Implementation of a Validation Environment for an Emotionalizing Sound Design in a Driving Simulator

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Abstract *– Active sound design is an emerging feature in premium electric vehicles, aimed at elevating the driving experience's emotional aspect. Musicology research has shown that emotions can be influenced by certain harmonic pitches and acoustical characteristics, while traffic psychology studies indicate emotions can impact driving behaviour. Surprisingly, little research has explored how modifying a vehicle's active sound affects driving behaviour. To investigate the impact of an emotionalizing vehicle sound on driving behaviour, a study with subjects needs to be conducted in a static driving simulator. This controlled environment ensures reproducible results and precise manipulation of driving scenarios. This paper details the validation environment's implementation for studying the effects of emotional sound design in a driving simulator. Initially the methodology for the developed sound design and the driving simulator study based on the IPEK X-in-the-Loop approach is described. It describes the necessary data output from the simulator, and the software interface connecting the sound generator to the driving simulator. The challenges of integrating an external sound speaker for a realistic soundscape and aligning vehicle sound with simulator dynamics are discussed. The paper also addresses data collection for evaluating driving behaviour and the impact of sound design on safety distances.*

Keywords: *Active Sound Design, Acoustics, Static Driving Simulator, Traffic Safety.*

Introduction

Vehicle cabin sounds have transitioned from unintentional noise to meticulously crafted audio in recent decades. This transformation results from both primary actions, such as modifying the powertrain system's design, and secondary approaches, including the installation of acoustic damping materials in component housings or the chassis. These measures aim to modify the spectral composition of cabin noise. In the last twenty years, NVH (Noise, Vibration, and Harshness) engineers have also introduced active sound design (ASD) to further refine a vehicle's auditory experience. ASD was primarily utilized to recreate specific acoustic qualities lost during engine downsizing or to enhance the perceived power and sportiness of the vehicle [Fuc16]. Given the distinct acoustic behaviour of battery electric vehicles, ASD may play an even more significant role [Tsc15]. While drivers appreciate the reduced noise in comparison to internal combustion engine vehicles ICEVs, they still value appropriate ASD for feedback [Fie15]. Pilgerstorfer et al. even suggested that the absence of acoustic feedback in electric vehicles might contribute to increased speeds in certain situations [Pil13]. Additionally, ASD can reintroduce the emotional aspect often lacking in the high-pitched sound of electric drives compared to traditional internal combustion engines [Cha16]. Current ASD research predominantly centres on enhancing sound fidelity, evaluating customer perceptions, and addressing implementation. Petersen et al. have introduced a novel research direction known as suggestive sound design (SSD) within the ASD field. This concept assumes that drivers rely on vehicle sounds for feedback and that these sounds inherently possess emotional characteristics, allowing modifications to actively influence and alter driving behaviour. [Pet21]. The suggestive sound design aims to increase the safety distance chosen by the driver and thus traffic safety by changing the sound when reaching insufficient levels of safety distance to a threatening sound design.

To determine the most suitable sound for suggestive sound design for electric vehicles and to validate the inherent emotional character and its emotionalizing impact, we created diverse emotionalising sounds based on proven emotionalising harmonic structures with professional tools and conducted an online listening experiment involving 45 participants. Additionally, the correlation between the sound perception of the participants and the analysis of psychoacoustic characteristics associated with the sounds were analysed to identify objective sound features that could potentially enhance specific emotional effects. This information was pivotal for optimizing the sounds for the subsequent validation phase of a suggestive sound design (SSD) [Pet23]. We then created new optimized versions of these sounds based on the found correlations, with our own sound generator developed for providing an active sound design based on the current vehicle status and an emotionalising stimulus based on the current safety distance. In a second study with 160 participants that is yet to be published we revaluated these sounds, and investigated, whether they influence the estimation and evaluation of safety distances shown in videos. For the investigation of the effects of an emotionalizing vehicle sound on the actual driving behaviour, a study with subjects needs to be conducted. The study is was conducted in a driving simulator, to ensure that the test environment delivers reproducible results, and guarantees a high level of control over the necessary driving scenario aspects, including traffic behaviour and weather conditions. The driving simulator is a static driving simulator from the Würzburg Institute for Traffic Sciences GmbH, and uses the inhouse SILAB simulation software [Wiv23]. For the sound design, a sound generator was developed in Native Instruments Reaktor 6, that is able to change its sound and thus the emotional character drastically based on real-time vehicle and traffic conditions. This paper will be about the implementation of the validation environment for the effects of an emotionalizing sound design in a driving simulator to enable the study. Initially the methodology for a validation of the sound design and the driving simulator study based on the continuous validation approach and the IPEK X-in-the-Loop approach is described. Further the necessary outputs from the driving simulator are discussed, and how they are translated and transmitted to the sound generator by a python software interface. Additionally, the necessary postprocessing and combination of vehicle parameters, to provide a continuous and artefact free generation of the active sound and the sound changes based on the traffic conditions are discussed. In the next step, the integration of an external sound speaker into the driving cabin is described, to provide a realistic soundscape. In the final part, the challenges of fitting the vehicle sound to the vehicle dynamics perceived in the driving simulator, as well as tackling the challenges of the acoustical environment of an open cabin driving simulator with its own sound elements as well as background noise will be described. In the last step, the vehicle and traffic data are discussed, that needs to be recorded to evaluate the general driving behaviour of the subjects, as well as to quantify the effects of the sound design on the chosen safety distance in a later stage.

State of Research

The driver's assessment of the ongoing driving situation encompasses various sensory inputs. Roach et al. demonstrate that the perceptual system strategically integrates information from multiple senses, including visual and auditory cues, to optimize the accuracy of the current situation assessment [Roa06]. Several studies have explored how modifications in auditory stimuli, such as volume [Hor08], [Hel11], or the frequency composition [Wan12] of the vehicle's engine noise, can impact the evaluation of driving speeds. This highlights the potential of an active sound design as a tool for enhancing driving feedback. Furthermore, it underscores that sound, in general, and ASD specifically, can quantifiably influence safety-related factors like speed estimation. ASD has the potential to serve as a means of communication between the vehicle and the driver or conveying the present status of the vehicle.

The suggestive sound design [Pet21] is developed utilizing the continuous validation approach in accordance with Albers et al. The continuous validation includes the definition of the validation objective, the selection of suitable validation or test environments and the definition of test cases. A validation environment (VE) is a concrete manifestation of the operation system for validation in terms of methods and the resource system for one or more combinations of a product, a moment in the product life cycle and a validation goal [Alb14]. The validation tests whether the system is suitable for its intended use or achieves the desired value. This includes driving manoeuvres and test cases, the driver and the rest of the vehicle in an X-in-the-loop environment [Alb14]. The necessary transformation of the subsystem behaviour into the overall system behaviour can be realised with corresponding residual system models that represent the necessary interactions within the overall system. The X-in-the-loop framework initially describes a consistent and integrated development environment for drive systems. The IPEK-X-in-the-Loop (IPEK-XiL) approach according to Albers takes up the established approaches (Model-in-the-Loop, Software-in-the-Loop, Hardware-in-the-Loop), integrates the respective advantages and consistently expands them to include the concerns of mechanics or mechatronics as well as developers from different disciplines. It initially referred exclusively to the testing of ECUs and ECU functions, but already consistently integrated "the actors" driver and environment. [Alb10] In terms of the different concrete validation activities, two different views of the "X" can be derived from this. On the one hand, and predominantly, the "X" is understood as a (partial) system that is under development or for which a developer is responsible. This is therefore defined from the point of view of a developer or a development team and is referred to as the system-in-development (SiD). The focus is primarily on the fulfilment of properties or functions. A second view arises when the focus is not on the development of a subsystem, but on the acquisition of knowledge about a subsystem for further use in the development process. In this context, the term system-under-investigation (SuI) is more appropriate. Accordingly, the SuI can be a part of the SiD or it can be the entire SiD. In some cases, the SuI can also be located outside the SiD, for example, if knowledge about the neighbouring systems is to be gained with the aim of being able to better map them for validation. [Alb16]

The driving simulator used as the validation environment is a static driving simulator from the Würzburg Institute for Traffic Sciences GmbH, and uses the inhouse SILAB simulation software. It is based on a VW Golf 6 automatic. Unlike the original vehicle, the simulator has a speedometer display and centre console display, and the mirrors have been replaced by displays. A curved screen and three projectors provide a 180-degree field of vision. Test tracks can be realised with the simulation software SILAB 7.0®. [Ehr23] The software also provides users with the capability to simulate the dynamics of the virtual vehicle, interactions with other road users, environmental conditions, and vehicle-related noises in a realistic and adaptable manner. This simulation platform allows for the monitoring of numerous parameters throughout the simulation process, including the recording and processing of driving parameters. Additionally, the software offers the integration or connection of external hardware or software components, such as our Sound Generator into the simulation via dedicated software interfaces [Wiv23]. As the suggestive sound design needs to be controlled by the external signals from the driving simulator, there needs to be a connection between the simulation software, and the sound generator. The SILAB software offers different options to realize such a connection via so called Data Processing Units (DPUs) which can be understood as separate software modules processing and or sending and receiving different kinds of data available in the driving simulator. These DPUs can be realised with an internal scripting language, or different programming languages like Python, C++, Java and MATLAB/Simulink. The processed data can then be sent internally to other programs on the simulator computers, or to external hardware via USB or ethernet.

In general, a vehicle's sound, stemming from its powertrain, is primarily influenced by two factors: engine RPM and engine torque. This holds true for both traditional internal combustion engine vehicles and electric vehicles, although the latter operates in higher-frequency domains. The fundamental element of our active sound design approach is an additive synthesizer featuring multiple oscillators capable of producing a Shepard-Risset-Glissando (SRG) reminiscent sound. [Pet21] Shepard-Risset Glissando is a psychoacoustic effect developed by psychologist Roger Shepard to prove his thesis of circular pitch perception [She64]. This approach sidesteps the challenges associated with creating a sound that corresponds proportionally to the broader RPM range of an electric vehicle. The SRG offers us the flexibility to define the frequency range for our vehicle sound while accurately representing changes in motor RPM through perceived pitch variations. The objective is to create a sound that is convincingly realistic for use as feedback. [Pet21] The rising or falling SRG, associated with forward and backward motion, effectively mirrors the vehicle's acceleration and deceleration. Denjean et al. even tested this sonification strategy in a perceptual test in a driving simulator and showed that the mapping of this acoustical feedback affects the drivers' perception of vehicle dynamics [Den21]. To enhance the overall immersion of the vehicle sound, it must exhibit a distinct timbre associated with the specific vehicle being simulated. It should strike a balance, avoiding excessive harmonics or frequency components to prevent noticeable changes in intervals or chords. [Pet21] The sound pressure level inside the cabin should further resemble real existing electric vehicle, which range between 58 and 68dB(A) according to [Swa16]. The sound generation process is realized within the Native Instruments Reaktor 6 platform, a visual audio programming language facilitating the creation of sound generators, instruments, or effects. These elements can be controlled through the Open Sound Control (OSC) protocol, a network-optimized communication protocol for multimedia devices. The sound generator is structured in a modular design, comprising the SRG basic framework, an additive synthesizer module, and a suggestive module. This separation serves to differentiate the behavioural aspects of the vehicle sound functions from the sound generation process. The sound generator features inputs receiving data from a vehicle via OSC: e.g. engine torque, engine RPM, and safety distance. Its output signals serve as control signals for the sound-generating modules, encompassing amplitude and frequency signals. These amplitude signals regulate the glissando elements' volume, while the frequency signals control their pitch. Additionally, the processed driving state variables, including torque, speed, and acceleration, offer the opportunity for driving state-dependent adjustments to the final audio signal using effects or filters. The suggestive module consists of the possibility of changing the fundamental chord of the sound design to a more threatening harmonic structure. This all happens proportionally to the lowering of the current safety distance, to create the influencing stimulus. [Pet21]

For enabling the evaluation of driving styles in regards to aggressiveness based on different driving measures Sagberg et al. conducted a literature review, that provides different examples of specific driving styles and related measures, grouped in categories. [SAG15]

Research Methodology

The general research methodology for the validation process of the suggestive sound design during the development process is based on the continuous validation approach and the IPEK X-in-the-Loop approach described in the state of research [ALB10, ALB14, ALB16]. The continuous validation in this case is always done via studies with subjects in different validation environments catered to the different stages of the development of the suggestive sound design. The approach is here to steadily validate the developed emotion-stimulating sounds at different system levels (degree of maturity) for identifying the most suitable and most affective sounds, while enabling an optimization of these sounds to develop them into a fully functional dynamic active sound design. At the same time, we are continuously increasing the use case affinity (e.g. level of realism) and the composition (virtual, mixed virtual physical, physical) of the validation environment throughout the validation process to increase the validity of the resulting findings. This is done by moving from an abstract, purely virtual validation environment to a very realistic, purely physical one. Initially the auralised sounds are evaluated with headphones and the mental setting of sitting in a vehicle while listening to the sounds. In the next step, they are accompanied by videos resembling driving and traffic scenarios. And finally, in the last virtual validation step, the subjects sit in an immersive driving simulator. The final validation step would be conducted with the sound design implemented in an actual vehicle, driving in real traffic. A representation of this overall methodological framework can be seen in figure 1.

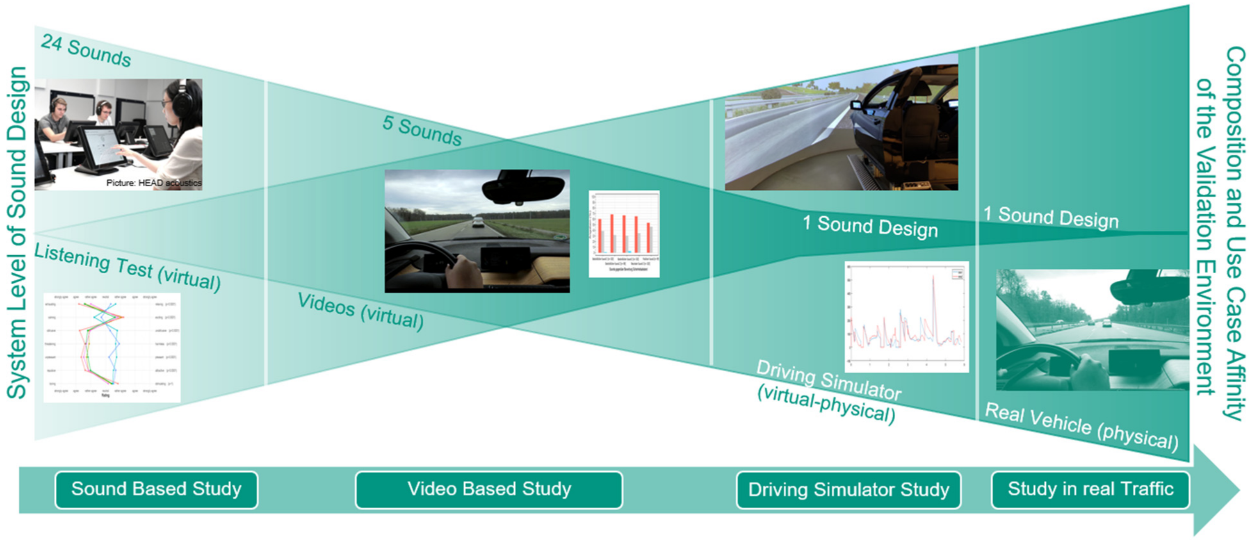

Figure 1. Continuous validation approach for the suggestive sound design.

In regards to the driving simulator study based on the IPEK X-in-the-Loop approach [ALB16] we have the suggestive sound design as the system-in-development, since the main goal for the overall research is to develop a sound design that is able to influence a driving person towards a more save driving behaviour. The system under investigation during the validation is the driver itself, since their reaction is the foundation to validate the ability of the sound to influence the driving behaviour. In the former studies, the focus was the stated reaction of subjects regarding how the sound design affects the emotions of the perceiving person, and how and if it influences their evaluation and estimation of different displayed safety distances. For the study in the driving simulator, the actual driving behaviour itself is the main focus in the SuI driver. This enables us to observe, if a dynamically changing active sound design is working as an emotionalizing stimulus that actually can influence the driving behaviour in certain driving scenarios. The validation environment consists of the vehicle (including the implemented active sound design) that was driven by the driver in the driving tasks, as well as the virtual environment and driving scenario for the study. An overview of the simulator study in accordance to the IPEK X-in-the-Loop approach can be seen in figure 2.

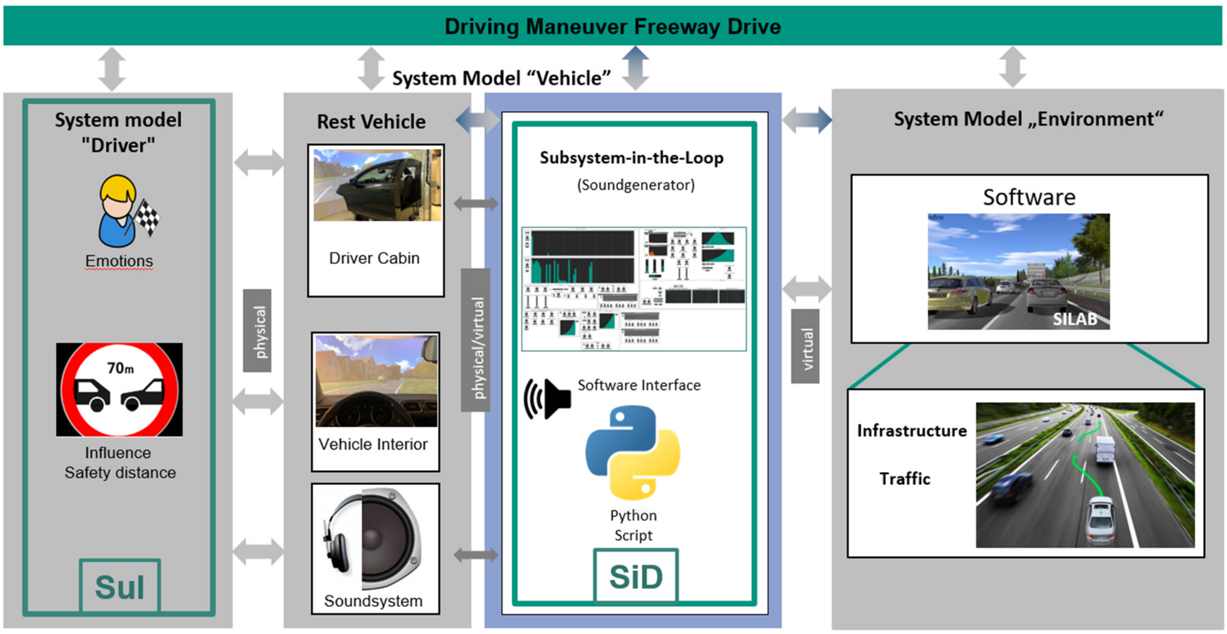

Figure 2. Driving simulator based validation environment for the suggestive sound design after IPEK X-in-the-Loop approach.

Implementation of the Validation Environment

This chapter describes the implementation of the validation environment consisting of an emotionalizing sound design implemented in a driving simulator to enable a study with subjects. The implementation consists of 4 major aspects. Firstly, the connection of the sound generator to the simulator to be able to dynamically generate an active sound design based on the current vehicle status, and further to control the emotionalizing stimulus based on the current distance between the driven ego vehicle and other traffic participants. Secondly, the proper acoustical integration of the sound design into the vehicle so that the driver can hear it while driving and perceives it as a natural part of the vehicle he is driving. Thirdly, the tuning of the behaviour of the sound generator to the vehicle status, so it properly matches what the driver perceives visually while driving. And lastly the determination of the driving parameters that provides an evaluation of the driving behaviour in general and whether it was altered by the addition of the emotionalizing stimulus.

Connection of the Driving Simulator and the Sound Generator

The first step for the implementation of the validation environment is to build a connection and an interface between sound generator and the driving simulator that can transmit the necessary real-time data from the vehicle and the virtual environment to the sound generator. For creating the general sound design, primarily two parameters are necessary: the motor RPM, and the motor torque. The RPM is used to change the frequency pitch of the sound design according to the current RPM. And the torque is utilized to give a better feedback for the current performance level of the vehicle. The vehicle model available in the driving simulator resembled a 6-gear automatic vehicle with a combustion engine. Since our goal is to develop the sound design for electric vehicles, the continuous gear shifting causes the RPM to not rise steadily with rising velocity, but only rising till the transmission shifts into a new gear. To circumvent this problem, we chose the velocity of the vehicle as a foundation to approximate an electric vehicle RPM that we can use for the sound design. Further another problem was, the simulator did not offer the motor torque as an accessible and processible parameter. To still be able to offer a feedback about the current performance level, we used the current longitudinal acceleration of the vehicle as substitute for the torque. Although the acceleration does not fully represent the motor torque by containing the inertia force of the vehicle, it sounded sufficiently realistic in the end to the evaluating experts. For the control of the emotionalizing stimulus the longitudinal distance to the car in front on the same driving lane needed to be transmitted. Further, the stimulus should also fade out, when the car in front of the driven ego vehicle moves out of the way to another driving lane. The simulation environment did not provide the current lateral distance of the car in front to the lane centre, to create a direct parameter to lower the stimulus in this instance. To create a workaround and not have an emotionalizing sound, when the car in front is already way on the other lane, the lateral distance of the ego vehicle to its lane centre, as well as the lateral distance between the vehicle ahead and the ego vehicle needed to be transmitted and combined. Afterwards they are summed up, to derive the missing value. The sound generator then fades out the stimulus, based on how far the vehicle is already on the other lane. The final list of parameter data from the simulator for the sound generator and its respective use is shown in table 1.

Table 1. Output Signals of Driving Simulator and their respective use.

Parameter	Use
Velocity in km/h	Approximation of RPM → Change of Pitch of active sound
Longitudinal Acceleration	Approximation of moto torque → Feedback about performance level
Longitudinal Distance	Control of emotionalizing stimulus
Lateral Distance of Ego Vehicle to Lane Centre + Lateral Distance of Ahead Vehicle to Ego Vehicle	Control of emotionalizing stimulus when lane changing.

With the necessary parameters for the sound generators now defined, the next part is the transmission of this data to the sound generator. Since the sound generator is very demanding on the computing resources of the computer its running on, it was determined, that it should not be run internally on the simulator computing units, and thus risking an erroneous driving experience. For the communication to the sound generator we use the open sound control communication protocol which utilizes in itself the user datagram protocol (UDP). So, the hardware connection between the simulator infrastructure and the sound generator computer is realized with an ethernet cable connection between the two systems. The driving simulator software is not natively capable of creating OSC messages that are necessary for the communication to the sound generator. It offers though the integration and interpretation of internal DPUs or external software modules (e.g. PPUS). For the translation of the real-time vehicle and environmental data we chose the python language to realize the software interface. Python was chosen, because of two reasons: It is reasonably fast to process and transmit the data at 60hz to the sound generator. And furthermore, it is already well established in the world of sound processing, and interaction between control and sound generators and instruments and thus, libraries or repositories are readily available for the creation and sending of OSC Messages via UDP on platforms like GitHub. For our validation environment python-osc [Pyp23] was used. In the final step, we extended the python-osc program by the initialization of the SILAB-python interfaces for the SILAB internal python interpreter, the allocation of the incoming vehicle variables, and the naming and specification of the send OSC Messages per variable.

The overall structure of the connection between the driving simulator and the sound generator can be seen in Figure 3:

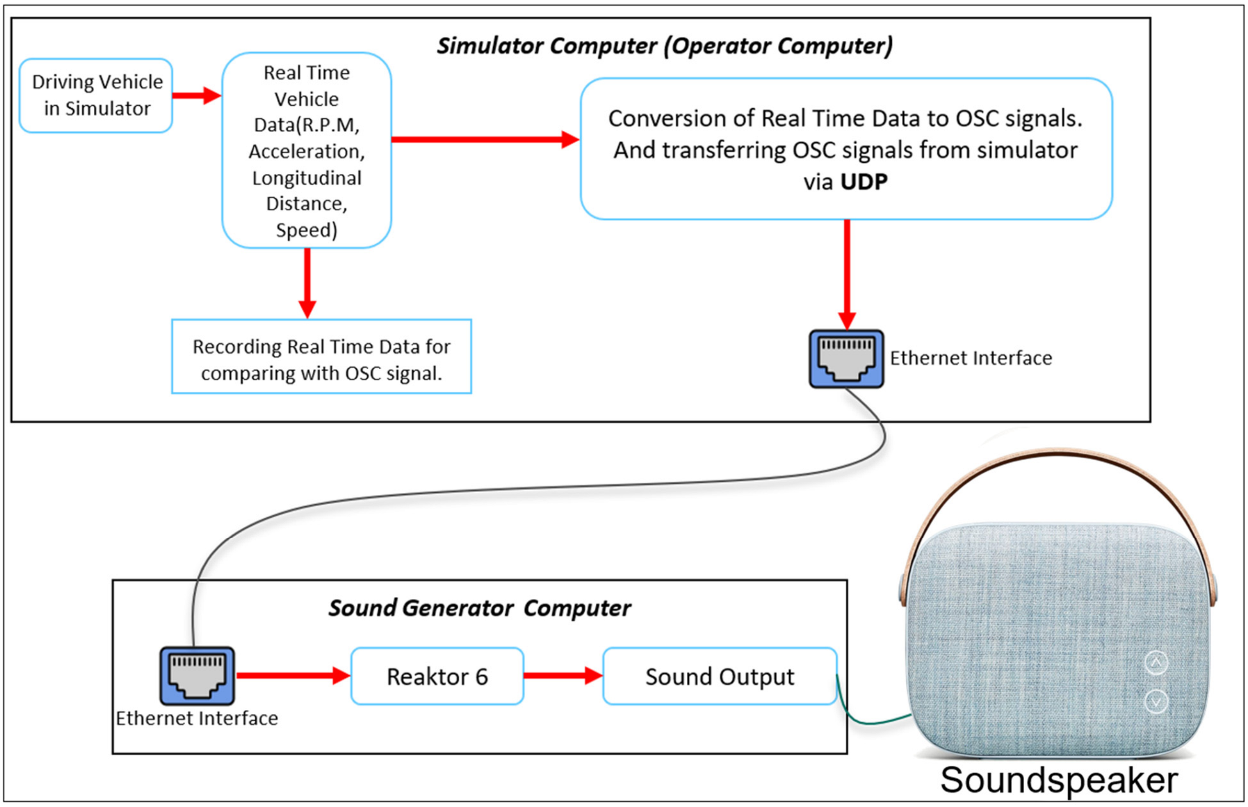

Figure 3. Overall structure of the connection between driving simulator and sound speaker

Tuning of the active sound design.

After the connection of the full sound design into the simulator environment, the first test drives with NVH Experts were conducted inside the simulator. Initially it was the consensus, that the perception of velocity in the simulator was not matching real driving very well, even with the original sound for the combustion engine-based vehicle model. In accordance to [Den21] the pitch change factor for the active sound was optimised, to improve this feeling. After an iterative process the best fitting relationship between the velocity in km/h and the pitch change was found. In conjunction with a dynamic changing of an abstract transmission ratio resembling a continuously variable transmission (CVT), this resulted in a perceived doubling of the pitch by one octave of the active sound design every 55km/h in velocity increase. This optimised the perception of the velocity change in the simulator to an acceptable degree according to the pre-test participants. To improve the perception further, fundamental changes to the overall driving model would be necessary. The expenditure to optimise this further was in no reasonable ratio to the benefits, since it already was perceived sufficiently to drive similar as one would in the real world.

Integration of the Sound into the Vehicle Cabin

After the connection of the full sound design into the simulator environment, the active sound design also needs to be properly hearable and convincingly integrated into the driver cabin. The driving simulator in general uses the original speakers of the Hi-Fi system for playing back different kinds of sounds. These entail the internal sound synthesis of the ICE vehicle sound, primarily consisting of an approximated engine sound. It further plays back roll and predominantly wind noises that are increasing with rising velocity. Additionally, external noises, like passing by cars or trucks during driving are played back over the same speakers. In initial tests, the internal vehicle sound of the driving simulator played back over the same Hi-Fi as the rest of the sounds already sounded insufficiently realistic in regards to coming from the actual vehicle, and not being just played back via the Hi-Fi system speakers close to the drivers' head. This feeling was increased when the internal ICE sound was replaced by the more abstract and futuristic sounding active sound design created for the subject studies. To mitigate that, an additional speaker was integrated into the driving cabin with the goal to increase the perception of the sound coming naturally from the vehicle itself. The speaker was a VIFA Helsinki speaker (figure 3 bottom right) which offers a very good and flat sound reproduction over the whole frequency spectrum, and is very detailed in the mid-range frequency area that is especially important for the used sound design. Furthermore, it also provides a good response in the very low frequency range (around 58Hz) which in the simulator were also perceived as slight vibrations in the driver seat. Also, it is fairly small so could fit in different places inside the driver cabin. Different positions were tested and subjectively evaluate. The most convincing position that was found was below the driver seat, with the speaker sticking out 7 cm to the front of the seat. In this position, there was no direct transfer path of the sound waves to the driver directly, but only the secondary transfer paths via reflected sound waves by the vehicle's interior geometry. This makes the sound very difficult to localise - compared to the Hi-Fi speakers with their direct transfer paths - and sound like its coming from multiple directions in the general front of the vehicle, similar to the sound in a real vehicle. The position and the representation of some exemplary transfer paths is shown in figure 4 (left).

With an immersive, subjectively optimized position being found, the last step is an appropriate volume level necessary for the sound playback. This is determined by two major factors. The first one being a realistic level of playback compared to the sound levels in a real vehicle, as described in [Swa16]. Also, the played back sound should not be masked by other noises existing in the driving simulator like the mentioned wind noise, noise of other traffic participants or external noise of the driving simulator infrastructure or air conditioning systems (AC). The last one being especially potentially problematic, since the driving simulator does not have any windows apart from the front windshield, and no sound insulating in the back of the driver cabin as seen in figure 4 (right).

Figure 4 (Left Figure). Transfer paths from Speaker to driver ear. Interrupted direct transfer path in white, and transfer paths via reflected sound waves in blue. (Right Figure). Open back side of the vehicle cabin in the driving simulator.

To find proper sound playback settings, acoustic measurements were conducted with an artificial head measurement system representing the geometrical boundary conditions of a person sitting in the simulator and hearing with their own ears. In figure 5 and 6, the measurements for six different sound scenarios are displayed.

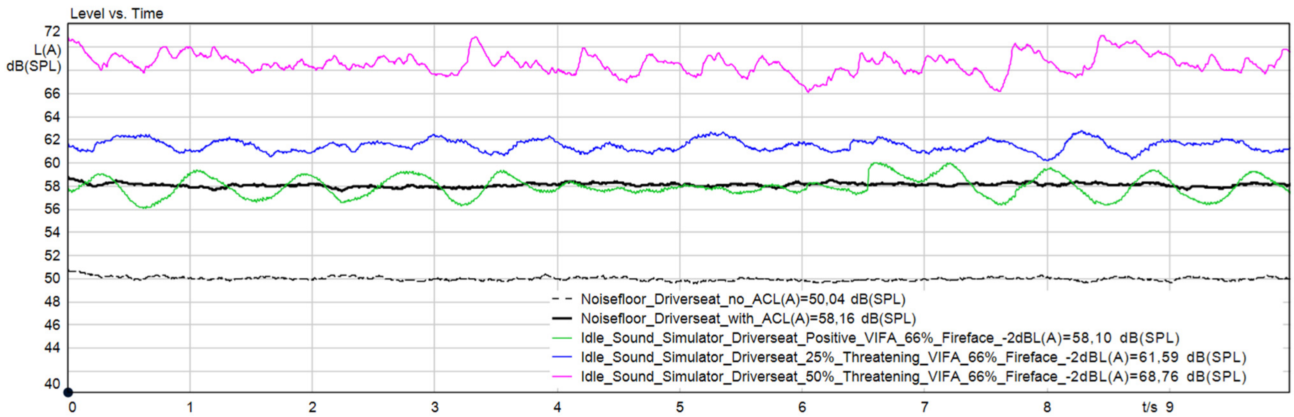

Figure 5. Sound pressure level vs time (top row) for artificial head measurement inside the vehicle cabin for the noise floor with and without AC, and with three different settings for the active sound design.

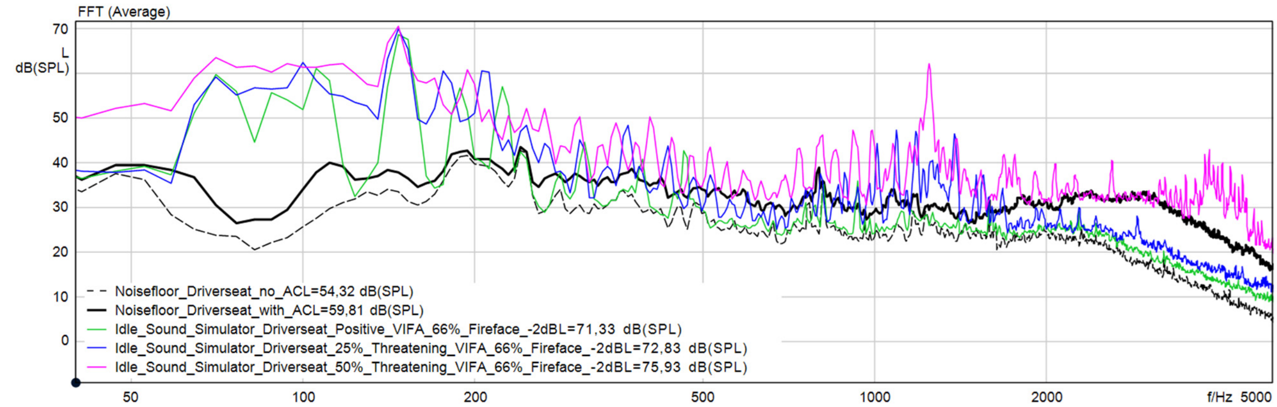

Figure 6. Spectrum for artificial head measurement inside the vehicle cabin for the noise floor with and without AC, and with three different settings for the active sound design.

The noise floor measurements with and without AC is shown with deactivated ASD. Further, the measurements for the final volume settings for the activated ASD with the car idling with the standard positive sound and the lower and middle threatening versions with 25% and 50% threatening stimulus is shown. Higher levels are not shown, since they further increase in volume level.

To be clearly audible, we aim for the active sound design to be twice as loud as the surrounding noise floor. So, the ASD should have an around 10 dB(A) higher sound pressure level than the noise floor. In figure 5, it can be seen, that the environmental noise with the AC turned on, has a similar level as the positive active sound design without AC at around 58 dB(A). So, with the goal in mind, that the internal vehicle sound pressure level should be somewhere between 60 and 70 dB(A), it is no option to leave the AC on during the study with subjects. The noise floor without the AC is 8 dB lower at around 50 dB(A). This leaves enough room when the active sound design is played back at around 58 dB(A) as long as the individual frequency components have a 10 dB higher sound pressure level than the noise floor. In figure 6 it can be seen that the individual frequency peaks of the positive active sound design at 160Hz, 190Hz, 215Hz and 320Hz, 380Hz and 415Hz have an at least 10 dB higher sound pressure level than the noise floor without AC. With enabled AC, the level difference is insufficient, in the higher frequency area.

To evaluate how well the active sound design stands out vs the wind, roll and traffic noises of the driving simulator, and additional measurement was conducted. For this measurement a 140 km/h drive along a rather crowded scenario part was conducted. The sound pressure levels vs. time for this drive without active sound design, with the active sound and with 25% threatening stimulus can be seen in figure 7.

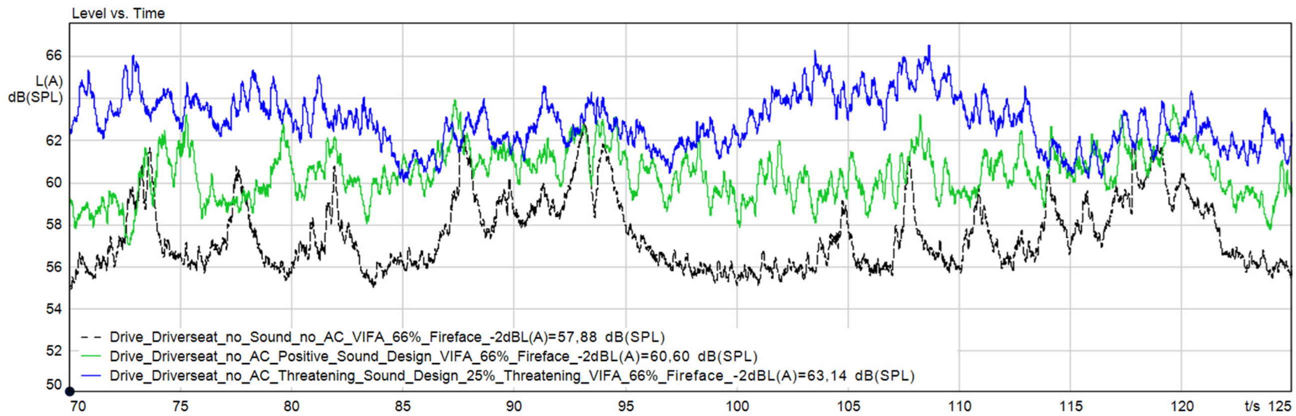

Figure 7. Sound pressure level vs time for artificial head measurement inside the vehicle cabin, driving 140km/h along a crowded scenario part. Two different settings: No active sound design, positive active sound design.

Apart from the peaks of increased levels when passing other participants, the level curves with activated sound design stay well above the wind noise + traffic noise. Subjectively the mix between wind noise, traffic noise and active sound design sounded sufficiently realistic and immersing.

Driving parameters for Evaluation of the Driving Behaviour

To investigate the effects of the suggestive sound design on the chosen safety distance by the driver, we need the same parameters, that are also relevant for controlling the sound design in the first place. To further evaluate, how the threatening influences driver groups with different driving behaviours, these groups need to be categorised based on their driving behaviour. For this we need to be able to quantify the driving behaviour in some form or another. Based on the literature the parameters that can be useful to quantify driving behaviour regarding an aggressive or more passive driving style are the following: Speed, acceleration behaviour (longitudinal and lateral), actuation behaviour of the throttle and break, lane change time, (variance of) distance to the lane border and of course safety distance. The simulator software offers the calculation of all of these via internal modules. Further, it offers the opportunity to record these during driving with the driving simulator. Also, the sample frequency can be set freely. For the planned study, the sampling frequency will be set to 60Hz, to have a sufficient resolution of the recorded driving by subjects, to even catch very jerky or impulsive driving manoeuvres.

Conclusion and Outlook

For the conduction of the driving simulator study to investigate how the emotionalizing stimulus can influence the driving behaviour in regards to safety distance, the validation environment including the driving simulator had to be implemented in accordance to the continuous validation approach and the IPEK X-in-the-Loop approach. For this, the driving simulator was connected via a UDP ethernet connection to the sound generator and a python script was used for sending the necessary vehicle and environmental signals. Even though not all of the necessary vehicle parameters were accessible, sufficient substitutes could be found. With these substitutes, the control of the sound design based on the vehicle and traffic status worked as intended. Afterwards, the sound design, was integrated into the driving cabin with an external speaker. A position for the speaker was found, that provided an immersive and sufficiently realistic perception of the artificial sound design from the sound generator. Further, it was matched to the acoustic boundary conditions of an open cabin driving simulator in regards to the noise floor, as well as the wind and traffic noise provided by the driving simulator via the driving cabins Hi-Fi system. This was done, so the active sound design provides a realistic level of volume comparable to an actual electric vehicle, as well as standing out enough from the background, to be perceivable and able to alter the emotional status of drivers during the driving scenarios. Further, the unrealistic perception of speed could be optimized, by adjusting the relationship between speed change and pitch change of the active sound design. In the last step, all of the necessary parameters that enable an evaluation of the general driving behaviour were possible to record with a sufficiently high sampling frequency. With this all of the necessary technical requirements are met to be able to conduct the necessary study. In the next step, the driving scenarios are defined and implemented, and the driving simulator study will be conducted.

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