Temporal and Spatial Factors of Traffic Noise and Its Annoyance

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(Received 28 September 2001; accepted 20 June 2002)

This paper describes and demonstrates procedures for indexing temporal and spatial factors of traffic noise, and report a laboratory experiment investigating the relationship between these indices and subjective annoyance with the noise. Primary sensations (loudness, pitch, timbre) and spatial sensations (source location, diffuseness, source width) of sounds are described by the autocorrelation function (ACF) and the inter-aural cross-correlation function (IACF) respectively. Especially, we focused on the primary sensations of traffic noise in relation to the subjective annoyance. A laboratory experiment was designed to examine the validity of the proposed noise indices described in terms of the ACF. Scale values of subjective annoyance were measured by paired comparison. Results showed that the effects of temporal fluctuation of sound level, tonal properties, and fluctuation of pitch become significant predictors of annoyance when the subjects heard various types of traffic noise with equal listening level. Contributions of these parameters correspond with earlier findings relating to annoyance. Thus, the results suggest that the proposed ACF factors can be possible measures to evaluate perceived annoyance in addition to the overall SPL.

Keywords: traffic noise, annoyance, acoustical parameters, autocorrelation, inter-aural cross-correlation

1. INTRODUCTION

This paper presents a procedure to describe acoustical parameters effective for the evaluation of subjective annoyance of noise. Annoyance is a part of psychological reaction to noise (e.g. Job [1]), a general feeling of displeasure or adverse reaction generated by noise. The psychoacoustical factor of annoying sounds can be described by a combination of hearing sensations caused by the physical properties of sounds. Zwicker and Fastl [2] called this factor as "psychoacoustic annoyance". Generally, it is recognized that the most influential sensation for annoyance is the loudness, which is predicted by the sound level. Annoyance depends on the sound level when sounds are roughly equivalent in other attributes, such as timbre and duration. Therefore a lot of efforts have been spent on noise reduction technologies in relation to reducing sound exposure level. For sound sources having widely different acoustical properties, however, this relationship may no longer hold. For example, a sound may exist that has a sound level below the exposure standards but that is perceived to be noisy or annoyed in a given situation. This means that annoyance cannot be predicted by sound intensity alone. We need to consider the other factors influencing perceived annoyance, in addition to reduce sound exposure.

There is a sizable study describing acoustic parameters relating to annoyance. They include, for example, the frequency distribution, tonality, temporal fluctuation, and impulsivity. As for tonal color or timbre, previous studies were intended to quantify sound qualities in terms of their spectral shapes. For example, Versfeld and Vos [3] and Cermak and Cornillon [4] proposed several measures for describing the shapes of the frequency spectra, such as the location and the level difference between the high frequency (500–2000 Hz) and low frequency (50–100 Hz) peaks in the spectrum. Also, as for the frequency distribution of noise, it is known that both of the high- and the low-frequency part of sound have effect on annoyance. The high-frequency components of a sound make it sound sharp, and sharpness of sound increases annoyance [2]. In contrast, some studies have demonstrated the much effects of low-frequency noise on annoyance [5].

As for tonality of sound, a number of tone corrections are proposed for the evaluation of the perceived noise level. This is based on the finding that the tone-to-noise ratio in the spectrum increases annoyance of noise. Generally, a corrected value for extracted tonal component is added to the "Perceived Noise Level" (PNL) to give the "Tone Corrected Perceived Noise Level" (PNLT). However, the calculation for this correction is lengthy, and their accuracy is not well established yet [6].

As for fluctuation of sound level, Hiramatsu [7, 8] investigated annoyance of temporally fluctuating white noise (duration of 50 s) and found that standard deviation, equivalent sound level (L_{eq}), and L_{10} were good measure for annoyance of fluctuating sound. Also, it was found recently that the fluctuation in the sound location and the diffuseness also much affects subjective annoyance [9, 10].

It is probable that most of the parameters mentioned above are included in the primary auditory sensations (loudness, pitch, timbre, and duration) and spatial sensations (localization, diffuseness, and source width), as Ando [11] said. In this paper, we try to characterize these primary and spatial sensations of traffic noise by use of the autocorrelation function (ACF) and inter-aural cross-correlation function (IACF) analysis as the authors did previously for aircraft noise [12]. It has been found that information about perceived pitch and its strength (i.e. tonality) of complex sounds is extracted from the maximum peak in the ACF, and loudness of narrowband noise is related to the decay rate of the ACF [13]. In addition, information of the source direction, diffuseness, and source width can be evaluated by the IACF as described later. For example, the peak value of IACF represents the degree of similarity of sound waves arriving at each ear, which is a significant factor in determining the degree of subjective diffuseness in a sound field. Continuous measurement of these factors can evaluate the fluctuation of sensations. These ACF and IACF factors could be possible measures for characterizing the primary and the spatial sensations of noise, and for describing the various parameters relating to annoyance.

In the following, this paper describes an analysis of traffic noise by a newly developed measurement system [14], and a laboratory experiment designed to explore the possible procedures for describing the acoustical properties of noise and its annoyance. Traffic noise was used as the example of noise stimulus that we are exposed in our daily life. It is considered that primary and spatial sensations may contribute to annoyance in a complex manner. To simplify the problem, only the effect of primary sensations and their temporal fluctuation are investigated in the laboratory experiment.

2. ANALYSIS OF SOUND PARAMETERS BY ACF AND IACF

2.1. Measurement procedure

Sound recordings were made of civil road traffic, such as a passenger car, a bus, a truck, and a motorbike. The measurement point was 5 m from the center of a road, along a line perpendicular to road. Sounds were received by two 1/2-inch condenser microphones set at the ear positions of a sphere representing a human head. Binaural measurement was adapted to evaluate spatial sensations of sound field. This dummy head was made of 20-mm-thick Styrofoam with a diameter of 200-mm. The ear positions were set at 1.5 m above the ground. Received sounds were recorded on a DAT recorder at a sampling rate of 48 kHz, and simultaneously stored on a hard disk of an analyzing computer at a sampling rate of 44.1 kHz for the following analysis.

2.2. Analysis of acoustical factors

2.2.1 Factors from the ACF ($\Phi(0)$, τ_e, τ_1, and ϕ_1)

To evaluate temporally varying noise, we calculated the running short time ACF and IACF. Running short time temporal and spatial factors were used to describe the primary and spatial sensations of a sound field.

The short-time ACF is defined by

$$\Phi_p(\tau) = \frac{1}{2T}\int_{-T}^{+T} p'(t)p'(t+\tau)dt \qquad (1)$$

where p'(t) = p(t)*s(t), in which p(t) is sound pressure and s(t) is ear sensitivity. For practical reasons, s(t) was chosen as the impulse response of an A-weighting network. The value of τ represents the time delay, and the value of 2T is the integration interval. The integration interval should have at least thirty times of the minimum value of effective duration, $(\tau_e)_{min}$, of the running ACF [12, 15], determined by a preliminary measurement. In the present study, the 2T was 0.5 s, and the ACF was calculated at intervals of 0.1 seconds. There are four significant factors extracted from the ACF [11]. The first factor is a geometrical mean of the sound energies arriving at both ears, $\Phi(0)$, which is expressed by

$$\Phi(0) = \left[\Phi_{ll}(0)\Phi_{rr}(0)\right]^{1/2} \qquad (2)$$

where $\Phi_{ll}(0)$ and $\Phi_{rr}(0)$ are the ACFs at delay time $\tau = 0$ for left and right ears. The sound pressure level (SPL) is obtained as

$$SPL = 10\log_{10}\frac{\Phi(0)}{\Phi_{ref}(0)}, \qquad (3)$$

where $\Phi_{ref}(0)$ is measured at a reference sound pressure of 20 μPa. Because the sampling rate of the sound is more than twice the maximum audio frequency, this value is much more accurate than the SPL measured by the usual sound level meter.

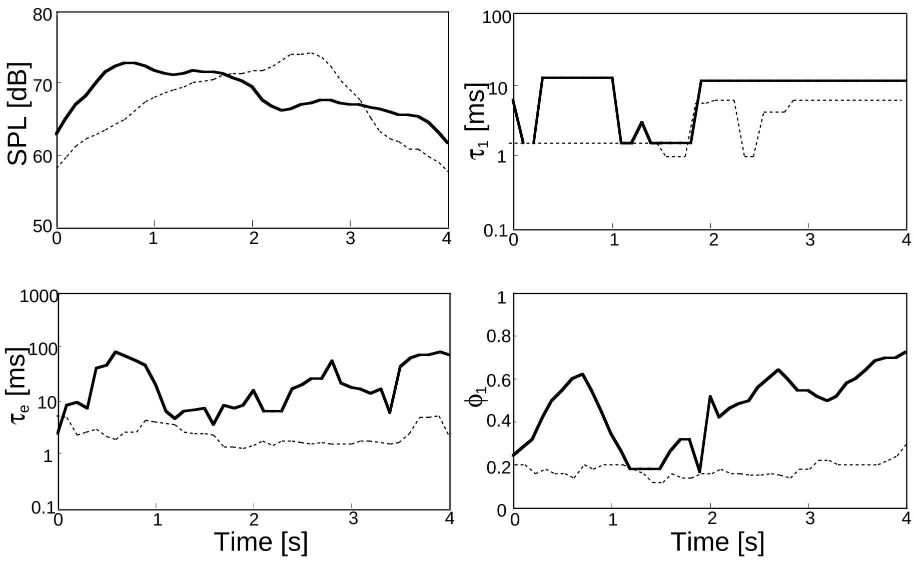

Fig.1. Two extreme examples of measured SPL and three ACF factors as time functions. Thick lines show factors of tonal noise (motor bike), and thin lines show factors of un-tonal noise (passenger car).

The second factor is the effective duration of the ACF, τ_e, which is defined by a 10-percentile delay of the normalized ACF, representing repetitive features and reverberation contained in the signal itself. It has been found that loudness of band pass noise is related to the ACF factor, τ_e, not only to the listening level [13]. The third and fourth factors are the delay time and the amplitude of the first peak of the normalized ACF, τ_1 and ϕ_1. These two factors are closely related to the pitch perception [16].

2.2.2 Factors from the IACF (IACC, τ_{IACC}, and W_{IACC})

For specifying the spatial characteristics of sound signals, three factors are extracted from the IACF. The IACF is given by

$$\Phi_{lr}(\tau) = \frac{1}{2T}\int_{-T}^{+T} f_l'(t) f_r'(t+\tau)\,dt, \tag{4}$$

where $f_l'(t)$ and $f_r'(t)$ are approximately obtained by signals $f_{l,r}(t)$ after passing through the A-weighting networks as in equation (1). The normalized IACF is defined by

$$\phi_{lr}(0) = \frac{\Phi_{lr}(\tau)}{\Phi(0)}. \tag{5}$$

The magnitude of IACF is defined by

$$IACC = \left|\phi_{lr}(\tau)\right|_{\max}, \quad \left|\tau\right| \le 1\ ms. \tag{6}$$

The value of IACC represents the degree of similarity of sound waves arriving at each ear, which is a significant factor in determining the degree of subjective diffuseness in a sound field [11]. When IACC decreases, the subjective diffuseness increases. The inter-aural time delay between −1 ms and +1 ms is defined as τ_{IACC} where the IACC is decided. The value of τ_{IACC} represents the horizontal sound location or direction, and the balance of the sound field. When τ_{IACC} is zero, a front sound source and a well-balanced sound field are perceived. The width of the maximum peak of IACF, W_{IACC}, is defined by the time interval at 10% below IACC. It is worth noticing that the apparent source width (ASW) could be evaluated by IACC and W_{IACC} [17].

2.3. Outcomes and discussion

The measured SPL and three ACF factors are represented in Fig. 1 as a time function. Thick lines (a motor bike) and thin lines (a passenger car) show the two extremes of measured sounds: one has a clear pitch sensation, and the other has a weak pitch. Here, we call expediently these two sounds tonal noise and un-tonal noise as in the previous paper [12]. As shown in Fig. 1(a), the SPL throughout the period varies in the same manner. When the vehicles pass through the receiver, the SPL rises above the ambient level, reaches a maximum, and decreases again. Rise and fall time, and fluctuation of the level depend on the vehicle type and the operating conditions. As you can see in Fig. 1(b)–1(d), the ACF factors also vary throughout the measurement period.

Informal listening test by the authors and their colleagues confirmed that these factors represented the subjective attributes of sounds. The value of τ_1 varied between 1 ms and 10 ms, meaning that perceived pitch varied between 1000 Hz

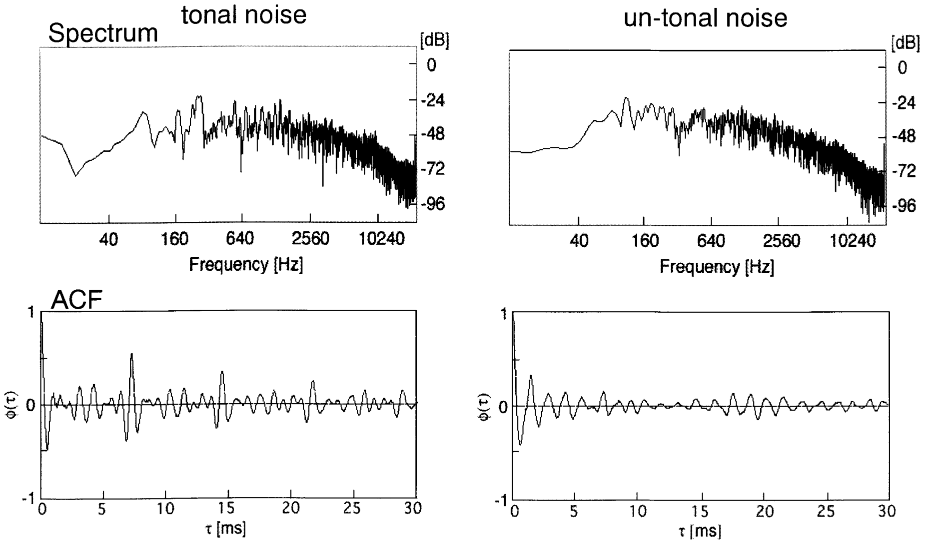

Fig. 2. Calculated power spectrum and ACF of tonal and un-tonal noises.

and 100 Hz for both noises. The strength of perceived pitch increases in proportion to the value of ϕ_1. For a tonal noise, the ϕ_1 value reaches maximum around 0.6 and 0.7. At this time, a strong tonal sound is heard having a pitch of τ_1. When the τ_1 value varies with a high ϕ_1 value, we can perceive the variation of the pitch. However, the ϕ_1 value for an un-tonal noise remained constant around 0.2, despite the variation of τ_1. The perceived pitch for an un-tonal noise is therefore very weak, and it is hard to discriminate pitch fluctuation.

The calculated power spectrum and ACF for tonal and un-tonal noises is shown in Fig. 2. For the "tonal noise", there are several peaks in the spectrum. Generally, the spectrum consists of harmonic components (discrete part) and noise component (continuous part), but it is difficult to identify which peak is a fundamental frequency in the spectrum for a complex sound. When the same sound is analyzed by the ACF, its harmonic structure is easily extracted. Strong periodical peaks in the ACF show that a periodicity corresponding to the pitch is present in the sound. Minor peaks within a period of the ACF give information about the higher-frequency components or timbre of the sound [18, 19]. This information can be used by the measurement system to identify the sound source. For the "un-tonal noise", there is no particular peak in the spectrum. This means that the sound has no particular periodicity perceived as pitch. In this case, the ACF decreases to zero without strong periodical peaks. Because the envelope of the ACF is related to the value of ϕ_1, the value of τ_e is a good measure of the periodical structure of the sound signal.

The perceived direction of a sound source is represented by the maximum peak of the IACF, because it corresponds to an inter-aural time difference. As a sound source moves from left to right, the value of τ_{IACC} varies from a minus to plus value, as illustrated in Fig. 3. The measured values of τ_{IACC} show that the vehicles passed through the receiver from left (right) to right (left). It is found recently that the temporal fluctuation in spatial sensations such as localization and diffuseness much affects subjective annoyance [9, 10]. Procedure and the obtained data of binaural recorded sounds in this study are to be used for the future investigation of the effect of such spatial sensations in annoyance.

3. RELATIONSHIPS BETWEEN THE ACF FACTORS AND SUBJECTIVE ANNOYANCE

3.1. Purpose of the experiment

A laboratory experiment was designed to examine the validity of the proposed analysis for evaluating the subjective annoyance of noise. As described in the previous section, the ACF and the IACF factors could be possible measures for characterizing primary and spatial sensations of noise. It is supposed that primary and spatial sensations may contribute to annoyance in a complex manner. To simplify the problem, only the effect of the primary sensations and their temporal fluctuation (the ACF factors) are investigated in the laboratory experiment. The sounds tested were recorded traffic noise chosen to cover a wide range of physical characteristics. For particular purpose of the experiment, we adjusted overall sound level to be roughly equal to emphasize the other physical properties. This manipulation could reveal the potential importance of further properties, or show that no additional parameters besides sound level are significant. In the latter

Table 1. Correlations among eight standard noise measures for nine traffic noises.

	max	min	mean	σ^2	L_{50}	L_{eq}	L_{90}	L_{10}
max	1.00							
min	−0.69*	1.00						
mean	−0.24	0.62	1.00					
σ^2	0.89**	−0.91**	−0.53	1.00				
L_{50}	0.06	0.24	0.84**	−0.11	1.00			
L_{eq}	0.57	−0.31	0.44	0.48	0.82**	1.00		
L_{90}	−0.85**	0.87**	0.66*	−0.97**	0.27	−0.32	1.00	
L_{10}	0.70*	−0.46	0.28	0.63*	0.70**	0.98**	−0.49	1.00

** $p < 0.01$, * $p < 0.05$

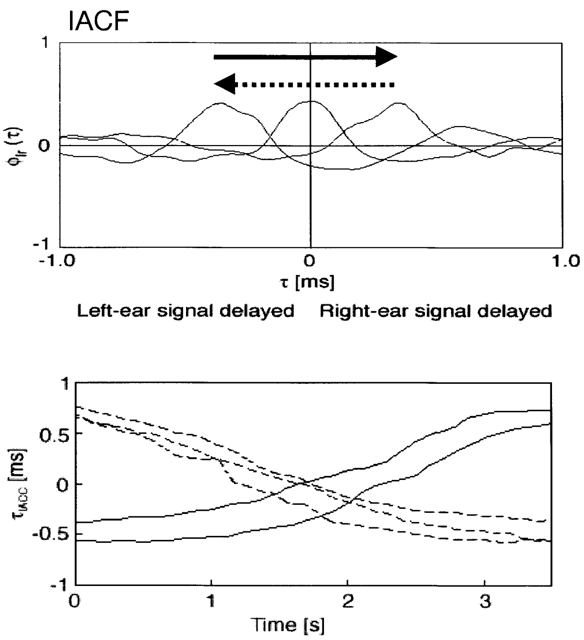

Fig. 3. Examples of IACF and the values of τ_{IACC}.

case, subject's response to the stimuli becomes random in the absence of an influence of sound intensity. To investigate only the effect of the primary sensations of sounds, the spatial properties were kept constant.

3.2. Method

3.2.1 Stimuli

Nine recordings of noise sounds were used in the experiment. Two sounds illustrated in Fig. 1 (motor bike and passenger car) are included. Other sounds are of two buses, truck, three scooters, and another motorbike. Each stimulus was edited on computer software to have a 4-sec duration, and contains single vehicle's passage. The maximum level was adjusted to be equal (73±2 dBA) and to occur near the middle of the sound. By this manipulation, the average level was also equated (69±1 dBA). To make the envelope of sounds equal, a 0.5-sec rise and fall time was added to all stimuli.

Based on the running short time SPL [dBA] measured for the experimental condition, eight standard measures were calculated for nine stimuli: (1) mean SPL, (2) variance σ^2 of the SPL, (3) maximum SPL, (4) minimum SPL, (5)–(7) the SPL values exceeded 10 % of the time (L_{10}), 50 % of the time (L_{50}), and 90 % of the time (L_{90}), and (8) equivalent sound level L_{eq}. Most of these standard measures were highly inter-correlated (see Table 1). Clearly, all of these factors contain information about the overall sound level and its variability. Therefore, only the median (L_{50}) and variance (σ^2) of the SPL were considered in the subsequent analysis.

The cumulative frequency of measured SPL and three ACF factors are shown in Fig. 4. These factors were calculated at intervals of 0.1 s for each sound. It can be seen that the range of the SPL is reasonably controlled. Other parameters than SPL were not controlled systematically, but it seems that these parameters covered a wide range suitable for the purpose of the experiment. To characterize the acoustical properties of a stimulus, we used the median and variance of each factor within stimulus durations.

Our assumption of perceived annoyance is as follows. (1) It has been reported that the median of SPL (L_{50}) is a good measure of annoyance. Therefore, a higher-level sound is considered to be more annoying than lower level sound. In this experiment, however, the range of the SPL is intentionally constrained to investigate the potential importance of the other factors. Thus, no correlation should have been expected between the SPL and the subjective annoyance. (2) Perceived pitch may be related to annoyance. It is said that loudness and annoyance vary in a roughly similar manner as a function of frequency [20]. Frequencies in the region of 2000 Hz to 8000 Hz are the loudest and the most annoying, and frequencies below 500 Hz and above 10,000 Hz tend to be less loud and less annoying for the same SPL. Traffic noise and other machinery noise consist of tonal and noise components. For

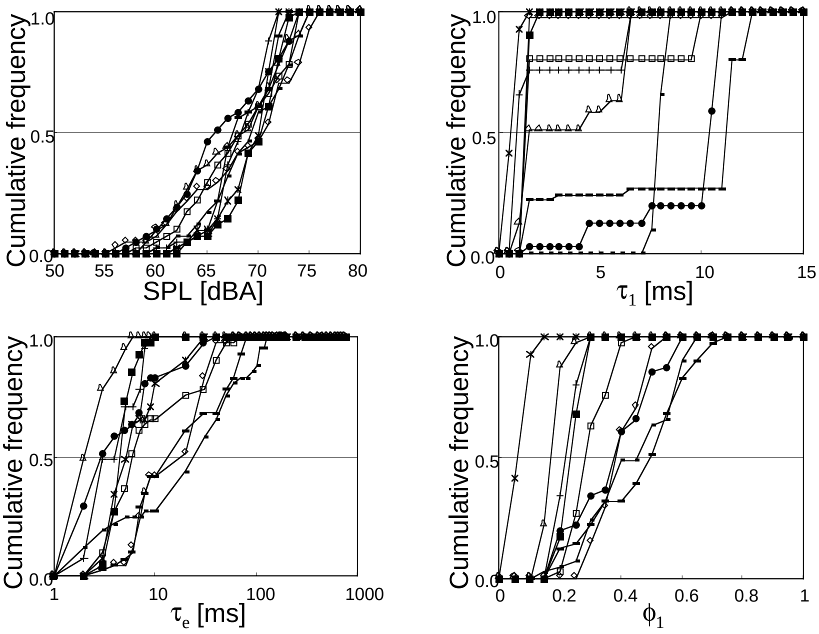

Fig.5. Relationship between measured and calculated annoyance by using linear combination of ACF factors.

such a complex sound, it has been found that annoyance increased at high frequencies of tone than at lower frequencies of tones. [21]. In this study, the calculated pitch ranges between 100 Hz and 1000 Hz, corresponding to the τ_1 value of 1 ms and 10 ms. It is assumed that the stimuli with a small value of τ_1 might be more annoying. (3) Hellman [21] showed that the tone-to-noise ratio increases perceived annoyance. Tone-to-noise ratio or the perceived pitch strength of sound is represented by the values of ϕ_1. Therefore, it is assumed that annoyance increases in proportion to the ϕ_1 values. (4) Annoyance is also corresponded to loudness [21, 22]. It has been found that the perceived loudness of band pass noise and complex noise increases in proportion to the value of τ_e [13,23]. Annoyance may be related to the τ_e values. (5) In general, a noise whose sound level fluctuates is more annoying than the same average noise having a constant sound level. Similarly, a noise whose pitch and timbre fluctuates is more annoying than one having a constant quality [20]. To estimate the effects of such fluctuations of sound level and sound quality, we added the variance of SPL and ACF factors to the variables for the annoyance calculation.

3.2.2 Apparatus

The traffic sounds were reproduced in an anechoic room through a laptop computer, a D/A converter, a power amplifier, and a loudspeaker. A single loudspeaker was used to keep the spatial properties of the sound field constant. The subjects sat 1.0 m in front of the loudspeaker.

3.2.3 Subjects

Ten subjects (nine males and one female) participated in the experiment. They were between the ages of 23 and 27, in good health, with normal auditory acuity. Except for two of the authors (FK and AJ), the rest of the subjects were unaware of the purpose of the study.

3.2.4 Procedure

Subjective annoyance was measured by a paired comparison method. Paired comparison is suitable for the laboratory experiment because of its simple judgment procedure and its reliability. All possible pairs from the nine sounds (36 pairs) were presented to the subjects in a random order in one session. After the presentation of paired stimuli, the subjects were asked to judge which of the two sounds was more annoying. All subjects had four series of sessions, giving a total of 144 comparisons.

3.3. Results and discussion

Collected data were processed by applying “the law of comparative judgment” (case V; Thurstone [24]). This law is used to produce one-dimensional scale values (SV) for each stimulus from the total matrix of superiorities collected from the paired comparisons. The results were reconfirmed by the goodness of fit [25], and the agreement of all subjects’ judgments was tested by the chi-square test ($p < 0.05$). Also, correlation coefficients were calculated between four sessions for each subject individually. The ten subjects produced high

Table 2. Correlations between the median and variance of the ACF factors and annoyance

	SPL	τ_1	ϕ_1	τ_e	Var_SPL	Var_τ_1	Var_ϕ_1	Var_τ_e
SPL	1							
τ_1	–0.66	1						
ϕ_1	–0.29	0.82**	1					
τ_e	0.34	0.33	0.74**	1				
Var_SPL	–0.11	0.02	0.22	0.03	1			
Var_τ_1	–0.57	0.46	0.37	0.35	–0.04	1		
Var_ϕ_1	–0.09	0.50	0.30	0.78**	–0.35	0.12	1	
Var_τ_e	–0.15	0.59*	0.77*	0.78**	0.13	0.33	0.58*	1
annoyance	0.11	0.30	0.57*	0.56*	0.64*	0.39	0.20	0.67*

** $p < 0.01$, * $p < 0.05$

correlation between 0.50 and 0.99, except for one combination of one subject ($r = 0.22$). The between-subject correlation, which was calculated for the averaged scores of four sessions, ranged between 0.33 and 0.96; the average correlation was 0.73. With these analyses it was ascertained that the subjects' judgments were reliable and reasonably consistent between the subjects for the following analysis.

Considering the consistency between subjects' response, the scale values (SV) of annoyance were averaged across subjects so that there is a single SV for each sound. Then the correlation coefficients, r, were calculated between SV and the physical measures. The correlation matrix between the physical measures and SV is shown in Table 2. As expected, the SPL and annoyance are not related. It is considered that the range of the SPL among the stimuli was too small (4 dBA) to affect annoyance. Instead, the variance of the SPL had much effect on annoyance ($r = 0.64$, $p < 0.05$). Although Cermak and Cornillon [4] did not find a significant contribution of measures other than L_{eq}, our results suggest the importance of other acoustical factors when the SPL is relatively constant.

The values of τ_e and ϕ_1 were significantly correlated to annoyance ($r = 0.56$ and 0.57, $p < 0.05$). This result shows that a sound having a strong tonal component was perceived to be more annoying than the un-tonal noise. The subjects' comment also indicated that they judged a sound having a clear pitch to be more annoying. In the evaluation of the perceived noise level for a tonal sound as used in the experiment, a number of tone corrections are proposed. Generally, a corrected value for extracted tonal component is added to the "Perceived Noise Level" (PNL) to give the "Tone Corrected Perceived Noise Level" (PNLT). However, the calculation for this correction is lengthy, and their accuracy is not well established [6]. Instead, by using the value of τ_e and ϕ_1, the effect of the tonal component on perceived annoyance is clearly extracted.

Before the experiment, it was assumed that the sound with a small value of τ_1 (i.e. it represents high pitch sound) might be more annoying. It means that annoyance and τ_1 should have negative correlation. But the result was contrary ($r = 0.30$ in Table 2). It is probably because the high pitch sounds tested in the experiment had weak pitch sensation (it is represented by small values of ϕ_1). The high correlation between τ_1 and ϕ_1 ($r = 0.82$ in Table 2) implies that low pitch sounds are tonal and high pitch sounds are un-tonal sounds. This tendency was generally observed for measured traffic noise in this study. As shown in Fig. 2(b), the un-tonal sounds tend to be estimated to have high pitch in the current analysis, because the structure of the ACF does not have dominant periodical peaks. Consequently, it is not distinguishable from the high-pitched tonal sound like an aircraft noise [12] by only seeing the pitch itself. The result suggests that the effects of pitch on annoyance should be considered together with its pitch strength.

Considering the results above, it is considered that the ACF factors and the variance of the SPL affect perceived annoyance with a complex manner. To calculate the effect of each factor on perceived annoyance more precisely, we examined multiple regression analysis by using a linear combination of eight variables shown in Table 2. To obtain an optimal equation, all possible combinations were examined. The correlation coefficients and significance levels were used to determine the goodness of fit. The best combination of variables was found as the variance of SPL, the median of τ_e, and the variance of τ_1. Multi-colinearity is avoided in this prediction because these three parameters are not correlated each other as shown in Table 2. Standardized partial regression coefficients of each variable, a1, a2, and a3 in Eq. (7) were 0.64, 0.50, and 0.36, respectively and these coefficients were statistically significant

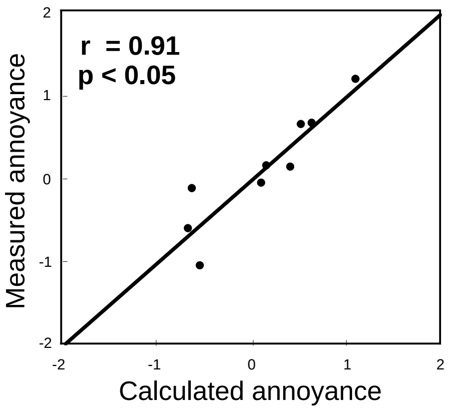

Fig.5. Relationship between measured and calculated annoyance by using linear combination of ACF factors.

($p < 0.05$ for a1 and a2, $p < 0.1$ for a3).

$$SV_{annoyance} \approx a1 * Var\_SPL + a2 * \tau_e + a3 * Var\_\tau_1 + c \quad (7)$$

Using these tentative values and constant $c = -1.62$ in Eq. (7), the total correlation coefficient 0.91 was obtained with the significance level $p < 0.05$. The line shown in Fig. 5 is drawn from Eq. (7). This result shows that the temporal fluctuation of SPL and tonal component had a major effect on annoyance. For sounds with pitch variation, subjects also perceived more annoyance.

4. CONCLUSION

The purpose of this study was to describe the acoustical properties of traffic noise and to explore the relationship between the described properties and perceived annoyance. From the results we concluded that: (1) The ACF analysis is effective for characterizing sound qualities, such as the perceived pitch and timbre. The IACF analysis is effective for describing the spatial information of the noise source. (2) Perceived annoyance is greatly affected by the variation of the SPL and other primary sensations, when the difference of the overall SPL is small. (3) The ACF factors can be possible measures to calculate perceived annoyance in addition to the overall SPL.

We need, of course, to approach the problem in a much more quantitative and thorough way before our results are applied to other experimental condition and actual noise evaluation. Large number of sound samples and subjects need to be tested. Also, in the present study, the intensity of the sound was constrained, but the other parameters were not controlled systematically. Future investigations might benefit from systematic variation of these parameters. Moreover, contribution of these factors should be examined when there is large effect of the overall sound level. As for the other acoustical parameters, which we did not concern in this study, such as roughness or sharpness should also be considered. At this point, we can say at least that important factors for evaluating subjective annoyance such as tonality and pitch fluctuation could be calculated by the proposed ACF analysis.

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