How new temporal and spectral indices improve indicators of noise annoyance due to urban road vehicle pass-by noise

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Summary
Road traffic noise-induced annoyance is one of the main problems affecting health and well-being of residents in urban areas. Many studies suggest that energy-based indices, such as L_{den}, insufficiently characterize noise annoyance. In order to identify annoyance-relevant sensations evoked by urban road pass-by noise and to propose adapted indices, a semantic differential test was carried out on urban road vehicle pass-by noises equalized to the same A-weighted equivalent sound pressure level (L_{Aeq}). The stimuli comprised powered-two-wheelers, heavy vehicles, buses and light vehicles varying in driving conditions. From the analysis two different modulation-related sensations and a spectral sensation influencing annoyance judgments emerged. To characterize these sensations, adapted temporal and spectral indices were proposed. In the current work, these indices are tested based on annoyance responses obtained from two experiments employing a larger number of urban road vehicle pass-by noises. In Experiment 1, the pass-by noises were equalized to the same L_{Aeq}. Experiment 2 was based on the same pass-by noises but with level differences corresponding to differences observed in situ according to the type of vehicles and their driving conditions. It is shown that in both experiments, the characterization of annoyance based on the proposed temporal and spectral indices is improved compared to the psychoacoustic indices, such as roughness, fluctuation strength and sharpness. The results of Experiment 2 show the benefit of using loudness and the proposed indices as opposed to L_{Aeq} to better characterize noise annoyance due to urban road vehicle pass-by noise.

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1. Introduction

Road traffic is the most widespread noise source in Europe affecting health and well-being of residents in urban areas. Due to ongoing urbanization more and more people are exposed to noise. The Directive 2002/49/EC set out with the aim to reduce noise exposure in Europe requires European cities of more than 100 000 inhabitants to represent community noise in the form of strategic noise maps for major roads, railways and airports. These are produced using the L_{den} (day-evening-night level) index which is also employed for dose-effect relationships in noise annoyance calculation. Numerous studies have shown that noise annoyance due to community noise is not solely based on the sound pressure level and other acoustical signal characteristics such as temporal and spectral features influence noise annoyance ratings (e.g. [1-7]).

In order to improve the perception-related characterization of annoyance due to urban road vehicle pass-by noises, a semantic differential test with a verbalization task has been carried out [5]. Fourteen stimuli were employed comprising pass-by noises of powered-two-wheelers, heavy vehicles, buses and light vehicles varying in driving conditions. From the analysis different sensations influencing noise annoyance due to urban road vehicle pass-by noises emerged: the sensation “dull/shrill” associated with high-frequency content and two different sensations “sputtering” and “nasal” related to amplitude modulations were identified. The correlation of these sensations with psychoacoustic indices, such as sharpness, fluctuation strength and roughness was found to be unsatisfactory. To improve the characterization of the spectral sensation "dull/shrill" and the modulation-related sensations "sputtering" and "nasal" evoked by urban road vehicle pass-by noises, adapted indices were proposed. These indices were found to adequately characterize both annoyance and the prominence of the sensations [5].

The aim of the current work is to check these indices based on annoyance responses obtained from two experiments employing a larger number of urban road traffic pass-by noises without and with A-weighted sound pressure level differences between stimuli.

2. Presentation of new annoyance-related spectral and temporal indices

In the following, the philosophies behind the proposed indices characterizing the spectral sensation "dull/shrill""and the modulation-related sensations "sputtering" and "nasal", that affect annoyance, are outlined.

2.1. TETC index

The *TETC* index (Total Energy of Tonal Components) calculated between 12 and 24 barks has been proposed previously to account for the annoyance effect of the high-frequency content due to squeal noise of tramway pass-bys [3]. In Klein *et al.*, the *TETC* index between 16 to 25 barks was found to adequately characterize the spectral sensation "dull/shrill" influencing noise annoyance due to decelerating urban road vehicles [5]. The *TETC* index between 16 and 24 barks is defined as follows:

$$TETC = 10\log_{10}\left(\int_{15}^{24} 10^{\frac{L(z)}{10}} dz\right) \mathrm{dB} \qquad (1)$$

where $L(z)$ represents the maximal (across time) level of the tonal components as a function of the critical-band rate z. The maximal tonal component level as a function of the critical-band rate is calculated from the auditory spectrogram. The *TETC* index is calculated based on this representation by summing the energy of the tonal components within critical bands from 16 to 24 barks.

2.2. "Sputtering" and "nasal" indices

For the calculation of the "sputtering" and "nasal" modulation indices, the most prominent modulation frequency components in different modulation frequency bands are considered. Figure 1 and Figure 2 show the modulation spectra of two powered-two-wheelers in acceleration.

As can be seen in Figure 1, the pass-by noise dau_5 comprises amplitude modulations between 2 and 100 Hz with peaks at 17 Hz and 34 Hz. The pass-by noise dao_2 mainly comprises amplitude modulations between 100 and 200 Hz with a distinct peak at 150 Hz. This analysis indicates that the sputtering and nasal pass-by noises could be distinguished based on their distribution of modulation components in the range [0, 200] Hz. To take into account these sensations adapted modulation indices were introduced.

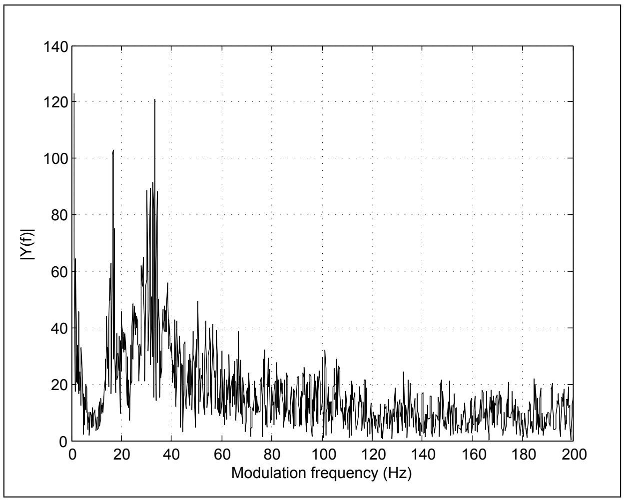

Figure 1. Modulation spectrum of the "sputtering" powered-two-wheeler in acceleration (dau_5).

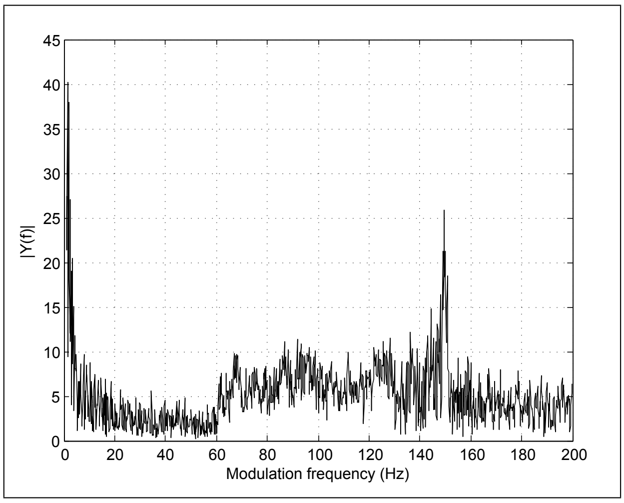

Figure 2. Modulation spectrum of the "nasal" powered-two-wheeler in acceleration (dao_2).

In order to extract parameters that refer to the temporal evolution of these sensations, the indices are estimated within successively overlapping time frames. The frame length was set to T = 400 ms and the step size to 23 ms. They are computed on the basis of the modulation spectra that are calculated using the instantaneous amplitude of the analytical signals that are built within the pass-by noise time frames. The "sputtering" index m_{sputt} is calculated by using the amplitude of the Fourier coefficient $|P_{\max}(2\mathrm{Hz} - 100\mathrm{Hz})|$ with the highest peak in the frequency range from 2 Hz to 100 Hz within a time frame i:

$$m_{\mathrm{sputt_i}} = \left[\frac{2 \cdot |P_{\max}(2\mathrm{Hz} - 100\mathrm{Hz})|}{P(0)}\right]_i \qquad (2)$$

The d.c. component $P(0)$ appears in the modulation spectrum in the range [0, 1.5] Hz (cf. Figure 1).

The "nasal" modulation index m_{nas} is calculated in a similar way by determining the amplitude $|P_{\max}(100\mathrm{Hz} - 200\mathrm{Hz})|$ of the strongest modulation frequency component in the range from 100 Hz to 200 Hz within a time frame i:

$$m_{\mathrm{nas_i}} = \left[\frac{2 \cdot |P_{\max}(100\mathrm{Hz} - 200\mathrm{Hz})|}{P(0)}\right]_i \qquad (3)$$

The indices are calculated for both the left and right channels but only maximal values across both channels are used.

In order to account for fast changes, the final indices to characterize the time-varying "sputtering" and "nasal" sound characteristics are the 90^{th} percentiles of the frame-dependent modulation indices, i.e. the values of the indices that are exceeded in 10 % of the time. They are denoted as:

- $m_{\mathrm{sputt,10}}$ for the "sputtering" index,
- $m_{\mathrm{nas,10}}$ for the "nasal" index of a pass-by noise.

In the following, these indices will be tested based on a broader range of stimuli without and with level differences between stimuli.

3. Testing the relevance of the indices

To test the relevance of the proposed indices, two experiments are carried out. In Experiment 1 (Exp. 1), urban pass-by noises are equalized to the same A-weighted equivalent sound pressure level, whereas in Experiment 2 (Exp. 2) they are equalized to different sound pressure levels. The objective of Exp. 2 is to assess the relevance of the modulation indices in combination with an index accounting for sound intensity (e.g. L_{Aeq}).

3.1. Stimuli

The urban road vehicle pass-by noises of the typology of Morel *et al.* [6] were divided into 7 perceptual and cognitive categories. Thirty-three pass-by noises were selected from the perceptual categories based on the following criteria: (i) for categories consisting of 4 pass-by noises, all the pass-by noises were chosen; (ii) regarding pass-by noises from categories comprising a larger number of stimuli, a maximum of 5 pass-by noises per category was selected according to their rating of category representation measured by Morel *et al.* [6]. The 33 stimuli consisted of powered-two-wheelers, buses, heavy vehicles and light vehicles in different driving conditions, including the 14 pass-by noises of the semantic differential test. Their durations ranged from approximately 3 s to 9 s. Based on these road vehicle pass-by noises, two experiments were carried out. In the first experiment (Exp. 1) pass-by noises equalized to the same L_{Aeq} of 60 dB(A) were used and in the second experiment (Exp. 2) pass-by noises with level differences corresponding to sound pressure levels measured *in situ* were employed.

Table I. Level differences (ΔL) between the average sound pressure levels measured *in situ* for light vehicles at constant speed and the average sound pressure levels measured *in situ* for other types of vehicles (B: bus, PTW: powered-two-wheeler, HV: heavy vehicle, LV: light vehicle) in different driving conditions (cf. [7]). The driving conditions are acceleration (acc.), deceleration (dec.) and constant speed (const.).

Vehicle type	Driving condition	Acronym	ΔL [dB(A)]
B	acc.	bao	+9.1
B	dec.	bdo	+4.2
B	const.	bfo	+7.5
PTW	acc.	dao	+7.2
PTW	dec.	ddo	+4.0
PTW	const.	dfo	+5.3
HV	acc.	pdo	+9.1
HV	dec.	pao	+4.2
HV	const.	pfo	+7.3
LV	acc.	vao	-2.4
LV	dec.	vdo	-4.5

The level differences (ΔL) applied to each pass-by noise correspond to mean level differences between the average sound pressure levels measured for the light vehicles at constant speed (vfo) and the average sound pressure levels measured for other vehicles in different driving conditions [7] (cf. Table I).

The reference level for light vehicles at constant speed was set to 54 dB(A) in order to obtain a sound pressure level range acceptable for listeners. From this level, the mean level differences ΔL were applied to the left and right channels of each pass-by noise depending on the vehicle type and the driving condition.

The resulting sound reproduction levels for the different pass-by noises ranged from 49 dB(A) to 62.5 dB(A).

3.2. Apparatus

The experiment took place in a quiet room with a background noise measured at 19 dB(A). The stimuli were reproduced employing a 2.1 audio reproduction system consisting of two active loudspeakers (Dynaudio Acoustics BM5A) and one active subwoofer (Dynaudio Acoustics BM9S).

Concerning the positioning of listener and loudspeaker, the center of the interaural axis of the listener and the loudspeakers formed an equilateral triangle. This was in accordance with the recommendations given by Bech and Zacharov [8]. The loudspeakers were placed at a height of 1.20 m from the floor, and the subwoofer was placed on the floor between the loudspeakers. The user interface was programmed using MATLAB©.

3.3. Procedure

For each experiment, the participants were asked to imagine themselves at home while relaxing (e.g. reading, watching television, discussing, gardening or doing other common relaxing activities). Prior to each experiment, the participants were trained. The stimuli were presented one by one in random order. This procedure has been used in previous work (cf. [3, 4]).

For each stimulus, a reminder of the imaginary situation was presented to the participants and they were asked "Does this noise annoy you?". The participants gave the ratings on a continuous scale ranging from "0" to "10", with 11 evenly spaced numerical labels and two verbal labels at both ends ("not at all annoying" and "extremely annoying").

3.4. Participants

Thirty-four participants (17 male, 17 female) aged between 20 and 54 years (mean age = 32.5; standard deviation = 11.8) took part in the experiment. All participants declared normal hearing abilities and were paid for their participation. In order to evaluate a potential effect of the experiment order (Exp. 1 followed by Exp. 2 or the reverse), the panel of participants was divided into two groups. One group consisting of 17 participants performed Exp. 1 and then participated in Exp. 2. The second group of participants carried out the two experiments in reverse order. Two-factor mixed-design ANOVAs (with one within-subject factor "Stimulus" and one between-subject factor "Order") were carried out on the annoyance responses obtained in Exp. 1 and Exp. 2, respectively. A non-significant effect of the experiment order was observed for Exp. 1 and Exp. 2 (respectively [$F(1,32) = 0.57$; $p = 0.45$] and [$F(1,32) = 2.15$; $p = 0.15$]). Hence, the annoyance responses from the 34 participants were grouped together in order to analyze the responses respectively gathered in Exp. 1 and Exp. 2.

4. Results

The two experiments allow for the validation of the proposed indices using a broader range of urban road vehicle pass-by noises. In order to be concise, the following analysis focuses on results obtained in Exp. 2 in which the stimuli exhibited differences in sound pressure level. The same tendencies could be observed for both experiments.

From Figure 3 clear differences between the annoyance ratings of the different urban road vehicle pass-by noises can be observed. The least annoying urban pass-by noises are light vehicles at constant speed (vfo_5) and in acceleration (vao_3, vau_1) whereas the most annoying urban road vehicle pass-by noises are powered-two-wheelers in acceleration (dao_2, dao_3).

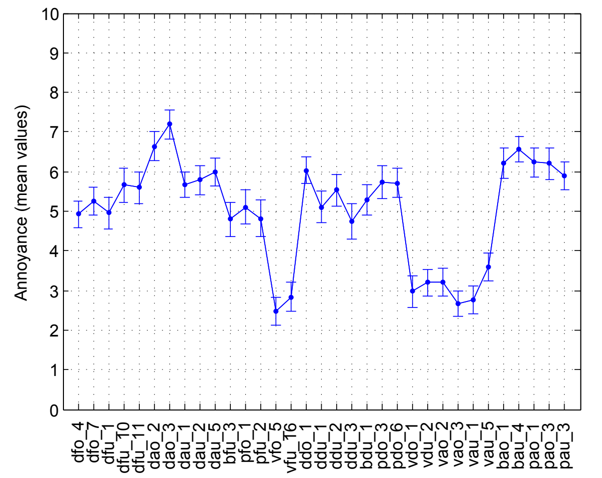

Figure 3. Mean annoyance ratings for each pass-by noise and their corresponding standard error (vertical bars).

A repeated measures ANOVA carried out on the annoyance responses showed a significant effect of the factor "Stimulus" [$F(10.36, 341.99) = 43.06$; $p < 0.001$]. To investigate the relationship between the values of different indices and the annoyance responses obtained for the 33 urban road vehicle pass-by noises, Bravais-Pearson correlation coefficients (r) were determined. Maxima, means and percentile values of loudness N and of the A-weighted equivalent sound pressure level L were determined in order to characterize sound intensity. Furthermore, indices are computed accounting for the spectral characteristics of the noises (A-weighted sound pressure level in high frequencies L_{HF}, sharpness S, Total Energy of the Tonal Components within critical bands from 16 to 24 Barks *TETC*, cf. [5]) and the temporal characteristics of the noises linked to amplitude modulations (fluctuation strength F, roughness R, "sputtering" index $m_{\mathrm{sputt},10}$ and "nasal" index $m_{\mathrm{nas},10}$). Correlation analysis revealed that intensity was well represented by mean loudness ($r = 0.89$; $p < 0.001$).

In order to identify indices which contribute to the annoyance characterization besides mean loudness, partial correlation coefficients (r_{part}) were also calculated controlling for mean loudness. Among the indices characterizing spectral features, the *TETC* index yielded the strongest partial correlation coefficient with mean annoyance ($r_{part} = 0.52$; $p < 0.01$). The partial correlation of sharpness with mean annoyance is not significant ($r_{part} = 0.26$; $p = 0.15$). The partial correlation correlation coefficient between L_{HF} and

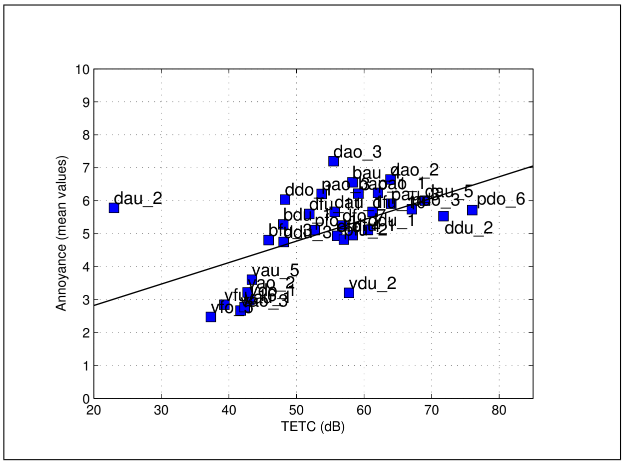

Figure 4. Mean annoyance ratings as a function of $TETC$ values for the 33 pass-by noises ($r = 0.55$; $p < 0.01$).

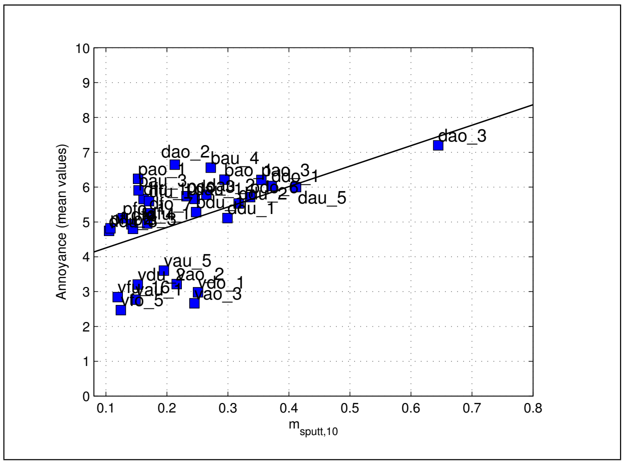

Figure 5. Mean annoyance ratings as a function of the $m_{\mathrm{sputt,10}}$ values for the 33 pass-by noises ($r = 0.5$; $p < 0.01$)

mean annoyance is either not significant ($r_{part} = 0.23$; $p = 0.2$).

As shown in Figure 4, the $TETC$ index leads to meaningful characterization highlighting the "shrill" character of the pass-by noise pdo_6. The Bravais-Pearson correlation coefficient determined between the $TETC$ values and the mean annoyance responses is significant and equal to 0.55. These findings are in agreement with the results of the semantic differential test and of the verbalization task [5].

Considering the indices characterizing sensations related to low amplitude modulations, controlling for mean loudness, the $m_{\mathrm{sputt,10}}$ index yielded the strongest partial correlation coefficient in comparison to F_{10} ($m_{\mathrm{sputt,10}}$: $r_{part} = 0.62$, $p < 0.001$; F_{10}: $r_{part} = 0.43$, $p < 0.05$). The "nasal" index $m_{\mathrm{nas,10}}$ was also significantly partially correlated with mean annoyance ($r_{part} = 0.4$; $p < 0.05$). However, the partial correlation coefficient calculated between the roughness index and mean annoyance is not significant ($r_{part} = 0.05$; $p = 0.8$).

Figure 5(a) and Figure 6 (b) depict the relationships between the mean annoyance responses and the values of the indices $m_{\mathrm{sputt,10}}$ (a) and $m_{\mathrm{nas,10}}$ (b). The corresponding Bravais-Pearson correlation coefficients calculated between the indices and mean annoyance are significant and equal to 0.5 and 0.4, respectively.

Considering the results of the semantic differential test and of the verbalization task [5], both indices contribute to the annoying character of the pass-by noises. For instance, based on $m_{\mathrm{sputt,10}}$, the pass-by noise dau_5 is characterized more annoying due to low amplitude modulations than the "nasal" pass-by noise dao_2. The $m_{\mathrm{nas,10}}$ index characterizes dfu_10 and dao_2 as very annoying due to their "nasal" characteristic.

The calculation of mean annoyance responses by a suited combination of the indices was carried out using multiple linear regression. Two regression models were created: the first model into which the in-

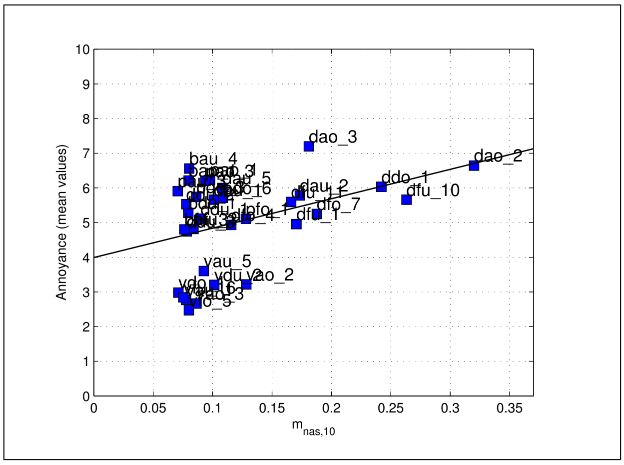

Figure 6. Mean annoyance ratings as a function of the $m_{\mathrm{nas,10}}$ values for the 33 pass-by noises ($r = 0.4$; $p < 0.05$).

dices N_{mean}, $m_{\mathrm{sputt,10}}$, $m_{\mathrm{nas,10}}$ and $TETC$ are inserted (model 1, also denoted URA for Urban Road vehicle pass-by noise Annoyance), and the second model for which the indices N_{mean}, F_{10}, and $TETC$ are considered (model 2). If the roughness index is included in model 2, its regression coefficient is not significant, which is in line with the result regarding the partial correlation. Both models fit mean annoyance responses well (model 1: $F(4,32) = 111.35$, $p < 0.001$; model 2: $F(3,32) = 65.39$, $p < 0.001$). The goodness-of-fit of each model was assessed using the determination coefficient (R^2), the adjusted determination coefficient (R^2_{adj}), and the standard error of the estimate (SE).

From Table II it can be seen that the best goodness-of-fit is obtained using model 1 as both R^2 and R^2_{adj} are maximal whereas SE is small. It must be noted that the regression coefficients are all highly significant for model 1 compared to model 2. An indicator only based on L_{Aeq} yields a determination coefficient

Table II. Multiple regression for noise annoyance calculation for the 33 urban road vehicle pass-by noises. R^2: the determination coefficient; R^2_{adj}: the adjusted determination coefficient; SE: the standard error; URA: Urban Road vehicle pass-by noise Annoyance. ^{a}: p < 0.01, ^{b}: p < 0.05.

Model	Regression models providing the calculated annoyance ratings (A_c)	R^2	R^2_{adj}	SE
1 (URA)	$A_c = 0.50^a\ N_{\mathrm{mean}} + 2.85^a\ m_{\mathrm{sputt,10}} + 3.51^a\ m_{\mathrm{nas,10}} + 0.026^a\ TETC$ - 0.79	0.94	0.93	0.35
2	$A_c = 0.51^a\ N_{\mathrm{mean}} + 0.02^b\ F_{10} + 0.025^a\ TETC$ - 0.13	0.87	0.85	0.50

of $R^2 = 0.72$. Just by replacing L_{Aeq} with N_{mean}, leads to an increase of the determination coefficient up to $R^2 = 0.79$ suggesting the importance to consider loudness for the characterization of annoyance due to urban road vehicle pass-by noises.

Based on the standardized regression coefficients, the contribution of each variable to the model can be determined. Mean loudness strongly contributes to model 1 (53 %), and the contribution of the other auditory attributes characterized by the indices $m_{\mathrm{sputt,10}}$, $m_{\mathrm{nas,10}}$ and $TETC$ is also important (47 %) (cf. [5]). This illustrates the relevance of the proposed indices besides mean loudness.

5. Discussion and conclusion

In order to assess the validity of the indices for specific sound characteristics, two experiments were carried out using an extended number of urban road vehicle pass-by noises without and with variations in sound pressure level.

As expected, in Exp. 2 it could be shown that the sound pressure level differences applied to the pass-by noises according to the vehicle type and driving condition had a large influence on the annoyance responses. Perceived intensity was well characterized using mean loudness. Based on partial correlations controlling for mean loudness, the importance of the indices $m_{\mathrm{sputt,10}}$ and $m_{\mathrm{nas,10}}$ and $TETC$ was demonstrated. Sharpness was not correlated with mean annoyance, supporting the results of Kaczmarek and Preis [1] who suggested that sharpness may have limited relevance for the characterization of annoyance due to road traffic noise.

The assessment of the combination of the proposed indices *via* multiple linear regression analysis showed that the annoyance model 1 (URA) comprising the modulation-related indices $m_{\mathrm{sputt,10}}$, $m_{\mathrm{nas,10}}$, mean loudness N_{mean}, and the $TETC$ index yielded a better model fit compared to an indicator comprising N_{mean}, F_{10} and $TETC$. Furthermore, it could be shown that using loudness instead of L_{Aeq} leads to an improved annoyance model fit.

The $m_{\mathrm{sputt,10}}$ and $m_{\mathrm{nas,10}}$ indices account for the "sputtering" and "nasal" characteristic of the pass-by noises, respectively. These indices are not taking into account sound pressure level or loudness differences. In contrast, fluctuation strength and roughness indices are loudness-dependent and consequently the combination of the indices $m_{\mathrm{sputt,10}}$ and $m_{\mathrm{nas,10}}$ used in model 1 (URA) allowed a more adequate calculation of annoyance than model 2. This finding confirms the findings of Paviotti and Vogiatzis [2]. They showed that roughness and fluctuation strength do not seem to be adapted for the characterization of annoyance evoked by powered-two-wheeler and light vehicle pass-by noises.

It would be interesting to assess in future studies the relevance of the proposed noise annoyance indicator when different urban road traffic compositions are considered rather than urban road vehicle pass-by noises.

Acknowledgement

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