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Dose-response relationships for wind turbine noise in Japan

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ABSTRACT

In order to obtain a base for wind turbine noise policy, a socio-acoustic survey was carried out throughout Japan from Hokkaido to Okinawa over three years (2010-2012). In total 747 responses were obtained with face-to-face interview method. The wind turbine noise was measured at several points in each site for successive five days. The $L_{\mathrm{Aeq,n}}$, which was precisely measured outdoor in a day, was taken as noise exposure. A representative exposure-annoyance relationship was drawn based on all data. The trend was consistent to those from Swedish and Dutch surveys. People at sites with sea wave sound were less annoyed by wind turbine noise than those at sites without. The effects of moderating factors such as interest in environmental problems, disturbance of landscape and sensitivity to noise were also investigated.

Keywords: Wind turbine noise, annoyance, dose-response relationships

1. INTRODUCTION

Wind turbines have been highlighted as one of renewable energy sources. As widely recognized across the world, wind turbine noise has emerged as a serious social problem among people living in areas close to wind turbines. Assessing the effect of wind turbine noise on people and the environment is essential to promote the clean energy production effectively. Thus several social surveys on the effects of wind turbine noise have so far been carried out in Europe and North America. For example, Pedersen et al. [1-4] have investigated the effects of wind turbine noise on people. They carried out social surveys at sites with small wind turbines in Sweden [1] and at sites with relatively big modern wind turbines in The Netherlands [2] and demonstrated dose-response relationships for wind turbine noise annoyance. Then Pedersen et al. [3] analyzed the impact of visual factors on annoyance with structural equation model by using Swedish data and indicated that

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visual attitude to noise source was strongly associated with wind turbine noise annoyance and that the aesthetic evaluation of noise source was important. From Dutch survey they investigated whether road traffic noise masked wind turbine noise and reduce its noise annoyance or not [4]. The result was not so simple in that wind turbine noise annoyance was reduced in 35-40 dB L_{den} when road traffic noise was 20 dB more than wind turbine noise.

While wind turbine generators have frequently been constructed since 1990s in Japan, the noise problems have occurred. A committee was organized under the auspice of the Ministry of the Environment of Japan which conducted “Research on the Evaluation of Human Impact of Low Frequency Noise from Wind Turbine Generators” from 2010 to 2012. This is the first systematic research project in Japan which consisted of wind turbine noise measurements, psycho-acoustic experiment of wind turbine noise and social surveys on community response to noise and health effects. It has been sometimes reported that community response to noise may be different among cultural backgrounds such as difference in railway bonus between Europe and Japan [5]. Therefore accumulating socio-acoustic survey data for wind turbine noise in Japan is the prerequisite for its policy.

This paper reports the results of a part of social surveys, community response to wind turbine noise, following the outlines of the social survey by Kuwano et al [6]. The objectives are to propose the representative dose-response curves for wind turbine noise in Japan and to investigate the effects of moderating factors on annoyance caused by wind turbine noise.

2. SOCIAL SURVEY AND NOISE MEASUREMENT

Social surveys were conducted with face-to-face interview method as a survey on living environment at 36 target sites with wind turbines and 16 control sites without wind turbines throughout Japan from Hokkaido to Okinawa, obtaining 747 and 332 responses in total, respectively. The response rates were 49% and 45%, respectively. Almost all sites were sparsely populated and the sample size per site was from 3 to 42. The key question was the one about annoyance (Q3.7, Appendix in Reference [6]) and the following moderating factors were used for multivariate analysis with noise exposure or distance from the nearest wind turbine and a respondent’s house: self-reported sensitivity to noise (Q10.6), interest in environmental problems (Q10.7), attitude to wind turbines (Q10.8), landscape disturbance by wind turbines (Q10.12) and benefit from wind turbines (Q10.14).

During the same period as social surveys, noise measurements were performed at several points of all target and control sites. The regular electricity generation of wind turbine was from 400kw to 3,000kw, mainly more than 1,500kw. Since wind turbine noise levels are usually low, it is very difficult to identify the noise events in even moderate background noise environments. Thus the average sound pressure level at the regular operation during nighttime ($L_{\mathrm{Aeq,n}}$) was measured. Based on the measurement values and distance reduction, 651 noise exposures to respondents’ houses were identified in total, ranging from 26 to 50 dB, and these were used for further analysis.

Annoyance was evaluated by ICBEN 5-point verbal scale: extremely, very, moderately, slightly or not at all. Prevalence of annoyance, % extremely annoyed, % extremely+very annoyed and % extremely+very+moderately annoyed were used as the annoyance indices. Table 1 shows the basic data for the following analysis.

Table 1 Noise exposure, the number of respondents and the prevalence of annoyance

$L_{\mathrm{Aeq,n}}$ (dB)	No. of respondents	%extremely	%extremely+very	%extremely+very+moderately
-30	30	10.0	10.0	26.7
31-35	114	2.6	9.7	31.6
36-40	247	6.5	12.6	36.0
41-45	207	14.0	19.8	38.7
45+	53	18.9	22.6	50.9

3. DOSE-RESPONSE CURVES

Dose-response curves are very important for practical use. Here $L_{Aeq,n}$-annoyance and distance-annoyance curves were drawn by logistic regression as shown in Figures 1 and 2. These are the representative dose-response curves for wind turbine noise annoyance in Japan. The coefficients of $L_{Aeq,n}$ for % extremely, % extremely+very and % extremely +very+moderately annoyed were all significant ($p=0.0013$, $p=0.0032$ and $p=0.0121$, respectively). Those of distance were also significant ($p<0.0001$, $p<0.0001$ and $p<0.0001$, respectively).

When $L_{Aeq,n}$ increased from 26 to 50 dB, % extremely, % extremely+very and % extremely +very+moderately annoyed gradually increased from 3 to 21, from 6 to 27 and from 25 to 48%, respectively. To express the dose-response relationships %highly annoyed (top 28%, top two categories from 7-point scale or top three from 11-point scale) is usually used as annoyance response. The curve for % highly annoyed is estimated to be in between those for % extremely and % extremely+very annoyed in Japanese scale since exposure-% highly curves for transportation noises are in between them in Japan and Vietnam [7]. This finding consistent to the trend of the relationships obtained from Swedish and Dutch surveys that % very annoyed increased from 2-3 % in 30-35 dB to 18-19% in 40-45dB immission sound level [2].

Respondents' houses were from 90 to 1466 m apart from the closest wind turbine. In Figure 4, % extremely, % extremely+very and % extremely+very+moderately annoyed decreased from 26 to 1, from 28 to 3 and from 51 to 14 %, respectively. % extremely annoyed rapidly decreased from 26 % at 100m point to 10% at 500m point.

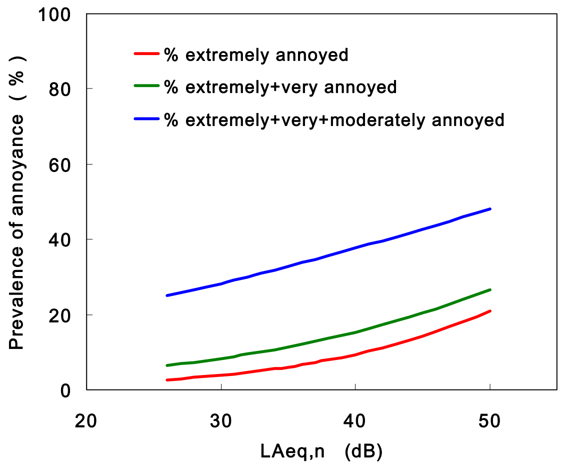

Figure 1 Relationships between $L_{Aeq,n}$ and annoyance

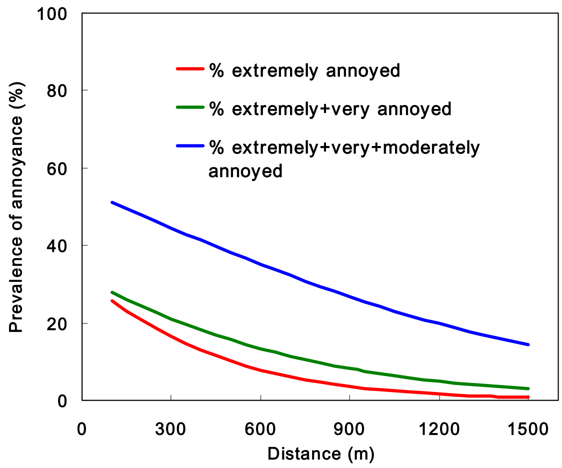

Figure 2 Relationships between distance and annoyance

20 sites in Hokkaido and facing Japan Sea in Honshu were classified into colder area of Japan (n=345) and the others into warmer area (n=306). $L_{Aeq,n}$-% extremely annoyed relationships in both areas were obtained in Figure 3. The relationship in warmer area was higher than that in colder area. The same trend as % extremely annoyed was found in the relationships for % extremely+very and %extremely+very+moderately annoyed. Multiple logistic regression analysis was applied by designating extremely annoyed or not as a dependent variable and $L_{Aeq,n}$ and dummy variable (warmer area:0, colder area:1) as independent variables. The coefficient of the dummy variable was significant ($Chi^2=4.73$, $p=0.030$). When the same analysis was applied to % extremely+very and %extremely+very+moderately annoyed, the results were not significant ($Chi^2=3.29$, $p=0.070$) and significant ($Chi^2=5.85$, $p=0.016$), respectively. When dose-response relationships for road traffic and railway noises were compared between Hokkaido, colder area of Japan, and Kyushu, a warmer area, no significant difference was found between the areas [8]. Therefore the difference in wind turbine noise annoyance may not be due to climate. The other possibility may be that wave sound from the sea during winter season masked wind turbine noise. Strong wind blows at some sites in the colder area during winter.

Nine sites were identified as those with strong sea wave sound during winter from the observations (n=121) and the others as those without (n=530). Of 530, 224 were in colder area and 306 were in warmer area. Figure 4 compares the dose-response relationships between these areas.

When the same analysis as in the former paragraph was applied, the coefficients of the dummy variable for % extremely, % extremely+very and % extremely+very+moderately annoyed were all insignificant (Chi2=0.73, 0.12 and 0.15, and p=0.39, 0.73 and 0.70, respectively). There appears to be no difference in wind turbine noise annoyance between colder and warmer areas as well as no climatic difference in transportation noise annoyance indicated by Morihara et al. [8]. The difference in annoyance between colder and warmer areas shown in Figure 3 is not due to climate but probably wave sound.

Then dose-response curves were compared between sites with sea wave sound (n=121) and those without (n=530) in Figure 5. At sites with strong sea wave sound almost all people were not extremely annoyed probably because wave sound masked wind turbine noise. When the same analysis as in the former paragraph was applied, the coefficients of the dummy variable for % extremely, % extremely+very and % extremely+very+moderately annoyed were all very significant (Chi2=11.39, 14.54 and 23.73, and p=0.0007, 0.0001 and <0.0001, respectively). Appelqvist et al. [9] modeled sea wave sound, investigated its masking potential on wind turbine noise and showed the SN ratio at which wind turbine noise was audible by listening tests. It is of significance that annoyance caused by wind turbine noise might be reduced by masking of sea wave sound in the real life conditions. However, the sample size at sites with sea wave sound was only 121 and hence more data should be accumulated.

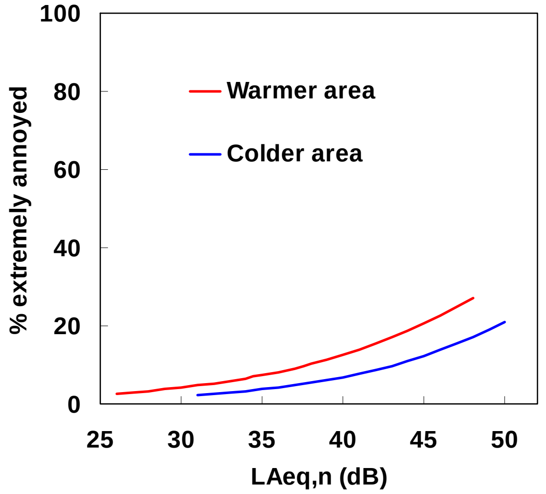

Figure 3 Comparison of dose-response relationships between colder and warmer areas

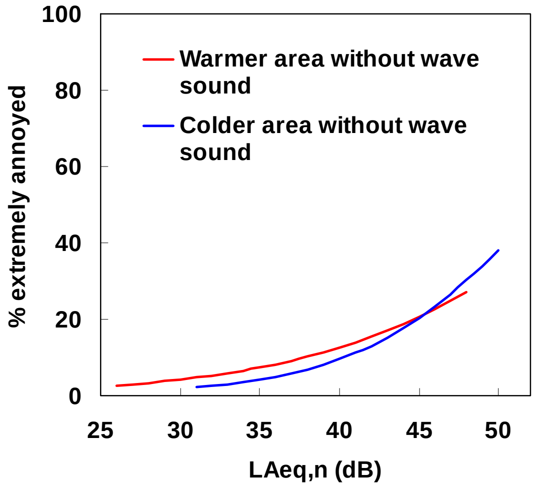

Figure 4 Comparison of dose-response relationships between colder and warmer areas without wave sound

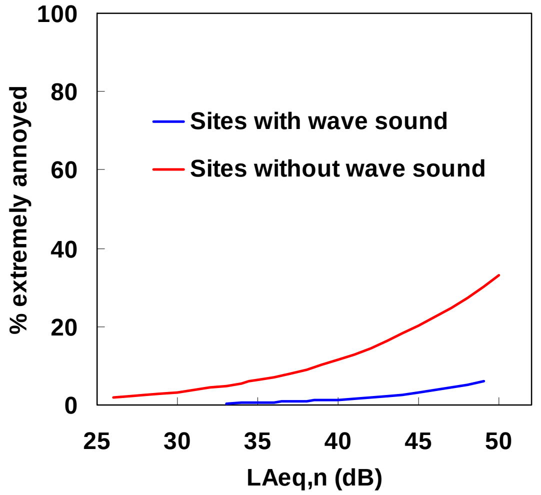

Figure 5 Effects of sea wave sound on dose-response relationships for wind turbine noise annoyance

4. EFFECTS OF MODERATING FACTORS

Since the % extremely annoyed in the range of 31-35 dB was the minimum in Table 1, this was taken as the reference category. For % extremely+very annoyed the rates in the ranges of -30 and 31-35 dB were almost the same and thus the range of -30 was set as the reference as well as % extremely+very+moderately annoyed. First the crude odds ratios for sex, age and categorized $L_{Aeq,n}$ were calculated. They were not significant for sex and age (the lower limit of 95% confidence interval was less than 1). On the other hand those for $L_{Aeq,n}$ were not significant when $L_{Aeq,n}$ was less than 40 dB or equal to 40 dB but significant when it was more than 40 dB.

Multiple logistic regression analysis was applied by designating extremely annoyed or not as a dependent variable and $L_{Aeq,n}$, sex and age as independent variables. The same procedure was applied to % extremely+very annoyed and % extremely+very+moderately annoyed. The sex/age-adjusted odds ratios for % extremely annoyed, % extremely+very annoyed and % extremely+very+moderately annoyed were calculated as shown in Figure 1. When $L_{Aeq,n}$ was more than 40 dB, the adjusted odds ratio for % extremely annoyed was significantly higher in Figure 6(a) (the lower limit of 95% confidence interval was more than 1). Though the adjusted odds ratios increased as $L_{Aeq,n}$ increased in Figures 6(b) and (c), they were not significant because the lower limit of 95% confidence interval was less than 1.

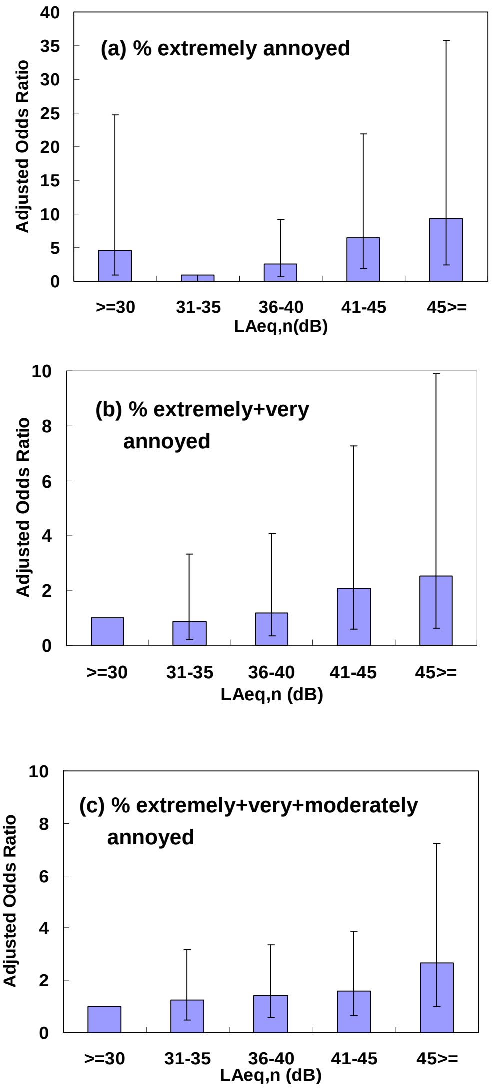

Figure 6 Sex/age-adjusted odds ratio
(I: 95% confidence interval)

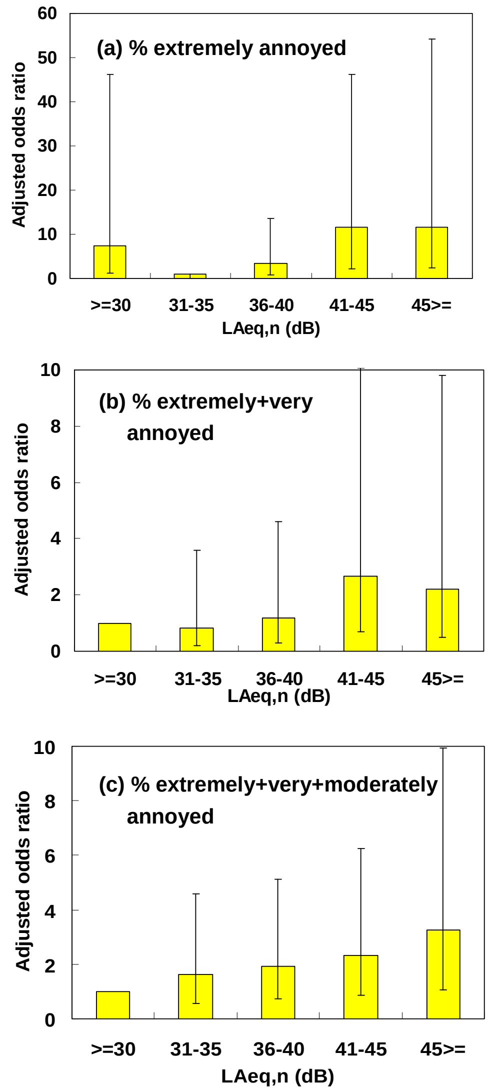

Figure 7 Adjusted odds ratio for moderating factors
(I: 95% confidence interval)

It was investigated whether interest in environmental problems, attitude to wind turbines, benefit from wind turbines and self-reported sensitivity to noise are associated with annoyance caused by wind turbines or not. The relations between the above mentioned five factors and % extremely annoyed were tested by Fisher's exact method and the relations between $L_{Aeq,n}$ and % extremely annoyed were tested by Mantel-Haenszel's Ch^2 (Chi$^2_{MH}$) when they are stratified by the factors.

As shown in Table 2, respondents who were interested in environmental problems, thought that wind turbine generator was not a good method, felt that landscapes were disturbed by wind turbines and were sensitive to noise, were more extremely annoyed than the others. When the relations were stratified by the moderating factors, the relation between $L_{Aeq,n}$ and % extremely annoyed was not significant for people who were less interested in environmental problems, did not think that wind turbine generator was a good method, obtained any benefit from wind turbines and felt that landscapes were disturbed by wind turbines. However, since the relations between $L_{Aeq,n}$ and % extremely annoyed were consistent in any subgroups, it is considered that $L_{Aeq,n}$ and the moderating factors were independently associated with % extremely annoyed.

By applying multiple logistic regression analysis with above four moderating factors which were significantly related to % extremely annoyed as independent variables, the adjusted odds ratios were calculated (Figure 7(a)). In the results of these analyses attitude to wind turbines was not significantly related to %extremely annoyed. As a result, $L_{Aeq,n}$, interest in environmental problems, landscape disturbance and sensitivity to noise were independently associated with % extremely annoyed. As well as Figure 6(a) the adjusted odds ratio was significantly high when $L_{Aeq,n}$ was more than 40 dB.

The same analysis as % extremely annoyed was applied to % extremely+very annoyed and % extremely+very+moderately annoyed (Figures 7(b) and (c)). By applying multiple logistic regression analysis with five moderating factors which were significantly associated with % extremely+very and % extremely+very+moderately annoyed as independent variables, the adjusted odds ratios were calculated. As well as the case of % extremely annoyed $L_{Aeq,n}$, interest in environmental problems, landscape disturbance and sensitivity to noise were independently associated with % extremely+very and % extremely+very+moderately annoyed. It is seen that the severe annoyance was more strongly associated with $L_{Aeq,n}$ than mild annoyance.

Table 2 Relation between $L_{Aeq,n}$ and % extremely annoyed per subgroup

Factors	Category	% extremely annoyed	Relation between $L_{Aeq,n}$ and % extremely annoyed (Chi$^2_{MH}$)
Are you interested in environmental problems?	No/neither "no" nor "yes"	2.5	2.53 (ns)
	Yes	18.4	9.67 ***
	Fisher's exact test	***	
Is wind turbine generator a good method?	Yes	5.9	9.23 **
	No	14.6	3.61 (ns)
	Fisher's exact test	*	
Do you receive any benefit from wind turbine?	Yes	4.9	0.36 (ns)
	No/do not know	10.0	12.15 ***
	Fisher's exact test	ns	
Does wind turbine disturb the landscape?	No	5.1	13.60 ***
	Yes	37.2	2.21 (ns)
	Fisher's exact test	***	
Are you sensitive to noise?	No/neither "no" nor "yes"	2.5	5.41 *
	Yes	15.9	26.04 ***
	Fisher's exact test	***	

5. RESPONDENTS' COMMENTS

Respondents commented various things as for what concrete effects those who selected wind turbine noise as the most annoying sound in Q4 were subjected to, what they concerned about the environment in Q10.16, opinions on their residential environment in Q12 and what concrete benefits they received in Q10.15. Of 121 respondents who selected wind turbine noise as the most annoying sound, 31 commented the concrete effects. The majority was sleep disturbances such as "difficult to fall asleep," "can not sleep" and "awaken." The others were "concerned," "fear of infrasound," "headache" and so on. More annoyed respondents were, more comments on the environments. They were attitude to wind turbines such as complaints against site selections, insufficient explanations of the constructions, complaints against wind turbine electricity generation itself and antipathy against wind turbines, visual effects such as visual disturbance, shadow flicker, blinking during night time, effects of landscape and shadow, and meteorological and ecological effects. As the opinions on their residential environments, the majority was attitude to wind turbine followed by audible effects, infrasound effects, radio wave disturbance and return of interests to individuals and communities.

Besides the complaints to wind turbines, they pointed out the benefits of wind turbines. For example, the majority was recognizing wind direction, followed by land marking, wind turbine's environmentally friendliness, good landscape, the fact that wind turbine areas were playgrounds for children and routes to take a walk, return to communities, land rental fee and so on.

6. SUMMARY

The first systematic social survey on community response to wind turbine noise was carried out throughout Japan from 2010 to 2012. The findings are summarized as follows:

1) The dose-response relationships for wind turbine noise annoyance are obtained, which are consistent to the trend in Swedish and Dutch surveys.
2) There was no significant difference in exposure-annoyance relationships between colder and warmer areas.
3) The annoyance at sites with sea wave sound was significantly lower than that at sites without probably because of masking by sea wave sound.
4) Of the five moderating factors, three factors, self-reported sensitivity to noise, interest in environmental problems and landscape disturbance by wind turbine significantly associated with annoyance.

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