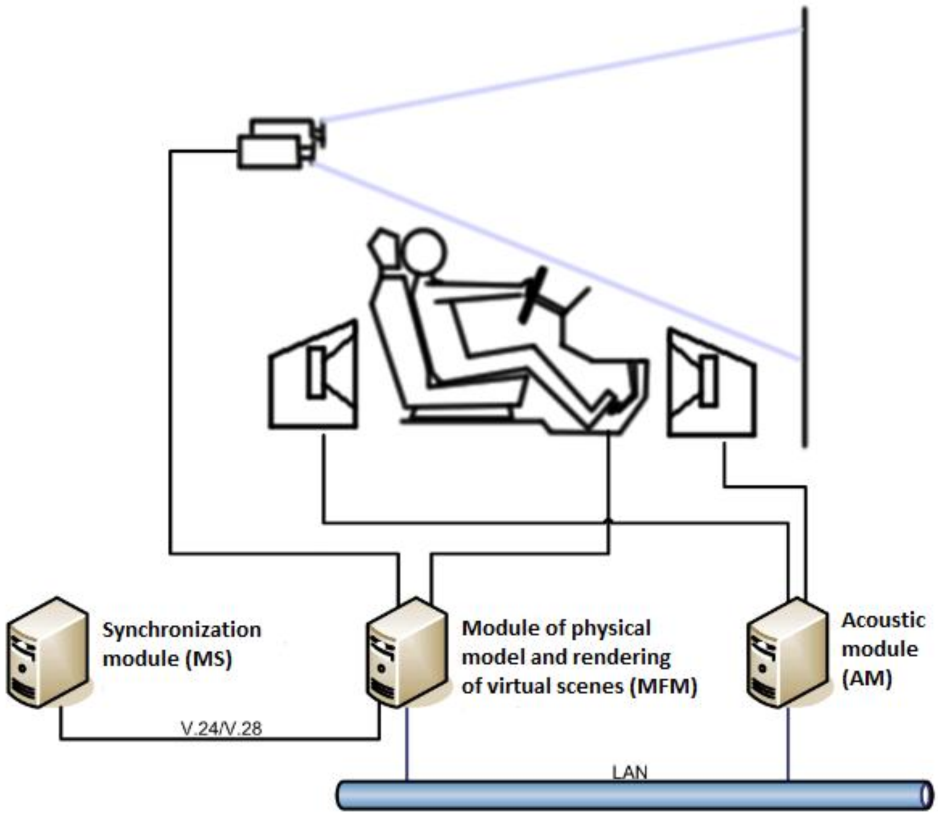


Figure 21: Structure of car simulator in CTU

For further reading, it is appropriate to terminologically clarify the terms "module," "model," and "functional block". In connection with the modular or distributed architecture of the simulator system we will be talking about the various "functional blocks" of the system, or less exactly the "modules". For a mathematical or computer modeling of individual components of the virtual world the term "model" will be used.

5.2 Communication system CEDSS

A car simulator is a complex computing system. It can run on a single computer in real time and evaluate individual components of the virtual world in the simulator, i.e. the physical model of the car, a graphic display and an acoustic model. However, we face a barrier in the limited computing power of such a system. If we want to continue to improve the virtual environment, it is necessary to distribute tasks among several computers that shares the task of calculating virtual reality. The easiest way how to do it, is to divide the different tasks asymmetrically according to function so that each computer is processing one part of the system. This minimizes the data stream, which is needed to be transmitted for the correct operation of the simulator. It also gives us a possibility to independently develop individual parts (modules) of the car simulator.

The communication system connects the entire modular system of simulator. Forming a communication interface consisting of components allowing data transfer between the systems modules regardless of their further configuration. High demands are placed in terms of reliability, flexibility and minimum delay in the data transfer for this CEDSS system.

For the needs of the simulator in the joint laboratory of system reliability of CTU a specific communication system was created by Martin Lalček [6] under the name CEDSS (Communication Engine for the Distributed Simulation Systems). Its structure is shown in Figure 22.

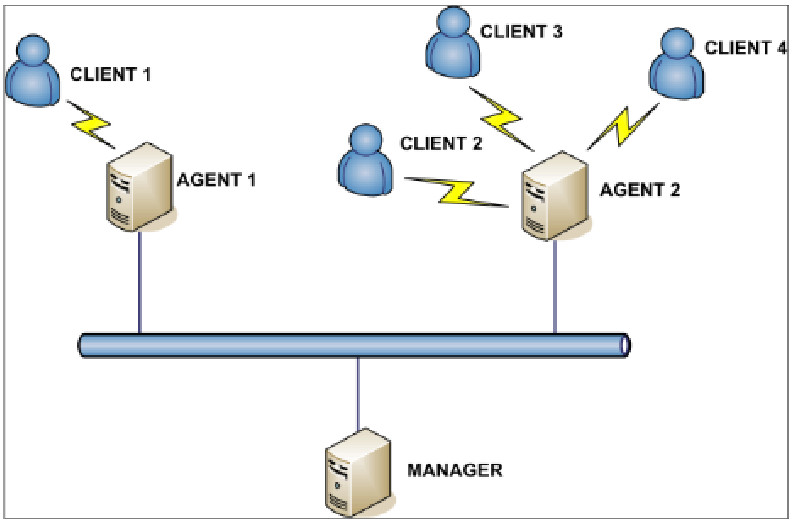


Figure 22: Structure of the communication system CEDSS

CEDSS system consists of three functional hierarchical layers:

- **Client** - is a separate component of a communication application (sometimes called module) which facilitates data exchange with other applications (modules) in the system. Communication between clients runs through message sending and is managed by processes running in the application. Clients don't communicate directly, but through agents, where they are registered.

- **Agent** - is a component that runs one for each network node, in practice, one agent on each computer in the system simulator. The agent connects the computer to the network, and via the network client runs the communication from this computer to other nodes in system. It also checks the strange behavior of individual clients.

- **Manager** - is the highest authority and is the only one in the system. It has an overview of all agents in the network, and all clients registered to them and it controls the exchange of data between them.

Communication between clients is served by so called, "goods". For sending data between clients, all participants must register goods with the same name. Those who want to receive it from others must also apply with a message about the possibility for adoption. Each client may have registered several types of goods, which have the option to transmit and receive at the same time.

The acoustic functional block (module) therefore involves creating of an application with the function of the client. This client connects with other clients via network, e.g. physical model functional block connects with acoustic functional block and exchange necessary data. It is therefore a bilayer structure of the application, where the higher layer module communicates with others via CEDSS functional layer. Using the communication system CEDSS is replacing relatively complicated interface between applications (including e.g. a protocol for establishing communication over the network, routing, etc…). Commands for communication are therefore incomparably simpler. In Figure 23 the structure of a module in the system CEDSS is shown.

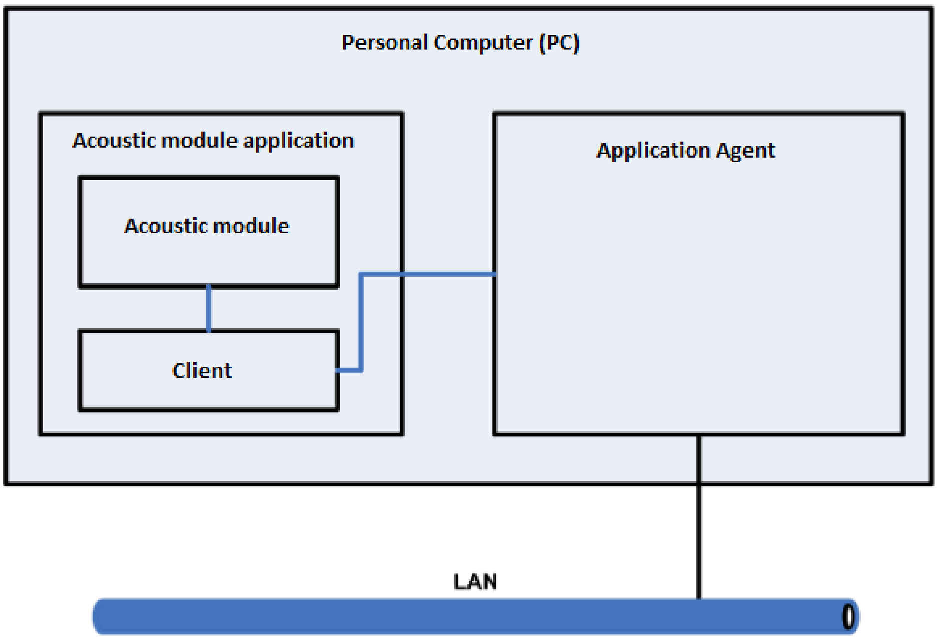


Figure 23: Structure of a client's application in communication system CEDSS

6 Analysis of car noises

In this chapter the term “noise” will be used more often than “sound”, because a lot of sounds produced from a car are usually not harmonic, periodical or expected.

The role of noise and vibration plays an important role concerning the overall harmony of the vehicle. Today’s vehicles have to perform all the capacities that passengers and drivers expect and in the same time provide a comfortable and enjoyable environment. There are plenty elements from the field of noises, which affect comfort, such as tire noise, wind noise, gear whine or boom. Other very important noises like engine noise in acceleration or ride have more impact on overall appeal. (Figure 24)

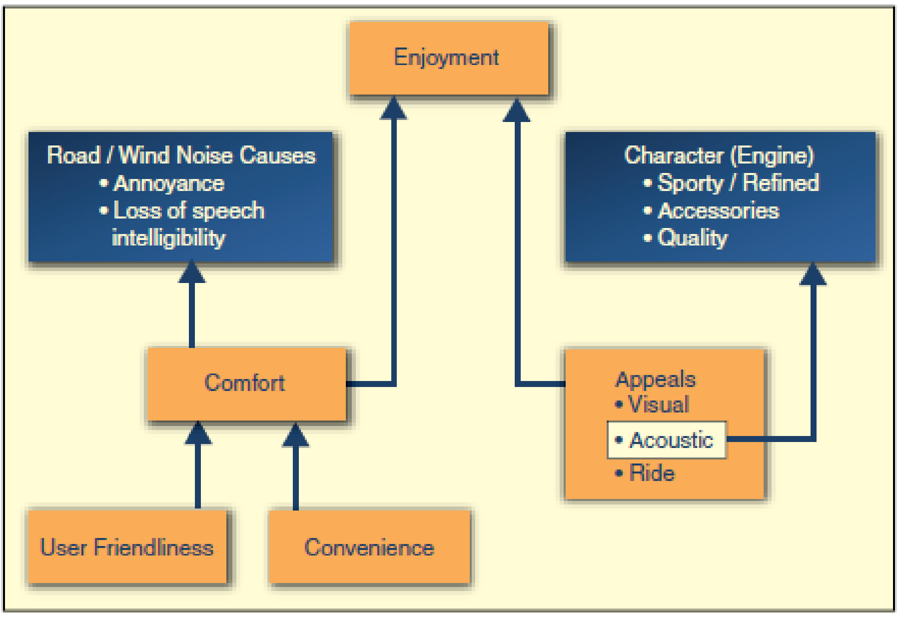


Figure 24: Impact of noises and vibrations on overall vehicle harmony [8]

Each type of vehicle or brand has different expectations for noise and vibration factors on the vehicle harmony (NVH). In Figure 25 an example how engine noise and wind/tyre noise affects brand sound design is shown. The two axes are showing noise attributes at speed 100 km/h. The diagonal lines are the thresholds for definition of sporty or comfortable vehicle.

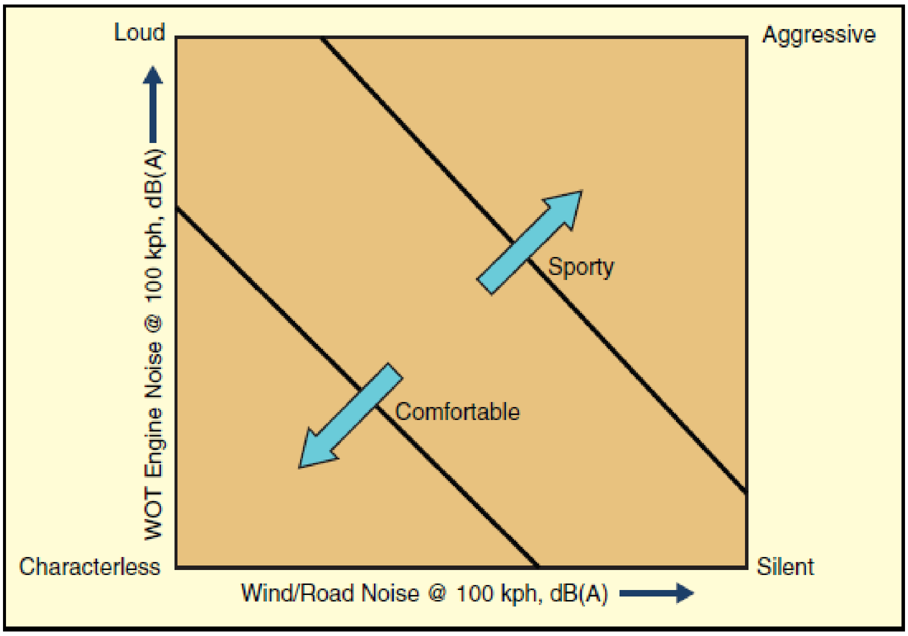


Figure 25: Sound design dependent on engine and wind/tire noises at 100 km/h. [8]

If we try to classify this noises and vibrations, we can say that there are some noises which should not be detected in normal driving conditions such as transmission, A/C compressor, alternator, fuel pump, power steering or gear. These noises should be eliminated or masked. Components which are expected to make audible noise and are specific for each vehicle type and brand can be split into these categories:

- Character – engine, exhaust noise
- Comfort – road (tires) and wind noise
- Quality – accessories (door closure, windshield wiper, power window) noise

On the other hand, the acoustic image of the vehicle is multidimensional, it combine several noise sources that are time and frequency dependent to create an overall vehicle sound. The highest impact on overall vehicle's sound has with no doubt the engine. We can say that each vehicle type and brand has an own acoustic signature which is expected from customers.

6.1 Engine noise

The sound quality of an engine may be considered from two different views. Firstly as an interior noise, which should represent an image of quality and coolness and secondly as an exterior noise for brand recognition and also to ensure safety for pedestrians (e.g. hybrid vehicles are from the view of engine noise almost noiseless compared to other noises from the surroundings). The two main sound quality criteria for the powertrain are:

- Maximum loudness (or weighted sound pressure level) for overall noise and fundamental engine orders (that is firing frequency and its first few even, odd and half-integer multiples), at idle and in hard and slow acceleration conditions.

- Linearity of overall noise and engine orders, that is the requirement for them to grow linearly with the RPM, with no significant peaks and valleys.

It is also important to mention that a vehicle with loud sound signature, where loudness grows linearly with engine RPM and vehicle speed is more acceptable by drivers than a quieter signature with no linear increase of RPM with speed of the vehicle.

6.2 Tire/road noise

In last year's the tire noise has become increasingly important for sound quality perception as a lot of noises from powertrain and driveline have been reduced. We can start to notice a road noise usually in speeds above 50km/h. Maximal contribution to overall interior noise is between speeds 60km/h to 100km/h. Then at higher speed is perception decreases and aerodynamic noise become predominant.

For this reason, usually tests measurements and recordings of road/tyre noises are conducted at constant conditions, which are speed 80km/h and small coast down on different surfaces. The main reason for coast down is to avoid interference of an engine noise with road noises. Road noise is generated by the interaction between the tire and the road surface and excites the vehicle through both airborne and structural paths as shown in Figure 26.

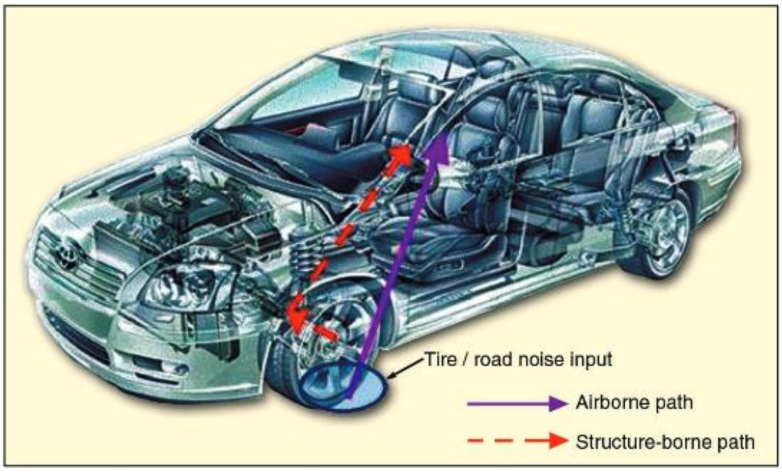


Figure 26: Road noise source and its paths [8]

6.3 Wind noise

Wind noise, also called aerodynamic noise, is the most important vehicle noise at speeds over 100km/h. It is measured and recorded at speeds between 100 km/h to

160 km/h, either on a road or in a wind tunnel. There are four types of aerodynamic noises:

- Aerodynamic noise made by a vehicle which is moving at high speed through a steady air. It is related to the drag coefficient of the vehicle. Drag or aerodynamic coefficient is a function of the vehicle's shape and its cross-sectional area.

- Aerodynamic noise made by air turbulence which occurs in areas around doors, hood and windshield and depends on how tightly sealed the vehicle is.

- Aerodynamic noise caused by fluctuating wind conditions. For example cross-wind on a highway, wind changes in open field compared to passing the road in forest. The main difference to the previous two aerodynamic noises is that here the wind noise is fluctuating.

- Very low-frequency (10 to 20 Hz) noise occurring when any vehicle window or the sunroof are partially opened. It is caused by Helmholtz resonance of the vehicle cabin. The resonance is excited by the air flow along the boundary of the opened window.

The last two types of aerodynamic noises are frequently referred to as wind buffeting noises. As they are impulsive noises e.g. cross-wind, their frequency is higher than the spectrum of frequencies for steady wind noise. For gusting noises frequency is around 300 Hz and higher, but for not fluctuating wind noises it is around 30 Hz to 60 Hz. [8]

6.4 Exterior noise and pass-by

Pass-by recording and measurement has nothing to do with sound quality. It is strictly a mandatory measure to ensure that a vehicle's exterior noise at specified operating conditions is below a defined threshold value. [8] This threshold value is expressed in decibels and it is the max value recorded while the vehicle is driven from entrance to exit of the pass-by course. Focus in this area is concerned mainly on diesel engines and its noise contribution to the overall soundscape in urban and residential areas. Therefore the conditions for measuring and recording are divided into these procedures:

- Driving steady at 70 km/h
- Vehicle approaching at 50 km/h
- Starting to brake at 25 m
- Full stop in front of the measuring equipment
- Drive away at moderate acceleration to simulate the traffic light scenario

6.5 Transmission paths

Under the term transmission path is understood an acoustic path of noises in construction of a vehicle or an air. These paths spread the noise from the source listed in the previous chapters into the cabin of the vehicle. The ratio between transmission paths spreading through the air and structure of the vehicle is shown in Figure 27.

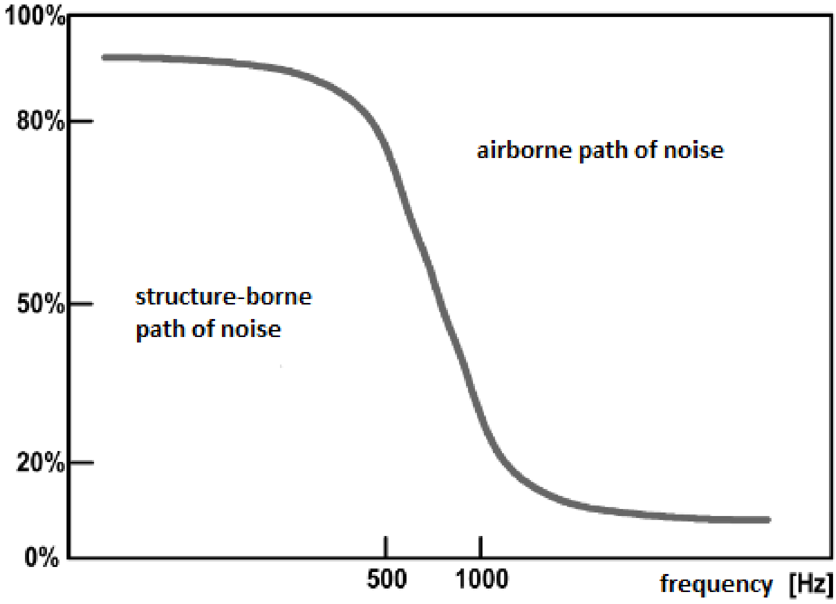


Figure 27: Diagram of the frequency dependence between airborne path and structure-borne path

Most of the interior noises in the vehicle cabin are caused by structure-borne path of noise, as vehicles in these days are well isolated from external noises. It explains that the noise inside the cabin compared with the noise outside is missing a spectrum of higher frequencies, see Figure 24.

6.6 Frequency analysis of engine noise

The noise of a car engine has a significantly different character, if it is recorded inside or outside of the vehicles cabin. The following spectrogram shown in Figure 28 indicates the frequency spectrum of the sound of the diesel engine Ford Transit 2.4D inside the cabin, under the feet of the driver and outside the vehicle. For illustration showing frequency band to 3000 Hz. The lighter color in spectrogram indicates higher presence of specific frequency in a sample.

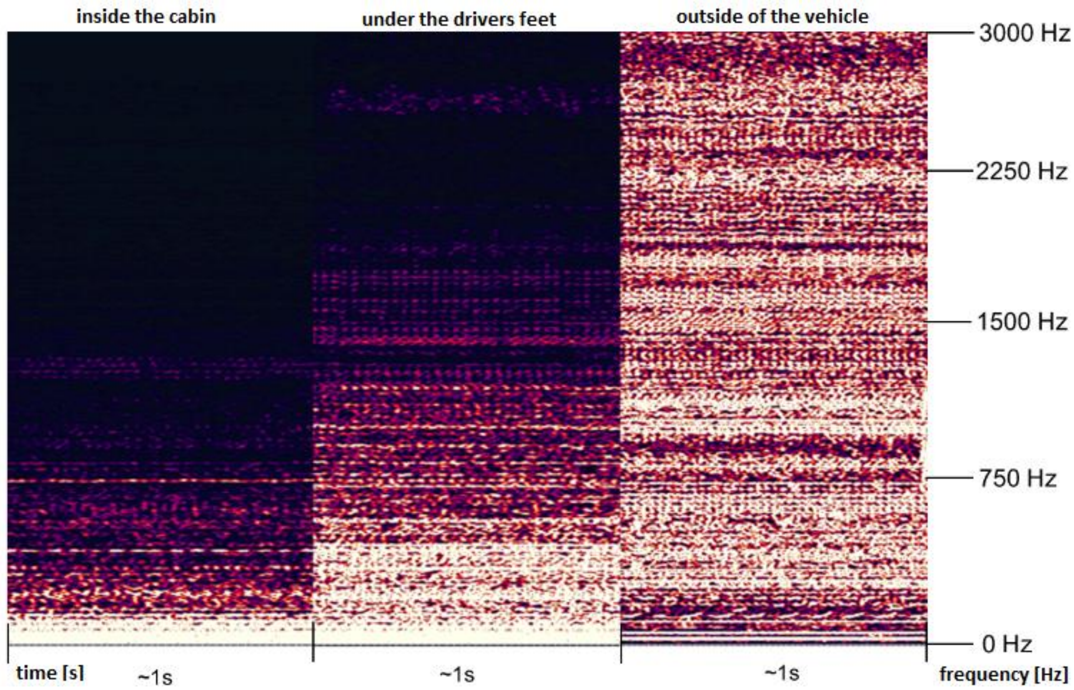


Figure 28: Comparison of the frequency spectrum for different position of noise recording

If we compare the frequency spectrum of the engine noise during an accelerating period, i.e. engine load and the free RPM fall, we find that the higher frequency components increase with the load of the engine. In Figure 29 the spectrogram of the engine sound (recorded under the driver's feet, second gear) is shown at the accelerating period and sequential stop. The lighter color indicates higher presence of specific frequency in a sample.

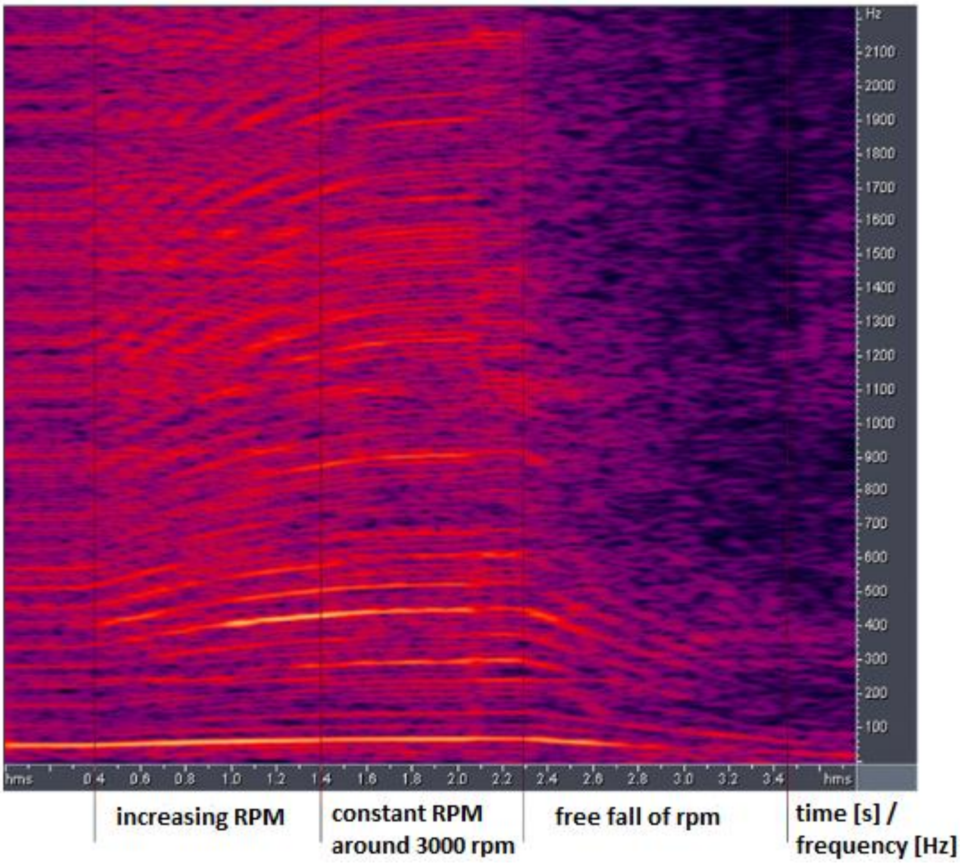


Figure 29: Comparison between frequency spectra for different engine loads

7 Recorded sound

Sounds and noises can be recorded or synthesized using a variety of methods. Stereophonic recordings at the driver's position in a vehicle cabin will better represent what a driver actually hears in the vehicle. The binaural head recording contains most characteristics of the acoustic filtering by a listener's head, torso, and pinnae. These characteristics include diffractions, reflections, and linear distortions of the incoming acoustic waves, which result in amplitude and phase modifications of the waves as a function of both frequency and spatial location. The human auditory system "decodes" these amplitude and phase modifications into spatial locations of the sound sources.

By measuring these head-related transfer functions (HRTFs) from a spatial location to the ear canal of the right and left ears, one can also incorporate binaural effects when synthesizing sounds. Merely filter the synthesized sound by a set of HRTFs that correspond to desired spatial locations.

7.1 Examples

	Dynapack	**Road recording**	**Dynamometer**
			
How it works?	- A direct to wheel attached dynamometer which applies friction to the engine - Two versions are available to meet specific horse-power requirements	- Driving the car on road while having microphones on the car and recorders on the sideline for exterior noises	- Rollers are mounted in the garage-floor which allow the car to freely spin the wheels while the rollers apply a load to the engine

When to use this method?	- To obtain clean steady states and acceleration ramps - If its conserved not to hear dyno in recordings -If you want to record the car outside	- To get pass by noises - To obtain realistic behavior sounds of the car - To record an engine deceleration sound - To record tire/round noises - To get onboard driving sounds	- To obtain steady, acceleration and deceleration ramps - Car have to be loud enough to hide the “whine” sound of the dynamometer - If the car is automatic or has undefeatable traction control
Plusses	- Clean recordings - Able to place microphones far away - Fairly easy to record - Able to record in any place where is electricity	- Capture the true sound of the vehicle - Able to capture interior and exterior noises in the same time - Possible to record in any place	- Readily available - Able to place microphones anywhere easily - Able to capture decelerations
Minuses	- Won’t handle automatics well - Difficult to capture deceleration - Not possible to record tire noise as no tires are on vehicle during recording	- Tire and skidding sounds can be problematic - Need to have a clean road to record - Much more difficult to get clean recordings - Problems with wind may occur	- Strong whine sounds with quieter cars - Internal, hard to get rid of reverb reflections - Recordings tend to sound lifeless with no movement

Table 2: examples of different recording methods

Noises recorded for a sound module, which is described in further chapter, were recorded at different spots of the vehicles cabin. The first tested position of the microphone was under the car dashboard. Sound samples from this place of the cabin were at much lower frequencies than for the other positions of microphone. The advantage of these samples was in the accurate recordings of tire and powertrain noises.

The second position of the recording equipment was at the place of the driver's head. These samples were the most realistic with all noises equally distributed. Aerodynamic noises were clearly recognized at higher speed, the same was case for the loudness of the engine or for decreasing tire noise. Disadvantage of this spot was in any other undesired recorded noise such as creaking seat of the driver, all his movement in a vehicle e.g. during changing the gear, turning the head for better view on the road, etc.

The third tested position for the recording was on battery under the engine bonnet (distance around 40 centimeters from engine). Samples from here were used for a starter sound and engine noise simulation. However any other noises like aerodynamic or transmission noise were not detected.

The last method for the recording of the samples was the recording of a standing car noise with neutral gear in a recording music studio shown in Figure 30. As the studio has the high quality equipment from microphones to sound blasters and so on, the samples had the best frequency spectrum from all of the records. The problem of those records was the absence of aerodynamic and road noises highly required for a realistic car sound simulation.

Figure 30: Noise recording of a standing vehicle in the recording studio

7.1.1 Comparison of recordings

When I take a closer look on the results of recordings in GoldWave software, I can say that for records from the cabin (recording position number one and two) are much more damped than others. As expected from previous text in chapter 6, many noises are absorbed and not transmitted into the car. Hard to distinguish in analysis of recorded sound wave, which sound source affected the change in frequency of the wave. The difference in waveshapes for car noise recorded in the car cabin and outside of it is shown in Figure 31. Upper diagram shows left and right channel of stereo record in the car cabin. Lower diagram shows much different waveshape of the same noise recorded on the position of car battery near to engine. Therefore I can say that records taken from outside of the cabin are more applicable for using in the sound simulation in case of clearer noise recognition.

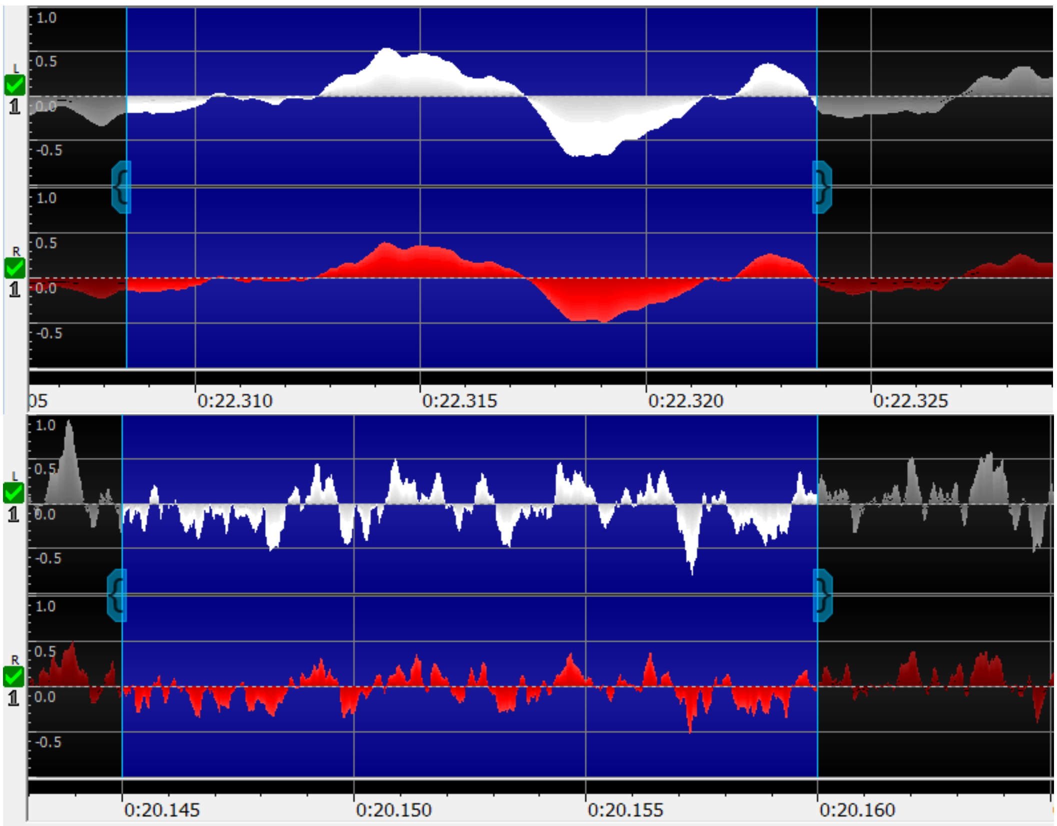


Figure 31: Waveshape comparison of noise recorded inside and outside of the car cabin

Waveshape of the car noise recorded in the studio is even more sharp and changes in frequencies of noise are more distinguishable as shown in Figure 32.

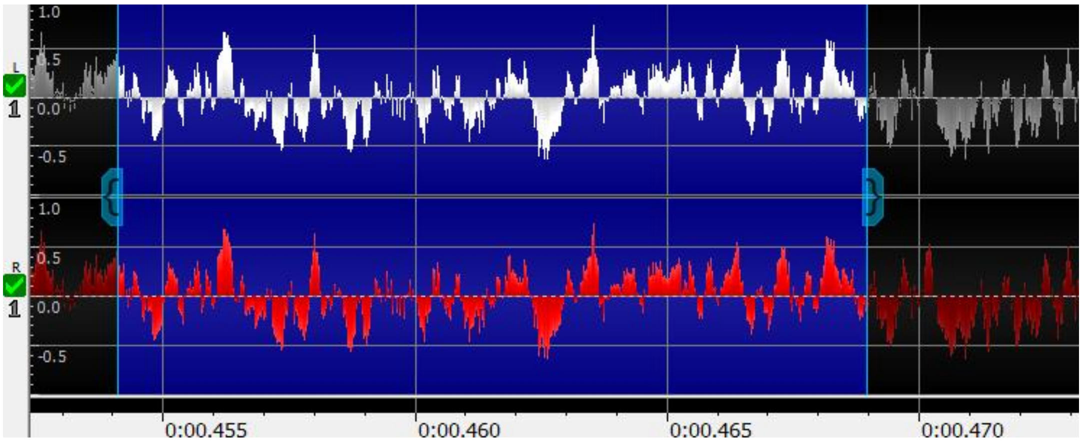


Figure 32: Waveshape comparison of noise recorded inside and outside of the car cabin

If I make a deep analysis of noises which are able to be heard by a human ear (16Hz – 16000Hz), I can definately say that the best results in recording are reached in music studio (Figure 33). The problem in this method of recording is that car have to stand still and in this condtions it is not possible to simulate an engine load.

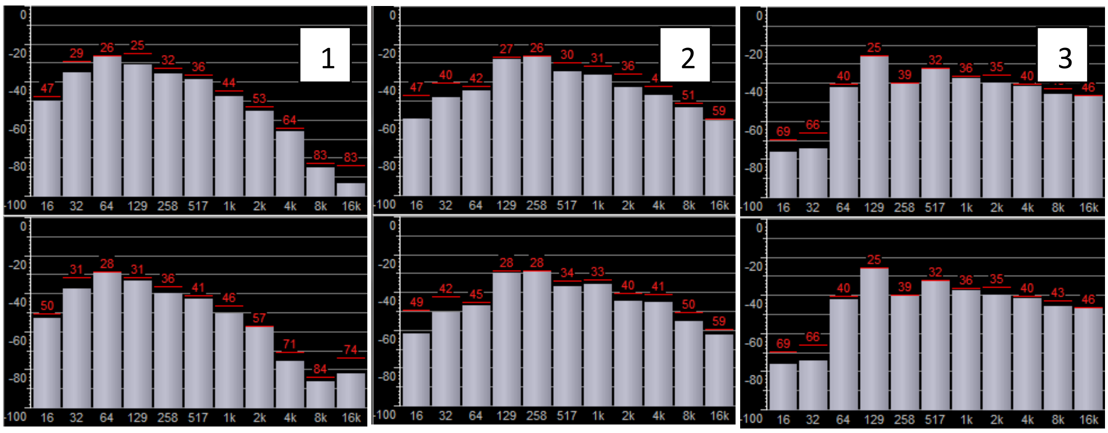


Figure 33: Presence of 16Hz-16kHz frequencies in record a) inside of cabin b) outside of cabin c) in music studio

8 Synthetic sound

Synthetic sounds are produced by electronic equipment or digital hardware simulation of filters and oscillators. Sound is created from no mass at all. It is just a group of equations which express functions of time and there are not any other data necessary. Synthesisers produce audio waveforms with dynamic shape, spectrum and amplitude characteristics. They may be generated for sounds corresponding to real instruments like drums, bass guitar or piano, or for completely imaginary ones. The combination of sequencers and synthesisers is mainly responsible for the genre of techno and dance music but can produce ambient backgrounds too. Synthesisers also play a non-musical role for creating sound effects like rain, wind, thunder or more specific car noises like bump caused by road surface etc. The power of synthetic sound is that it has an unlimited potential, just as long as you know how to figure out the equations needed for a certain sound.

8.1 Effects

Generating interactive effects such as echo, reverberation and Doppler shifts are considered as standard in today's software for sound creation. For example many Windows based software applications generate these effects using Microsoft DirectSound. These effects can greatly enhance the perception of 3D sound, with an example being the Doppler shift due to a passing vehicle.

8.1.1 Doppler Effect

Also called Doppler shift is the change in frequency of a wave(or other periodic event) for an observer moving relative to its source. It is named after the Austrian physicist Christian Doppler, who proposed it in 1842 in Prague. It is commonly heard when a vehicle sounding a siren or horn approaches, passes, and recedes from an observer. Compared to the emitted frequency, the received frequency is higher during the approach, identical at the instant of passing by, and lower during the recession (Figure 34).

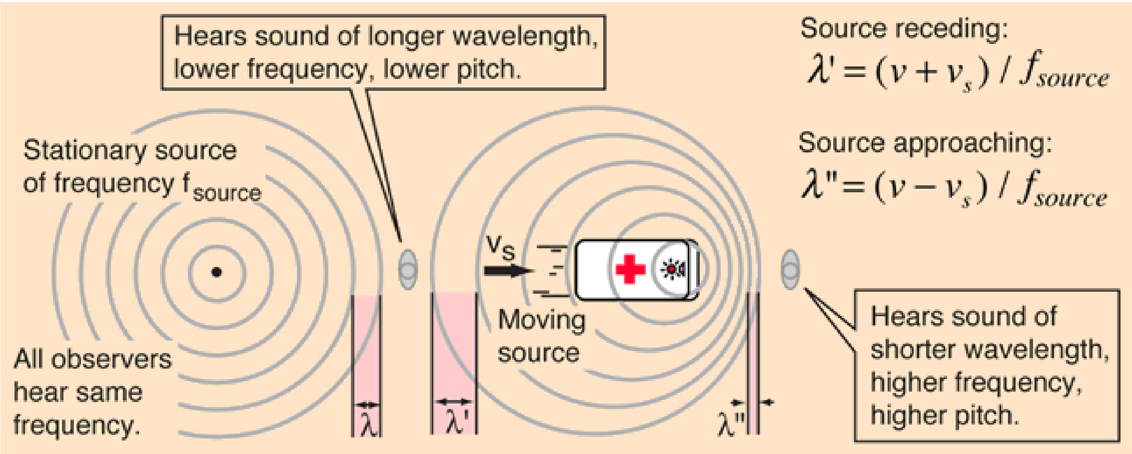


Figure 34: Doppler Effect wavelength calculation [9]

When the source of the waves is moving toward the observer, each successive wave crest is emitted from a position closer to the observer than the previous wave. Therefore, each wave takes slightly less time to reach the observer than the previous wave. Hence, the time between the arrivals of successive wave crests at the observer is reduced, causing an increase in the frequency. While they are travelling, the distance between successive wave fronts is reduced, so the waves "bunch together". Conversely, if the source of waves is moving away from the observer, each wave is emitted from a position farther from the observer than the previous wave, so the arrival time between successive waves is increased, reducing the frequency. The distance between successive wave fronts is then increased, so the waves "spread out"[9].

8.2 Pure Data

Pure Data (Pd) is a visual signal programming language which makes it easy to construct programs operating on signals. The primary application of Pure Data is processing sound, which is the point what it was designed for. However, it has grown into a general purpose signal processing environment with many other uses. There is a very powerful idea behind "The diagram is the program". Each patch created in Pure Data contains its complete state visually so you can reproduce any example just from the diagram. That makes it a visual description of sound. Pure Data has a strong and diverse community of people around it: media artists, developers, researchers, musicians, etc. [10]

It uses a kind of programming called dataflow, because the data flows along connections and through objects which process it. The output of one process feeds into the input of another and there may be many steps in the flow. Dataflow graph is navigated by the interpreter to decide when to compute certain operations. This traversal is right to left and depth first, which is a computer science way of saying it looks a ahead and tries to go as deep as it can before moving on to anything higher and moves from right to left at any branches. This is another way of saying it wants to know what depends on what before deciding to calculate anything. Although we think of data flowing down the graph the nodes in Figure 35 are numbered to show how Pd really works with diagrams and their inputs.

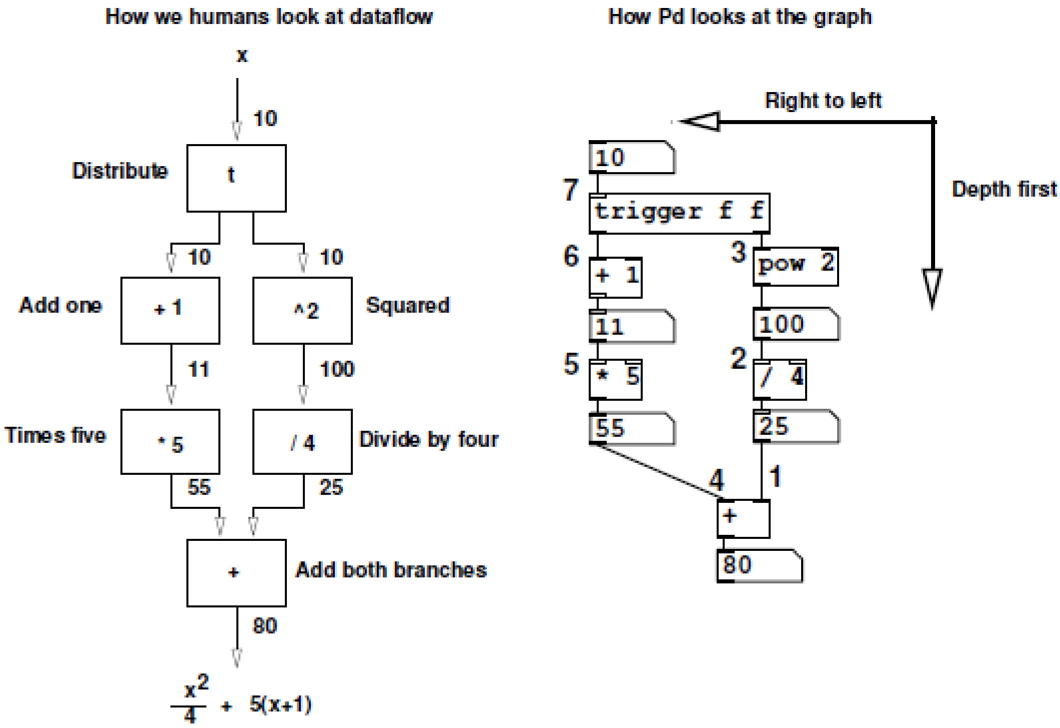


Figure 35: Pure Data diagram orientation and data flow [10]

8.2.1 Pd software architecture

Pure Data actually consists of more than one program. The main part called pd performs all the real work and is the interpreter, scheduler and audio engine. A separate program is usually launched whenever you start the main engine which is called the pd-gui. This is the part you will interact with when building Pure Data programs. It creates files to be read by pd and automatically passes them to the engine. There is a third program called the pd-watchdog which runs as a completely separate process. The job of the watchdog is to keep an eye on the execution of programs by the engine and try to gracefully halt the program if it runs into serious trouble or exceeds available CPU resources. The context of the pd program in terms of other files and devices is shown in Figure 36.[10]

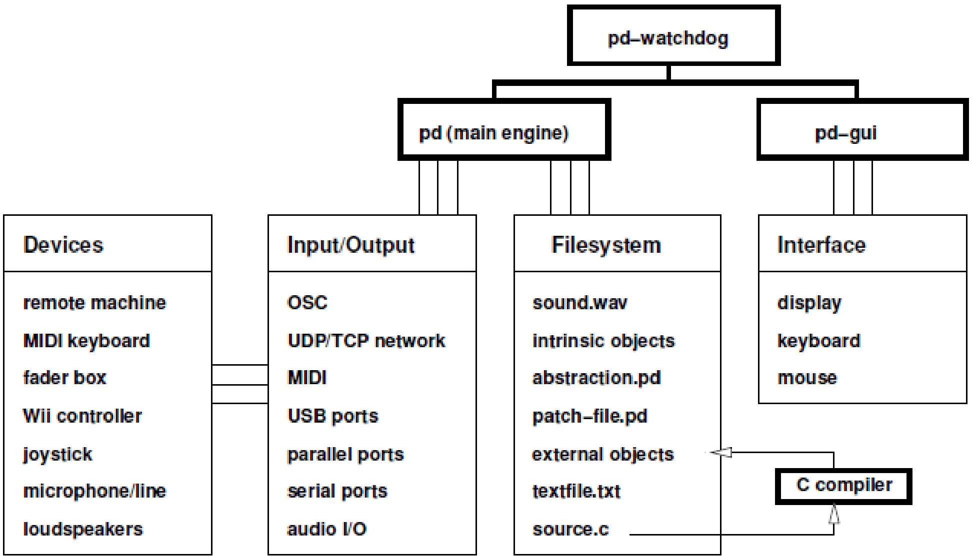


Figure 36: Pure Data diagram software architecture [10]

There are many examples and tutorials how to work in pure data for different types o simulations or sound synthesis. The main aspect why is this programming language so largely utilized is that you can use many prepared GUI boxes and attach any parameter to work with.

9 Sound module

As a result of all obtained sounds is a proposal of sound module. There are two different ways how to simulate the car sound for the simulator in the CTU. First approach is to make synthesis of artificial noises, created as a mathematical function of signals and frequencies. It means that Pure Data library have to be fully implemented for this simulator. Second approach is to use a combination of recorded sounds and synthetic sounds. For both approaches have to be considered that the simulator sends data about simulated drive each 1 millisecond and cause a huge dataflow. If it would be used in real time application for simulator it would cause the time latency. The output data structure from the simulator is shown in table 3, where rows stands for:

1. # Index
2. Time[ms]
3. Position in X coordinate [m]
4. Position in Y coordinate Y[m]
5. Position in Z coordinate [m]
6. Roll
7. Yaw
8. Pitch
9. Speed[m/s]
10. RPM
11. 0 (Synchro[#])
12. 0 (City[#])
13. 0 (Timeline[#])
14. Light State
15. Steer
16. Throttle
17. Brake
18. 0 (Clutch)
19. Gear

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
6359	12718	-28.685675	0.538967	36.736748	-2.140505	35.208523	1.033773	10.231740	3972	0	0	0	0	-233	767	0	0	1
6360	12720	-28.701506	0.538976	36.749111	-2.142677	35.276169	1.034463	10.240767	3975	0	0	0	0	-233	767	0	0	1
6361	12722	-28.717337	0.538985	36.761505	-2.144803	35.343925	1.035155	10.249801	3979	0	0	0	0	-233	767	0	0	1
6362	12724	-28.733168	0.538994	36.773926	-2.146892	35.411789	1.035849	10.258842	3982	0	0	0	0	-233	767	0	0	1
6363	12726	-28.748999	0.539002	36.786373	-2.148953	35.479763	1.036544	10.267886	3986	0	0	0	0	-233	767	0	0	1
6364	12728	-28.764830	0.539010	36.798851	-2.150993	35.547848	1.037241	10.276935	3990	0	0	0	0	-233	804	0	0	1
6365	12730	-28.780661	0.539018	36.811359	-2.153019	35.616013	1.037939	10.285986	3993	0	0	0	0	-233	767	0	0	1
6366	12732	-28.796490	0.539026	36.823898	-2.155034	35.684284	1.038639	10.295040	3997	0	0	0	0	-233	767	0	0	1
6367	12734	-28.812317	0.539030	36.836460	-2.156992	35.752644	1.039321	10.304095	4000	0	0	0	0	-233	767	0	0	2
6368	12736	-28.828136	0.539032	36.849049	-2.158901	35.821053	1.040021	10.267847	3175	0	0	0	0	-233	743	0	0	2
6369	12738	-28.843948	0.539032	36.861660	-2.160774	35.889519	1.040742	10.265871	2762	0	0	0	0	-233	767	0	0	2
6370	12740	-28.859755	0.539029	36.874298	-2.162616	35.958069	1.041472	10.269644	2556	0	0	0	0	-233	767	0	0	2
6371	12742	-28.875555	0.539023	36.886959	-2.164429	36.026695	1.042198	10.274409	2454	0	0	0	0	-233	767	0	0	2
6372	12744	-28.891346	0.539014	36.899647	-2.166215	36.095383	1.042908	10.279416	2403	0	0	0	0	-233	780	0	0	2
6373	12746	-28.907131	0.539002	36.912357	-2.167973	36.164120	1.043597	10.284540	2379	0	0	0	0	-233	767	0	0	2
6374	12748	-28.922911	0.538987	36.925091	-2.169704	36.232941	1.044265	10.289733	2367	0	0	0	0	-233	780	0	0	2
6375	12750	-28.938683	0.538968	36.937851	-2.171412	36.301788	1.044913	10.294950	2361	0	0	0	0	-233	780	0	0	2
6376	12752	-28.954447	0.538947	36.950638	-2.173098	36.370720	1.045543	10.300167	2359	0	0	0	0	-233	804	0	0	2
6377	12754	-28.970203	0.538923	36.963448	-2.174764	36.439705	1.046158	10.305375	2359	0	0	0	0	-233	780	0	0	2
6378	12756	-28.985952	0.538897	36.976280	-2.176413	36.508743	1.046759	10.310571	2359	0	0	0	0	-234	780	0	0	2
6379	12758	-29.001696	0.538867	36.989140	-2.178049	36.577839	1.047349	10.316664	2360	0	0	0	0	-234	767	0	0	2
6380	12760	-29.017431	0.538836	37.002026	-2.179675	36.646988	1.047928	10.321807	2361	0	0	0	0	-234	780	0	0	2
6381	12762	-29.033159	0.538802	37.014935	-2.181294	36.716190	1.048497	10.326817	2362	0	0	0	0	-234	780	0	0	2
6382	12764	-29.048880	0.538766	37.027870	-2.182908	36.785450	1.049058	10.331829	2363	0	0	0	0	-234	791	0	0	2
6383	12766	-29.064592	0.538727	37.040829	-2.184517	36.854763	1.049612	10.336861	2365	0	0	0	0	-234	780	0	0	2

Table 3: Output data structure from the CTU simulator

The most significant change in dataflow from simulator, which affects the noise perception of the driver are rotates per minute (RPM). Therefore it will be the main aspect to create ranges of samples, when the recorded sample will be played. Ranges for RPM are: 700-1300, 1301-1600, 1601-1750, 1751-2000, 2001-2100, 2101-2350, 2351-2700, 2701-4000. Lower RPM’s are just damping the sound to lower volume, higher RPM’s are increasing output volume.

9.1 Synthetic sound module

Sound module created with Pure Data is shown in Figure 37. Main controllers in this module are the “RPM bar” and the “Pedal bar”, which are affecting a “Last bar”. Input for RPM is number from 680 – 8000 which corresponds to output from the simulator. Pedal bar is just checking if gas pedal is pressed to know if a volume of the car noise has to be increased or decreased (Figure 38)

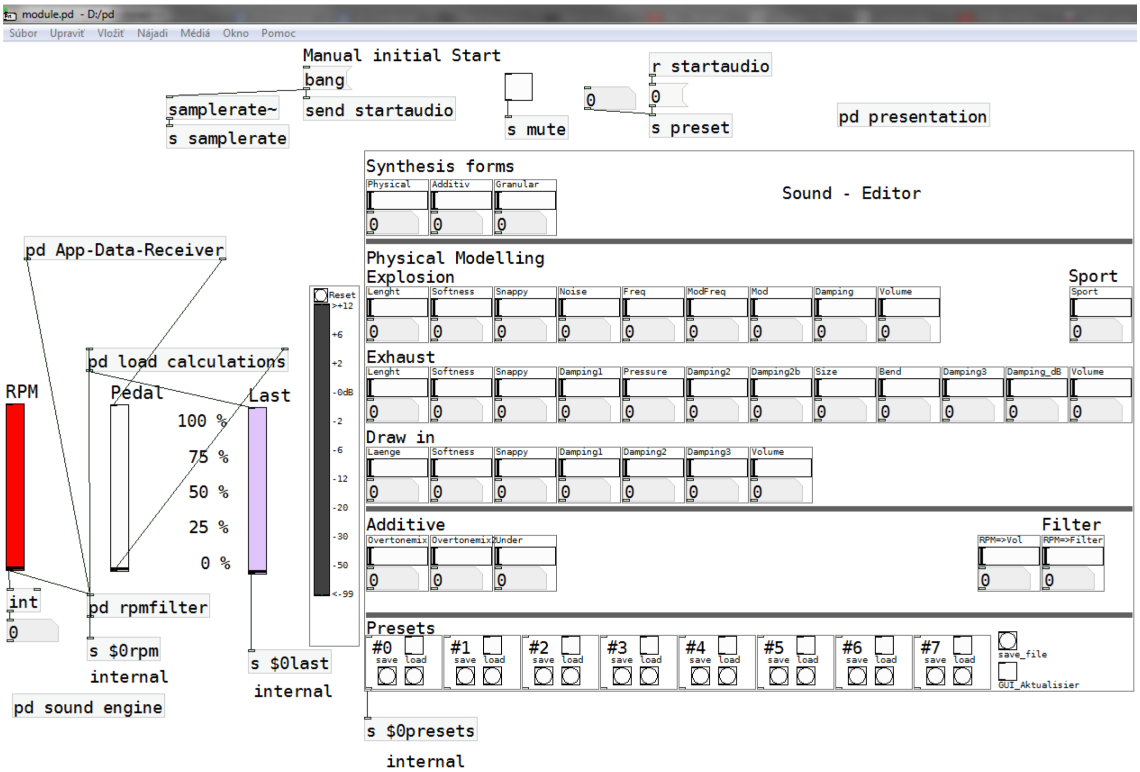


Figure 37: Sound module for generating synthetic sounds

In a column “pd App-Data-Receiver” is hidden following diagram, which shows that only those two parameters of rpm and pedal pressed/not pressed are taken into consideration. All others have to be synthesized.

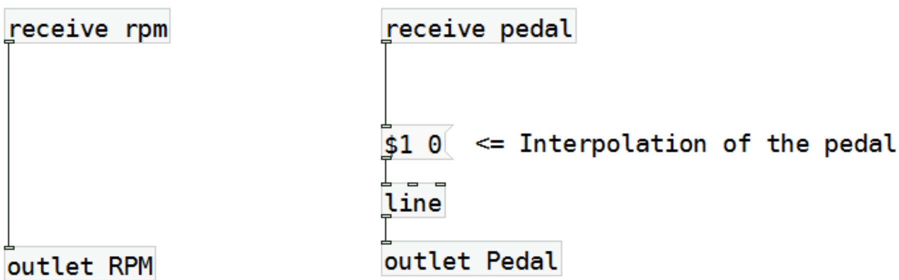


Figure 38: Input and output data for RPM and Pedal position

Dependence between RPM bar and Pedal bar is calculated by a "column" named "pd load calculations" shown in Figure 39, where are data from "pd rpmfilter", pedal and "pd App-Data-Receiver" encountered.

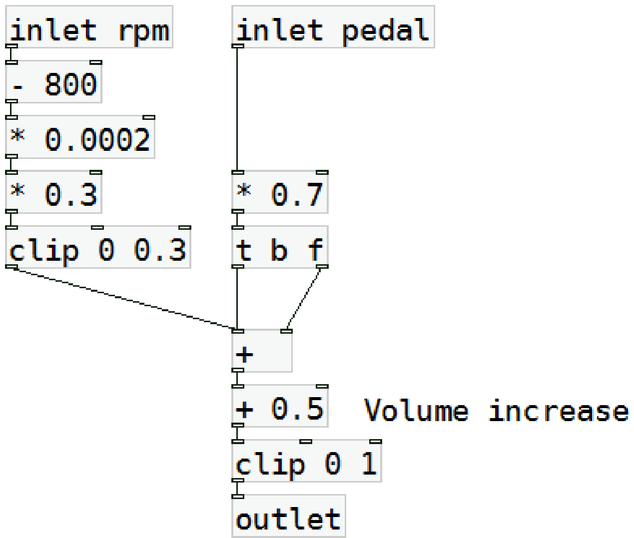


Figure 39: Dataflow in diagram "pd load calculations"

There have also been created three different physical models with several parameters to simulate the engine noise more realistic. Models are: Explosion, Exhaust and Draw in and their detailed diagrams are shown in Appendix A. Advantage of this diagrams are that if any change in creation of sounds are needed everything might by removed or relocated.

When a specific situation needs to be synthesized you can easily add new "column" and create a new filter for generated sound. Results then might be very impressive from a simulation of historical car or sports cars to fancy horn noises creation etc.

9.2 Sample based module

Second module is based on composition of sounds recorded in different places (e.g. outside of car, recording studio or inside of car). The samples of maximal length of one second are looped and reproduced from loudspeakers dependent on actual speed of car and growing or descending RPM. The maximum length is set to one second for keeping latency of sound response authentic with real drive in a car. Data from simulator of CTU needs to be adjusted before using them for this sound module. Those data are then averaged to find out mean value of speed and RPM and used for the module each one second to play correct sound sample. Also rising and decreasing of those values before adjustment the data is observed and influence, which sound sample will be played to ensure the closest simulation of the real car drive. Recorded samples can be found in Appendix B.

10 Conclusion

The main aim of this thesis is to propose and subsequent to create a sound functioning block also called the sound module, which generates the sound for vehicle simulators. To fulfill this task, it was necessary to obtain appropriate sound samples, analyze them and postprocess to the form which is the closest to the reality.

In the first chapters of this thesis I summarized the theoretical bases, which were necessary for the fulfillment of the tasks. First of all, there had to be outlined the basics between sound and noise, physics of sound to introduce eight main parameters of sound. Further chapters are focused on sound propagation and human perception. Three methods for modeling the sound generation were introduced, which are crosstalk cancellation, multiple speakers modeling and Head Related Transfer Function. Multiple speakers were used for reproduction of created noises.

After this brief introduction into problematic of sound I could advance to the vehicle simulators and different types of them to show what the requirements for sound module for those simulators are. Also the vehicle simulator in the joint laboratory of system reliability in Czech Technical University, Faculty of Transportation Sciences was introduced.

The most important chapter for whole thesis creation is the analysis of car noises. Without deep analysis of sound it would be impossible for me to understand connections between the sounds which need to be recorded or created for further use in the sound module. The main categories of noises were evaluated as: engine noise, tire noise, wind noise, exterior noise and pass-by. These categories can be used for simulation of any vehicle (car, bus, truck, motorcycle, etc…). Transmission paths specific for each vehicle will give us the importance of each noise category to set the major parameter which will influence changes in generated sound. In this case for simulation of a car drive I chose RPM and pedal position (pressed / not pressed).

Chapter seven is dedicated to recorded sound. Different methods of recording and their comparison is shown to come to the thought that the best records are from music studio but in these conditions car have to be standing and it is not possible to simulate an engine load.

Only way how to fulfill all requirements for appropriate sound generation is to create own synthetic sound. Synthetic sound is just a group of equations which express functions of time. Therefore it is much easier to simulate some effects common for transportation as echoes in tunnel or ambulance sirens wailing than to manually record them in a tangle of different noises produced by car or its surroundings.

The end result of work is the sound module application created with Pure Data programming language, which can simulate different situations using simple bars (rpm and pedal) and samples to create specific sound for all eight channels. Loudspeakers than reproduce this sound for every channel and create sound field in the cabin of the car simulator.

It looks that the future in simulation of sounds and noises connected with means of transport is in synthetic sound generation, but I still think that in some cases are recorded sounds still needed. Those are special types of noises which are not affected by other noises e.g. engine starting, gear shift, etc. Final conclusion to obtain the most realistic sound simulation of the car drive is to combine synthetic noises with recorded noises.

Next development of this thesis may lead to creation of a mobile application used for commercial use in real vehicles. As today’s regulations push producers of cars to reduce the petrol consumption, which is equal to engine cubage and radical change in sound effect of a car, this application can become a “bottleneck” on the market.

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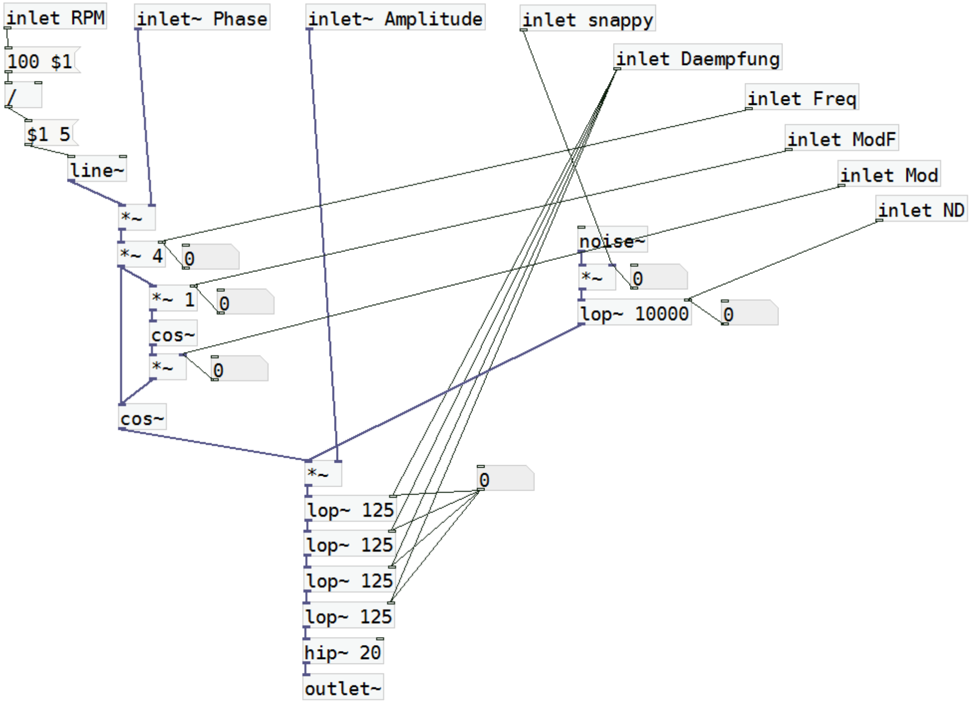
List of Abbreviations

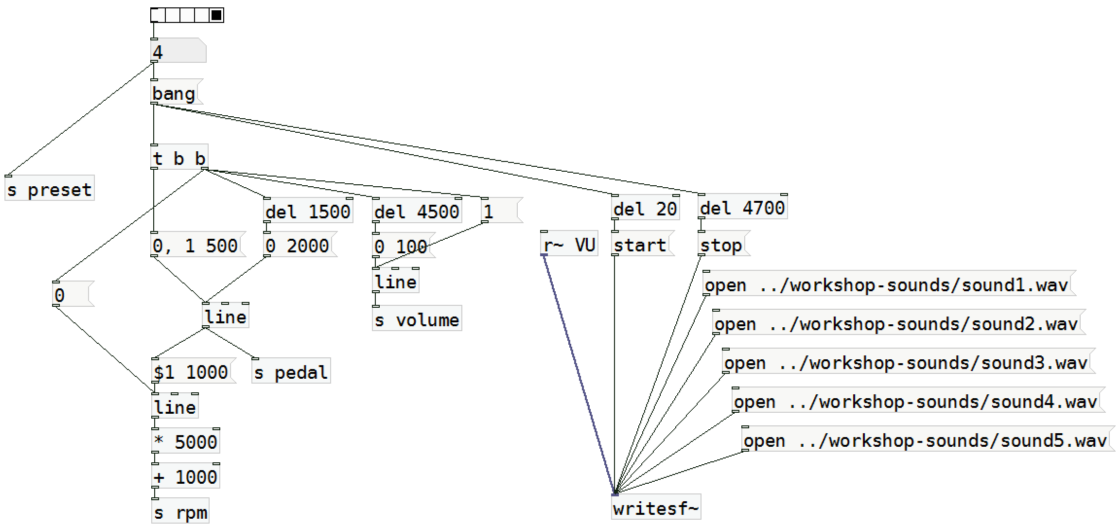
Abbreviation	Full Name
HRTF	Head Related Transfer Function
HATS	Head and Torso Simulator
HRIR	Head Related Impulse Response
FFT	Fast Fourier Transform
CTU	Czech Technical University
CEDSS	Communication Engine for the Distributed Simulation Systems
RPM	Rotations Per Minute
NVH	Noise Vibrations Harshness
LSS	Joint Laboratory of System Reliability
PD	Pure Data
GUI	Graphical User Interface

Appendix A

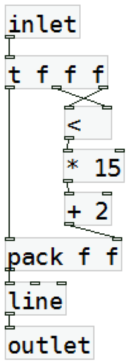
Explosion



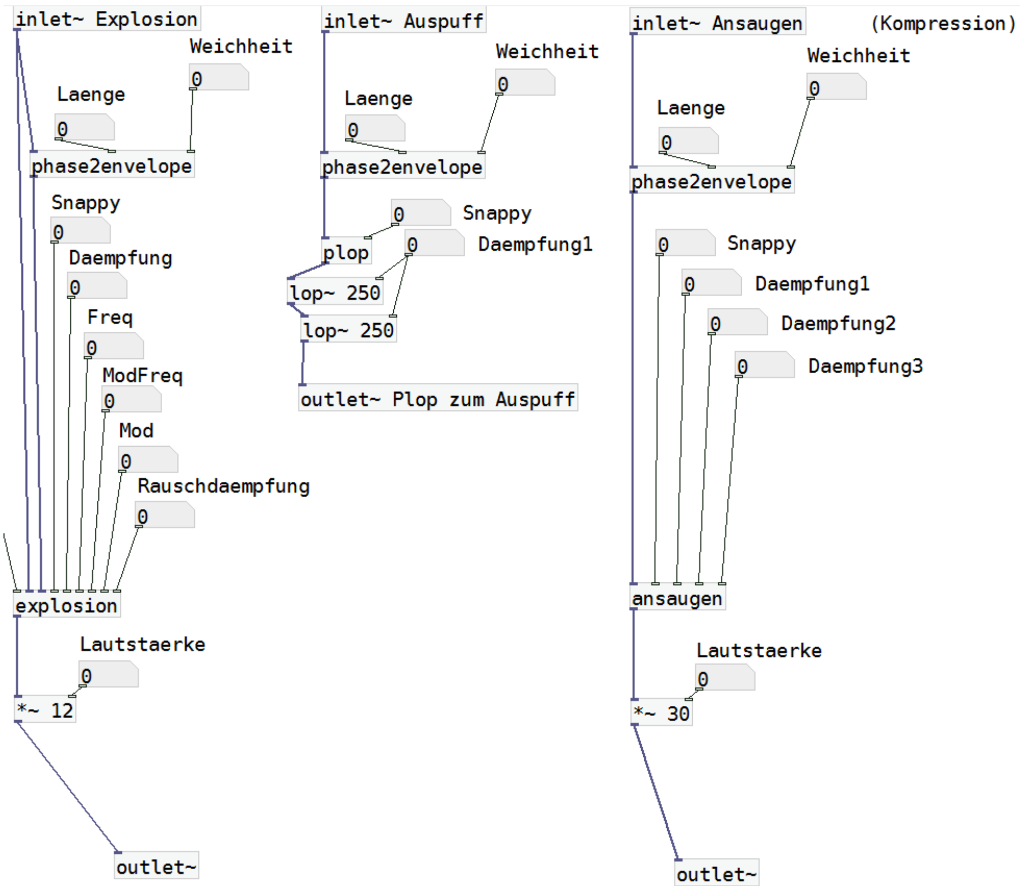
Pd presentation



Pd rpmfilter



Physical modules



Appendix B

Examples of recorded sounds, which were used for the simulator, are shown in the list below. As the uncompressed sound has a large file size only the most important were attached.

..\sounds\battery_position.wav

..\sounds\music_studio.wav

..\sounds\music_studio_stable.wav

..\pd\700.wav

..\pd\1300.wav

..\pd\1600.wav

..\pd\1750.wav

..\pd\2000.wav

..\pd\2100.wav

..\pd\2350.wav

..\pd\2700.wav

..\pd\4000.wav