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Psychoacoustic analysis of HVAC noise with equal loudness

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ABSTRACT

In order to guarantee maximal comfort inside vehicles, noise pollution has to be minimized. When considering developments especially in electro mobility, one major sound source - the combustion engine - is eliminated. Hence, the ancillary units as sound sources become increasingly unmasked and thus, prevalent. The sound field developed by the heating, ventilation and air conditioning system (HVAC) then essentially affects the perceptible sound field inside the car cabin. For identifying the relevant psychoacoustic parameters for assessing the sound quality of HVAC noise, a listening test, using the preference paired-comparison technique, was performed on seven sound samples of different vehicles in the defrost mode. The sounds were equalized in their loudness on an average level. Thus, the aim of this study was to analyze the correlation between the listeners' preference and additional parameters beside the dominant parameter loudness. It was found that the sharpness, the articulation index and the roughness determine a preference decision when the loudness is eliminated from the sound samples.

Keywords: HVAC, Psychoacoustics I-INCE Classification of Subjects Number(s): 63.7

1. INTRODUCTION

The disturbance by noise pollution in a human's daily routine steadily increases. While driving, a person is subjected to plenty of sound sources within the vehicle. The main sound sources in a car are the powertrain, including the combustion engine and the transmission, the air flow around the vehicle and noise induced by the tires as well as the ancillary units such as the heating, ventilation and air conditioning (HVAC) system. Taking into account the continuous acoustical optimization of those sound sources and new technologies, such as the start stop system, the noise induced by the HVAC system becomes increasingly prevalent. As shown by Biermeier (1), the HVAC system in a vehicle with combustion engine dominates interior car noise in high frequencies, which leads to the need of investigating and optimizing the sound quality of HVAC noise.

The perception of sounds and furthermore of sound quality is subjective. A sound is considered as noise if it is disruptive towards personal silence and welfare. This again depends on personal and cultural characteristics, as well as on the situation and mood when perceiving the respective sound. Thus, acoustical optimization of HVAC noise cannot be accomplished by using the overall sound pressure level as the only evaluation criterion. The aim is to develop a HVAC sound which is perceived pleasantly for the occupants and hence, to reduce noise pollution. In order to reach this goal, suitable evaluation criteria have to be identified.

In former investigations, the acoustic parameter articulation index as well as the psychoacoustic parameters loudness, sharpness and roughness have been derived as relevant evaluation criteria for assessing HVAC noise. This was shown by analyzing preference values and measures of acoustic as well as psychoacoustic parameters in (2). In this study, the loudness was identified as the dominant evaluation criterion, which means that the perception of other characteristics within the sounds was possibly masked. Moreover, other psychoacoustic parameters might be influenced by the loudness. Figure 1 exemplarily shows possible interdependencies of loudness and roughness. Figure 1a shows the identified correlation between roughness and the measured sound quality in terms of listener's preference. In addition to that figure 1b shows the interdependencies between loudness and roughness for the class of HVAC noise. It becomes obvious that the roughness decreases with increasing values of loudness, which is caused by the mechanisms of sound generation in the HVAC system. Thus, the cause-effect relationship of roughness on perceived sound quality needs further investigation. In this study, different HVAC sounds with equal loudness were investigated using listening tests.

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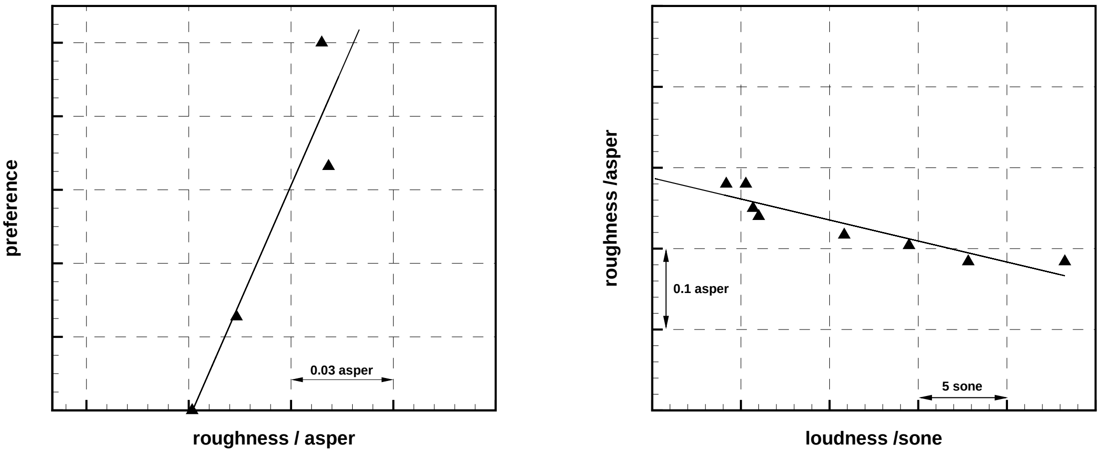


(a) Preference as a function of roughness.

(b) Roughness as a function of loudness.

Figure 1 – Impact of roughness on subjective preference (a) and interdependency of loudness and roughness (b).

2. EXPERIMENTAL SETUP

In order to investigate subjective preferences concerning HVAC noise, different test sounds were assessed in a listening test with seven sound samples (A-G) which were recorded in seven different vehicles of the same class. The chosen operating mode was a defrosting mode with a mass flow of approximately 7 kg/min. After analyzing the individual loudness N of each test sound, an average level for the loudness of $N = 17.5$ sone was derived. All sound samples have been equalized on this loudness by iteratively scaling the time signal.

Due to the equal loudness of the test sounds, the hearing impression of the sounds become more similar. In order to evaluate the differences between the sounds, the test methodology has to be as easy as possible for the test persons. Hence, the preference paired-comparison technique was used.

The listening test was performed with 34 test persons (average age 28.5 years; standard deviation 4.9 years) under laboratory conditions. The test sounds were presented via calibrated headphones.

3. RESULTS

The ordinal-scaled data that result from preference judgements firstly were transformed into interval-scaled data using the Law of Comparative Judgement (LCJ) by Thurstone (3) and into a ratio scale using the Bradley-Terry-Luce Model (BTL) (4, 5). In the scale according to LCJ, the differences between the values can be interpreted while the BTL scale has an absolute zero and therefore, the ratio between scale values are interpretable. For both methods, high values are in line with high preference and vice versa.

In a first step an analysis of the applicability of the sound pressure level for quality judgements was carried out. The results are summarized in table 1. It shows the values of loudness, sound pressure level - unweighted (SPL) and A-weighted (SPL(A)) - as well as the preference values according to LCJ and BTL for all sound samples A-G. The corresponding rank orders of each measure is displayed right beside the measure, respectively. The rank 1 marks the best and rank 7 the worst test sound assessed using the corresponding measure.

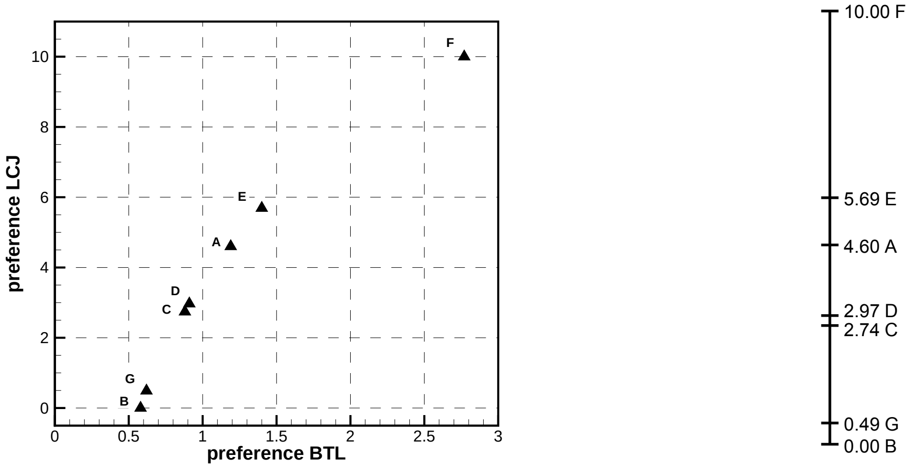
As mentioned above, all test sounds were equalized to an average loudness of 17.5 sone. Although all sounds belong to the same sound class of HVAC noise and thus, have similar frequency spectra, a difference of 5.5 dB between the sounds with the highest and lowest unweighted SPL exist. The difference of the maximal and minimal A-weighted SPL is 1.3 dB(A) and hence, the A-weighted SPL is more suitable for evaluating the sound quality of HVAC noise. Nevertheless, when comparing the rank orders of the A-weighted SPL and the preference values derived from the judgements in the paired comparison (LCJ and BTL), a discrepancy is noticeable. This indicates that both SPL are no reliable parameters to evaluate the sound quality of HVAC noise.

The rank orders derived from the preference values out of the LCJ and BTL-Model are identically. As shown in figure 2a, a further correlation analysis between both scales shows a high correlation. Hence, both models deliver same results and are both applicable for analyzing correlations between psychoacoustic parameters and

Table 1 – Summary of different measures for test sounds A-G and corresponding rank orders.

	loudness /sone	SPL /dB	rank order	SPL /dB(A)	rank order	preference LCJ	rank order	preference BTL	rank order
A	17.5	72.8	4	63.7	6	4.60	3	1.19	3
B	17.5	72.7	3	63.2	3	0.00	7	0.58	7
C	17.5	70.3	1	63.4	4	2.74	5	0.88	5
D	17.5	72.2	2	62.4	1	2.97	4	0.91	4
E	17.5	73.3	5	63.7	6	5.69	2	1.40	2
F	17.5	75.8	7	63.5	5	10.00	1	2.77	1
G	17.5	74.8	6	62.4	1	0.49	6	0.62	6
minimum	17.5	70.3	-	62.4	-	-	-	-	-
maximum	17.5	75.8	-	63.7	-	-	-	-	-
max - min	-	5.5	-	1.3	-	-	-	-	-

subjective preference. For better comparability with former results, the preference values from the LCJ, as shown in figure 2b have been used. It is remarkable that six of the seven test sound have preference values in the lower half of the scale while test sound F has a much higher preference.



(a) Correlation of preference values according to BTL and LCJ. (b) LCJ.

Figure 2 – Preference scales: BTL vs. LCJ (a) and visualization of LCJ (b)

In order to physically explain the subjective preference values, a correlation analysis between the preference values correspondent to LCJ and different acoustic and psychoacoustic parameters was performed. Table 2 shows the correlation coefficients r of the particular parameter and the corresponding error probabilities α. A correlation was considered as relevant for error probabilities of less than $\alpha = 5\%$.

In accordance to the comparisons of the rank orders above, the unweighted and A-weighted SPL do not show a linear correlation and therefore, have a low correlation coefficient r. Moreover, the fluctuation strength and tonality are not correlated with the listener's preferences. Significant correlations to the preference exist for both calculation methods of sharpness and the articulation index as well as for roughness.

The sharpness was analyzed according to DIN 45692 (6) as well as Aures (7). The basic equation for calculating the sharpness S is given in equation 1, where N' is the specific loudness and g is a weighting function. Both measures depend on the critical band rate z, which reflect the 24 critical bands of hearing.

$$S = 0.11 \cdot \frac{\sum_{z=0}^{z=24\text{Bark}} N'(z) \cdot g(z) \cdot z/\text{Bark} \cdot dz}{\sum_{z=0}^{z=24\text{Bark}} N'(z) \cdot dz} \tag{1}$$

The difference between both methods is the weighting function g. While the weighting function of DIN (6)

Table 2 – Correlation analysis between preference after LCJ and physical parameters.

	r	α
SPL	0.45	0.3095
$SPL(A)$	0.55	0.2049
roughness	0.78	**0.0403**
fluctuation strength	-0.03	0.9523
tonality	-0.10	0.8284
sharpness (DIN)	-0.93	**0.0024**
sharpness (Aures)	-0.93	**0.0024**
articulation index	0.97	**0.0018**

is independent of the test sound's loudness the weighting function of Aures (7) considers the loudness. Both weighting functions are displayed in equation 2 for DIN and equation 3 for Aures.

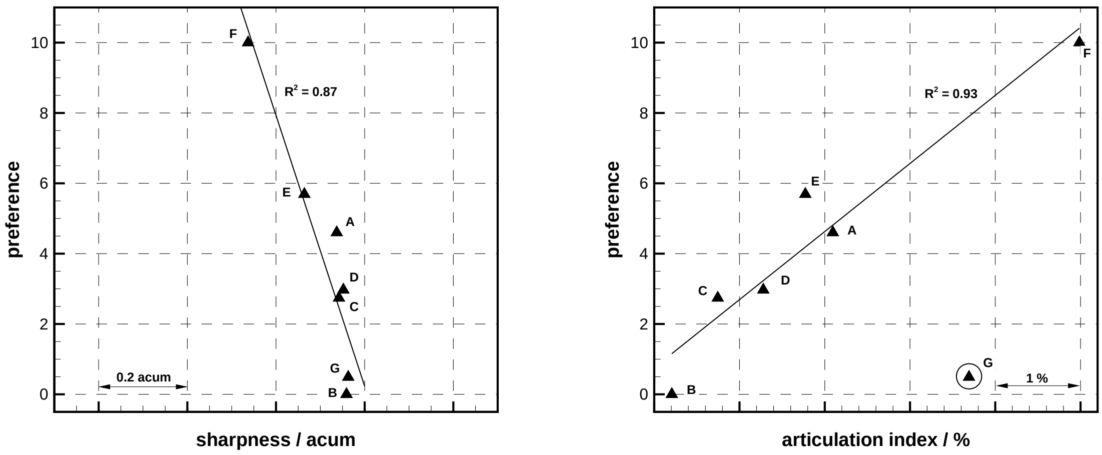
$$g_{\mathrm{DIN}}(z) = \begin{cases} 1 & \text{if } z \leq 15.8 \text{ Bark} \\ 0.15 \cdot e^{0.42(z/\mathrm{Bark}-15.8)} + 0.85 & \text{if } z > 15.8 \text{ Bark} \end{cases} \tag{2}$$

$$g_{\mathrm{Aures}}(z) = 0.078 \cdot \frac{e^{0.171 \cdot z/\mathrm{Bark}}}{z/\mathrm{Bark}} \cdot \frac{N/\mathrm{sone}}{\ln(0.05 \cdot N/\mathrm{sone} + 1)} \tag{3}$$

Due to the equalization of all test sounds on the same loudness level, the weighting function by Aures has no specific influence on the sharpness. Therefore, the correlation coefficients in table 2 have the same values and thus, only the DIN sharpness was considered.

The articulation index is a measure for speech intelligibility. In this study the closed articulation index (AI) according to equation 4 was used. It can take values between 0 and 1, where 1 means perfect and 0 no speech intelligibility. It is determined by summing up the weighted (g_i) differences of useful sound and background noise (L_i) for all third-octave bands between 200 and 5000 Hz. In this case, the background noise is induced by the HVAC system. The useful sound are typical levels of speech, which are standardized in ANSI S3.5-1969 (8). Figure 3 shows the correlations of DIN sharpness and the AI with the preference.

$$AI = \sum_{i=1}^{n} (g_i \cdot \Delta L_i) \tag{4}$$



(a) Sharpness.

(b) Articulation index. The encircled data point was not considered for the regression line.

Figure 3 – Preference as a function of DIN sharpness (a) and closed articulation index (b).

The correlation between preference and sharpness (figure 3a) has a negative slope, which means that the preference decreases with increasing sharpness. The coefficient of determination is $R^2 = 0.87$ and thus, 87% of the variance within the preference values are explainable by this linear regression model. The data points of the articulation index display test sound G as an outlier. This data point was therefore encircled and was not considered for determining the slope of the regression line and the coefficient of determination. It becomes obvious that the preference increases with higher values for the articulation index. The coefficient of determination is $R^2 = 0.93$.

The third identified parameter for assessing HVAC noise of equal loudness is the roughness. The roughness describes the hearing sensation that is induced by modulations in frequency or amplitude of the sound. The sensation of roughness is generated for modulation frequencies between 20 and 250 Hz. Lower modulation frequencies are perceived as fluctuation strength and modulation frequencies above 250 Hz are not audible. In this analysis, the roughness was calculated as introduced by Fastl (9). The connectedness between roughness and preference is displayed in figure 4.

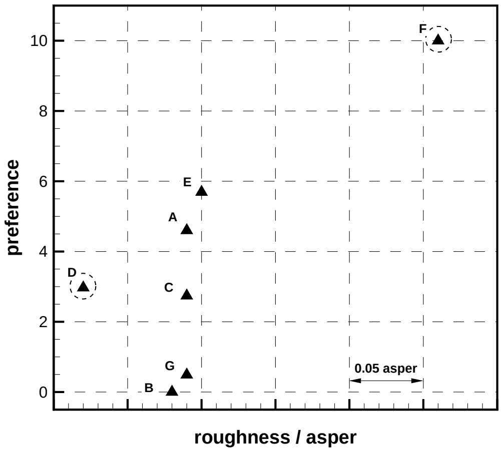


Figure 4 – Preference as a function of roughness.

It does not show a real linear correlation but a trend with a positive slope. Hence, the preference increases with increasing values of roughness. Moreover, it is remarkable that test sounds A-E and G form a cluster on a similar level of roughness. The roughness of test sound F differs towards higher roughness from the cluster. It is remarkable that the preference of test sound F and its roughness stands out in a similar way. This could mean that a high roughness generates a high perceived quality of the sound. Due to relatively small absolute differences in roughness, this finding needs further investigation.

Spectral analysis

In a next step, the characteristics of the frequency spectra were compared in order to identify the crucial frequency ranges that influence the identified parameters. For reasons of better clarity, only four spectra of the investigated seven sound samples are displayed in figure 5. The test sounds were chosen by forming preference clusters on the LCJ scale. Test sounds B and G form one group with the lowest preferences near 0. The second group was formed by test sounds C and D with a prefence of 2 - 3. The third group includes test sounds A and E, with preference values around 5 and the fourth plotted spectrum is the one of test sound F with the highest preference of 10. The test sounds with the higher preference within their group are plotted in figure 5.

Basically, all test sounds show a qualitatively similar spectrum, which is expectable for sounds of the same sound class. In a medium frequency range between circa 100 and 3000 Hz, the shape of all spectra is relatively similar and due to the equalization of comparable SPL. Moreover, the spectra cross each other in this frequency range and thus, no obvious influence on preference can be derived. Hence, the high and very low frequencies seem to have an impact on the perceived quality in terms of preference values. It becomes apparent that the sound pressure levels of sound F above 3000 Hz are approximately 5 dB(A) lower than the ones of sound D and G and about 2-3 dB(A) lower than sound E. Furthermore, it is remarkable that the sound pressure levels show the same rank order (from low to high) as the preference values. Conversely, this is valid for low frequencies between 40 and 100 Hz. In this range, sound F shows considerably higher levels of about 5 dB(A) except for the peak at 60 Hz of sound D, which marks the rotations per second of the HVAC system's fan. Again, the order of the spectra matches with the order of preference values. In this frequency range high

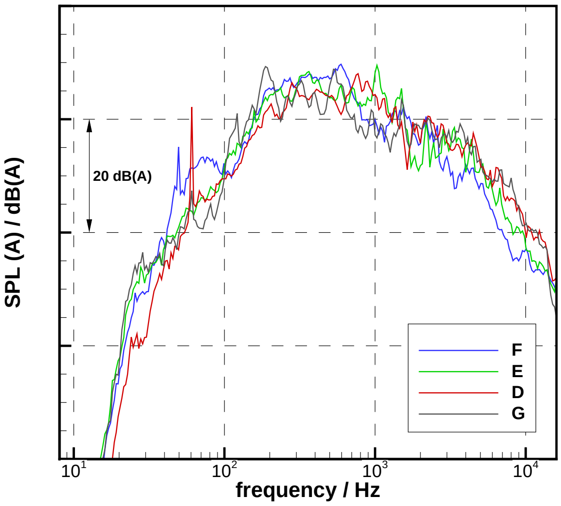


Figure 5 – A-weighted frequency spectra for test sounds D, E, F and G.

levels generate high preference.

The characteristics of the frequency spectra related to the preference values correspond to the definition of sharpness and the identified correlation above. Due to high levels in low frequencies as well as low levels in high frequencies, sound F has a low sharpness and thus, a high preference.

4. CONCLUSIONS

In this study, a listening test was performed on sound samples of HVAC noise with equalized loudness. Due to the high similarity of the test sounds, the preference paired-comparison technique was used.

Different rank orders of various evaluation criteria were compared. It was shown that neither the unweighted nor the A-weighted sound pressure level is suitable for assessing sound quality of HVAC noise. Both preference scales - according to Law of Comparative Judgement (LCJ) and Bradley-Terry-Luce Model (BTL) - show highly correlated results and the same rank order.

The subsequent correlation analysis between the preference values and psychoacoustic parameters showed that the parameters sharpness, roughness and the acoustic parameter articulation index determine the sound quality for HVAC noise of equal loudness. Sound F, which stands out due to its very high preference within the test group, also shows much higher values in all identified parameters.

The conclusive spectral analysis supports the importance of sharpness for determining sound quality on HVAC noise. High frequencies above 3 kHz and low frequencies below 100-200 Hz seem to have a major impact on sound quality of HVAC noise. Nevertheless, the eliminated parameter loudness still constitutes the dominant parameter and needs to be considered in acoustic optimization of HVAC noise.

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