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Perception of tones below 1 kHz in electric vehicles

Dr. David Lennström[1]
Volvo Car Group
Dept. 91600 PV3A, SE-405 31 Gothenburg, Sweden

Amanda Gutierrez Melian[2], Dr. Arne Nykänen[3]
Luleå University of Technology
Engineering Acoustics, SE-971 87 Luleå, Sweden

Dr.-Ing. Julian Becker[4], Prof. Dr.-Ing. Roland Sottek[5]
HEAD acoustics GmbH
Ebertstr. 30a, 52134 Herzogenrath, Germany

ABSTRACT

The perception of tonal sounds is one of the most important psychoacoustic sensations of NVH sound engineering. Much work has been done in the past to quantify tonal sound events. Previous studies resulted in several metrics for quantifying tonality, such as Prominence Ratio, Tonality DIN 45681 and the recently standardized Psychoacoustic Tonality (ECMA-74). Although these metrics are designed to assess the tonality of a sound, they do not explain how the pleasantness of a sound is affected by tonal events.

This article describes an experiment aimed at evaluating the relationship between tonality and pleasantness of electric vehicle interior sound at different speeds with tonal components between 200 Hz and 900 Hz. It also explores how the established metrics for tonality calculation can be used to predict the pleasantness of these sounds. The results of the listening test are analyzed and compared with the calculated tonality values of the various metrics. The detectability of the tones was also analyzed and could be linked to the pleasantness observations.

Furthermore, a hierarchical cluster analysis was performed to further examine the subjective results. Two main groups were categorized from this analysis where one cluster had higher detectability.

Keywords: Electric vehicles, Sound quality, Psychoacoustics
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[1] david.lennstrom@volvocars.com, [2] amanda.agr30@gmail.com, [3] Arne.Nykanen@ltu.se
[4] Julian.Becker@head-acoustics.de, [5] Roland.Sottek@head-acoustics.de

1. INTRODUCTION

Electric vehicles are currently penetrating the market in a rapid pace. Car makers in the premium segment are releasing long range battery electric vehicles (BEV) with impressive acceleration performance. Although the power unit relative to their internal combustion engine (ICE) counterparts are generally quieter, tonal components from the transmission and electric machine are inevitably emitted to some extent. Since today's BEVs are equipped with single speed transmissions, the emitted motor orders from the electric drive unit (EDU) are present in a very wide frequency range. The majority of the tonal events are appearing in the kHz range, in contrast to the main firing orders of ICEs which typically excite frequencies up to a few hundred Hz.

Sound quality aspects of electric cars is a topic that is gaining more and more interest. Generally, previous work within the field can be categorised as follows:

- Investigations of the inherent acoustic character of electric cars' propulsion systems and preferences linked to it. Examples of work related to this is the development of adjective lists and exploration of the perceptual space for EV sound [1-5].
- Sound design and acceptance of synthetic acoustic feedback, both with respect to interior and exterior (for pedestrian warning alerts) sounds [6,7,8].
- Investigations of different sound quality/psychoacoustic metrics for assessing the high frequency tonal components related to EDUs [9,10,11].

In a former work by the author(s) [12], the acceptance levels of tones was studied. The metric prominence ratio (PR) was used to quantify the tonal intensity in sound stimuli that a jury evaluated subjectively. It was concluded that even a very low tonal intensity (PR levels at 2-3 dB) could yield significant annoyance when the tones/orders are above 1 kHz. Hence, high frequency single tones in premium cars should not be audible.

In this study, the sensation of tones below 1 kHz has been studied in order to close the knowledge gap of what is expected in terms of single tones in the low/mid frequency range. Instead of rating perceived annoyance, the attribute pleasantness was used since the presence of orders in the low/mid frequency range was assumed to possibly contribute positively to the driver. Another aspect that was explored was which one(s) of a number of sound quality metrics that correlated best to the rated pleasantness.

The methodology used in this study for creating the sound stimuli that were played back to the participants in the listening test was as in the previous study [12]: sinusoidals of varying strength were mixed with recordings of a car's interior compartment sound at different speeds. However, in addition to the sinusoidals the tones of varying strength were created from an e-motor order. The hypothesis that a true signal which is not as steady in level or in frequency as a generated sinusoidal could be perceived differently was tested.

The contribution of this article is to provide more insight related to the acceptance of tones in electric cars and to further evaluate the suitability of different acoustic metrics for quantifying tones immersed in broadband noise. This knowledge will aid automotive engineers in the process of understanding the new specific acoustic challenges.

2. METHOD

The used methodology and procedure for the study can be summarized in the following steps:

- Test track binaural recordings of an electric car.
- Creation of sound stimuli created by combining tones of varying level with recorded interior cabin sound (dominated by tyre/road and wind noise).
- Conduction of listening test.
- Statistical analyses of the data.

2.1 Test track recording

A Volvo XC90 T8 plugin hybrid equipped with 235/55 R19 tires was used for recording interior sound in order to create stimuli for the listening test. The temperature was 0 degrees Celsius and the car was driven on a flat test track with smooth asphalt in pure electric drive mode. A portable HEAD acoustics 4-channel SQuadriga with integrated binaural recording headset was used to record 10 second samples at 10 different constant speeds. The 8th rotor order of the e-machine is the first main motor order of the EDU and the corresponding frequency of that component was mixed with the background noise for each speed/sound stimuli in the listening test. The recorded speeds and corresponding tonal frequencies that were later used for the listening test are summarized in Table 1.

Table 1. Recorded speeds and corresponding tonal frequencies.

Vehicle speed	Frequency
22 km/h	200 Hz
44 km/h	400 Hz
66 km/h	600 Hz
99 km/h	900 Hz

A Brüel & Kjaer model 4507 uniaxial accelerometer was mounted on the center of the EDU housing. The speed of the car was controlled by the driver, so some fluctuation around the stated constant speeds in Table 1 occurred for each driving speed.

2.2 Creation of sound stimuli

For each vehicle speed, the following sound stimuli were created for the listening test:

- A baseline sound, comprising the interior car sound where eventual tonal components were filtered out.
- Four modified recordings referred to as “natural recordings”. They were generated by band pass filtering of the interior car sounds for obtaining the tone only. The accelerometer signal was used to note the spectral content of the tone. The sound files with only tones were then added, in augmented level, to the original broad band sound files. The result was four sound files with varying tonal strength per

speed and with some fluctuations in absolute frequency and amplitude over the 10 seconds.

- Five recordings that correspond in level both with respect to the background noise as well as to the tone with the “natural recordings”, but in this case the tone added was a pure sinusoidal, generated with the software Audacity. The purpose for creating such sound samples was to investigate whether there would be any significant differences in perception between “artificially” made tones that don’t exhibit any fluctuations in level and frequency compared to the “natural” tones.

In order to have sufficiently long stimuli, each sound sample was looped three times in order to yield 30 seconds of uninterrupted playback per sound stimulus.

2.3 The listening test

Twenty participants took part in the test. This number of subjects was chosen to fulfill a criterion with respect to the Latin Square method when using 10 sound samples for each speed. This method was used to balance the playback sequence of the sounds for avoiding order effects.

Information on the hearing status of the participants, their driving habits and driving experience that was collected is summarized in Table 2.

Table 2: Summary of data about participants in the test.

Mean age	24,7	
Women	7	35%
Men	13	65%
Average years with driving license	6	
Average km driven per year by car	5720	
People who have driven an electric or hybrid car	12	60%
Known hearing loss	0	0%

The listening test took place in the sound studio of the Acoustics Lab at Luleå University of Technology; most of the participants were students there.

The test consisted of a training session for familiarizing the participants with what type of sounds they were about to rate. In the training session participants listened to eight recordings, two for each speed in increasing order.

In the real test, the participants were informed about which speed each part of the listening test corresponded to and the questions that were asked were the following:

- *Please rate pleasantness of the sound on the scale ranging from "very unpleasant" to "very pleasant".*
- *Could you hear a specific tone in the sound? Answer yes or no for each recording.*

The participants were asked to rate on an 11 point scale (from 0 to 10). A value of 0 corresponded to very unpleasant and 10 corresponded to very pleasant.

The word pleasantness was chosen because it is easy to understand and does not have negative connotation. Therefore, the participants were not biased towards negative thoughts towards the sound.

The equipment used for the test was a Programmable Digital Equalizer (PEQ V) from HEAD acoustics, connected via USB to a computer. This device was used for an accurate and equalized playback of the recordings.

3. RESULTS

The results of the listening experiment were first analyzed to obtain information about the perception of the tones for the different scenarios. In a second step, the results were compared to established metrics, to analyze how well these metrics are capable of predicting pleasantness and detectability of tones.

3.1 Perceived pleasantness and detectability

The average results for pleasantness and detectability over all participants are displayed in Figure 1. The following observations can be made regarding the pleasantness of the sounds:

- For low frequency tones (200 Hz and 400 Hz), the ratings of the pleasantness are rather constant, indicating that the participants did not find the tones disturbing, independent of the level of the tones.
- For higher frequencies (600 Hz and 900 Hz), the perception of pleasantness changes depending on the level of the tones. Sounds with a louder tone are consistently rated as less pleasant than sounds with a tone with lower level.
- Regarding the natural and the artificial tones, no significant difference in the perception of pleasantness can be observed.

The results for the detectability are shown in Figure 1 on the right. The following observations can be made:

- The sounds including tones with a frequency of 200 Hz have a very low detection rate independent of the level of the tone. Thus, it can be assumed, that the constant pleasantness ratings for these sounds originate from the fact that the tones are not perceived by most of the participants.
- The sounds including tones with a frequency of 400 Hz have an increasing detection rate for increasing level of the tone. This result is interesting because the pleasantness was rated rather constant for these sounds. Thus, it can be assumed, that the participants were able to detect the tones with higher levels better, but did not find the tones unpleasant.
- The sounds including tones with a frequency of 600 Hz and 900 Hz have an increasing detection rate for increasing level of the tone. These tones however do influence the pleasantness of the sound, as can be seen in the decreasing pleasantness ratings for higher levels of the tones.
- Regarding the natural and the artificial tones, no significant difference in the detectability can be observed.

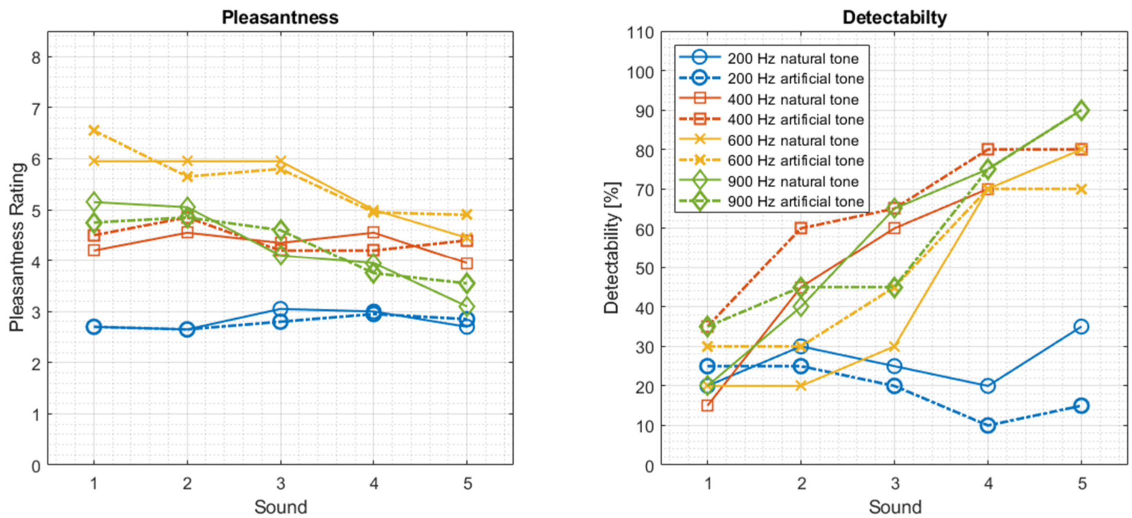

Fig. 1 – Results for pleasantness and detectability over all participants. Sound 5 has the highest tonal intensity and sound 1 has the lowest.

Furthermore, a hierarchical cluster analysis was performed on the results of the listening test. The clusters were calculated using Ward's method [13]. The resulting clustering tree is displayed in Figure 2.

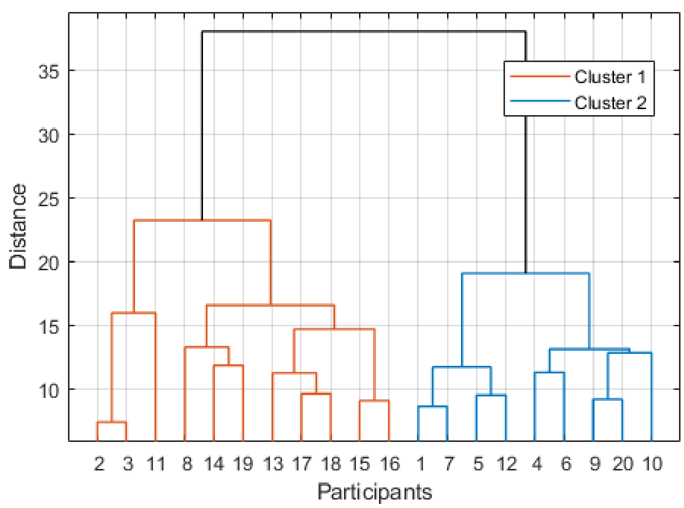

Fig. 2 – Results of the cluster analysis.

It can be seen, that there are two clusters that have a rather large distance from each other. Thus, in the following, these two clusters are analyzed independently. The average pleasantness over both clusters is shown in Figure 3. The results show, how the clusters can be interpreted. Cluster 1 is a group of participants who perceive sounds with tones of 600 Hz and 900 Hz as more unpleasant with increasing level of the tone.

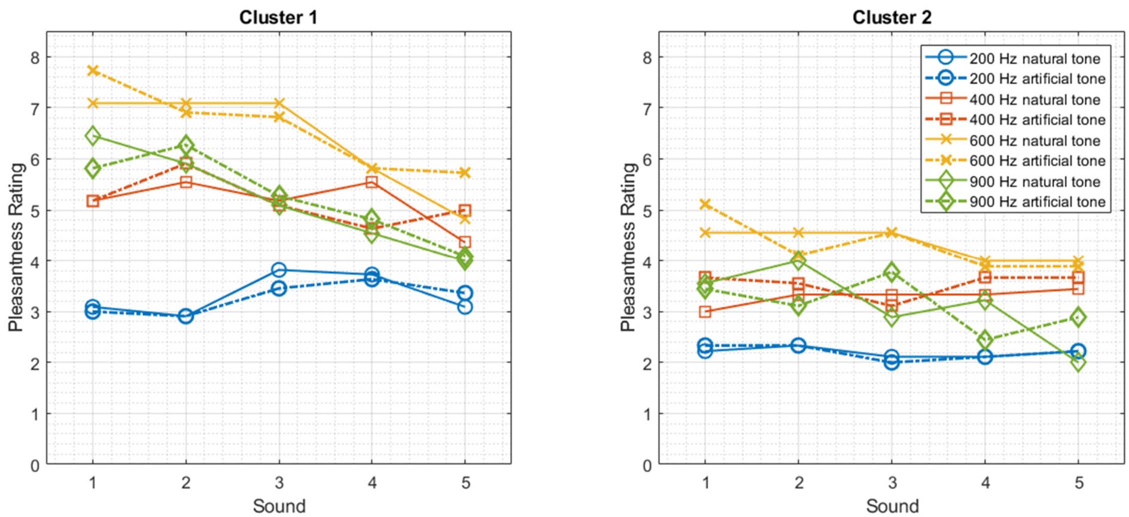

Fig. 3 – Results for pleasantness for the two clusters.

For the participants in cluster 2 on the other hand, the level of the tones doesn't influence the perception of pleasantness significantly, independent of the frequency of the tones. It is also interesting to note that this group generally rates the sounds as more unpleasant than the first group. Figure 4 shows the average results for detectability for the two clusters. It can be observed that the participants in cluster 1 have a higher detection rate of the tones with increasing level of the tones. An exception are the tones with a frequency of 200 Hz, which seem to be difficult to detect for all levels.

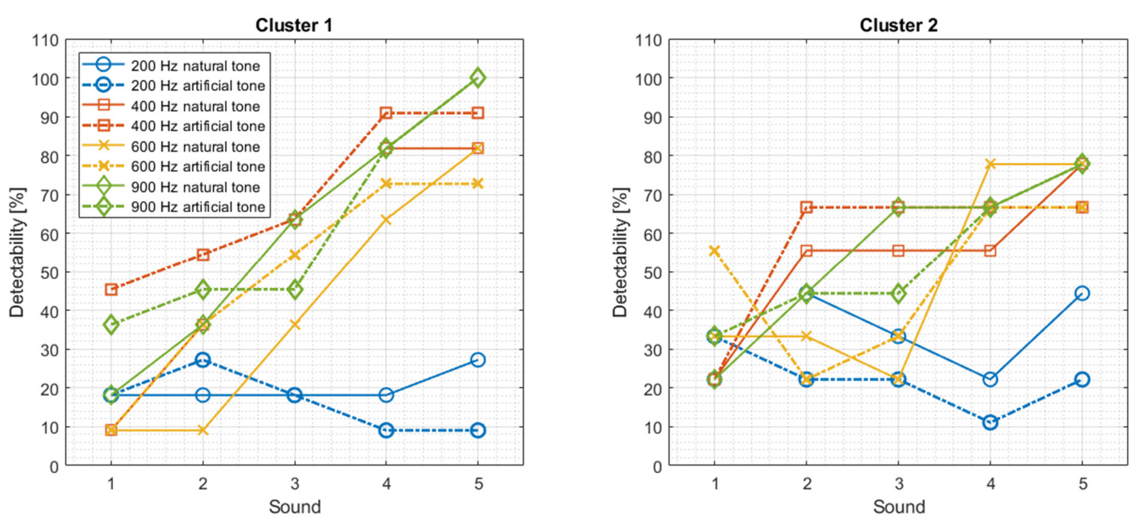

Fig. 4 – Results for detectability for the two clusters.

The result for the participants in cluster 2 looks different. The detection rates only change slowly over time. There is a slight tendency to higher detection rates for higher levels, however these results can be interpreted such that this group of participants has difficulties detecting the tones. This interpretation fits well to the result of the pleasantness for this group. It does make sense that the participants who are not capable of detecting a tone are also not disturbed by the tone, thus resulting in a perception of pleasantness independent of the tone. The first group on the other hand consists of participants that are more sensitive to tonal sounds and thus feel a higher influence of tonal sounds on the pleasantness of the sound.

3.2 Comparison to established metrics

The results of the listening test were correlated against the following four sound quality metrics:

- Prominence Ratio (PR) - A method which calculates the prominence of critical bands [14].
- DIN Tonality - A method for the calculation of tonality which was described in the German DIN 45681 standard [15].
- ECMA-74 Tonality - A method which is completely based on psychoacoustics to measure the perceived tonality of a sound [16].
- Modified ECMA-74 Tonality - A modification of the ECMA-74 Tonality which mainly reduces the estimated tonality at low frequencies, since these tend to be overestimated in the ECMA-74 Tonality.

In Figure 5, the correlation analysis for the first cluster is shown. The data was only analyzed for the first cluster, because this cluster contains the participants which were able to detect the tones better with increasing level.

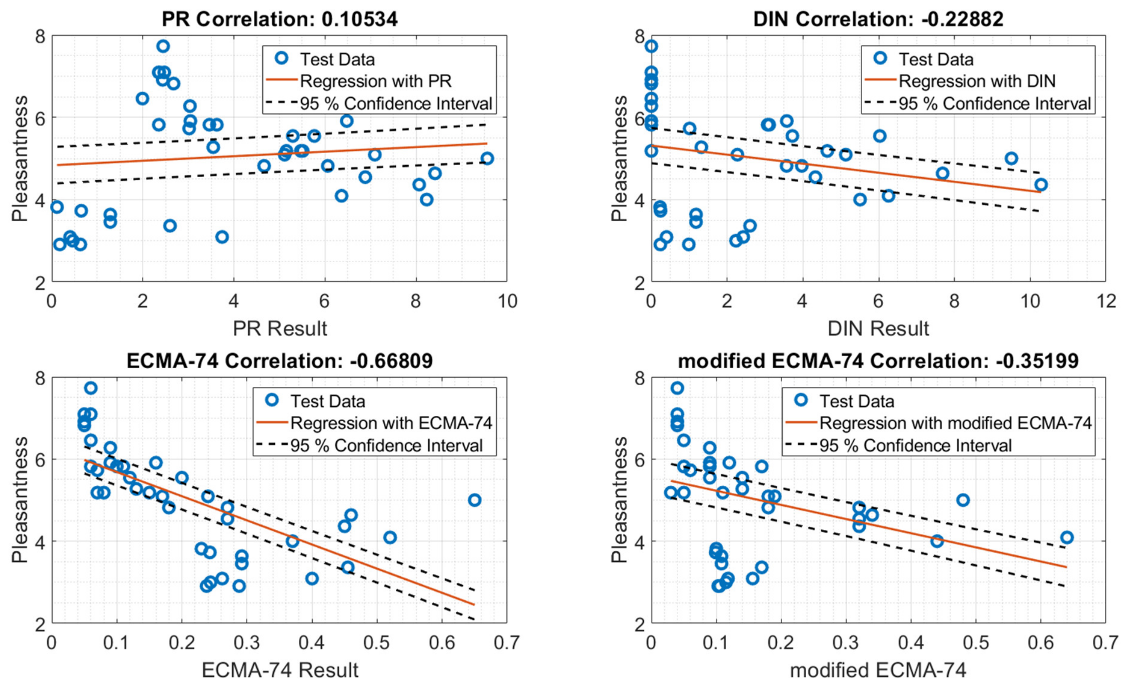

Fig. 5 – Correlation analysis of different established methods with the pleasantness ratings.

It can be seen that none of the metrics is capable of describing the perception of pleasantness well. The only metrics which shows a significant correlation is the original ECMA-74 metric. It is not surprising that the metrics do not have a very high correlation with the pleasantness ratings since they do not aim at modeling pleasantness but at modeling tonality. The results in Section 3.2 showed that pleasantness is not influenced by tonality for all frequencies. Especially the 200 Hz signals did not show any tonal components but still were perceived as the most unpleasant sounds.

For this reason the correlation analysis was also performed for all data except for the 200 Hz signals. The results are shown in Figure 6.

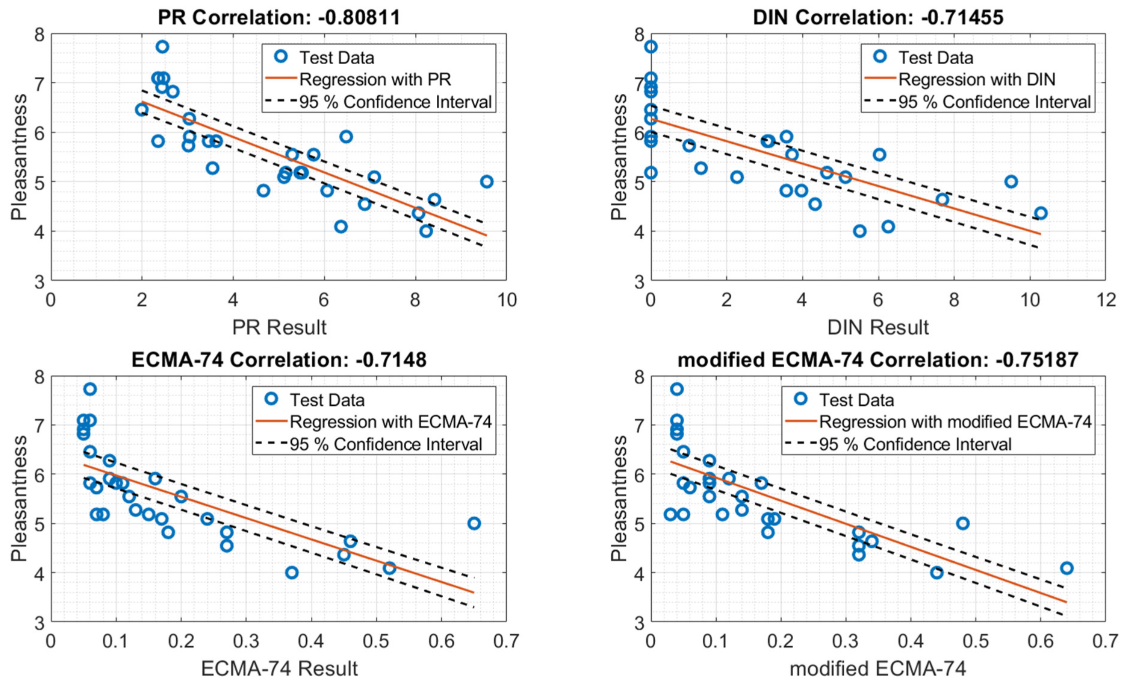

Fig. 6 – Correlation analysis of different established methods with the pleasantness ratings without considering the 200 Hz signals.

The correlation increases significantly for all metrics in this case. All metrics are correlated with a correlation coefficient of 0.7 or higher. This result shows that even though pleasantness is not only influenced by tonality, there is a high correlation between these two sensations in the range from 400 to 900 Hz.

In the listening test, the detectability was rated by a binary choice (yes/no). For this kind of ratings, a correlation analysis with the four metrics is not valid. To evaluate the tone detectability ability of the metrics, it was tested how well a threshold can separate the sounds into sounds with detectable and non-detectable tones. For this purpose, it is assumed that a sound is detectable when more than 70 % of the participants are able to detect it. This is a common assumption for this kind of tests, considering that some participants answer "yes" even when no tone is audible. This behavior can be observed in the current experiment, since a significant amount of the participants indicated to hear a tone even for the first signals, where no tone was added.

With this assumption, the optimal threshold was calculated for each metric and the corresponding accuracy A was calculated as

$$A = \frac{TP + TN}{TP + TN + FP + FN}, \quad (1)$$

where TP, TN, FP and FN stand for true positive, true negative, false positive and false negative detections respectively. For this analysis all sounds were taken into account.

Table 3: Optimal thresholds and corresponding accuracy for detectability.

	PR	DIN	ECMA-74	Modified ECMA-74
Threshold	5.6 dB	3.8 dB	0.3 tu_{HMS}	0.3 tu_{HMS}
Accuracy	0.875	0.875	0.8	0.9

The results show that all metrics are able to identify the detectability of a tone with an accuracy of more than 80 %. It can also be seen that the modifications of the ECMA-74 method increase the detection ability of this method (increase of accuracy from 0.8 to 0.9).

4. SUMMARY

In this study, the perception of tones in the interval 200 to 900 Hz was investigated. Interior noise recordings of a hybrid/electric car at four constant speeds were mixed with tones of varying strength in order to explore the relationship between the perceived pleasantness of the sounds and the tonal intensity. The tonal components were extracted in two different ways. At first, the tone was an e-motor order from the constant speed driving, resulting in a tone that was not totally steady in terms of amplitude or frequency during each drive event. Secondly, tones were instead generated from pure sinusoidals yielding constant frequency and amplitude for each sound stimuli to be evaluated.

It was found that the perceived pleasantness was unaffected by the way that the tones were created, hence the findings regarding the effect on pleasantness depending on the tonal strength and frequency content are valid for both artificial as well as for natural tones.

The main observations were that the 200 Hz and 400 Hz cases provided rather constant ratings of the pleasantness despite large differences (15 dB) in tonal strength between stimuli with minimal tonal intensity and maximal tonal intensity. Interestingly, the detectability of the tone was very low for the 200 Hz case but rather high, at least for the stimuli with strong tonal content, for the 400 Hz case. For the 600 Hz and 900 Hz cases, the observations were more according to expectations and in line with previously reported findings of sensations of tonal sounds: the sounds with a louder tone were consistently rated as less pleasant than the sounds with a tone with lower level.

Using cluster analysis, it was shown that the participants can be divided into two groups. One group which has a higher sensitivity for tones which results in a better performance in detectability. This group has a stronger correlation of pleasantness and detection of tones, especially for higher frequencies. The other group of participants was much less sensitive in detecting tones and consequently the tones did not influence the perception of pleasantness for this group.

Furthermore, the three established metrics Prominence Ratio, DIN 45861 Tonality and ECMA-74 Tonality as well as a modified version of the ECMA-74 Tonality were compared to the results of the listening test. The correlation of these methods with the pleasantness ratings was rather low when considering all sounds. When only sounds in the frequency range from 400 Hz to 900 Hz are considered, the correlation increases drastically for all of the metrics. This result indicate that pleasantness is only influenced by tonality for sounds in a frequency range above 200 Hz.

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