Annoyance penalty of impulsive noise

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Abstract

Many guidelines require an adjustment k (penalty, sanction) to be applied on the measurement result of L_{Aeq}, if noise is impulsive. The adjusted level, $L_{\mathrm{Aeq}}+k$, should describe noise annoyance better than L_{Aeq} alone. ISO/PAS 1996-3 (Model A) provides a model where the penalty k depends on measured properties of an impulse: onset rate (R_{on}) and level difference (D_{L}). Recent evidence showed that Model 1 overestimates subjective annoyance for many types of impulses. Our purpose was to test five alternative Models 1–5 for predicting the subjective annoyance penalty. Models 2–5 predicted both subjective annoyance and annoyance penalty with higher precision than Model 1. Model 5 is recommended for practical measurements because of its simplicity. It is based on the measurement of sound level variability, L_{A1}–L_{A99}. The model is applicable for the impulsive noise within 45–65 dB L_{Aeq}, which is usual in residential yards. Another model may be needed for lower sound levels (25–40 dB) which are usual inside homes.

Keywords: *impulsive noise, noise annoyance, penalty, sanction, psychoacoustics*

1. Introduction

Many kinds of environmental sound sources involve impulsive character, e.g., shooting ranges, logistic centres, playing fields, industrial plants, and construction sites. Many guidelines define a sound level penalty (a.k.a. adjustment or sanction), if the measured noise has impulsive character. The penalty used in regulations and standards is usually a constant value, k [dB], that is added to the measured sound level, L_{Aeq} [dB]. The outcoming adjusted value, $L_{\mathrm{Aeq}}+k$, should then describe noise annoyance better than L_{Aeq} alone. Very usual penalty value is k=+5 dB.

However, there is strong experimental evidence that constant penalty values do not correspond to human perception, but more sophisticated models are needed, which depends on the prominence of impulse [1].
Therefore, ISO/PAS 1996-3 [3] provides a floating prediction model where the penalty k depends on measurable parameters of an impulse: onset rate (R_{on}) and level difference (D_{L}). They are explained in Fig. 1a. However, there is strong experimental evidence [1] that the model of ISO/PAS 1996-3 overestimates the perceived annoyance for many types of impulses.
The purpose was to test alternative prediction models for predicting the annoyance penalty of impulsive noise. The purpose was to determine their prediction accuracy against the subjective psychoacoustic data of Ref. [1]. The full version of this study is available in Ref. [2].

2. Materials and methods

The experimental annoyance data of this work is based on the psychoacoustic experiment of Rajala & Hongisto [1]. They studied how the annoyance of impulsive sounds at level 55 dB L_{Aeq} depended on different combinations of R_{on} and D_{L} (Table 1). The experiment had 32 participants. The number of stimuli was 41. All of them had the same spectrum shape. Altogether 33 of stimuli were impulsive sounds. The impulses were created from pseudorandom noise by modifying the time profile to the desired R_{on} and D_{L} values (Table 1). The spectrum corresponded to Beranek's proposal of sound masking (close to Brown noise within 100–10000 Hz). The impulses were presented periodically every 2.5 seconds. Some examples are given in Fig. 1b. In addition, 8 steady-state reference sounds were presented within 49–70 dB L_{Aeq} in 3-dB steps. The annoyance vs. L_{Aeq} of the reference sounds formed a straight reference line and this line was used to determine the annoyance penalty of each impulsive sound. The penalty values obtained by Ref. [1] for the 33 impulsive sounds are shown in Table 1.

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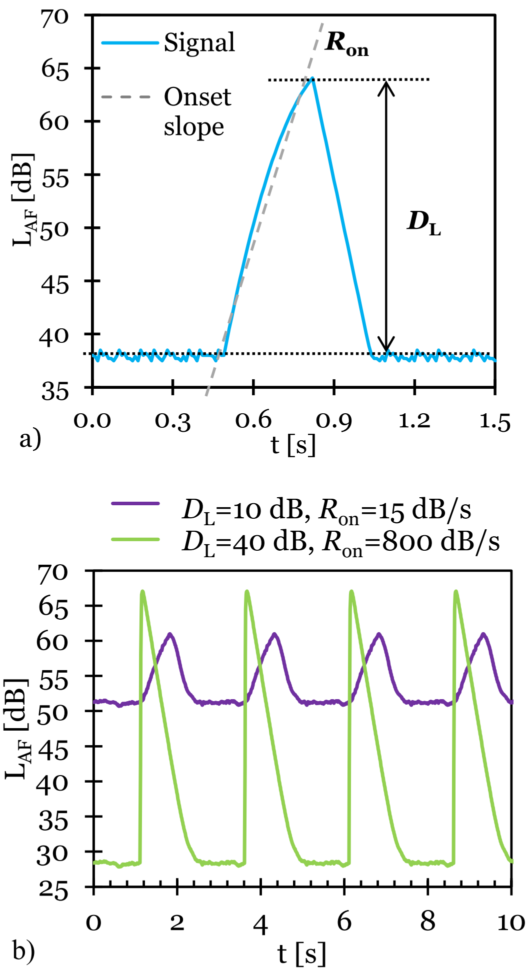

Figure 1. a) Fast-time weighted SPL, L_{AF}, of an impulse as a function of time, t, for a single impulse. The sampling time is 10 ms. b) Comparison of the time profiles of two different stimuli of Ref. [1]. NOTE: the A-weighted SPL was 55 dB L_{Aeq} for all stimuli.

Table 1. The dependence of subjective annoyance penalty on level difference, D_L, and onset rate, R_{on}, of the impulse according to Ref. [1].

R_{on} [dB/s]	D_L [dB]						
	5	10	15	20	25	30	40
5	-2.4						
10	-1.5	-1.4					
15	-1.5	-1.1	0.9				
20	-1.9	1.8	0.8	2.8			
50	-0.7	1.2	2.5	3.3	3.2	4.9	6.5
100		-0.1	4.4	5.3	5.4	5.6	7.4
200				3.0	6.3	7.7	6.6
400					6.5	7.7	8.1
600						6.6	7.9
800							8.1

Model 1 corresponds to ISO/PAS 1996-3 [3]. The idea of the penalty model was adopted from the Nordtest method [4]. Model 1 is based on the microstructural analysis of every impulse using the variables R_{on} and D_L (Fig. 1). First, the prominence P is calculated for each impulse by

$$P = 3 \cdot \log_{10}\left(R_{on}\right) + 2 \cdot \log_{10}\left(D_L\right) \tag{1}$$

P shall be limited to 15 dB. Thereafter, the penalty k is calculated by

$$k = \begin{cases} 1.8 \cdot (P-5), & P > 5 \\ 0, & P \le 5 \end{cases} \tag{2}$$

Model 2 is also based on R_{on} and D_L but the functional form of penalty is different. The form was based on more advanced fitting the psychoacoustic data of Table 1. The fitting procedure is explained in detail in Ref. [2]. The penalty is calculated by

$$k = 11 \cdot \log_{10}\left(\frac{D_L}{7}\right) - \frac{100 \cdot D_L - D_L^{\,2}}{25 \cdot R_{on}} \tag{3}$$

The penalty shall be limited to 12.7 dB.

Model 3 uses a definition of impulsiveness, which is based on a European directive [5]. It is calculated by

$$I_3 = L_{A,I} - L_{A,S} \tag{4}$$

where $L_{A,I}$ [dB] is the A-weighted sound pressure level (SPL) using Impulse (I) time weighting of 35 ms, and $L_{A,S}$ [dB] is the A-weighted SPL using Slow time weighting (1000 ms). Sampling time resolution shall be set to 10 ms. Sound is considered impulsive, if $I_3 \geq 4$ dB. Model 3 was developed using simple linear regression ($k = aI_3 + b$) between the explaining objective quantity I_3 and the observed penalty of Table 1. The penalty is calculated from

$$k = 0.744\left(L_{A,I} - L_{A,S}\right) - 2.039 \tag{5}$$

The criterion of Ref. [5] for non-impulsive sound (I_3<4 dB) was considered by forcing the calculated k to zero in such situations.

Model 4 is like Model 3 but $L_{A,I}$ was replaced by $L_{AF,max}$. Model 4 is justified because $L_{A,I}$ is no longer available in many sound level meters. First, impulsiveness is calculated from

$$I_4 = L_{A,F,max} - L_{A,min} \tag{6}$$

where $L_{A,F,max}$ [dB] is the maximum A-weighted SPL using Fast time weighting and sampling rate of 250 ms, and $L_{A,min}$ [dB] is the minimum SPL that appears between the impulses (background noise). Model 4 was developed using simple linear regression ($k = aI_4 + b$) between the explaining objective quantity I_4 and the observed penalty of Table 1. The penalty is calculated from

$$k = 0.240\left(L_{\text{A,F,max}} - L_{\text{A,min}}\right) - 1.280 \quad (7)$$

Model 5 is based on statistical sound level quantities which are also available in most sound level meters. First, impulsiveness is calculated using

$$I_5 = L_{\text{A,1\%}} - L_{\text{A,99\%}}, \quad (8)$$

where $L_{A,1\%}$ [dB] and $L_{A,99\%}$ [dB] are the SPLs of 1% and 99% percentiles. Analysis is made using Fast time weighting and 10 ms sampling rate. Model 5 was developed using simple linear regression ($k = aI_5 + b$) between the explaining objective quantity I_5 and the observed penalty of Table 1. The penalty is calculated from

$$k = 0.241\left(L_{\text{A,1\%}} - L_{\text{A,99\%}}\right) - 1.365 \quad (9)$$

Prediction error E [dB] for each impulsive sound i of Table 1 was calculated, for each model M, by

$$E_{M,i} = k_{p,i} - k_{o,i} \quad (10)$$

where $k_{p,i}$ [dB] is the predicted penalty of the sound i, and $k_{o,i}$ [dB] is the observed penalty for the same sound i (Table 1). The error was calculated for all 33 sounds and standard statistical quantities of the error distribution are reported.

3. Results

The precisions of the Models 1–5 are shown in Table 2. All Models provided statistically significant associations between predicted and observed penalty ($p<10^{-11}$, 2-sided). This means that all Models can be used to explain how the penalty changes due to the physically measurable changes in impulsive sound.

The association between observed and predicted penalty for Model 5 is visually demonstrated in Figure 2. More analysis and demonstrations are given in Ref. [2].

Closer inspection of Table 1 shows that Model 1 overestimates the penalty almost by E_M=2 dB. The largest overestimations occurred at large R_{on} and D_L values. All other models have their E_M values close to zero which means that there is no clear trend of overestimating or underestimating the penalty.

Models 2–5 provide similar E_M values, but Model 3 seems to have the largest individual errors (E_{min}, E_{max}). This scattering caused also the smallest correlation coefficient. The outcome is that the best Models are 2, 4, and 5.

4. Discussion

This work is unique since previous studies have not compared both existing and completely new models for predicting the annoyance penalty of impulsive noise.

The analysis showed that Models 2, 4, and 5 were the most precise for predicting the experimental psychoacoustic penalties of Ref. [1]. Since no other similar scientific work exists, they can be proposed to be the most useful models for real-life applications.

Next, the applicability of these models is discussed from practical or engineer's viewpoint.

Models 1 and 2 presume that R_{on} and D_L (see Fig. 1) must be determined for every impulse in sound. In this study, this was not needed since each impulse in an experimental sound i was identical in Ref. [1]. However, this is not the case for real-life situations where subsequent impulsive sounds always carry very different R_{on} and D_L values. The fact is that a long-term noise recording may lead to a massive number of impulses and prominences P of Eq. (1). ISO/PAS 1996-3 does not advise how all these prominences should be statistically treated. This leads to large reproducibility errors between different acoustic engineers (between-laboratory differences) with both Models 1 and 2.

Models 3 and 4 are based on the difference between maximum and minimum sound levels. Onset rate is not determined. Models 3–4 were successful in our work because the observed penalties depended very much on level difference at all onset rates. Ignorance of onset rate seems to be justified for the experimental data of Ref. [1]. The challenge of Models 3 and 4 in real-life measurements is the same as for Models 1–2: impulsiveness must be measured for every impulse and some kind of statistical analysis is needed for the assessment of the long-term noise recordings. This analysis is not advised in any regulation.

Model 5 solves this problem since impulsiveness I_5 of Eq. (8) is a statistical parameter. Since the percentile sound levels L_{A1} and L_{A99} are available in most commercial sound level meters, it seems to be the easiest approach to use Model 5 in real-life noise measurements. However, it must be kept in mind that Ref. [1] used identical impulses so that statistical variation between impulses in the same sound did not take place.

Table 2. Performance of Models 1–5. Statistical descriptors of the prediction error E (M=mean, SD=standard deviation, min=largest individual negative error, max=largest individual positive error), and descriptors of the linear association between observed and predicted penalty (r_P=Pearsons' correlation coefficient, a=slope of linear fit, b=intercept of linear fit).

	Model				
	1	2	3	4	5
E_M	1.8	0.0	0.1	0.0	0.0
E_{SD}	1.6	0.8	1.3	1.1	1.1
E_{min}	-0.6	-1.8	-3.1	-2.2	-2.2
E_{max}	5.4	1.7	3.6	1.6	1.6
r_P	0.91	0.97	0.89	0.93	0.93
a	1.16	0.97	0.74	0.86	0.86
b	1.15	0.07	1.09	0.55	0.54

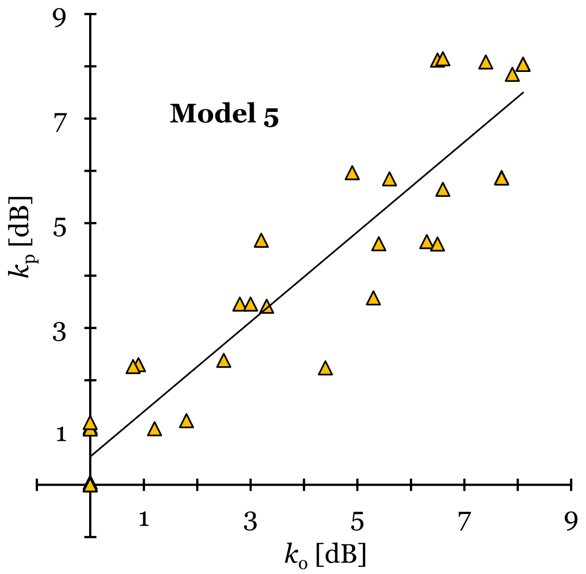

Figure 2. Association between the predicted penalty using Model 5, k_p, and observed subjective penalty based on the psychoacoustic experiment of Ref. [1], k_o.

Because Models 3–5 ignore the onset rate, they may lead to erroneous results for intermittent sound scenarios where level differences are large, but onset rate is small (e.g., pass-by sound of individual vehicle). In such cases, subjective decision must be made that Models 3–5 should not be applied.

The weakness of this work is that the subjective data was based on a single experiment (Ref. 1). The outcomes may depend on the stimuli choices made in the original experiment of Ref. [1]. The experiment of Ref. [1] was originally conducted to assess the penalty model of ISO/PAS 1996-3. Therefore, it focused on the broad coverage of R_{on} and D_L values. Because the ranges of both R_{on} and D_L were extremely broad, other features that impulsive noise in real-life can be, had to be strictly controlled. First, the impulses were synthetically created by modifying the time profile of pseudorandom noise. Second, identical impulses were periodically presented with 2.5 second intervals in each stimulus. Third, the A-weighted SPL was 55 dB L_{Aeq} for all impulsive sounds. Real-life impulsive noises are almost never fulfilling these limitations at the same time.

For example, there is recent evidence [6] that the annoyance penalty due to shooting noise (large R_{on}) agreed with Ref. [1], when L_{Aeq}=55 dB. However, the penalty values were significantly larger, when L_{Aeq}=35 dB. That is, penalties seem to increase by reducing overall sound level although the sound level profile of the impulse does not change.

Therefore, more experimental research should be conducted in the field of impulsive noise. Future studies should also focus on sound levels which are even more usual inside residential apartments: 25–35 dB (typical regulated indoor levels).

5. Conclusions

This work showed that the noise annoyance penalty model of ISO/PAS 1996-3 for impulsive noise overestimates the true penalty. This work provided an alternative model, which predicts the penalty better than ISO 1996-3, and it is based on sound level variability L_{A1}-L_{A99}. More work is needed in this field since this work is among the first that critically assessed alternative models of annoyance penalty.

6. Acknowledgements

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