Kurzfassung

Das Innengeräusch ist ein wesentliches Kriterium beim Kauf eines neuen oder gebrauchten Fahrzeugs. Sowohl bei reinelektrischen Fahrzeugen, als auch bei solchen mit Hybridantrieben können tonale Geräuschanteile die Angenehmheit des Innengeräuschs maßgeblich beeinflussen. Bisherige Studien zeigten, dass neben den Reifen-/Fahrbahn- und Windgeräuschen insbesondere hochfrequente Geräuschanteile die Angenehmheit reduzieren. Die Hörbarkeit dieser Komponenten wurde mittels einer angepassten Version eines auditorischen Verdeckungsmodells bestimmt. Tonale Komponenten sind insbesondere während transienter Fahrzustände hörbar, weshalb eine dynamische Betrachtung der psychoakustischen Einflussgrößen auf die Angenehmheit erforderlich ist. Der Modellansatz eines Long Short-Term Memory (LSTM)-Netzwerks ermöglicht hierbei die Modellierung der Angenehmheit als Einzahlwert in Abhängigkeit von zeitabhängigen psychoakustischen Parametern. Die Angenehmheit wurde in zahlreichen Hörversuchen erhoben, wobei sowohl Originalaufnahmen aus dem Fahrzeuginnenraum, als auch Geräusche mit gezielten Pegelveränderungen einzelner Geräuschkomponenten und solche mit hinzugefügten synthetischen Komponenten verwendet wurden. Das übergeordnete Ziel der Dissertation ist, ein Vorhersagemodell für die Angenehmheit von Fahrzeuginnengeräuschen von Fahrzeugen mit elektrifizierten Antrieben zu entwickeln. Die Vorhersagewerte können als Grundlage für die Entwicklung von entsprechenden aktiven und passiven Geräuschverbesserungsmaßnahmen dienen.

Abstract

The interior sound of vehicles is a major criterion when buying a new or used vehicle. For both pure-electric and hybrid vehicles, separately audible tonal components severely influence the pleasantness of the interior sound. Previous studies revealed that for sounds of vehicles with electrified drives, besides the tire-road and wind noise components, mainly higher-frequency tonal components influence the pleasantness. Within the present work, the audibility of those components has been determined by a modified version of an auditory masking model. For those vehicles, disturbing sound components are usually prominent during transient driving conditions. Therefore, the temporal changes of psychoacoustic parameters should be considered for the pleasantness prediction. A long short-term memory neural network depicts the relationship between time series of psychoacoustic parameters and a single value of pleasantness, which has been acquired by conducting auditory experiments with both original and augmented electric and hybrid vehicle interior sounds. The general scope of the dissertation is to develop a model of pleasantness for interior sounds of vehicles with electrified drives using a long short-term memory model approach. The predictions form the basis for constructive countermeasures or active sound design concepts to improve the pleasantness of the interior sound.

1 Introduction

The pleasantness of the interior sound is a major criterion for the purchase decision of a new or used vehicle. Specifically, the audibility of tonal components in the interior of vehicles with electrified drives (pure-electric and hybrid) is the major challenge in the field of interior sound research and active sound design measures. For these vehicles with electrified drives, the sounds are typically observed in transient driving conditions, such as run-up and coast-down conditions, and considerably reduce the perceived pleasantness. At constant driving conditions, the emission of tonal components is low. A common approach is to assess the perception of these interior sounds with jury evaluations, which are time-consuming and therefore costly. Thus, the development of a pleasantness assessment model for vehicles with electrified drives is desirable. It is reasonable to assume that pleasantness is based on psychoacoustic parameters. In contrast to previously developed models for vehicles with combustion engines, the dynamic changes of the psychoacoustic parameters are particularly relevant and therefore have to be considered during the development process of the pleasantness assessment model.

Thus, the main scope of this dissertation is to develop a dynamic pleasantness model based on psychoacoustic sensations and to provide suggestions for an active sound concept for vehicles with electrified drives.

The second chapter of the thesis provides a brief overview of the current state of research. This includes an introduction to the different types of noise, which are commonly audible in the interior of vehicles with electrified drives. Since some of the experiments are based on separated sound components, a separation algorithm is introduced that allows for a separation of recorded vehicle interior sounds into their components and allocates the components to the emitting sound sources. Finally, a short overview of the previously developed models is provided, which includes both equation-based regression and machine-learning approaches.

The third chapter describes three different approaches to estimate the audibility of sound components. This is a key element of the analysis of tonal components since only audible components contribute to the pleasantness. The first one is the experimental approach using an alternative forced choice (AFC) method. This approach is very time-consuming.

Hence, in the other approaches, the audibility is estimated using model simulations. In the first model approach, the AFC experiment is simulated by using the model as an artificial observer. Since those simulations are relatively time-consuming and require a high computational power, which might hamper the practical usage of the simulation, a second model approach is presented for tonal components that is based on the critical masking ratio of the tonal component to the relevant background noise.

The fourth chapter describes the preliminary experiments, which were conducted to gain first insights into the relevant parameters and possible measures to actively improve the pleasantness of vehicle interior sounds. To this end, artificial stimuli were generated, which contain key elements of vehicle interior sounds, i.e. tonal components and background noise. The use of artificial sounds allows for full control of the stimulus parameters. Several studies indicated that the magnitude of tonal content (MOTC, German translation “Tonhaltigkeit”) has a significant influence on pleasantness. Since the currently available models to assess the MOTC sometimes provide contradictory results [1], the perceived MOTC was additionally evaluated for all investigated stimuli. The results of the preliminary experiments formed the basis for the selection of the stimuli and the design of the subsequent experiments with recorded sounds and revealed the suitability of different active sound design measures for recorded stimuli.

The fifth chapter shows the experiments of the recorded stimuli. Together with the experiments with augmented sounds described in the sixth chapter, the recorded stimuli provide the time-variant psychoacoustic parameters as inputs and the single-valued pleasantness values as targets used for the development process of the pleasantness assessment model.

The sixth chapter describes the data augmentation approach to increase the number of stimuli. The machine-learning approach to estimate pleasantness requires a high number of stimuli, which is beyond the scope of this measurement campaign. Therefore, the separated sound components were used to either increase or decrease the level of different sound components and to conduct controlled variations of certain stimulus parameters. The separated sound components were further used to generate subharmonics, whose frequencies were set relative to the frequencies of the related sound components using a vocoder-based approach. Besides the increase of the dataset, the experimental results reveal the influence of different real and artificial sound components on the variables pleasantness and MOTC and demonstrate the applicability of active sound design measures.

The seventh chapter describes the development process of the long short-term memory model (LSTM), which includes the calculation of the time-varying psychoacoustic parameters and the data preprocessing. Afterward, the architecture of the model and its estimation is described in detail. The validation process as a part of the estimation process ensures the applicability of the model to sounds, which were not used for the training process of the model. Furthermore, a temporal analysis was conducted to evaluate how relevant certain time segments of the input signals are for the pleasantness perception.

The last chapter of the work draws a conclusion about the applicability of the developed model and provides an outlook on the relevant measures, which should be carried out to improve the pleasantness of the interior sound based on the experimental results and the pleasantness estimation of the model.