Relationship between road and railway noise annoyance and overall indoor sound exposure

Antonio J. Torija[a,*], Diego P. Ruiz[a], Bert De Coensel[b], Dick Botteldooren[b], Birgitta Berglund[c], Ángel Ramos-Ridao[d]

[a]Department of Applied Physics, University of Granada, Avda. Fuentenueva s/n, 18071 Granada, Spain

[b]Acoustics Group, Department of Information Technology, Ghent University, St. Pietersnieuwstraat 41, B-9000 Ghent, Belgium.

[c]Institute of Environmental Medicine, Karolinska Institutet, and Department of Psychology, Stockholm University, SE-106 91 Stockholm, Sweden.

[d]Department of Civil Engineering, University of Granada, Avda. Fuentenueva s/n, 18071 Granada, Spain

Author to whom correspondence should be addressed. Electronic mail: ajtorija@ugr.es.

Tel.: (+34) 958 241533. FAX: (+34) 958 243214

Abstract

Starting from an experiment conducted in a realistic setting, with recorded traffic sounds reproduced in an ecologically valid way, the relationship between indicators of magnitude, spectrum, and temporal evolution of the sonic environment and the reported annoyance was analyzed. In contrast to the bulk of noise annoyance research, the exposure was characterized by the binaurally recorded overall indoor sound. It was shown that a series of proposed parameters, related with temporal and spectral structure of the sound pressure level, allows modeling reported annoyance using multiple linear models (r^2 =0.94) more accurately than the overall indoor A-weighted equivalent noise level, L_{Aeq} (r^2 =0.43). The proposed descriptors thus complement this indicator, at least when exposure is based on overall indoor sound. Principle components amongst the studied exposure indicators relate to the detectability of the sound indoors and to the typical temporal difference between road and rail traffic. Linear regression models based on these indicators also outperform linear regression models based on source related façade L_{Aeq} (r^2=0.80).

Keywords: Temporal Structure, Spectral Structure, Noise Annoyance, Railway Traffic, Road Traffic, Maglev.

1. Introduction

Exposure-effect relationships for traffic noise annoyance have mainly been derived on the basis of equivalent sound pressure levels at the façade of the dwelling (Miedema and Vos, 1998). Although relating effects to façade levels is straightforward, in terms of measurements, calculations or simulations, there may be a specific interest in using indoor observations. This would, for example, allow to account more accurately for sound insulation and the availability of rooms oriented towards more quiet sides of the dwelling (Berglund and Nilsson, 2006). In addition, if the use of personal noise monitoring devices is envisaged as a way to obtain accurate exposure data in field studies, it would be useful to find some guidelines for how to process indoor noise recordings.

Moreover, Botteldooren et al. (2006) have stressed the need for additional indicators to characterize noise annoyance caused by road and railway traffic. In using the energy-equivalent sound pressure level, L_{Aeq}, as the main physical indicator of noise pollution, characteristics of sound important to annoyance may be neglected, such as the spectrum or the temporal structure (Kjellberg et al., 1997). For example in Yifan et al. (2008), it is established that sound containing a lot of low-frequencies is more annoying than sound with another spectral composition but the same A-weighted level. Therefore, A-weighted level cannot be used for assessing noise annoyance caused by sounds dominated by low-frequency components (Goldstein and Kjellberg, 1985).

The main goal of this research is to analyze the influence on annoyance of the temporal and spectral structure of indoor noise caused by transportation, next to its overall sound level. Thus, a number of specialized indicators for spectral and temporal structure will be introduced. The predictive power of these indicators will be tested against annoyance of transportation noise obtained in a field experiment conducted by De Coensel et al. (2007).

In Section 2, the reader is reminded of the methodology and design of the field experiment described in (De Coensel et al., 2007). In Section 3, several indicators are presented for characterizing temporal structure (Section 3.1.) and spectral structure (Section 3.2.) of sound. In Section 4, the results on the acoustic characteristics of indoor exposures and their effects on noise annoyance are presented and discussed.

2. Design of the experiment

The experiment was conducted in a realistic and ecologically valid setting: participants were seated in an actual living room of a house, and transportation noise was reproduced through loudspeakers placed outdoors, that were not visible from inside the living room. As a consequence, during the experimental sessions, participants did not have to wear headphones as is usually the case in noise annoyance experiments, and were free to engage in light daily activities, such as reading a magazine or having something to drink. The house was located in a quiet area, and there were no disturbing sound sources outside the house other than sounds from nature (wind, some birds).

The sound exposure in the field experiment consisted of passages of TGV (train a grande vitesse) trains at high speed (approx. 140 and 300 km/h), Dutch intercity (IC) trains (approx. 140 km/h) and Maglev trains (Transrapid 08 train) at high speed (approx. 200, 300 and 400 km/h), all passing by at different distances (25, 50, 100, and 200 m). In addition, sounds from a highway and from a local road at the same distances were also included. All experimental sounds were recorded in the field at the stated distances from the source track/road using 2 microphones, spaced about 10 m from each other. For playback, 2 loudspeakers and a subwoofer were placed outside the experimental house at a distance of 3 m from the façade. Using a microphone at the façade, the playback equipment was calibrated in such a way that playing back the stimuli would give the same levels and spectral content (full hearable spectrum) at the façade as if the house would be located at the stated distances from the track/road. The noise exposure stimuli all had a duration of 10 minutes, and consisted of 2 or 4 passages of the same train type at the same distance and speed, or alternatively, of highway/road traffic noise.

One hundred participants were selected to be representative of the Dutch population. For this, a questionnaire was administered at the doorstep of the homes of approximately 1500 persons, all living within a distance of 15 km from the experimental site. In an introductory letter, one inhabitant of the house was invited to participate in the experiment. The prerequisites were that (s)he had to complete and return the questionnaire. A compensation of 100 euro was offered for participation. The questionnaire contained selected questions that had been asked to a representative sample of the Dutch population in a recent nation-wide survey. Included were evaluations of the quality of the neighborhood in terms of housing and environmental pollution, overall satisfaction with the current living situation, questions on mental health, hearing ability and environmental sensitivity, as well as basic demographic variables. From the 255 replies received, a subset of 100 participants was selected in order to get the same distributions as the ones from the Dutch reference questionnaire survey, for the most critical criteria of annoyance surveys, such as age, gender, education, noise sensitivity.

Four to six participants jointly participated in an experimental session. The overall structure of the field experiment was identical for each group of participants: 14 stimuli

(10 minutes duration each) were presented (2 with road traffic sounds and 12 with railway traffic sounds or 14 with only road traffic sounds), with a break after the first 7 stimuli. At the end of each stimulus, the participants were asked to write down how annoyed they were by the sound during the past 10 minutes. In order to circumvent the problems associated with imposing a predefined answering scale to the participants, the method of free-number magnitude estimation was used for scaling noise annoyance. Participants were asked to use a number to scale their annoyance on a relative scale (e.g. if one is twice as much annoyed by a subsequent stimulus, one had to use the double of the previous number), with the condition to use zero if they were not annoyed at all by the sound. Before the start of both series of 7 stimuli, a short training session was held, in which short noise fragments at varying sound pressure level were presented. These sounds helped the participants to define their own scaling context, and more importantly allowed every participant to produce individual reference functions to be used for calibrating their annoyance scales (Berglund, 1991). The empirically derived individual reference functions were then used to transform the free-number magnitude estimations for the train or road traffic stimuli for each individual to the corresponding annoyance values in units of a common master scale.

During the experiment, the sound was recorded outside at the façade of the house using a standard microphone, as well as inside the living room, using a binaural head and torso simulator seated among the participants. The sound analysis in (De Coensel et al., 2007) is based on the outdoor A-weighted sound pressure level reproduced at the façade of the house, because this indicator is important in legislation. In contrast, the present sound analyses are based on the sound recorded inside the living room during the listening tests. All acoustic indicators are calculated on the basis of 10-minute sound fragments exactly matching the stimuli scaled by the participants. The sounds made by the participants themselves and the natural sounds originating outdoors are also included in the binaural measurements obtained in the experimental living room.

For more details on the experimental setting, the recording and playback procedure, the stimuli used in the experiment (including spectral characteristics), the selection of the participants, the master scaling of annoyance answers and results in function of façade levels, we refer to (De Coensel et al., 2007).

3. Indicators for temporal and spectral structure

3.1. Temporal structure of the sound pressure level

Time patterns in the fluctuation of sound pressure level or frequency play an important role in the perception of sound (De Coensel et al., 2005). Depending on the type of transportation considered, the temporal structure of the sound environment is affected differently. In the case of railway traffic, relatively large increases in sound level will be observed whenever a train passes by. In the case of road traffic, the temporal structure of the sound environment will be differently affected depending on traffic-flow characteristics. In the present field experiment, local road and highway traffic noise stimuli were included. Whereas the local road stimuli have a strongly varying sound level in which the individual pass-bys of vehicles can be discerned, the highway traffic stimuli are more constant and are characterized by a more symmetrical and narrower sound level distribution.

The focus of this research is on the influence on annoyance of the temporal "macrostructure" of the sound environment. In characterizing the latter, we will mainly focus on the following factors: the Temporal Sound Level Variance (TSLV) and the Crest Factor (CF) of the sound level. The first factor, TSLV, characterizes sound level fluctuations, while the second factor, CF, determines the sound level impulsiveness.

Let $L_p(t)$ with t in [0s,600s] be the instantaneous sound pressure level measured inside the living room among the panelists, during the presentation of the 10-min stimuli. The standard deviation of the instantaneous sound pressure level is noted as σ_L. Furthermore, let us define the energy-equivalent sound pressure level $L_{eq}(t)$ of the sound measured up to time t (Torija et al., 2007), as

$$L_{eq}(t) = 10 \cdot \log_{10}\left[\frac{1}{t}\int_0^t 10^{L_p(u)/10} du\right]$$

(1)

and let us note the standard deviation of $L_{eq}(t)$ as σ_{eq}. We then define the Temporal Sound Level Variance (TSLV) as

$$TSLV = \sigma_L * \sigma_{eq} \qquad (2)$$

In this indicator, the more commonly used standard deviation of the instantaneous sound level, σ_L is multiplied or 'weighted' by σ_{eq}. This weighting stresses fluctuations that appear at the beginning of the sound fragment under study. It makes TSLV very sensitive to sudden sound-level maxima, in particular, if they appear at the beginning of the sound fragment. For characterizing continuous sound, the calculation of the equivalent sound level in Equation (1) could be replaced by an exponential averaging with a time constant of 10 min.

The Crest Factor (CF) measures the impulsiveness of the sound pressure level within the 10-min stimuli, and is defined as the ratio between the maximum sound pressure and the RMS value of the sound pressure:

$$CF = \frac{\max_t 10^{Lp(t)/10}}{10^{L_{eq,10min}/10}} \quad (3)$$

with $L_{eq,10min} = L_{eq}(600s)$.

3.2. Spectral structure of the sound pressure level

The spectral composition of the noise is a second important factor in characterizing the sound environment. Sound environments affected by road and railway traffic noise have a large amount of low frequency content. The latter may cause various auditory and non-auditory effects, which are not accounted for when A-weighting is applied to the sound pressure level. In particular, sound with high proportion of low-frequencies is perceived as more annoying (Goldstein and Kjellberg, 1985). Furthermore, Berglund et al. (1996) found that, although L_{Aeq} may be a good metric for assessing the risk for hearing impairment, it is less suited for estimating annoyance evoked by sounds with a large portion of low-frequency components. For this reason, we will conduct an analysis to find the critical frequency bands, that best describe the variance in noise annoyance caused by road and railway traffic. The percentage of the sound pressure in these critical bands (PSP) will then be used in further analyses and model construction.

Another aspect of the spectral structure of the sound pressure level is the appearance of tonal components, which has been shown to have a great impact on noise annoyance (Landström et al., 1995). The effect of a tonal component depends on its central frequency, its level, the total spectral character and level of the noise (Hellman, 1986). Consequently, we will analyze the influence on annoyance of the number of tonal components in the spectrum of each of the studied stimuli, and the influence of their position within the spectrum. The criterion adopted for identifying a tonal component was that the third-octave band must reach a sound level of at least 4.75 dB above the adjacent third-octave bands (Landström et al., 1995). The indicator Tonal Component Appearance (TC), used in the analyses and modeling, is limited to the critical bands defined above. Tonal components appearing outside these bands are not considered.

A third factor used to characterize the spectral structure of the sound pressure level is the Spectral Level Deviation (SLD). SLD is simply calculated as the standard deviation of the 1/3 octave band spectrum $L_p(f)$ of the stimulus, with f in [20Hz, 20kHz].

4. Results and discussion

4.1. Critical frequency bands and tonal components

Table 1 presents coefficients of correlation between master scaled self-reported annoyance and indoor sound level in each 1/3-octave band of the spectrum of the set of 10-min stimuli. A significant correlation was found for the 1/3-octave bands between 31.5–160 Hz, at 315 Hz, and between 630-2500 Hz. The 630-2500 Hz range of 1/3-octave bands coincides with the maximum sound level of the spectra for most of the experimental noise exposures generated at the facade during the experiment, and ahigh correlation between annoyance and sound level in these spectral bands was therefore to be expected. Below 160Hz, the reproduced outdoor sounds also show a slight secondary sound-level maximum, roughly 20 dBA below the highest spectral maximum. The importance of sound level at low frequencies may be more than just an indication of the presence of traffic noise. In predicting the outdoor noise annoyance, A-weighting has been shown to put too low weight on the low-frequency bands (Nilsson, 2007; Nilsson et al., 2008). Note that the acoustic insulation of the house did not give the low-frequency coloration that one might expect because one of the windows of the house was slightly open during the experiment. In view of these results, the percentage of sound level (PSP) in these critical frequency bands (31.50-125 Hz, 315 Hz and 630-2500 Hz) will be used in our further analyses.

Table 2 shows coefficients of correlation between annoyance and the occurrence of tonal components in the frequency bands identified to be critical. These results indicate that tonal components in 1/3-ocatave bands at critical frequencies, in general, strongly affect annoyance (Pearson's coefficient $r = 0.79$). In particular, tonal components in the low frequency bands (<125 Hz) contribute significantly ($r = 0.44$).

4.2. Temporal and spectral structure for the prediction of noise annoyance

Table 3 shows that all correlation coefficients between noise annoyance and different acoustic indicators referring to indoor sound level of the 10 min stimuli are significant. The commonly used L_{Aeq} does not outrank the other indicators (Pearson's coefficient $r = 0.66$). Given that the spectral analyses in Section 4.1 already showed that low frequencies were quite important for annoyance (Nilsson, 2007; Nilsson et al., 2008), it is not surprising that unweighted L_{eq} (Pearson's coefficient r = 0.77) correlates better with annoyance than L_{Aeq}.

Moreover, it becomes clear that successful annoyance-related indicators of indoor noise exposure should not focus on determining loudness as accurately as possible, but rather on measuring the ability to detect intruding traffic noise within the overall noise environment. In earlier work (De Coensel et al., 2007), noise annoyance was related to the traffic noise load at the facade, using measures of L_{Aeq} as a descriptor. In De Coensel et al. (2007) the model fit was r^2=0.80 for noise annoyance indoors and facade L_{Aeq}.

The two indicators representing temporal structure of sound level (TSLV and CF) both show strong correlations with perceived annoyance (Pearson's coefficient r = 0.62 and 0.57, resp.). The three indicators representing spectral structure (PSP, TC and SLD) have even higher coefficients of correlation with noise annoyance (r = 0.80-0,89.

To analyze the capacity of subsets of the various acoustic indicators to predict noise annoyance, a multiple linear regression analysis (MLRA) was carried out (Table 4). Seven models were developed. The stepwise MLRA shows that Model 1 (only L_{Aeq}) explains 44 % of the variance (F-change = 42.80). As already suggested, A-weighting may not be well suited for predicting annoyance. Furthermore, when only L_{Aeq} is used, no distinction is made between intruding traffic noise and other ambient indoor noise. Model 2 (only L_{eq}) explains 59 % of the variance (F-change = 48.72). Thus, in the MLRAs to be presented below, we will opt for L_{eq} as a measure of the overall sound level.

Model 3, with two independent variables TSLV and CF, was found to explain 43 % of the variance (F-change = 47.60). Thus, indicating level fluctuations help to predict annoyance, but as will be shown further on, this will work mainly for the event-type noises (particularly trains) included in our experiment. Model 4, with three independent variables PSP, TC and SLD, was found to explain 86 % of the variance (F-change = 68.60). Although the three indicators included in this model are all related to spectral content, PSP is the most important contributor to annoyance in Model 4. It should be noted that PSP is also related to the fraction of the spectrum that is mainly caused by traffic noise and thus also "measures" traffic to background noise ratio, a level indicator.Model 5 proves that a combination of measures for overall indoor sound level, spectral and temporal structure will explain 94 % of the variance (F-change = 75.86) in annoyance of the 10-min stimuli. To further investigate the underlying mechanisms, which make this psychophysical model work, a principal components analysis (PCA) was used to evaluate the impact of the reduction in the input indicators on the final value of explained variance (with the varimax rotation method for normalization according to Kaiser, convergence on 3 iterations). Two factors were obtained. Factor F1 was composed of the variables L_{eq}, PSP, TC and SLD and, Factor F2 was composed of the variables TSLV and CF. By using the composition of Factor F1 (Model 6 in the MLRA), 87 % of variance can be explained. After incorporating also temporal structure, Factor F2 (Model 7), the variance explained would increase by 7 % up to the value of $r^2 = 0.94$ (see Table 4).

The hypothesis was raised that the apparent success of F1 in explaining variability in annoyance among 10-min stimuli may be due to its ability to identify intruding outdoor traffic noise in the indoor noise environment. Therefore, the relationship between the indicators measured indoors and the sound level of the traffic noise stimuli at the facade was studied. Note that the façade levels were calculated from the traffic sounds played back via the loudspeakers, and do not include the influence of any environmental sound (birds, wind) that might occasionally be present at the experimental site. We observed that the indicators included in Factor F1 are those four, which have the largest coefficients of correlation with facade L_{Aeq}. In particular, the measures related to spectral structure: PSP ($r^2 = 0.68$), TC ($r^2 = 0.61$), and SLD ($r^2 = 0.52$) and L_{eq}, the unweighted sound level inside the house, ($r^2 = 0.58$). Conversely, the indicators that compose Factor F2 (temporal structure) do not correlate highly with the facade L_{Aeq}. In the next section, we will show that F2 mainly distinguishes between train and road traffic noise reproduced with similar façade L_{Aeq} in the experiment.

4.3. Analysis of the effect of the type of source: road-traffic and railway noise

In Section 4.1 and 4.2, reported annoyance was analyzed without taking into account the source of the sounds; in this section source information is added. In Fig. 1 average values for the stimuli are plotted in the plane spanned by the two principle factors, F1 and F2. Stimuli containing road/highway traffic noise result on average in low values in Factor F2. Thus, F2 can be used for distinguishing stimuli with railway noise exposures from those with road/highway noise exposures, in indoor measurements. Because F2 was identified to measure mainly temporal structure, impulsiveness and sound-level fluctuations, this would correspond to the obvious fact that typical train sound fluctuates more than road/highway sound.

The road/highway traffic stimuli have low values in the acoustic indicators related to temporal structure of the sound level. Nevertheless, they differ greatly in annoyance. An increase of 40 % and of 35 % in the TSLV (Fig. 2(a)) and CF (Fig. 2 (b)) indicators, respectively, of road/highway traffic stimuli would be necessary in order for the railway traffic stimuli to generate the same annoyance as the road/highway stimuli.

5. Conclusions

In this research, the relationship between traffic noise annoyance and acoustic indicators of overall indoor sound level was analyzed.A reduced number of 1/3-octave bands (31.5-125 Hz, 315 Hz, and 630-2500 Hz) was found to be relevant for annoyance of road/railway traffic noise. A series of indicators for temporal and spectral structure of the indoor sound environment were introduced: the temporal sound level variability (TSLV) measures the fluctuation of instantaneous sound pressure level, focusing strongly on early variation; the crest factor (CF) deals with the sound-level maxima occurring during the observation interval; the percentage of sound level in critical bands (PSP) relative to all bands; tonal components appearing in these critical bands; and spectral level variability measured as the standard deviation over 1/3-octave bands. A principal components analysis (PCA) was used to group the indicators in two factors. The first factor contains all indicators, which correlate strongly with source specific facade L_{Aeq}. Consequently, these measure the contribution of intruding road/highway or railway traffic noise to the indoor sound environment. This factor alone explained 87% of the variance in annoyance. It thus outperforms the traditionally used facade exposure in L_{Aeq}. The second factor includes two indicators measuring temporal variability and distinguishes environments with road/highway traffic noise from environments dominated by rail traffic noise. Both for road/highway and for rail traffic there is still a strong correlation between annoyance and the indicators for temporal fluctuation. When adding the second factor in a linear regression model, 94% of variance can be explained.

The indicators proposed, taken together with a multiple linear regression model, perform extremely well on the experimental data obtained from 100 carefully selected listeners and 32 10-min stimuli containing traffic noise used in this field experiment.

However, it has to be noted that this does not necessarily mean that the results can be generalized and considered representative to other situations without due caution.

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Figure/table captions

Fig. 1. Distribution of the different stimuli against the factors F1 and F2, labeled by source.

Fig. 2. Relationship between the temporal sound level variance factor (TSLV) (a) and crest factor (CF) (b) and the annoyance in master scaling units for railway and highway/road traffic.

Table 1

Correlation between sound pressure level in each of the 1/3-octave bands and annoyance in master scaling units. *p<0.05, **p<0.01.

Table 2

Correlation between appearance of tonal components in the different frequency ranges and annoyance in master scaling units. *p<0.05, **p<0.01.

Table 3

Correlation between L_{Aeq}, L_{eq} and temporal and spectral structure factors and annoyance in master scale units. *p<0.05, **p<0.01.

Table 4

Multiple linear regression analysis of acoustic variables and annoyance by train and road traffic sound. *p<0.05, **p<0.01.

Table 1

1/3-Octave Band	Pearson Correlation (r)	
	Coefficient	Bilateral sig.
20 Hz	0.083 (*)	0.022
25 Hz	0.071 (*)	0.027
31.50 Hz	0.424 (**)	0.000
40 Hz	0.547 (**)	0.000
50 Hz	0.411 (**)	0.000
63 Hz	0.586 (**)	0.000
80 Hz	0.530 (**)	0.000
100 Hz	0.406 (**)	0.000
125 Hz	0.227 (**)	0.000
160 Hz	0.159 (**)	0.000
200 Hz	0.114	0.059
250 Hz	0.137 (*)	0.023
315 Hz	0.186 (**)	0.002
400 Hz	0.102	0.092
500 Hz	0.052	0.389
630 Hz	0.173 (**)	0.004
800 Hz	0.426 (**)	0.000
1000 Hz	0.522 (**)	0.000
1250 Hz	0.404 (**)	0.000
1600 Hz	0.183 (**)	0.002
2000 Hz	0.295 (**)	0.000
2500 Hz	0.211 (**)	0.000
3150 Hz	0.002	0.978
4000 Hz	-0.036	0.556
5000 Hz	-0.041	0.500
6300 Hz	-0.028	0.642
8000 Hz	-0.071	0.242
10000 Hz	-0.071	0.241
12500 Hz	-0.065	0.280
16000 Hz	-0.080	0.186
20000 Hz	-0.080	0.186

Table 2

Appearance of Tonal Components	Pearson Correlation (r)	
	Coefficient	Bilateral sig.
< 125 Hz	0.443 (**)	0.000
125-400 Hz	-0.276 (*)	0.039
> 400 Hz	0.202 (*)	0.021
1/3-Octave Band of Critical Frequencies	0.792 (**)	0.000

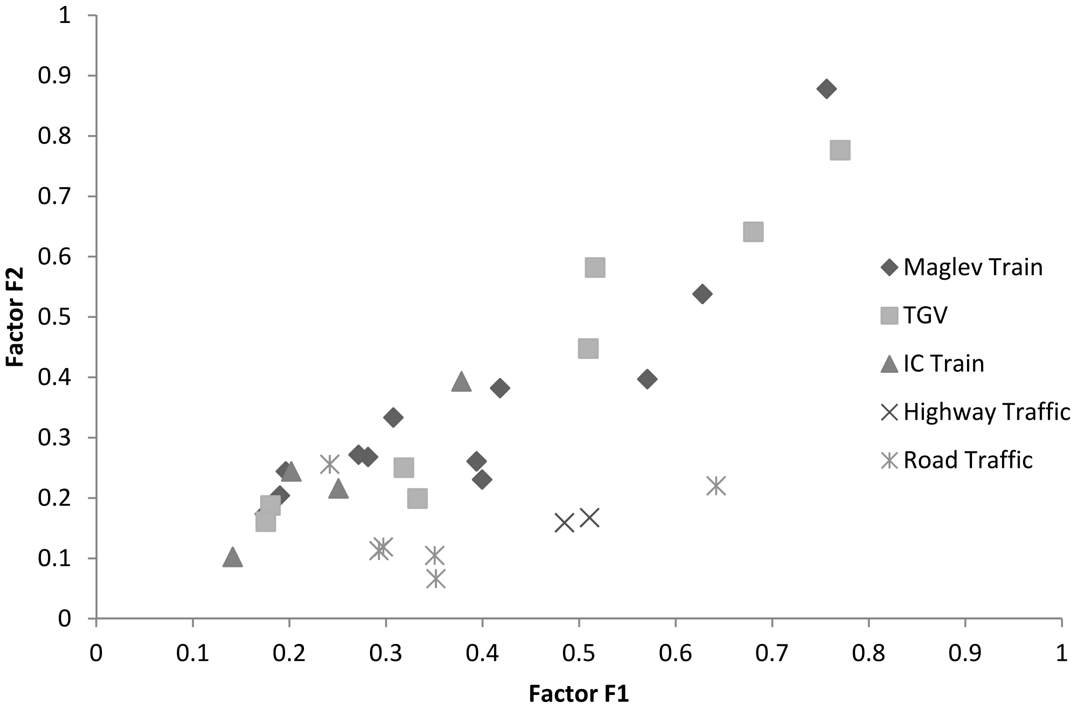
Table 3

Acoustic Indicators	Pearson Correlation (r)	
	Coefficient	Bilateral sig.
L_{Aeq}	0.661 (**)	0.002
Leq	0.770 (**)	0.000
TSLV	0.615 (**)	0.000
CF	0.570 (**)	0.000
PSP	0.892 (**)	0.000
TC	0.800 (**)	0.000
SLD	0.839 (**)	0.000

Table 4

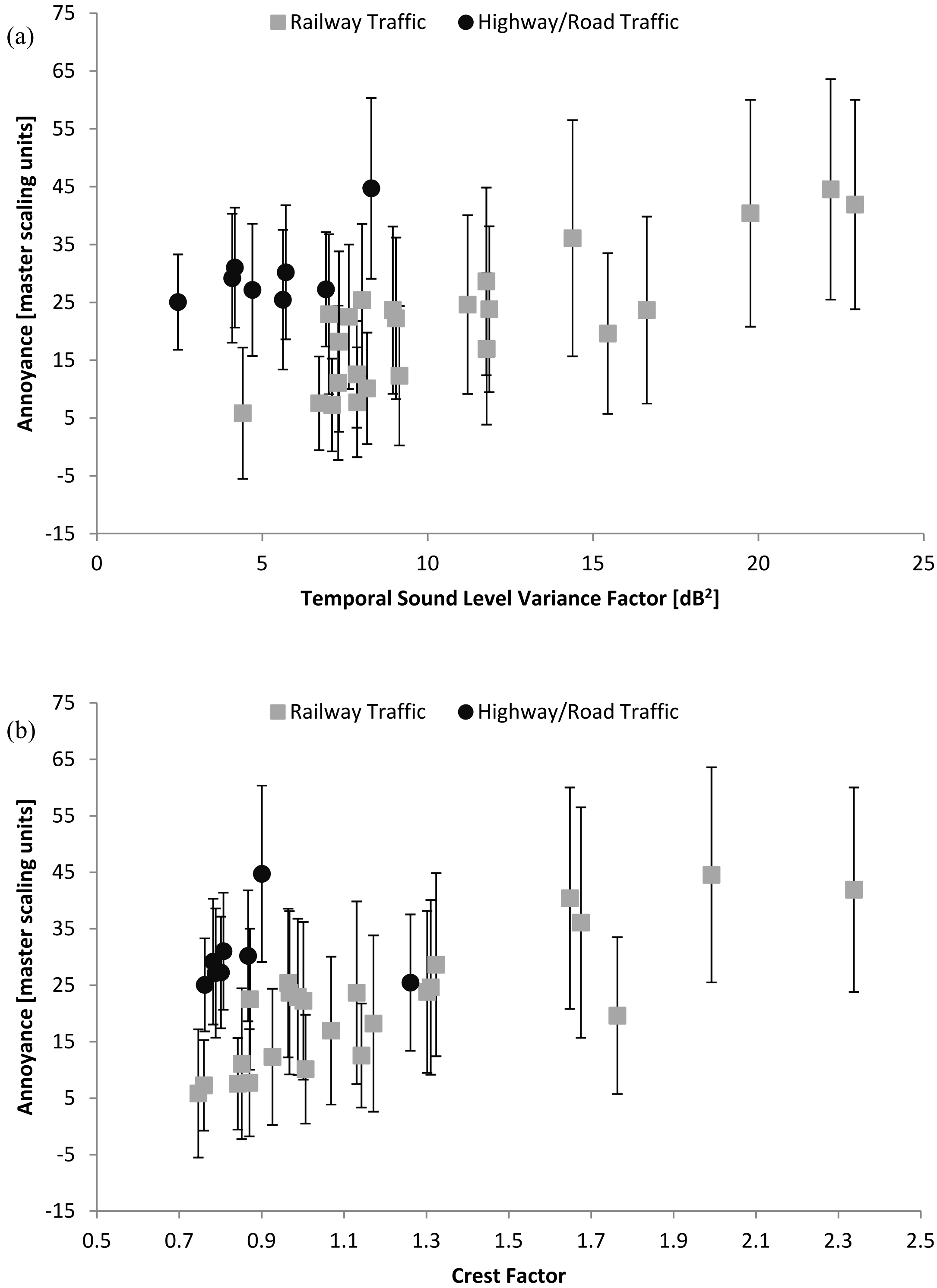
Model	Model fit (r^2)	F-change	Independent Variables	Coefficient
1	0.436	42.80	$L_{Aeq,10\ min}$ [dB(A)]	3.117**
2	0.593	48.72	Leq [dB]	3.223**
3	0.429	47.60	TSLV [dB^2] CF	-0.857** 6.529*
4	0.861	68.60	PSP TC SLD [dB]	3.402** 2.696** 2.962**
5	0.940	75.86	Leq [dB] TSLV [dB^2] CF PSP TC SLD [dB]	0.343* -0.683** 1.194* 5.272** 2.373** 2.563**
6	0.870	220.77	F1	114.164**
7	0.940	258.42	F1 F2	121.553** -4.904*

Figure 1



Factor F2
Factor F1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Maglev Train
TGV
IC Train
Highway Traffic
Road Traffic

Figure 2



(a)
Railway Traffic
Highway/Road Traffic
Annoyance [master scaling units]
Temporal Sound Level Variance Factor [dB²]
(b)
Railway Traffic
Highway/Road Traffic
Annoyance [master scaling units]
Crest Factor