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NOISE EVALUATION BASED ON HEARING SENSATIONS

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ABSTRACT

The hearing sensations loudness, sharpness, roughness and their simulations in computer programs are described. With respect to noise emissions, data for the evaluation of noise from railways, cars, electric razors as well as the sounds (noise?) of waterfalls are given. In the domain of noise immissions, the effects of "railway bonus" and "aircraft malus" are discussed in view of subjective evaluations and physical measurements by percentile loudness. Predictions of noise immissions from data of noise emissions are discussed in the domain of subjective as well as physical measurement. Noise evaluations based on hearing sensations show great potential for the assessment of noise emissions as well as noise immissions.

Keywords: Hearing sensations, noise emission, noise immission, loudness, sharpness, roughness, railway noise, car noise, electric razor noise, sound of waterfalls, railway bonus, aircraft malus, noise predictions.

INTRODUCTION

Noise evaluation based on features of the human hearing system shows great potential since (involuntarily) the human hearing system is the final receiver of noise. A systematic approach of noise control can be based on principles known from network theory: The transmission of (electric) power is optimal, if the impedance of the receiver is matched to the impedance of the source. Since noise frequently is defined as unwanted sound, a general principle of noise control should be to maximise the mismatch between source and receiver. Therefore, the features of a noise source have to be tailored in such a way that an optimum mismatch to features of the human hearing system is achieved. To arrive at this goal, it is indispensable to exactly know the features of the receiver, i.e. the human hearing system. Therefore, endeavours to elaborate a "data sheet" of the human hearing system can be regarded as a systematic and extremely useful way for noise control. The compilations necessary usually are found in anthologies on psychoacoustics (Fastl, 1982, Hellbrück, 1993, Blauert, 1996, Moore, 1997, Terhardt, 1998, Zwicker and Fastl, 1999).

In this paper, some of the basic features of the human hearing system, called hearing sensations are displayed and their simulations in computer programs are discussed. Practical examples for the subjective evaluation and physical measurement of noise emissions as well as noise immissions are given. Early results of ongoing research to predict noise immissions from data of noise emissions are reported.

HEARING SENSATIONS

Loudness represents one of the basic hearing sensations important for noise evaluation. When dealing with noise questions, these days usually values are given in A-weighted level with the unit dB(A). However, only a minority of the users of dB(A)-values is aware of the fact that already this rather simple measurement is based on features of the human hearing system. Results displayed in figure 1 (left) enable a comparison of equal loudness contours with A-weighting. For soft narrowband sounds (L_N=20 phon) there is fair agreement between subjective and physical evaluation when using A-weighting. However, at larger loudness (L_N=80 phon), the loudness of narrowband sounds at low frequencies is underestimated by A-weighting. This discrepancy is of practical relevance since many everyday sounds show a spectral distribution which is dominated by low frequency components. Moreover, the perceived loudness also depends of the bandwidth of sounds. The right panel in figure 1 illustrates that for sounds with same level L_A=60dB(A) (circles) the loudness N can increase with increasing bandwidth (filled triangles). In extreme cases, for sounds with same L_A-value, loudness differences up to a factor of four may occur (Zwicker and Fastl, 1999).

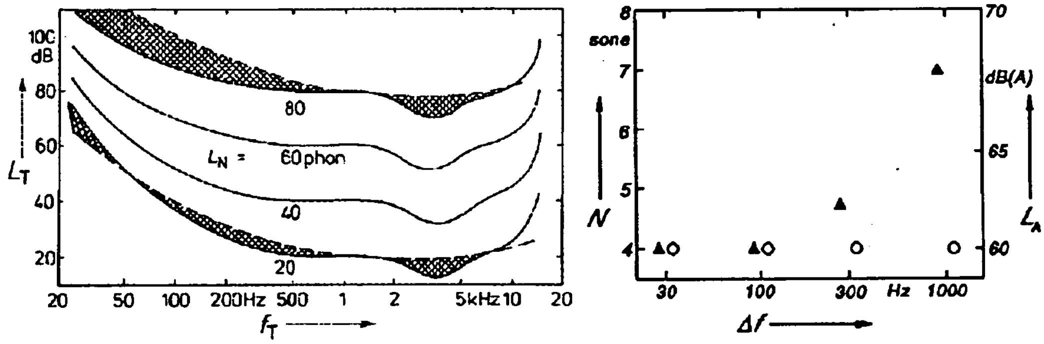

Fig. 1 Left: Equal loudness contours (solid) in comparison to A-weighting (dashed). Right: A-weighted level L_A (circles) and loudness N (filled triangles) of narrowband noise centred at 1 kHz with different bandwidth Δf.

In order to account for the spectral effects of loudness, instead of a single channel analysis as usually used in sound level meters, a multi-channel spectrum analysis is necessary. From the several procedures to assess loudness by physical simulations, the procedure proposed by Zwicker will be discussed in detail (Zwicker, 1960). In figure 2 the main features are displayed in a block-diagram. The sound is filtered by critical band filters from which the envelopes are extracted. The resulting outputs are transformed into specific loudness and temporal non-linearities of the human hearing system are simulated. After spectral integration and temporal integration loudness N as a function of time is obtained. In addition, figure 2 illustrates that other hearing sensations like sharpness, S, fluctuation strength, F, and roughness, R can be derived from loudness patterns (Fastl, 1998, Zwicker and Fastl, 1999).

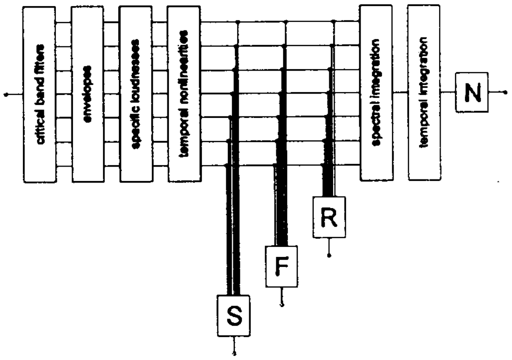

Fig. 2 Schematic block diagram of simulations of the hearing sensations loudness, N, sharpness, S, fluctuation strength, F, and roughness, R.

Using loudness models for stationary sounds (DIN 45 631, Zwicker et al., 1991) also the effects of bandwidth on loudness can be described quantitatively. Present day loudness measurement equipment can assess loudness of stationary sounds with high precision and deviations of only few percent (Fastl and Schmid, 1997).

The temporal processing of loudness is not yet achieved with the same accuracy by all apparatus available on the market. As an example figure 3 shows specific loudness-time patterns for 1 kHz tone impulses at 70 dB sound pressure level with a duration of 10 ms, 50 ms, and 500 ms. The solid curves display the indications of a system in perfect agreement with human perception, the dashed lines results of a bunch of analysis systems which are within ±5% on target, and the dotted areas illustrate the range of indications of all systems considered (see Fastl and Schmid, 1998, Fastl, 2000a).

Although some sound analysis systems available on the market can already mimic temporal features of loudness with high precision, others may be way off.

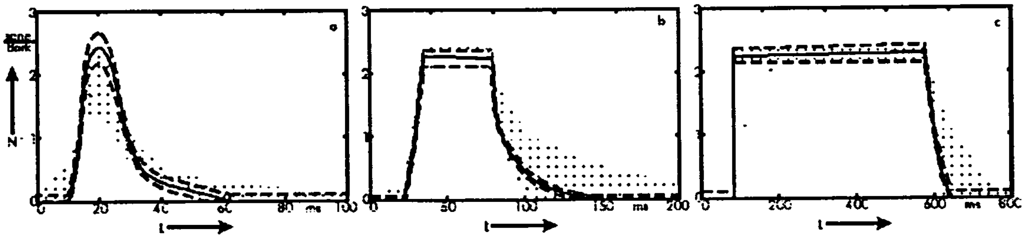

Fig. 3 Specific loudness-time patterns for 1 kHz tone impulses at 70 dB sound pressure level with a duration of 10 ms, 50 ms, and 500 ms.

With respect to the hearing sensation sharpness (v. Bismarck, 1974, Zwicker and Fastl, 1999), sound analysis systems available generally are in line with the subjective data, and the better systems achieve this goal with an accuracy of ±5% (cf. Fastl 2000a).

For modulated sounds, the hearing sensations roughness and fluctuation strength play an important role (Terhardt, 1968, Fastl, 1984). As a function of modulation frequency, roughness shows a maximum at about 70 Hz, fluctuation strength at about 4 Hz (Fastl, 1982). Simulations by a computer program (Widmann and Fastl, 1998, Zwicker and Fastl, 1999) are in line with psychoacoustic data.

In summary, present day simulations of hearing sensations in sound analysis systems can achieve a high degree of accuracy.

NOISE EVALUATION

Noise emissions. Subjective evaluations were performed in psychoacoustic experiments for a multitude of noise sources (cf. Namba et al., 1987, Kuwano et al., 1988, Zwicker and Fastl, 1999). Therefore, only few examples will be given here.

Data displayed in figure 4 give in the left part an overview of the train sounds evaluated. The right part of figure 4 enables a comparison of subjective evaluation (circles) with physical evaluation (stars) for train noise. The results displayed in figure 4 reveal that the length, speed, and type of train clearly can influence its noise emission. There is good agreement between evaluations in psychoacoustic experiments (circles) and physical measurements of percentile loudness N_5 (stars).

	Type of train	Length [m]	Speed [km/h]
A	Freight train	520	86
B	Passenger train	95	102
C	Express train	228	122
D	Super Express train ICE	331	250
E	Super Express train ICE	331	250
F	Freight train	403	100
G	Freight train	175	90

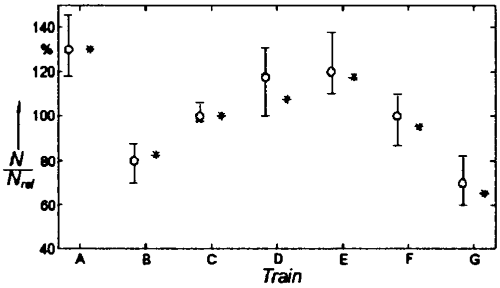

Fig. 4 Left: Overview of train sounds evaluated. Right: Comparison of subjective (circles) and physical (stars) loudness evaluation of train sounds.

Results displayed in figure 5 enable a comparison of subjective and physical evaluation of sounds produced by a middle-class car at different speed using different gears. The subjective data are given by circles, physically measured data of N_5 by stars. In Germany it is discussed to enforce a speed limit of 30 km/h within cities. Regarding the results displayed in figure 5, the public would benefit from such a speed limit, if car drivers adopt a noise-sensitive attitude: When using the 3rd gear, for a speed of 30 km/h the loudness of the car noise is by more than 30% smaller than for a speed of 50 km/h, and hence a relief from noise can be expected. On the other hand, if noise-insensitive drivers use the 2nd gear for a speed of 30 km/h, they produce almost the same noise as a noise-sensitive driver using the 4th gear for 50 km/h. Again data displayed in figure 5 show good agreement of subjective (circles) and physical (stars) evaluation.

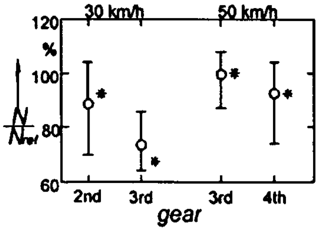

Fig. 5 Noise emission by a typical middle-class car at speeds of 30 km/h vs. 50 km/h using different gears. Circles: Subjective evaluation; Stars: Physical evaluation by N_5.

It is well known that the sound quality of products crucially depends on their loudness (Brennecke and Remmers, 1983, Widmann, 1998, Zwicker and Fastl, 1999). For the example of electric razors, figure 6 shows their ranking of sound quality as a function of their percentile loudness N_5 (Fastl, 2000b). Subjects assign the best rank (1) to the softest product and the worst rank (9) to the loudest product. This relation between sound quality and loudness is illustrated in figure 6 by the regression line. There is high correlation (r_S=0.85) between the loudness and the sound quality of electric razors. However, products with almost the same loudness N_5=17 sone can clearly differ in ranking of sound quality. This is due to other aspects like roughness and sharpness of their sound image (cf. Fig. 2).

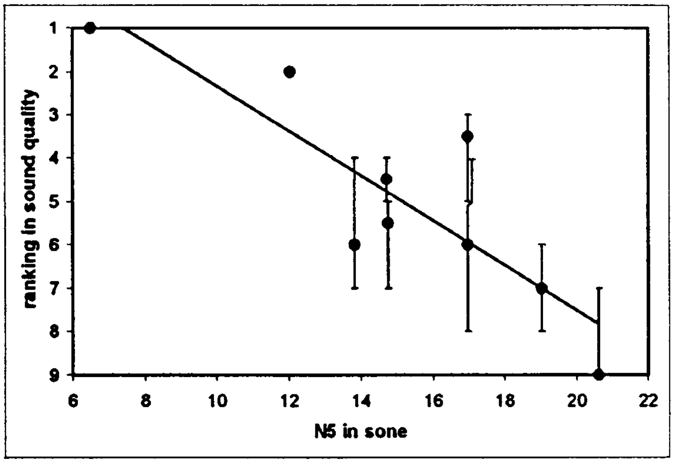

Fig. 6 Relation between percentile loudness N_5 and sound quality ranking of electric razors.

Our last example of noise emissions is somewhat unusual, since the sounds of waterfalls generally are not considered as unwanted sounds = noise. However, recently we got the first complaints about the sounds (noise?) of waterfalls in connection with a power plant at the dam of a river. Therefore, in cooperation with colleagues from the Institute of Hydraulic Engineering, we systematically studied the "loudness of waterfalls". A model of a waterfall with 1.70 meter height was realized in the Bavarian Alps in three different ways (cf. Fig. 7): a cascade with four steps (left), a cascade in four steps with basins (middle), and a gradual decline (right). In a distance of about 2 meters, the sound produced by the different waterfalls was measured for different amounts of water. Results displayed in figure 7 clearly reveal that the softest sound is produced by the gradual decline (right), whereas the largest loudness is obtained for the cascade in four steps without basins (left). However, with respect to sound quality, several subjects preferred the sound of the cascade with basins despite the fact that the loudness of the sound was larger than for the gradual decline. For the cascade with basins, a murmuring sound was obtained which reminds the subjects of the sound of a creek in a nice landscape. This result can be regarded as an example that for questions of sound quality other aspects in addition to loudness may be considered like other hearing sensations (Zwicker and Fastl, 1999), the meaning of sound as well as emotional aspects (Blauert, 1986, Namba, 1994, Kuwano and Namba, 2000). In addition, also visual aspects can considerably influence the rating of sound quality. The same sound, when presented together with a picture of a natural sound source can be preferred in comparison to presentation with a picture of an industrial sound source (Suzuki et al., 2000).

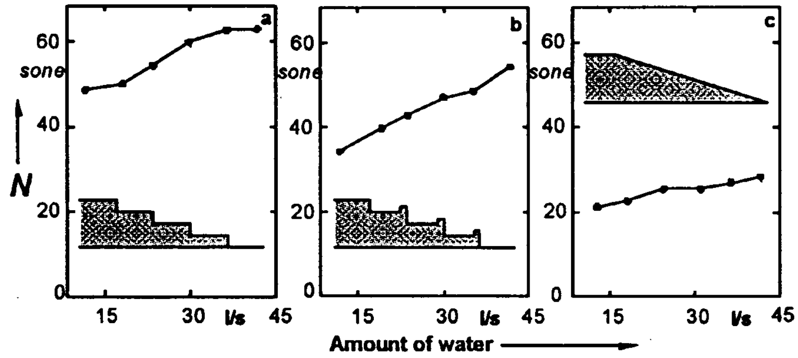

Fig. 7 Sound of a waterfall of 1.7 meter height for different amounts of water. (a) cascade in 4 steps, (b) cascade in 4 steps with basins, (c) gradual decline.

Noise immissions. For the evaluation of noise immissions, in many countries the A-weighted energy equivalent level L_{Aeq} is used (Kuwano and Namba, 2000, Tachibana, 2000). However, even at same L_{Aeq}, the subjective evaluation for different kinds of noise sources may be different. When comparing noise immissions from railway noise vs. road traffic noise, at same L_{Aeq}, railway noise produces less annoyance (Möhler, 1988). This effect was termed "railway bonus" and could be confirmed in laboratory studies (Fastl et al., 1996). On the other hand, at same L_{Aeq} aircraft noise is considered more annoying than road traffic noise (Green, 1993, Taylor, 1993). This effect was termed "aircraft malus", and similar effects were also found in the laboratory (Fastl and Hunecke, 1995). Together with colleagues from Osaka University, Japan, the effects of "railway bonus" and "aircraft malus" were studied in the laboratory (Fastl et al., 1998). Figure 8 shows in the left part the loudness-time patterns of noise immissions from railway noise (a), road traffic noise (b), and aircraft noise (c) for the same L_{Aeq}=71 dB(A). The right part of figure 8 shows the histograms of the categories assigned to the overall loudness of the different noises by 16 subjects from Japan and Germany. Filled circles indicate medians of the histograms, unfilled triangles quartiles.

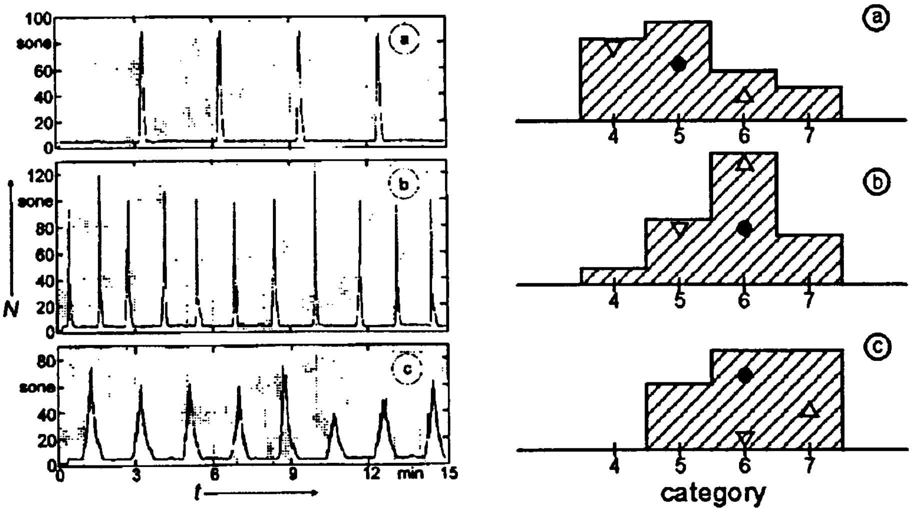

Fig. 8 Left: Loudness-time patterns for railway noise (a), road traffic noise (b), and aircraft noise (c) with same L_{Aeq}=71 dB(A). Right: Histograms for subjective evaluation of overall loudness in 7 categories. Medians (filled circles) and quartiles (unfilled triangles).

Despite the fact that for all noises the same value L_{Aeq}=71 dB(A) was chosen, the histograms indicate that the overall loudness increases from railway noise over road traffic noise to aircraft noise. This means that the data are in line with the concepts of "railway bonus" and "aircraft malus". In many psychoacoustic experiments it could be shown that for the subjective evaluation of noise immissions the prominent parts of a sound play a crucial role (Kuwano and Namba, 1985, Namba et al., 1988, Zwicker and Fastl, 1999). In addition, the percentile loudness N_5 showed good correlation to the subjective evaluation of noise immissions (Fastl, 1997a, 1997b). Therefore, the magnitude of the "railway bonus" or the "aircraft malus" were predicted on the basis of physical measurements of percentile loudness N_5. In essence, the loudness-time patterns displayed in the left part of figure 8 were statistically analysed and the results are given in table 1. The values of percentile loudness N_5 amount to 22.95 sone for railway noise, 35.10 sone for road traffic noise, and 45.60 sone for aircraft noise. Hence, they clearly reveal the effects of railway bonus and aircraft malus. To enable a comparison with more traditional methods, transformations were performed as follows: The loudness values in sone were transformed to the corresponding values of loudness level in phon (see Fastl, 2000c). In addition, for 1 kHz tones the loudness level in phon is easily transformed to the A-weighted level in dB(A), since the numerical value is the same and only the unit is exchanged. In this way, as displayed in table 1, for the "railway bonus" a value of 6.13 dB(A) is calculated which is well in line with data from the literature (Gottlob, 1994). For the "aircraft malus", a value of 3.77 dB(A) is reached which also is in the range of data from field as well as laboratory studies (Taylor, 1993, Fastl, 2000d).

Table 1: Railway bonus or aircraft malus calculated on the basis of percentile loudness N_5

	N_5	L_N	L_{A1kHz}	ΔL_A
	sone	phon	dB(A)	dB(A)
rail	22.95	85.21	85.21	
				6.13
road	35.10	91.34	91.34	
				3.77
air	45.60	95.11	95.11	

Although physical descriptions of noise immissions by the percentile loudness N_5 have proven very useful (Zwicker and Fastl, 1999) it is of interest to check whether effects of "railway bonus" and "aircraft malus" can also be described using other physically measured values (for details see Fastl, 2000c). For maximum loudness N_{max}, a reasonable "railway bonus" would be predicted but a negative value of "aircraft malus", i.e. an "aircraft bonus" which is at variance with the evidence from both field and laboratory studies. Data derived from the percentile loudness N_1 also would predict an "aircraft bonus". Although the percentile loudness N_{10} would predict a "railway bonus" and an "aircraft malus", the magnitude of the "railway bonus" with 18.05 dB(A) seems to be extremely large. On the other hand, for the percentile loudness N_{50}, a "railway malus" would be obtained. In summary then, in line with psychoacoustic evidence, the assessment of noise immissions by the percentile loudness N_5 seems to produce rather reasonable values.

PREDICTION OF NOISE IMMISSIONS FROM NOISE EMISSIONS

Subjective evaluations. Since the measurement of noise immissions in psychoacoustic experiments is very time consuming it would be desirable to have a procedure where the subjective evaluation of noise immissions can be predicted on the basis of subjective evaluations of noise emissions. From results of numerous psychoacoustic experiments it is clear that the prominent parts of sounds have a crucial influence on the magnitude of noise immissions (e.g. Kuwano and Namba, 1985). Presumably, loud events are memorized over longer times, and for the subjective evaluation of noise immissions memory effects may play a crucial role (Hellbrück, 2000). A preliminary simple approach to mimic memory effects may be to add to peaks in the loudness-time pattern an exponential decay, and to average across the modified loudness-time patterns. This reasoning is illustrated in figure 9. In psychoacoustic experiments, subjects vary the length of a bar displayed on a monitor in such a way that at each instant of time, the bar length BL corresponds to the perceived loudness. After a period of say 15 minutes, the subject gets a questionnaire and indicates by a line length LL the overall loudness of the preceding 15 minutes. The data displayed in figure 9 reveal that eight passby sounds are clearly reflected in the corresponding pattern of bar length BL as a function of time. In addition, at each peak, an exponential decay with a time constant of 5 minutes is attached to "simulate" to some extent memory effects. The average value of the bar length modified by the decay curves is given by the dashed line in figure 9. The arrow at the right ordinate indicates the line length given on the questionnaire. Since the height of the arrow and of the dashed line are very similar, it can be assumed that the procedure described may be useful to predict overall loudness from instantaneous loudness (Fastl, 1997a).

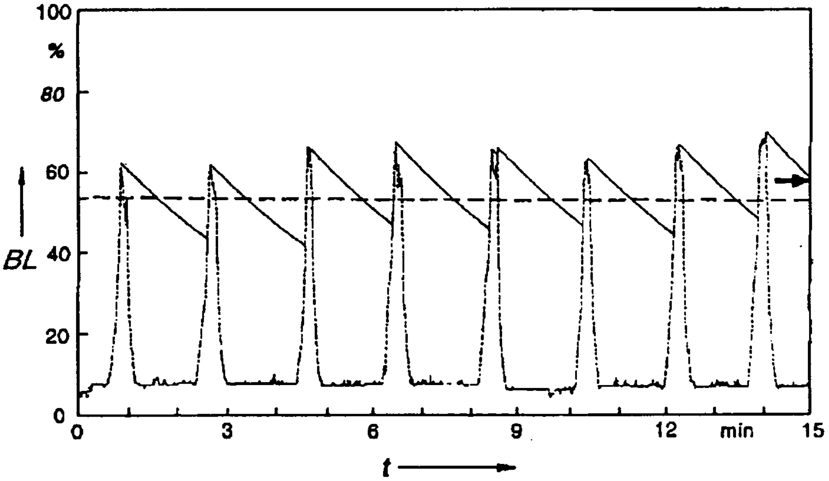

Fig. 9 Instantaneous loudness indicated by the bar length BL, modified by exponential decays with a time constant of 5 minutes. Dashed: Average of modified bar length. Arrow: Subjective evaluation of overall loudness by line length.

Results displayed in figure 10 enable a comparison between subjectively measured values of overall loudness, expressed in line length LL (dots), and calculated overall loudness, based on the bar length of instantaneous loudness with exponential decay BL_e (circles). Data displayed in figure 10 show for 16 scenarios that in many cases overall loudness can be predicted from instantaneous loudness. An agreement between subjective measurement (LL, dots) and prediction (BL_e, triangles) within 10% is achieved in all but two scenarios (1, 4). For 10 out of the

16 scenarios, the agreement between prediction and measurement is even better than 5%. These results are very encouraging to assess further the relations of subjective evaluations for instantaneous loudness and overall loudness, taking into account memory effects.

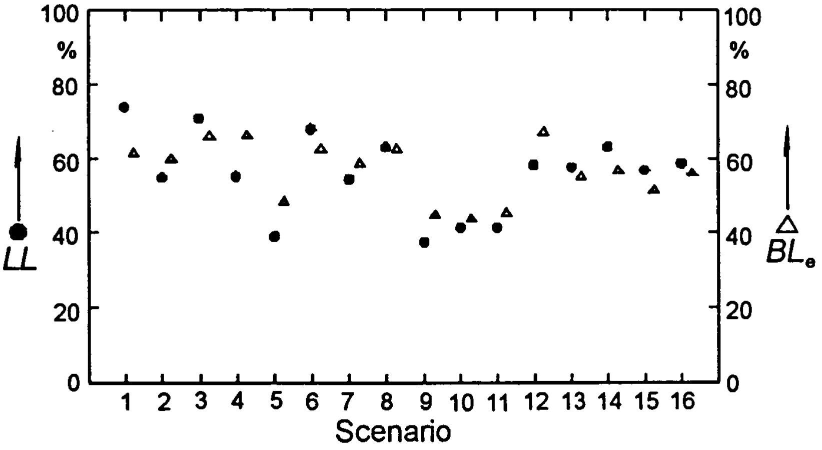

Fig. 10 Comparison of overall loudness, measured by line length, LL (dots), and predicted by bar length with exponential decay, BL_e (triangles).

Physical evaluation. In particular with respect to future means of transportation like magnetic levitation trains, it would be desirable to predict the future noise immissions from available data on noise emissions. Since it could be demonstrated (Zwicker and Fastl, 1999) that noise immissions show strong correlation to percentile loudness N_5, a procedure was put forward to predict the N_5-value of the noise immission from available loudness data of the noise emission. Let us assume that we have measured the distribution of percentile loudness for a passing magnetic levitation train in a time window of 30 seconds and the loudness of the noise emission can be characterized by percentile values N_{xe}. In order to predict a noise immission, we want to calculate the percentile loudness N_{5i}. With some simplification (for details see Fastl 2000d), we can assume that the loudness N_{5i} of the noise immission is governed by the loudness of the noise emission, and the ratio of the related time intervals. If for a longer period of time we have every 3 minutes a passby, we get a ratio of evaluation times $\frac{3 \cdot 60\,\text{sec}}{30\,\text{sec}} = 6$. This means that the percentile index of the noise emission N_{xe} is by a factor of 6 larger than the percentile index of the noise immission N_{5i}. In other words, the noise immission N_{5i} can be predicted on the basis of the noise emission N_{30e}. In this simple example, only one type of passby sound is considered. However, the predictive value of the procedure described was also verified for combinations with different vehicles producing different noise emissions (Stemplinger, 2000).

CONCLUSION

A principle well known in engineering, namely to match the impedance of source and load, can be applied with great success also for questions of noise control. In this case, the best solution is a mismatch between features of the noise sources and features of the receiver, the human hearing system. Therefore, it is very promising to study features of the human hearing system in order to arrive at cost-effective solutions for noise problems.

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