Predictive Model of Annoyance Induced by Combined Transportation Noise

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Abstract

A series of studies on the subjective response to aircraft, railway, and road traffic noise has previously been carried out. However few studies have examined the optimal physical parameters for this type of measurement and evaluation. To date, several physical parameters, such as the equivalent sound level (L_{eq}), day-night average sound level (L_{dn}), and day-evening-night average sound level (L_{den}), have been used to evaluate various types of transportation noise. However, physical parameters that are universally applicable to all types of transportation noise have not been developed. The present study was designed to analyze the relationship between transportation noise and the subjective response. The study is currently in the preliminary stages of developing a physical parameter that can evaluate both individual and combined transportation noises. In conclusion, the regression model, which includes a set of variables that describe sound levels for single and mixed source noise, predicts annoyance levels with an accuracy of >95%, as measured by the determination coefficient.

Keywords: annoyance; transportation noise; combined noise

1. Introduction

People are disturbed by transportation noises during sleep, conversation, and concentration[1,2,3]. The degree of subjective responses, such as annoyance, varies depending on the noise source (transportation type), social background, and survey method. The transportation noises that have the largest effect on humans and animals are those emanating from road traffic, railways, and aircraft. Methods have been developed to measure and evaluate sound levels for single sound sources. Each source has distinct volume, frequency, and prevalence limits, depending on the local environment. However, no measurement or evaluation methods have been developed in Korea for combined noise, even though many areas are subjected to mixed transportation noise. Mixed noise is problematic for noise pollution control. In response to a noise complaint, the exact source of the offending noise must be identified, a particular regulation must then be applied, and compensation allotted accordingly. Therefore, regulations should be designed around the subjective response to noise disturbances.

Schultz[4] analyzed the relationship between annoyance levels and individual transportation source noise using data from earlier research performed in Europe and the United States. Later, Taylor[5] tested five models such as the energy summation model, independent effects model etc. Among those tested the energy difference model produced the best prediction of overall annoyance. This model uses two variables with the continuous sound level of combined sources and the absolute difference between the sound levels for the separate sources.

Kryter[6], Vos[7], Miedema *et al.*[8] and Miedema[9] applied the percentage of highly annoyed respondents (%HA) as a parameter in their research on the relationship between annoyance and physical measures. Vos proposed a model to predict total annoyance for mixed noise using experimental impulse, road traffic, and aircraft sounds, and concluded that the total annoyance is equal to the maximum annoyance induced by the separate sources. Miedema sought an annoyance equivalence model to describe annoyance from single source aircraft, road traffic, or railway noise data that had been published in an earlier international dataset. However, this research is still insufficient for predicting annoyance levels from combined transportation noise.

In an attempt to extend previous research, this study proposes an annoyance model that predicts the

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degree of annoyance for individual or combined (two to three simultaneous sources) transportation noises. The results from this study may be applied to different types of combined noise.

2. Psycho-acoustic Test

2.1 Sound source

The objective sound sources used in the study were three transportation noises: aircraft (AC), road traffic (RT), and railway (RW) noise. These noises were divided into seven sound sources on the basis of their sound characteristics: AC was divided into military (ACM) and commercial (ACC), RT into country (RTC) and highway (RTH), and RW into KTX (Korean Express Train) (RWK), Saemaul (RWS), and Mugungwha (RWM). The sound levels of each source were adjusted between seven discrete levels within a range from 35 dBA to 65 dBA, at 5 dBA increments. Fig.1. shows the spectrum of sound sources from military aircraft, road traffic from city roads, and KTX railway, measured using a head and torso simulator (HATS) with background noise that was at the same listening level as the subjects.

To produce a combined sound, two or three sound sources were mixed. The following sound pairs were used: road traffic and railway; road traffic and aircraft; and railway and aircraft. A combination of all three sound sources was mixed in the same way. The sound levels of each sound were incremented in three steps: 40 dBA, 50 dBA, and 60 dBA.

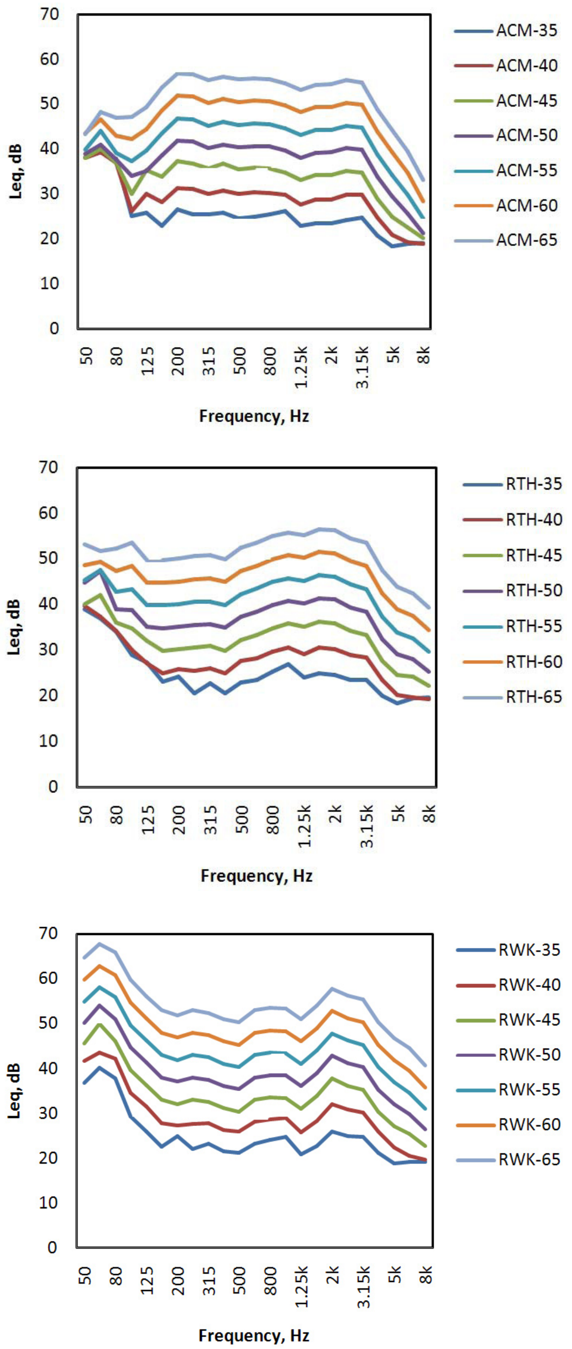

Fig.1. Spectrum of Sound Sources Used for the Psycho-acoustic Test. Top: Military Aircraft; Middle: Road Traffic; Bottom: Railway Sound Used for Test

Table 1. Sound Levels of Single Sources Used for the Test

sound SPL (dBA)	Aircraft		Road traffic		Railway		
	ACC	ACM	RTC	RTH	RWK	RWM	RWS
35	35.1	35.2	35.1	35.4	34.9	35.3	35.1
40	40.0	40.0	40	39.7	40.0	39.9	40.2
45	45.1	45.2	45.1	45.1	45.2	45.1	45.1
50	50.2	50.1	50.1	50.1	50.2	50.2	50.1
55	55.1	55.1	55.1	55.1	55.2	55.2	55.0
60	60.1	60.2	60.2	60.2	60.2	60.2	60.2
65	65.1	65.2	65.2	65.2	65.1	65.2	65.2

Table 2. Sound Levels of Sources Composed of Two or Three Mixed Sources

Type				Sound level (dB) of the source in the 2nd column of the table		
				40	50	60
Two sound sources	RTH	ACM	40	42.8	50.4	60.1
			50	50.4	53.1	60.5
			60	60.1	60.5	63.1
		RWK	40	42.7	50.3	60.1
			50	50.5	53	60.4
			60	60.1	60.5	63.1
	RWK	ACM	40	42.9	50.5	60.1
			50	50.4	53.1	60.5
			60	60.1	60.5	63.1
Three sound sources	RTH	RWK40 ACM	40	44.4	50.8	60.1
			50	50.7	60.8	60.5
			60	60.2	60.5	63.1
		RWK50 ACM	40	50.7	53.2	60.5
			50	63.2	54.8	60.8
			60	60.5	60.9	63.3
		RWK60 ACM	40	60.1	60.5	63.1
			50	60.4	60.8	63.2
			60	63.1	63.3	64.8

2.2 Subjects

The subject group was composed of 24 students (19 males and 5 females) attending the Chonnam National University or Graduate School, between the ages of 18 and 30 years. Before starting the main test, subjects were given an explanation of the purpose of the test and were asked to rate the degree of annoyance, as if they were resting in their home. According to the study by Yano *et al.*[10], the degree of annoyance elicited by transportation noise is not affected by the numerical scale used for the purpose of rating. Therefore, a scale ranging from one (not at all annoying) to seven (extremely annoying) was used to rate the level of annoyance in this study. Fig.2. shows a schematic diagram of the testing setup.

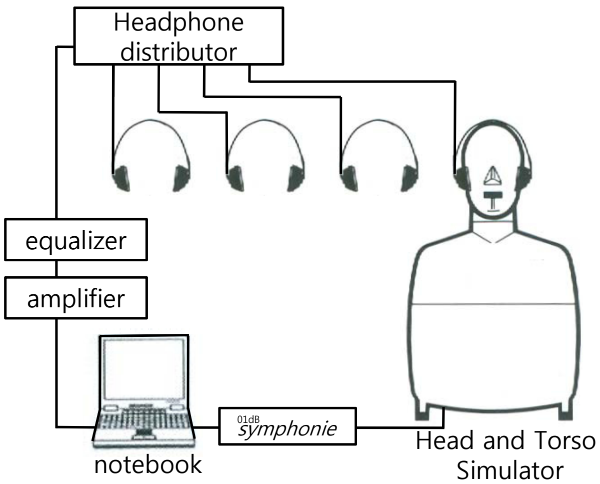

Fig.2. Experimental Setup Using Headphones

2.3 Analysis method

The annoyance was compared with the A-weighted equivalent sound level (L_{Aeq}). The relationship between annoyance and sound level was analyzed by the Boltzmann equation, and a multiple linear regression analysis was applied to establish the prediction model for annoyance when multiple sound sources were mixed.

The Boltzmann equation represents a sigmoidal shaped curve that approaches asymptotically to 1 to 7 degree of annoyance for the extreme values of the traffic noise. This equation will be compared with the multiple linear regression analysis, whose fitting line is linear. Multiple linear regression analysis is widely used for the prediction model that has two or more explanatory variables and a response variable by fitting a linear equation to observed data.

The Boltzmann equation is given by,

$$y = \frac{A_1 - A_2}{1 + e^{(x - x_0)/dx}} + A_2$$

where,

A_1 = y-value for x= -∞ (1 or 7);

A_2 = y-value for x= +∞ (1 or 7);

x_0 = x-value of the mean y-value, that is, the x-value when y = 4 in our case;

dx = is the slope of the midpoint of the regression line.

2.4 Test procedure

To avoid an order effect in the subjective test, the sound sources were randomly arranged, regardless of the transportation type. The test was performed under conditions that were as comfortable as possible, to simulate resting conditions in the subjects' homes. The test sound was monaurally played once per sound, so subjects listened to the same sound with each ear. Its duration was 20 sec, and a signal sound was played to notify the subjects of the subsequent test sound (Fig.3.). In the middle of the test, subjects were given a recess to reduce stress and avoid fatigue and apathy.

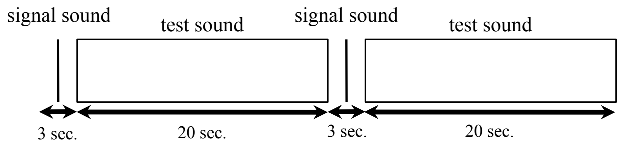

Fig.3. Schematic of Playback of the Test Sound and Signal Sound

3. Analysis

3.1 Annoyance due to a single test sound

As shown in Fig.4., the annoyance due to the railway sound was higher than that due to other sounds, and road traffic produced the lowest annoyance. The differences between median annoyances L_{Aeq} were approximately 3 dBA between AC and RW, and 4 dBA between RT and RW.

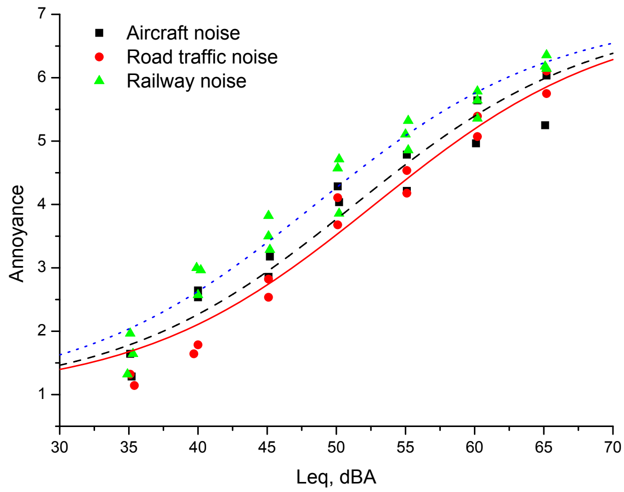

Fig.4. Relationship between Annoyance and Sound Level for Single Test Sounds: Aircraft, Road Traffic and Railway

As reported in several studies, the relationship between annoyance and sound level depends on the people tested and on the country in which the tests are conducted, implying that the measured annoyance prediction model may not be universally applicable. Table 3. gives the determination coefficient from the Boltzmann fit, the median value, and the slope.

Table 3. Coefficients of Parameters in the Boltzmann Model of Annoyance Level as a Function of Sound Level and Transportation Noise Type

No.	Sound source	Determination coefficient (R^2)	Median (x_0)	Slope (dx)	Remark
1	AC	0.934	51.34	8.6	
2	RT	0.965	52.77	8.6	
3	RW	0.960	48.48	8.6	Most annoying

3.2 Annoyance for combined test sounds

The relationship between sound level and annoyance for combined transportation noise was analyzed, as shown in Fig.5. Annoyance was more closely related to the sound level than to the type of sound or to the total number of sounds. Sound level, however, was insufficient for the prediction of annoyance level.

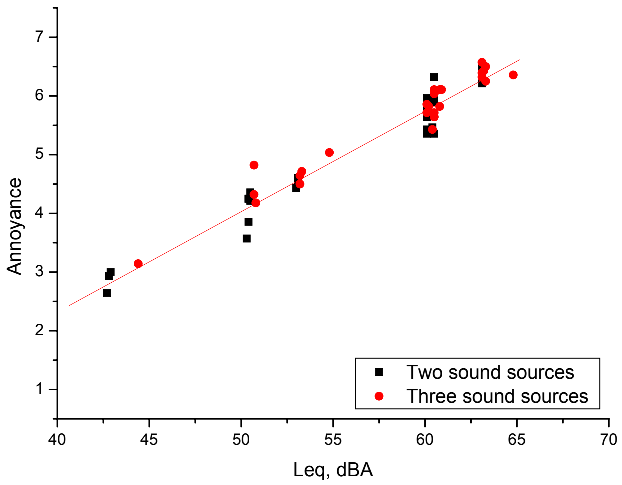

Fig.5. Relationship between Sound Level (L_{eq}, dBA) and Annoyance for Mixed (Two or Three) Transportation Sound Sources

Using the Boltzmann equation, the effect of combined noises was analyzed. Fig.6. shows that the annoyance from two combined sounds is higher than that for a single sound, which was shown in the research of Vos (1992)[7]. Fig.7. shows the annoyance level of triple-source mixed transportation sounds. These figures show that the difference between single and mixed source annoyance levels increases as the sound level increases. Therefore, annoyance is higher in situations in which multiple sounds with high sound levels are mixed.

Table 4. summarizes the fit coefficients for the Boltzmann models given in Fig.6. and Fig.7. for single, double, and triple component sound sources. The determination coefficient (R^2) is not less than 0.925, suggesting that the form of the model is appropriate for the data. The slopes, dx, for the combined sounds fell between 7.45 and 7.79, steeper than the slopes for single sounds, 8.6. This implies that annoyance as a function of sound level increases more dramatically as the number of components in the mixed sound is increased.

4. Prediction Model of Annoyance for Combined Noises

The Boltzmann equation has been used previously to evaluate the relationship between dose and response, and is, therefore, a first approximation for the relationship between sound level and annoyance. However, this model has trouble in predicting the total annoyance of combined sounds, because it assumes that individual sounds contribute linearly to the total annoyance.

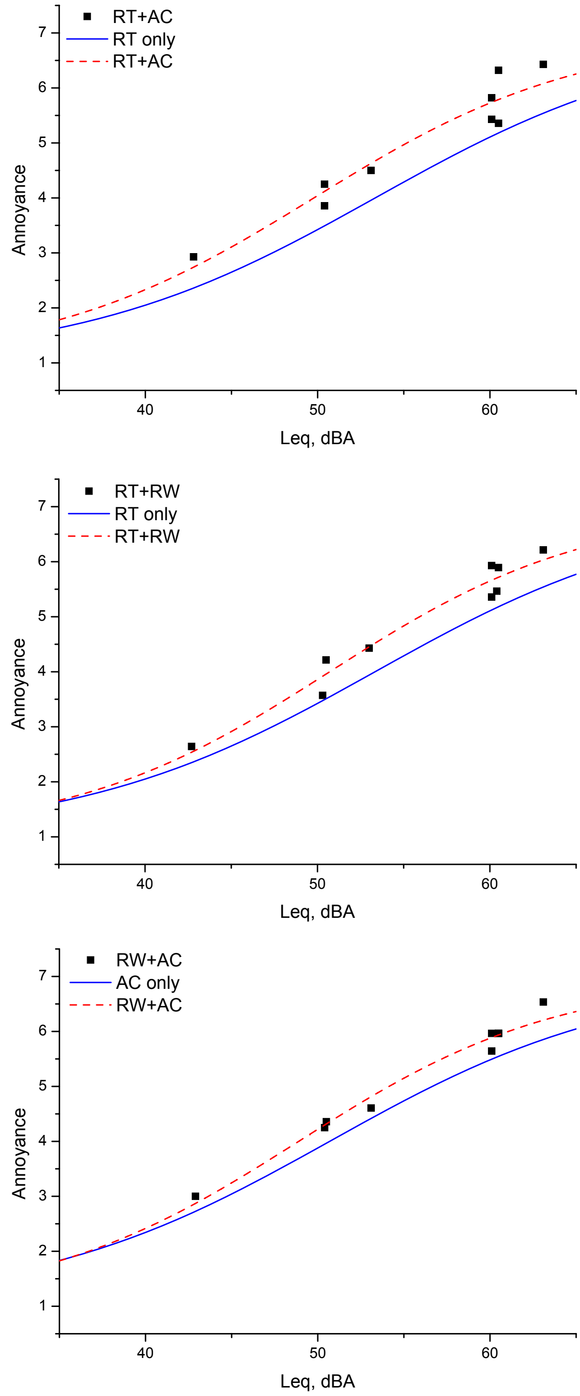

Fig.6. Comparison of the Annoyance for Single and Double-source Mixed Transportation Sounds.
(a) AC/RT Combination; (b) RT/RW Combination; and (c) RW/AC Combination

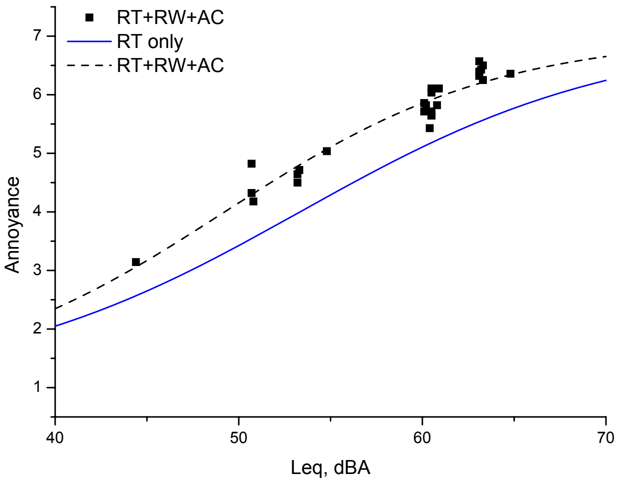

Fig.7. Comparison of the Annoyance for Single and Triple-source Mixed Transportation Sounds

Table 4. Boltzmann Fit Parameters for Fits Shown in Fig.6. and Fig.7., for Single, Double, and Triple Component Sound Sources

No.	Type of sound source			R^2	X_0	dx	Remarks
	Sound 1	Sound 2	Sound 3				
1	AC			0.934	51.34	8.6	Single sound
2	RT			0.965	52.77	8.6	
3	RW			0.960	48.48	8.6	
4	RT	AC		0.925	49.78	7.79	Two sounds
5	RT	RW		0.959	50.71	7.52	
6	RW	AC		0.977	48.89	7.57	
7	RT	RW	AC	0.932	49.23	7.45	Three sounds

The relationship between dose and response is expressed as a second order polynomial or as an S-shaped curve. In such curves, if the response below 20%, and the response above 80% are excluded, the response in the middle portion of the plot is approximately linear. Therefore, multiple linear regression analysis was applied to the prediction of total annoyance, assuming linearity[11], because sound sources are mixed, in the middle portion of the response curve, at sound levels of 40, 50, and 60 dBA.

The dependant variable was the subjective response (annoyance), and the independent variables were the sound levels of individual sources and the combined sound(independent and energy summation model). Table 5 summarizes the variables for each experiment. The sound levels of single sounds were X_1, X_2, and X_3, and the sound level of the combined sound was X_4, which improved the accuracy of prediction. Variable X4 was anticipated to have high correlation with the other variables, but the correlation coefficient was at most 0.65, so that we can judge that there is no multicollinearity between variables.

The regression analysis for the combined sound shows a very high degree of prediction with the coefficient of determination (R^2) above 0.97 for two sounds and with 0.962 for three sounds significantly ($p<0.001$). To compare the equation with that used in previous research by Taylor, both the independent effects model and energy difference model were applied, which yields the best prediction of annoyance among the five models he examined. This does not mean that the authors used the same equation as Taylor, because the annoyance from the traffic noise would not be the same from the viewpoint that the subjective test was carried out in a different country and different situation in the field and in the lab. Therefore only the method that uses an independent level of each sound for the independent effects model, and both total level and absolute level difference for the energy difference model, was adopted.

First, the independent effects model was compared in the Table 6. What is different from the model tested in the present study is the use of a combined level of complex sounds. As a result, the R^2 is very low compared with the value when the combined level is considered, even though the absolute R^2 value is not very low above 0.84 for two sounds and 0.74 for three sounds.

In the energy difference model, the R^2 was higher than in the independent effects model, but still lower than the R^2 of the independent and energy summation model from this study. While the R^2 value between the two models was almost the same with 0.51 and 0.52 in Taylor's test, the difference in this study is remarkably large. The reason that the R^2 value is large is considered to be related to the test condition. Taylor's test was performed in the field, and it is hard to control the test conditions, which might cause a relatively low determination coefficient. In contrast, this study was carried out in the lab where test conditions are easy to control.

5. Results and Discussion

The subjective response to ambient transportation noise experienced at places of residence varies by noise type and person. Thus, it is important to characterize the subjective response to noise, as a function of noise type, and to establish regulations based on this analysis. In addition, the evaluation of noise conditions in which two or more sounds are mixed enables the identification of optimal routes to improving the comfort of residential environments.

This study analyzed the subjective annoyance induced by single and mixed source transportation noise. Single source sounds were rated as follows: railway noise was most annoying, aircraft noise was the second most annoying, and road traffic was the least annoying. This ordering differed somewhat from previous research, which measured high annoyance levels for both aircraft and road traffic noise. This discrepancy may have arisen from differences in test conditions, country, the cross section of test subjects, and the survey method.

The combined noise results showed that the sound

Table 5. Variables Used for Multiple Linear Regression Analysis

Symbol	Sound source			Dependent variable (Y)	Independent variable 1 (X_1)	Independent variable 2 (X_2)	Independent variable 3 (X_3)	Independent variable 4 (X_4)	Remarks
	Sound source 1	Sound source 2	Sound source 3						
C1	Road traffic noise (RT)	Aircraft noise (AC)	-	Subjective response (Annoyance)	Sound level of RT (dBA)	Sound level of AC (dBA)	-	Sound level of complex sound (dBA)	Two sounds
C2	Road traffic noise (RT)	Railway noise (RW)	-		Sound level of RT (dBA)	Sound level of RW (dBA)	-	Sound level of complex sound (dBA)	Two sounds
C3	Railway noise (RW)	Aircraft noise (AC)	-		Sound level of RW (dBA)	Sound level of AC (dBA)	-	Sound level of complex sound (dBA)	Two sounds
C4	Road traffic noise (RT)	Railway noise (RW)	Aircraft noise (AC)		Sound level of RT (dBA)	Sound level of RW (dBA)	Sound level of AC (dBA)	Sound level of complex sound (dBA)	Three sounds

Table 6. Coefficients of the Regression Model of Annoyance for the Combined Transportation Noise

Symbol	Dependant variable (Y)	Variable				Constant (C)	Determination coefficient (R^2)	F-value
		Independent variable 1 (X_1)	Independent variable 2 (X_2)	Independent variable 3 (X_3)	Independent variable 4 (X_4)			
C1	Annoyance (Independent and energy summation model)	–0.00151	0.0342	–	0.14161	–4.52949	0.976	68.57 (P<0.001)
C2		–0.01537	0.02069	–	0.17069	–4.90498	0.995	368.49 (P<0.0001)
C3		0.0046	0.01379	–	0.01379	–4.32737	0.990	280.95 (P<0.0001)
C4		–0.00888	0.00664	0.00746	0.15759	–3.92491	0.962	142.10 (P<0.0001)
C1	Annoyance (Independent effects model)	0.07024	0.10595	–		–3.82143	0.867	19.57 (P<0.005)
C2		0.07083	0.10774	–		–4.07143	0.842	16.09 (P<0.0005)
C3		0.08214	0.09107	–		–3.51786	0.858	18.25 (P<0.005)
C4		0.03988	0.05575	0.05675		–2.05688	0.740	21.83 (P<0.0001)

Table 7. Coefficients of the Regression Model of Annoyance Using Energy Difference Model

Symbol	Dependant variable (Y)	Variable		Constant (C)	Determination coefficient (R^2)	F-value
		Independent variable 1 (X_1)	Independent variable 2 (X_2)			
C1	Annoyance (Energy difference model)	0.17338	-0.01071	-4.56603	0.941	48.44 (P<0.001)
C2		0.17632	-0.00248	–4.92945	0.962	77.41 (P<0.0001)
C3		0.17127	-0.00545	–4.34611	0.991	340.78 (P<0.0001)
C4		0.16223	-0.00062	-3.9277	0.946	213.25 (P<0.0001)

level played an important role in the annoyance rating. In particular, when the sound level was relatively low, the subjective annoyance was proportional to the linear sum of the sound levels, not to the level of any specific sound. As the sound level increased, the annoyance increased at a higher rate than the sound level increase. Therefore, annoyance was higher for combined noises with relatively high sound levels.

Multiple linear regression analysis was carried out to model the relationship between sound level and subjective response for combined transportation noise. The independent and energy summation model included the sound levels of each sound and the composite sound level as independent variables. This regression model predicted annoyance levels with a high determination coefficient compared with both the independent effects model and energy difference model tested and proposed by Taylor. This model may assist future studies by establishing standards for measuring and evaluating the response to combined noise.

The regression model used to predict annoyance in response to transportation noise can be summarized as follows:

(1) Annoyance from road traffic and aircraft noise:
$Y_{RT+AC} = 1/10\times(-1.51\times L_{RT} + 34.20\times L_{AC} + 141.61\times 10\log(10^{(Lrt/10)} + 10^{(Lac/10)}) - 4529.49)$;
(2) Annoyance from road traffic and railway noise:
$Y_{RT+RW} = 1/10\times(-15.37\times L_{RT} + 20.69\times L_{RW} + 170.69\times 10\log(10^{(Lrt/10)} + 10^{(LrwC/10)}) - 4904.98)$;
(3) Annoyance from railway and aircraft noise:
$Y_{RW+AC} = 1/10\times(4.60\times L_{RW} + 13.79\times L_{AC} +$

$13.79\times10\log(10^{(Lrw/10)} + 10^{(Lac/10)}) - 4327.37)$;

(4) Annoyance from road traffic, railway, and aircraft noise:

$$Y_{RT+RW+AC} = 1/10\times(-8.88\times L_{RT} + 6.64\times L_{RW} + 7.46\times L_{AC} + 157.59\times10\log(10^{(Lrt/10)} + 10^{(Lrw/10)} + 10^{(Lac/10)}) - 3924.91),$$

where Y is the annoyance level defined between 1 (not at all annoyed) and 7 (extremely annoyed), and Lx is the sound level of the transportation noise (X) (dBA, the objective sound level for this equation ranged from 35 dBA to 65 dBA).

6. Conclusion

In this study, the annoyance response to single and multiple source transportation sounds was modeled using the Boltzmann equation and multiple regression analysis. The annoyance from railway sound was higher than the annoyance from aircraft or road traffic sounds. The annoyance from multiple sounds increased faster, with increasing sound level, than the annoyance from single sounds. The authors established a predictive model, and an independent and energy summation model, for annoyance using the sound levels of individual and composite sound sources as independent variables. In conclusion, the regression model accurately predicted annoyance with a determination coefficient of >95%. The results from this study may be useful for predicting the response to combined noises.

Acknowledgments

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