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Annoyance of Time-Varying Road-Traffic Noise

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The aim of the study was to investigate how the time structure of a road-traffic affects the noise annoyance judgment. In a psychoacoustic experiment, the listeners judged noise annoyance of four road-traffic noise scenarios with identical numbers of vehicles and $L_{Aeq,T}$ value but different time structure of a road traffic. The traffic structure varied from even to highly clustered across different scenarios. The scenarios were created in the laboratory from a large set of a single vehicle pass-by recordings. The scenarios were additionally filtered with filters corresponding to a typical window transfer function to simulate the situation inside the building. The experimental results showed that there is a significant difference in annoyance judgment for different traffic structures with the same $L_{\mathrm{Aeq},T}$ value. The highest annoyance ratings were obtained for even traffic distribution and the most clustered distribution resulted in the lowest annoyance rating. These results correlated well with the averaged loudness, whereas the percentile loudness (N_5) and level (L_5) predict the opposite results.

Keywords: noise annoyance, ICBEN scale, time varying noise.

1. Introduction

In the traditional approach to the study of noise annoyance, annoyance scales are directly related to scales of physical properties of isolated noise. These physical properties of isolated noise are usually recognized as noise metrics or noise ratings (for recent reviews see MARQUIS–FAVRE *et al.*, 2005a, 2005b; KRYTER, 2007). There are many noise ratings, for example, energy-based ratings like $L_{Aeq,T}$, L_{DEN}, L_{AE}, or ratings directly related to the sound pressure level like L_A, $L_{A,\max}$. Currently, still the most popular approach defines noise annoyance in terms of a single physical variable, that is, sound pressure level defined in a different way, which is easily identified and measured, both in field or laboratory conditions.

The problem with such an approach is that the results of different studies carried out during the last decade have shown a very weak correlation between the noise annoyance scales and noise metrics. To improve this correlation, several solutions have been proposed to both components of this relationship. According to Zimmer and Ellermeier (1996) and Kaczmarska and Łuczak (2008), large differences in listeners' evaluations of noise annoyance of the same noises are caused by individual noise sensitivity. However, we could always find people who are of the same age, with the same experience and they should show the same noise sensitivity.

Another approach, that allows to neglect the noise sensitivity problem, was proposed for the first time by Zwicker (Zwicker, Fastl, 1990) and was called unbiased annoyance (UAB). It means that "noise annoyance does not depend on the relationship of the listener to the sources of the noise" (Zwicker, Fastl, 1990 page 289). In the original model published in the book (Zwicker, Fastl, 1990), the value of UBA is calculated from N_{10} loudness (the loudness value reached or exceeded in 10% of the measurement time), averaged sharpness, and fluctuation strength together with a day-night correction. In this formula, noise annoyance is defined as a multicomponent concept depending on more than one acoustical variable. In literature there are more similar multicomponent approaches (for a recent review see Marquis–Favre *et al.*, 2005b) to noise annoyance. Let us mention two of them. Preis (1995), proposes to represent noise annoyance (An) as a result of linear combination of three terms: annoying loudness (AL), intrusiveness (IN) and distortion of informational content (DR). In a second (Zwicker, Fastl, 1999) and a third edition (Fastl, Zwicker, 2007) of their book, a corrected formula for the UBA, now called psychoacoustic annoyance, (PA) is published. Compared to the UBA, in the new formula N_{10} values are changed to $N5$ and roughness is added as a component of psychoacoustic annoyance. How to calculate UBA, PA and DR is presented in Eqs. (1), (2) and (5).

Unbiased annoyance, UBA, is defined as follows:

$$UBA = d\left(\frac{N_{10}}{\text{sone}}\right)^{1.3}\left[1 + 0.25\left(\frac{S}{\text{acum}} - 1\right)\log\left(\frac{N_{10}}{\text{sone}} + 10\right) + 0.3\left(\frac{F}{\text{vacil}}\,\frac{1 + N_{10}/\text{sone}}{\frac{N_{10}}{\text{sone}} + 0.3}\right)\right], \tag{1}$$

where N_{10} stands for percentile loudness in sone, S for sharpness, F for fluctuation strength, and d for day/night factor.

Psychoacoustic annoyance PA is defined as follows:

$$PA = N_5\left(1 + \sqrt{w_S^2 + w_{FR}^2}\right), \tag{2}$$

with N_5 percentile loudness in sone, w_S describing the effect of sharpness S,

$$w_s = \left(\frac{S}{\mathrm{acum}} - 1.75\right) 0.25 \lg \left(\frac{N_5}{\mathrm{sone}} + 10\right) \quad \text{for} \quad S > 1.75\,\mathrm{acum}, \tag{3}$$

w_{FR} describing the influence of fluctuation strength F and roughness R

$$w_{FR} = \frac{2.18}{(N_5/\mathrm{sone})^{0.4}} \left(0.4\frac{F}{\mathrm{vacil}} + 0.6\frac{R}{\mathrm{asper}}\right). \tag{4}$$

DR is defined as follows:

$$DR = \left(\sum_i \Delta t_i\right) / T, \tag{5}$$

where T is the total duration of the noise, Δt is the total on-time for any component of noise appearing irregularly above the background noise in each noise scenario.

In any multicomponent formula of noise annoyance it is emphasized that loudness is the main factor of annoyance. This fact creates a new problem. How do we know that listeners, when they are asked to judge annoyance, are actually judging loudness? Fortunately, just recently, it has been proven that listeners are capable of separating annoyance and loudness of the same stimuli (Dittrich, Oberfeld, 2009).

The last problem which has not been solved yet is how to measure noise annoyance of time-varying noise? Again there are several proposals in the literature, among others simple $L_{Aeq,T}$ is recommended to be used for noise annoyance evaluation of a real-world noises (Hiramatsu *et al.*, 1983; Kuwano, Namba, 2000). However, the presently valid noise index based on the averaged energy does not "see" the time structure of the signal. It means that two noises with the same $L_{Aeq,T}$ but having different time structures are assumed to have the same noise annoyance. There are several studies showing that this is not the case (among others, Sandrock *et al.*, 2008; Dittrich, Oberfeld, 2009).

One possible explanation is that the difference in noise annoyance of noises with the same $\mathrm{L}_{Aeq,T}$ is caused by different loudness. Loudness explains, for example, the train bonus (Fastl *et al.*, 1994) or tram bonus (Kaczmarek *et al.*, 2006). As a consequence, the alternative noise indices have been proposed in literature based on the calculated loudness like N_{10} or N_5. Concerning non-stationary sounds (i.e. the characteristics of which vary with time), two main models have been developed. The first one was published by Zwicker and Fastl in their book (Zwicker, Fastl, 1999) and the second one by Glasberg and Moore (2002). Despite the fact that the calculations of N_{10} or N_5 performed by these two different models led to different values, the ranging of the noises is the same. However, even if we apply one of these models to calculate the loudness of time-varying noise, there is still a lack of satisfactory measure that represents loudness of such a noise. For example, loudness of sounds with temporal variable intensity estimated by subjects, could not be predicted by the value of N_5 only (Meunier, Marchioni, 2002). On the other hand, there are publications where N_5 is accepted as an appropriate measure of loudness of time-varying sounds, for example for aircraft noise (Fastl, Zwicker, 2007, page 324).

Finally, results obtained for loudness prediction based on the noise index depend on the type of stimuli used in an experiment. For example, from research concerning the loudness perception (Kuwano *et al.*, 1988; Neuhoff, 2001; Grimm *et al.*, 2002; Meunier, Marchioni, 2002; Patrick *et al.*, 2002; Canévet *et al.*, 2003; Susini *et al.*, 2007), it appears that not only total energy, but also time distribution of this energy is important for subjective sound assessment. It has been shown in all of these studies that loudness of time-varying sounds is different from loudness of the same sounds with constant level, both having the same $L_{Aeq,T}$. On the contrary, there is a study with results which show that certain noises with the same $L_{Aeq,T}$ have the same loudness (Dittrich, Oberfeld, 2009).

One conclusion of this literature review is that the stimuli investigated in the study of noise annoyance should represent as closely as it is possible the real noises, which occur in our environment. The variation of the traffic structure from even to highly clustered across different scenarios, resembles the situation which could occur in real life. It may be caused by the traffic-lights management, speed limits, number of lanes, types of road crossings (regular vs. roundabout) and the number of vehicles per hour. Management of all these traffic noise characteristics usually aims at the maximum smoothing of a traffic flow. However, knowing the relations between the traffic structure and noise annoyance assessment, one could predict the consequences of changes in these characteristics on noise annoyance changes. It could be possible that these characteristics can also be used to some extent to minimize the noise annoyance.

In the present study, the influence of time distribution of passenger vehicles on noise annoyance ratings was investigated. We assumed the same $L_{Aeq,T}$ value of four different noise scenarios, trying to point out the other possible noise characteristics responsible for noise annoyance assessments of the investigated noise scenarios.

2. Method

2.1. Noise samples

Four different noise scenarios were created as the stimuli for psychoacoustic experiment. The duration of each scenario was 10 minutes. Each scenario contained the same number of passenger vehicles, namely 120. The scenarios were created in the laboratory by appropriately distributing of single vehicle pass-by recordings over the time. The single pass-by recordings were chosen from a large vehicle-noise database, established within the SILENCE Integrated European Project. Each scenario was created exactly from the same set of vehicles, thus the 10 minutes average one-third octave band spectra and $L_{Aeq,10\ \mathrm{min}}$ were identical. The $L_{Aeq,10\ \mathrm{min}}$ of all scenarios was 55 dBA. For each scenario the background noise was added at a -15 dB level. The background noise was the quasi-stationary noise recorded at a large distance from a city road infrastructure. Scenarios were additionally filtered with a filter, which corresponded to a transfer function of a double-glazed standard window in order to simulate the situation of the noise inside the building. The filter was obtained by averaging of the set of field measurements of windows provided by different window-makers. The frequency response of a filter based on these data is presented in Fig. 1. All scenarios were prepared as 24 bits 44100 Hz mono-files.

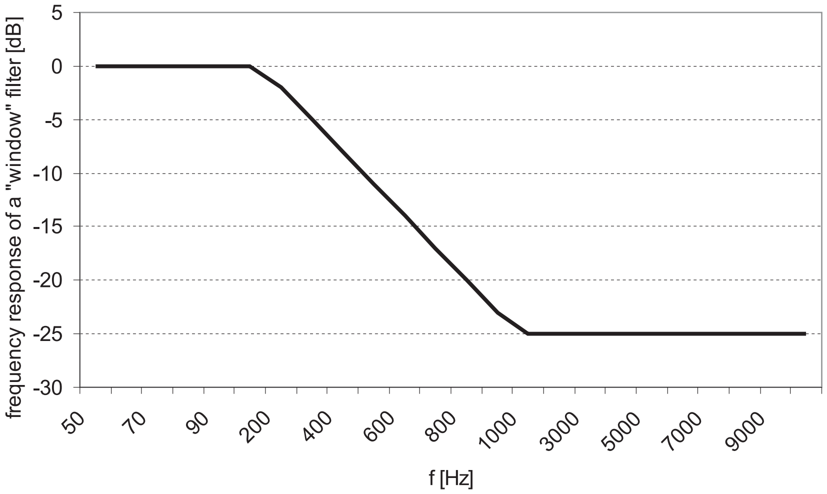

Fig. 1. Frequency response of a filter used to simulate the transfer function of a typical wall with a window.

Four different structures of traffic were simulated:

1 – even vehicle distribution – equal distance between vehicles (5 seconds – with small random variations),
2 – 5 groups of vehicles – 24 vehicles in each group, equal distance between each group (with some random variations), average distances between vehicles within the group – 4 seconds,
3 – 5 groups of vehicles – 24 vehicles in each group, equal distance between each group (with some random variations), average distances between vehicles within the group – 2 seconds,
4 – 5 groups of vehicles – 24 vehicles in each group, equal distance between each group (with some random variations), average distances between vehicles within the group – 0.5 second.

The example of the time pattern of each type of scenario is presented in Fig. 2. Before the experiment, an objective analysis of all scenarios was performed with

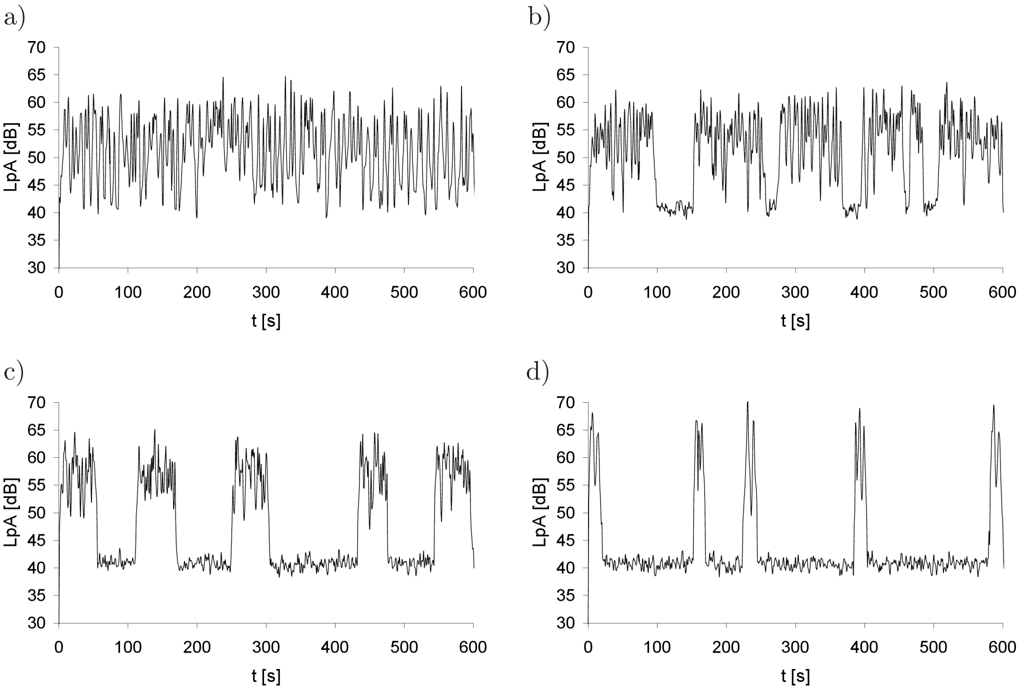

Fig. 2. Examples of four different time patterns investigated in the psychoacoustic experiment. The panels a–d correspond to the scenarios 1–4 defined in the text above.

the help of the HEAD acoustic software called ArtemiS Analyzer. The A-weighted sound pressure level, loudness, sharpness, fluctuation strength and roughness (Fastl, Zwicker, 2007) were calculated. For each mentioned sound characteristic, the averaged as well as the percentile (5%) values were calculated. In addition, three constructions were tested: unbiased annoyance (UBA), (Zwicker, Fastl, 1990; 1999), psychoacoustic annoyance (PA), (Fastl, Zwicker, 2007) and distortion of informational content (DR), (Preis, 1995). The results of all calculations are presented in Table 1.

Table 1. Results of the objective analyses.

$L_{pA\,\mathrm{max}}$	N	S	R	L_5	N_5	S_5	R_5	N_{10}	FS	PA	DR	UBA
64.8	8.2	1.4	1.2	60.2	14.6	1.7	1.9	13.2	0.0034	22.5	0.9	32.1
64.2	8.2	1.4	1.2	60.3	14.5	1.7	1.9	13.2	0.0034	22.2	0.8	32.2
65.4	7.0	1.3	0.9	61.3	15.7	1.7	2.0	14.0	0.0026	21.6	0.6	34.4
70.5	5.2	1.2	0.5	63.2	17.5	1.7	2.1	12.3	0.0022	21.3	0.3	28.2

From Table 1 it can be observed that maximum A-weighted sound pressure level, L_5 percentile level, as well as the percentile loudness N_5 and roughness R_5, increases as the clustering of a traffic flow increases. The increase of maximum

A-weighted sound pressure level and L_5 percentile level can also be found in Fig. 2. The reason for that is that the vehicles in scenarios 2–4 are closer to each other and the noise of different vehicles overlaps, resulting in an increase of maximum A-weighted sound pressure level. The $L_{Aeq,T}$ – as expected – does not depend on the vehicles time distribution, however the averaged over 10 minutes values of N, R, FS, PA and DR decrease as the clustering of a traffic flow increases. The N_{10} and UBA do not follow this tendency. There are no differences between the S_5 for all noise scenarios. It is difficult to judge the differences in PA and S for all noise scenarios, however, it is reasonable to assume that they are too small to be responsible for different *ICBEN* annoyance ratings.

2.2. Procedure and equipment

In the conducted experiment, the participants judged noise annoyance of 12 different noise scenarios (each of four types of scenarios was prepared in three independent realizations). The whole experiment was carried out in three 40-minutes sessions – one session per day. During each session, four 10 minutes noise scenarios were presented with 10 minutes breaks between the scenarios. Participants were seated in a 32 m^2 damped room in armchairs. They judged noise annoyance of each scenario using 11 points (0–10) numerical scale. The scale used in this study is recommended for noise surveys by ICBEN (Fields *et al.*, 2001; Preis *et al.*, 2003) and defined in the ISO/TS 15666:2003(E) standard (ISO, 2003). However, the question about annoyance was adapted to the laboratory situation, e.g. there was no question about the last 12 months but about the present situation. In accordance with the recommendations of earlier studies (Berglund *et al.*, 1976; Hellman, 1982; Song *et al.*, 2008) and with the ICBEN recommendations (Fields *et al.*, 2001; Preis *et al.*, 2003), the participants were given the following instructions: *Please sit comfortably in the armchair. Imagine that you are resting at home. You will hear road traffic noise. What number from zero to ten shows how much you are bothered, disturbed or annoyed by the noise? If you are not at all annoyed, choose zero, if you are extremely annoyed, choose ten, if you are somewhere inbetween, choose a number between zero and ten.* In order to avoid simple loudness scaling, the instructions were carefully explained. The signals were presented via the Sennheiser HD600 open headphones and were sent from the computer through the HEAD acoustic PEQ IV.1 programmable equalizer. After calibration procedure, the $L_{Aeq,T}$ level of each scenario corresponded to 55 dBA.

2.3. Participants

Nineteen participants (between 19 and 24 years old) took part in the experiment. All participants qualified as having normal hearing (normal hearing was defined as the audiometric threshold of 20 dB HL or better, for the frequency range from 250 to 8000 Hz, according to the ANSI standard (ANSI, 1996)) and were paid for their participation.

3. Results

As a result of the psychoacoustic experiment, the annoyance ratings of 12 different noise scenarios were obtained. The results of three repetitions of each type of noise scenario were then averaged giving four average annoyance ratings for each participant. The individual results are presented in Fig. 3. The results were grand mean – centered. This means, that a normalizing coefficients were created for each subject by dividing the overall mean of all results by the mean of the results obtained by a given listener. Then, the results of a given listener were multiplied by these factors.

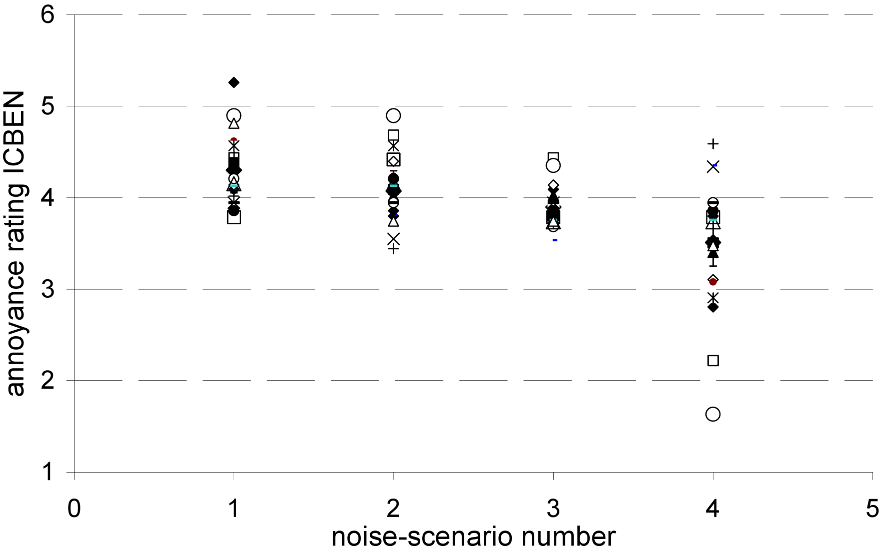

Fig. 3. Individual results of psychoacoustic experiment (19 listeners) – mean annoyance ratings for four different traffic distributions (after grand-mean centering).

The repeated measurements ANOVA design resulted in a significant main effect – namely noise scenario type, $[F(3, 54) = 7.36;\ p < 0.05]$. The results are also presented in the averaged form (across participants) in Fig. 4. Despite the significant main effect, the detailed pair comparisons showed significant differences only between the scenario 2 and 4 ($p = 0.03$), 1 and 4 ($p = 0.003$), 1 and 3 ($p = 0.001$). To point out the other possible noise characteristics responsibly for noise annoyance assessments of the investigated noise scenarios, the correlation coefficients between all objective measures (presented in Table 1) and annoyance ratings were calculated. The calculated correlation coefficients are presented in Table 2.

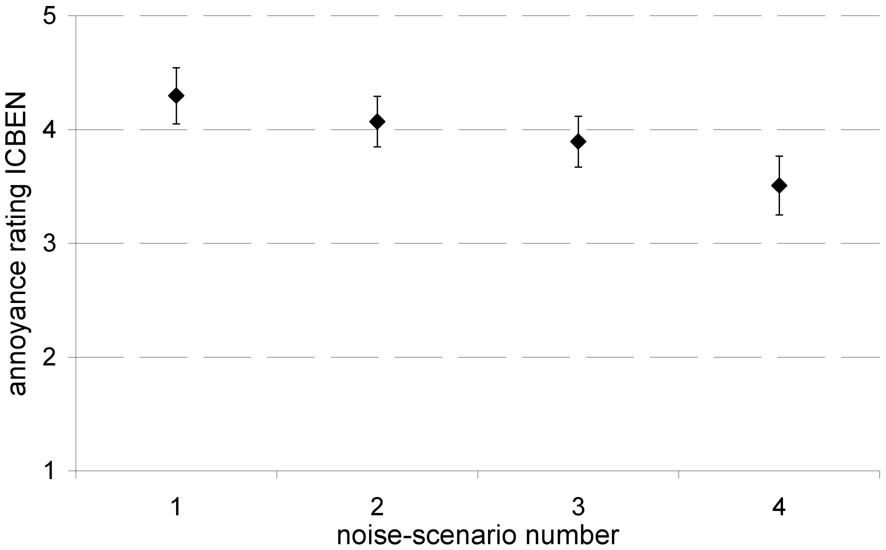

Fig. 4. Results of psychoacoustic experiment (averaged over the listeners) – mean annoyance ratings for four different traffic distributions.

Table 2. Correlation coefficients for ICBEN annoyance ratings and calculate noise indices.

R	$L_{pA\,\max}$	N	S	R	L_5	N_5	S_5	R_5	N_{10}	FS	PA	DR	UBA
	−0.89	**0.96**	–	**0.97**	−0.97	−0.95	–	−0.96	0.49	**0.93**	–	**0.98**	0.62

The statistically significant correlation coefficients are marked as bold. It means that following characteristics correlated significantly with the annoyance rating: N, R, FS, and DR. For sharpness S, S_5 and PA, correlation coefficients were not calculated, since the values of these metrics were the same or almost the same for all noise scenarios. Both the loudness, N, and time characteristics R, FS and DR, contribute to the annoyance assessment of noise scenarios. However, only loudness, N, takes into account both the energy and time pattern characteristic of the noise. As a result, loudness is the first candidate to replace the $L_{Aeq,T}$ as a noise index for time-varying noise.

4. Conclusions

The present study shows, that for traffic noise received inside the building the structure of traffic flow (and the resulting shape of a time pattern) can influence annoyance judgments. However, the phenomenon is not very sensitive to subtle changes in the time pattern and the effect is significant only for a large differences in the time pattern. The present study found that the averaged loudness, N, better correlates with the annoyance ratings than the percentile value of loudness N_5.

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