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Prediction of annoyance evaluations of electric vehicle noise by using artificial neural networks

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ABSTRACT

Road traffic noise is the most annoying form of environmental noise pollution. The enforcement of using artificially generated noise for electrically powered vehicles is currently on the rise. Regarding to that, it is important to generate sounds regarding to the regulations which are not annoying. While many annoyance models are available around the world, these models cannot be simply generalized for these new sounds and while it is very time consuming to measure the annoyance for each newly generated noise with an listening test, the idea came up to use artificial neural networks instead. The aim of this work is to determine the annoyance of different electric vehicle sounds for a constant speed, single car pass-by situation. For this purpose, the differences in annoyance are investigated with perception studies. The correlation between physical-psychoacoustical parameters and annoyance estimations obtained from jury testing is also investigated in this study. Moreover, an artificial neural network (ANN) is also used as a prediction tool of annoyance estimations for further evaluations of different possible stimuli. Overall, a total of 150 ANN models with different hidden layers were undertaken in this research. The best-performing models were compared with linear regression models based on psychoacoustic parameter. Lastly, advantages and shortcomings of using ANNs for detectability estimations are also discussed.

1. Introduction

In today's urban environment, the inhabitants are permanently exposed by increased noise levels, which are mostly dominated by traffic noise. For years, traffic noise has been one of the most prominent noise sources in urban areas. Sound quality evaluation and annoyance evaluation play a big role in science of urban environment. Thanks to the process of electrification of vehicles, the noise level and the noise characterization of city centres could be changed in the near future. However, decreasing noise levels has also a disadvantage that cars could be hardly detected. For that reason, car manufacturers are implementing external sound emission systems in electric cars. Regulations are also prepared accordingly, for example, all new electric vehicles in Europe should emit an external sound from 2019 [1,2]. The external sounds should be designed regarding to the perceptions of the listeners, i.e. pedestrians and residents. The goal of making electric vehicle sounds is both detectability as well as interpretability while keeping the noise levels under allowable limits [3,2,4–6].

But noise pollution is a major environmental health problem in Europe, therefore there is a need to study noise annoyance due to synthesized electric vehicle sounds. In order to investigate annoyance due to electric vehicle sounds and taking the safety issues into account, two experiments were conducted in controlled conditions. The first experiment (Exp. A) was conducted to ensure the detectability of the electric vehicle sounds. The second experiment (Exp. B) was carried out to measure the annoyance of these sounds. Section 3 details the experimental methodology of both experiments and highlights results regarding annoyance responses. Section 5 deals with the prediction of total annoyance due to the use of Artificial neural network (ANN).

2. Literature review

Because there are many predicting models for annoyance estimations, therefore the main focus of this paper is ANN modelling. Today ANNs have potential applications in several areas, e.g. automated detection and diagnosis of machine conditions, industrial processes, seawater environment, acoustic matters or virtual reality [7–9]. The main advantages is the time reduction by using ANN. Tenenbaum et al. used ANN for computer modelling auralizations which were validated through articulation tests. The results of

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these study showed even good results between actual and simulated articulation values, including noisy and reverberant situations [10].

Çelebi et al. [11] used an ANN to predict sound pressure level (SPL) and vibration of the engine. The generated model was able to predict vibration and SPL in an acceptable range. ANN results were also compared with linear regression results and it was concluded that ANN modelling gave more accurate predictions than linear regression. They used the Levenberg-Marquardt training algorithm. The best ANN architecture was chosen by trying different number of hidden layer. Finally it was concluded that 4 and 5 neuron of hidden layer for vibration and SPL gave best network performance. Numbers was generally concluded by trial-and-error method.

Huang et al. [12] used ANN for modelling traffic noise. Eleven different Input-parameter were used and they divided their dataset in 287 training stimuli, 20 test stimuli and 20 stimuli for validation. Multi-layer Perception (MLP) was selected to train the network. The minimum and maximum numbers of hidden layer units were selected to be 3 and 50. Their ANN got a correlation coefficient of 0.98.

In 2007 Wang and some of his colleagues created a new concept to predict the sound quality with a pre-processing neural network model [13]. This model consists of a combination of wavelet analysis and neural network classification. Verification results showed that the trained models are accurate and effective for sound-quality prediction of nonstationary vehicle noise. Another model were designed in 2014 to predict the annoyance on interior noise [14]. Wang et al. used a prediction tool based on finite element method (FEM) and ANN in 2017 [15]. Based on these two methods they presented a hybrid approach called FEM-ANN model for acoustic behaviour prediction of a human auditory system. The verification of the model showed a high accuracy. In terms of applications, they predict, the newly FEM-ANN model could be used for sound quality prediction of vehicle noise. The researchers measured the loudness, sharpness and roughness of the vehicle sounds. The output of the ANN was sound quality of the vehicle interior sounds, which were estimated by listening tests by using an anchored semantic differential procedure. The verification tests suggest that the proposed ANN model is accurate and effective and could be used to estimate sound quality of vehicle interior sounds.

Also in 2017 Ma et al. [16] presented a method for evaluate quantitative sound quality of interior of a pure electric vehicle (PEV) based on neural network. They used A-weighted sound pressure level, loudness, fluctuation strength, tonality, roughness, articulation index, and sharpness of the left ear and the right ear as inputs. The outputs were five semantic evaluation indexes of the interior noise: annoying and pleasing, harsh and sweet, weak and powerful, promiscuous and pure, and unobservable and perceptible. The results showed, that this model can be used for SQ prediction and evaluation of the interior noise of the PEV considering that the average error is 9%.

Two indian researcher developed a noise prediction model suitable for the Indian conditions, because the number of vehicles is increasing very fast in India which leads to overcrowded roads and pollution. Their regression based model is developed for predicting the equivalent continuous sound level (Leq). The correlation of the regression leads to a coefficient of $R^2 = 0.76$, which indicates a very good correlation. They said based on correlations, roughness is one of the variables that should be considered in measuring traffic noise (in terms of sound pressure levels of single vehicles).

The purpose of a paper from Sarafraz et al. [17] is to optimize noise emission level associated with two types of speed reducers for different speeds of a vehicle (20, 40, 60 km/h) by genetic algorithm and ANN. They used a basic neural network to predict the effect of speed bump on tire noise. Their best fitting network consist of 21 hidden neurons and the regression is calculated (0.89) for the whole data sets (training, testing and validation).

3. Listening test

Two listening tests were conducted. The first experiment (Exp. A) was a preliminary experiment for Exp. B.

3.1. Exp. A: Detectability of electric vehicles

The aim of the experiment is to measure the reaction time required by subjects to react to the detectability of a vehicle passing by in a background noise.

3.1.1. Apparatus

The experiment took place in a quiet sound isolated room with a background noise measured at 19 dB(A) and were conducted individually for each subject. The stimuli were randomized presented via a calibrated Sennheiser HD 600 headphones. The graphical user interface was programmed using MATLAB (see Fig. 1).

3.1.2. Stimuli

Within this study 90 different pass-by sounds of electric vehicle with a constant speed of 10 km/h were generated. For this purpose a module was programmed before in PureData [2]. The subjects evaluated a total of 90 stimuli. All of them are synthetic sounds. The stimuli we used in this study are general basic vehicle sounds, which can be adapted by the manufacturer to the respective requirements in the sense of a brand design. All designed sounds are compatible with the UN ECE guideline [1]. This guideline suggests, at least two of the one-third octave band levels should be above the defined minimum level and one of these bands should be lower than 1.6 kHz. In the case of all the variants, the required minimum level is reached in at least two 1/3 octave bands. The overall minimum level of 50 dB(A) is also achieved in all cases. The stimuli differ in terms of minor systematic changes. For example, three different noise characters were used: narrowband noise, sinusoids, and sinusoids over narrowband noise. Furthermore, the number of bands used (2–6 bands) was varied. In addition, the frequency range has also been changed so that there are sounds in the low, middle, high frequency range and also sounds that have several parts in the entire frequency range. Fig. 2, some example spectrograms of the stimuli are given.

Furthermore, a realistic background noise (55 dB(A)) was used for masking. To create a realistic background noise (TU-Dresden Background) acoustic recordings with a dummy head was carried out at different locations in the city centre of Dresden. After listening by experts from the chair, a recording was chosen for the use of the experiment. The homogeneity of the noise was the main criterion, since the dominance of individual events should be avoided. Fig. 3 shows the average FFT of the TU-Dresden Background noise.

3.1.3. Participants

22 participants performed this experiment (12 male, 10 female; mean age = 27,8 years). They all declared normal hearing abilities and were paid for their participation.

3.1.4. Procedure

Before starting the experiment, the participants were told that they would listen to vehicle sounds within a realistic background noise. The main aim of the study was to measure the detection time of an approaching vehicle in a realistic background noise.