Quantitative model of combined annoyance caused by simultaneous exposure to outdoor traffic sounds

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ABSTRACT

Laboratory experiments which include the simulation of simultaneous exposure to the multiple traffic sounds and the assessment of subjective annoyance have been used to study the interaction between the noise sources, it's influence on overall annoyance, and the modeling of exposure-response relationships. The aircraft (or railway) noise annoyance is masked by road-traffic noise and the higher levels the road-traffic noise has, the lower aircraft (or railway) annoyance the subject rates. For combined noise which two sources have similar sound levels or equally annoying levels, the overall annoyance is higher than the maximum source-specific annoyance, while, for combined noise in which the level of one source was 10 dB or higher than that of the other, the overall annoyance was equal to the maximum source-specific annoyance. An annoyance model for a combined noise exposure was developed using a weighted summation method, and the integration of noise perception resembles the summation of the acoustic pressure of each source.

INTRODUCTION

Several large-scale surveys on the annoyance response to transportation noise have been conducted by the support from the Korean government and the exposure-response relationships for single exposure to aircraft, railway, and road-traffic sounds outdoors have been established by field surveys and reported at ICBEN 2008 (Lee et al. 2008). The results shown that the annoyance response is source-dependent and the responses show a similar trend to the annoyance curves recorded in Japan, although they are somewhat different from those obtained from most European surveys.

There have been a few significant developments diversifying research topics for community noise studies. Targeting sounds have been expanded to include military arms and wind turbines, and the methodologies used to assess the effects of noise on humans have been further developed with a multi-disciplinary approach in mind. Figure 1 shows the exposure-response curves for transportation and wind turbine noise reported in Korea, derived from field and laboratory studies, respectively (Lee et al. 2008, 2011).

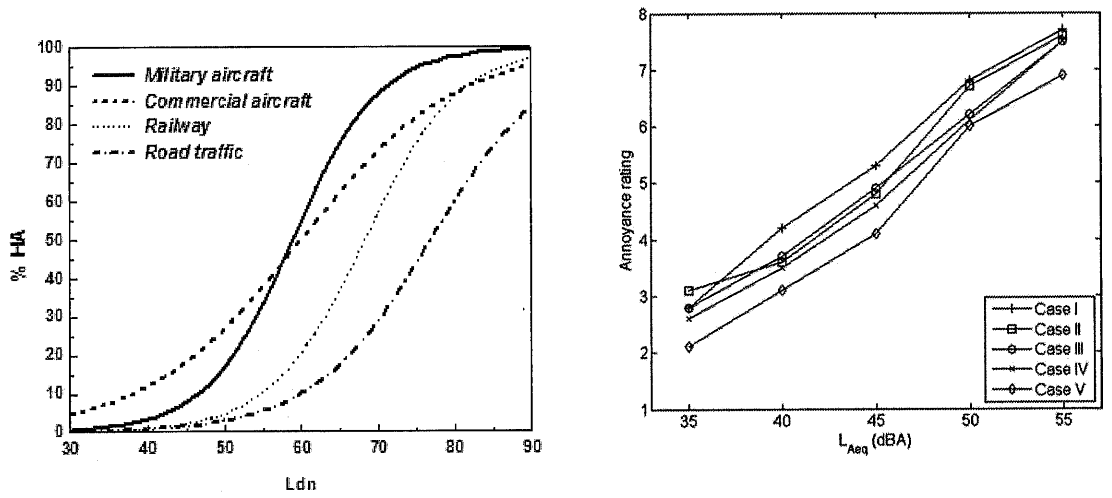

Figure 1: (a) %HA for transportation noise (Lee et al., 2008) (b) Annoyance ratings for modulation depth spectrum of wind turbine noise (Lee et al., 2011, modulation depth: Case I> Case II> Case III> Case IV> Case V)

With regard to the practical problems with noise, such as noise mitigation, prevention and policy making, combined effects caused by simultaneous exposure to multiple sounds should be considered. Pearsons points out that the perceived noisiness of aircraft noise decreases as background noise is added (Pearsons 1966). The annoyance reaction to the target noise according to changes in the level of background noise has also been investigated (Wells 1971; Robinson 1972; Powell & Rice 1975). Powell and Rice examined the influence of background noise on the annoyance caused by aircraft noise, and found that there was a trend of decreased aircraft noise annoyance as background noise level increased for a continuous background noise.

Izumi (1988) reported that total annoyance caused by simultaneous railway and road-traffic noise is lower than the source-specific annoyance for railway noise with a relatively low level of road-traffic noise. In conditions in which railway noise was combined with a high level of road-traffic noise, total annoyance was slightly higher than the maximum source-specific annoyance. Taylor (1982) found that total annoyance is lower than the maximum source-specific annoyance from a field study in Toronto. In addition, such results were reported by Berglund et al. (1981) and Yano and Kobayashi (1990), who investigated that total annoyance was higher than or equal to the maximum source-specific annoyance in various combinations of impulsive and traffic noises.

Similar results were obtained from previous research conducted by these authors. Lim et al. (2008) found that a trend of reduced subjective annoyance to aircraft noise if background noise level is high, and a recent field study on the combined annoyance of aircraft and road-traffic noise also shows that the source-specific annoyance of combined noise decreases as the level difference between the sources decreases (Hong et al. 2009).

These findings differ from the idea that annoyance has a linear correlation with the exposed energy and it might seem counterintuitive that annoyance caused by two noise sources is lower than each specific single noise. In this paper, the source-specific annoyance with regard to different levels of road-traffic noise will be investigated, and the interaction between two noise sources is analyzed. An appropriate model for the evaluation of combined noise will then be developed, based on the analyses of the interaction effects.

METHODS

Stimuli

Aircraft, railway, and road-traffic were presented as the various combinations of two simultaneous sounds during 15-s periods, and the A-weighted levels of the sounds were separated into 10 dB steps from 40 to 80 dB. Binaural recordings were made to obtain the signals of each noise source, with a dummy mannequin in a field test, and they were fed into a mixing console (Cool Edit Pro *Ver.* 2.0) to produce the combined noise stimuli to simulate combinations of aircraft and road-traffic sounds and railway and road-traffic sounds. They were a total of 50 experimental stimuli.

Subjects

Forty-one subjects, 20 males and 21 females between the ages of 20 and 40 years, participated in the experiment for rating 25 combined noise stimuli of aircraft and road-traffic sounds (experimental group 1). The other 41 subjects, 21 males and 20 females between the ages of 20 and 40, participated in the experiment for rating 25 combined noise stimuli of railway and road-traffic sounds (experimental group 2). Audiometric screening tests were performed on each subject to examine the hearing thresholds for both ears at the center frequencies of the octave bands. All of the participants had normal hearing [i.e., the hearing level (HL) was smaller than 15.0 dB of the reference equivalent threshold sound pressure level (RETSPL) (ISO 389-1, 1998) in this research].

Experimental design

The 'Within-Subjects' design was employed for the experiment and the combined noise stimuli of aircraft and road-traffic sounds were randomly played back to experimental group 1 and those of railway and road-traffic sounds were randomly played back to experimental group 2 in a listening room. Subjects were asked to rate the overall annoyance of the two noise sources and the source-specific annoyance of each specific single noise at various noise levels. The eleven-point (0-10) numeric scale recommended by ICBEN was used to rate the subjective annoyance.

RESULTS

Interaction between two noise sources

To examine the effects of the interaction between the two noise sources on overall annoyance, the correlation analysis between source-specific and overall annoyance score were performed under every experimental condition. The significance of each correlation coefficient was tested using the T-test comparison. The combination in which the level of one noise source was the same or similar to the other, overall annoyance and source-specific annoyance were significantly correlated ($p<0.05$). At relatively low levels (less than 50.0 dB in aircraft-road combined noise, and less than 60.0 dB in railway-road combined noise), the overall annoyance was correlated with the source-specific annoyance. At relatively high levels, the overall annoyance was correlated with aircraft or railway noise annoyance (not correlated with road-traffic noise annoyance). The cause might be that at peak energy levels, aircraft or railway noise higher than road-traffic noise.

The pair-wise comparison of the mean rating scores for the source-specific and overall annoyance was conducted. The overall annoyance was significantly higher than the maximum annoyance of individual sources if two constituent sounds had a similar level, or they were equally annoying. The results of the Pair-wise comparison are shown in Figures 2 and 3. Figure 2(a) shows the observed overall annoyance and its expected model caused by combined exposure to aircraft and road-traffic sounds with the level of road-traffic sounds fixed at L_{eq} 60 dB. Figure 2(b) shows the overall annoyance as a function of the levels of road-traffic sounds with the level of aircraft sounds fixed at L_{eq} 60 dB.

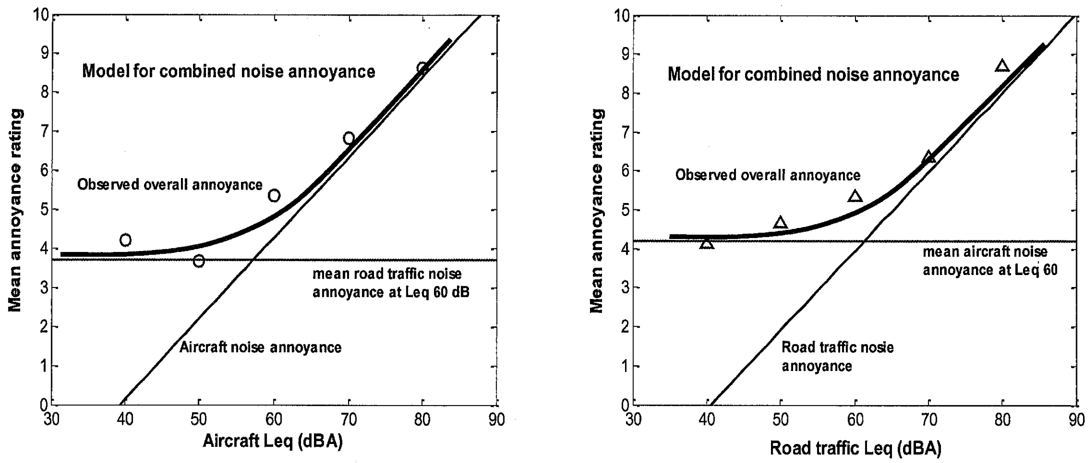

Figure 2: (a) Overall annoyance for aircraft noise combined with road-traffic noise at *Leq* 60 dB as a function of the *Leq* of aircraft noise. (b) Overall annoyance for road-traffic noise combined with aircraft noise at *Leq* 60 dB as a function of the *Leq* of road-traffic noise

The observed overall annoyance and its expected model, caused by combined exposure to railway and road-traffic sounds, are shown in Figure 3; in which Figure 3(a) indicates the case of the level of road-traffic sounds fixed at L_{eq} 60 dB, and Figure 3(b) indicates the case of the level of railway sounds fixed at L_{eq} 60 dB.

Kim et al. (2010) conducted a correlation analysis between various noise metrics and annoyance responses and determined that the A-weighted L_{eq} was a good acoustic measure for annoyance responses to short-term noise exposure. To establish the combined annoyance model, the overall level of combined sources has to be defined and the summation of the noise level of each source might be presented as follows.

$$Leq_{overall} = k\log_{10}\left(\sum_{i=1}^{n} 10^{\frac{L_i}{k}}\right) \tag{1}$$

For the summation of the conventional L_{eq}'s, an energy summation in a free-field condition, k=10, however, it is obvious that aircraft, railway, and road-traffic cause different annoyance responses and the k-values should be different for each source.

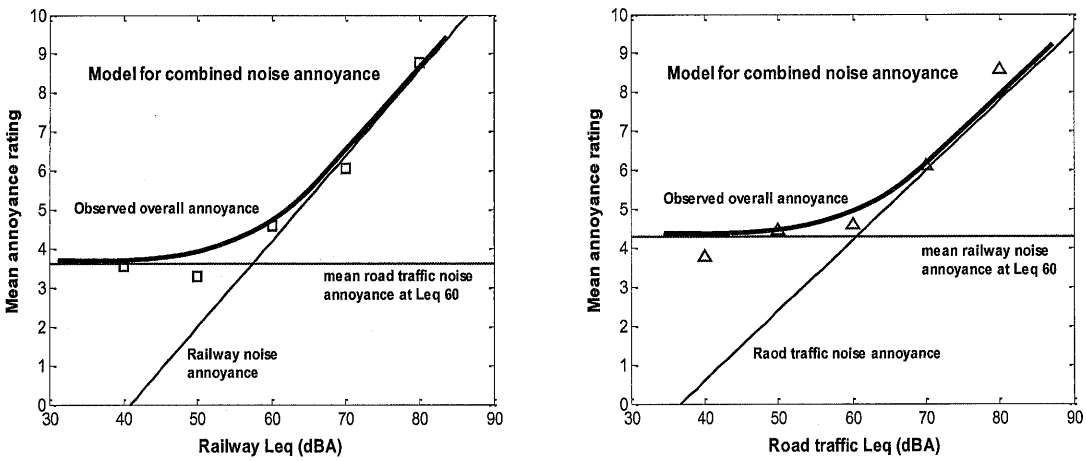

Figure 3: (a) Overall annoyance for railway noise combined with road-traffic noise at Leq 60 dB as a function of the *Leq* of railway noise. (b) Overall annoyance for road-traffic noise combined with railway noise at *Leq* 60 dB as a function of the *Leq* of road-traffic noise

First of all, the levels of aircraft and railway sounds have transformed into equally annoying levels of road-traffic sounds with their exposure-response relationships and the equally annoying levels have been obtained by adding a source dependent penalty (or bonus) to the level of the source considered. The equation for the summation of the noise levels of the two noise sources might be presented as follows.

$$Leq_{overall} = k\log_{10}\left(10^{\frac{Leq_{road}}{k}} + 10^{\frac{Leq_{source}+P_{source}}{k}}\right) \tag{2}$$

Varying the parameter k, the best fit model between the $Leq_{overall}$ and overall annoyance was obtained by using a least square method. For aircraft-road combined noise, the variance of errors was minimized when the value of 'k' was about 21. The highest correlation was 0.730 in the range of 'k' from 18 to 24. For railway-road combined noise, the variance of errors was minimized when the value of 'k' was about 19. The highest correlation was 0.767 in the range of 'k' from 16 to 22. In considering the results of both cases, the annoyance model for combined noise with k=20 seems reasonable.

In this experimental study, the procedure of the methodology adopted that of Vos's weighted independent effect model to obtain the combined annoyance model (Vos

1992). The summation of the *Leq*'s of the two noise sources was performed by adding the level-dependent penalties and the parameter k was determined to be 20 in the overall annoyance model. The significant result is that the mental integration in the cognition of two simultaneous sounds resembles the acoustic pressure summation (k=20), rather than the energy summation.

CONCLUSIONS

For combined noise caused by two sources with similar sound levels or equally annoying levels, overall annoyance was significantly higher than the maximal annoyance of individual sources, while, for combined noise in which the level of one source was 10 dB or higher than that of the other, overall annoyance was equal to the annoyance caused by a dominant source between two sources. The annoyance caused by a dominant source is significantly correlated with overall annoyance in both cases, similar to the results found in a field study of combined noise annoyance (Hong et al. 2009). These results show that the perception and cognition of two simultaneous sounds are performed differently with a summation of the sound energy.

The quantitative model of combined noise annoyance demonstrates that a mental integration of noise perception (i.e. annoyance) caused by two simultaneous traffic sounds resembles the summation of the acoustic pressure of each source, rather than the summation of the L_{eq}'s, and consequently, two equal levels, in terms of L_{eq}, yield an overall noise level which is 6.0 dB higher than each individual source level. However, Vos (1992) proposed that two equal levels yield an overall noise level which is 4.5 dB higher than each individual source level. The difference might be derived mainly from the difference of annoyance rating conditions (indoor vs. outdoor) and the range of the level difference of two noise sources was expanded to 40 dB in this study while the range was limited to 15-20 dB in Vos's study. However, the findings in this study explain Flindell's proposal, in which the pressure *Leq* was superior to the conventional (energy average) L_{eq} (Flindell 1983). Further research with various noise sources and differing annoyance rating conditions should be conducted to apply a summation of the acoustic pressure for the combined annoyance model of traffic sounds.

ACKNOWLEDGEMENTS

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REFERENCES

Berglund B, Berglund U, Goldstein M et al. (1981). Loudness (or annoyance) summation of combined community noises. J Acoust Soc Am70: 1628-1634.

Flindell I (1983). Pressure leq and multiple noise sources: a comparison of exposure-response relationships for railway noise and road traffic noise. J Sound Vibr 87: 327-330.

Hong J, Jaehwan K, Kyutae K et al. (2009). Annoyance caused by single and combined noise exposure from aircraft and road traffic. J Temp Des Architec Environ 9: 137-140.

Izumi K (1988). Annoyance due to mixed source noises: a laboratory study and field surve on the annoyance of road traffic and railroad noise. J Sound Vib 127: 485-489.

Kim J, Lim C, Hong J et al. (2010). Noise-induced annoyance from transportation noise: short-term responses to a single noise source in a laboratory. J Acoust Soc Am 127: 804-814.

Lee S, Hong J, Kim J et al. (2008). Exposure-response relationships on community annoyance to transportation noise. In: Griefahn B (ed): The 9th Congress of the International Commission on the Biological Effects of Noise: Noise as a Public Health Problem, Proceedings, Mashantucket, CN, July 21-25, 2008.

Lee S, Kim K, Choi W et al. (2011). Annoyance caused by amplitude modulation of wind turbine noise. Noise Contr Eng J 59: 38-46.

Lim C, Kim J, Hong J et al. (2008). Effect of background noise levels on community annoyance from aircraft noise. J Acoust Soc Am 123: 766-771.

Pearsons K (1966). The effects of duration and background noise level on perceived noiseiness. Storming Media.

Powell CA, Rice CG (1975). Judgments of aircraft noise in a traffic noise background. J Sound Vibr 38: 39-50.

Robinson D (1972). An essay in the comparison of environmental noise measures and prospects for a unified system. NPL Acoustics Report Ac 59.

Taylor SM (1982). A comparison of models to predict annoyance reactions to noise from mixed sources. J Sound Vibr 81: 123-138.

Vos J (1992). Annoyance caused by simultaneous impulse, road traffic, and aircraft sounds: a quantitative model. J Acoust Soc Am 91: 3330-3345.

Wells R (1971). Noise complaint potential, ambient noise versus intrusive noise. In: Proceedings of the Seventh International Congress on Acoustics, Budapest.

Yano T, Kobayashi A (1990). Disturbance caused by various fluctuating single noises and combined community noises. Environ Int 16: 567-574.