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Exposure-response relationships for annoyance by wind turbine noise: a comparison with other stationary sources

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ABSTRACT

There are indications that, given a certain level of noise exposure, the expected annoyance by wind turbine noise is higher than that by noise from other sources such as industrial noise or transportation noise. The aim of the present study was to establish the exposure-response relationship between wind turbine noise exposure and the expected percentage annoyed residents on the basis of available data. Data from two surveys in Sweden (N=341, N=754) and one survey in the Netherlands (N=725) were combined to achieve relationships between Lden and annoyance indoors as well as annoyance outdoors at the dwelling. In addition, the influence of several individual and situational factors was assessed. In particular, annoyance was lower in residents who received economical benefit from wind turbines, and higher in residents for whom the wind turbine was visible from the dwelling. Age and noise sensitivity had similar effects on annoyance to those found in research on annoyance by other sources. The exposure-response relationship for wind turbine noise is compared to previously established relationships for industrial noise.

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1. INTRODUCTION

Recent studies investigating the community response to wind turbine noise have shown that a proportion of the residents living in the vicinity of wind turbines perceive the noise generated by them as being annoying[1,2]. Findings suggest that, at equal noise exposure levels, the expected annoyance due to wind turbine noise might be higher than annoyance due to other environmental noise sources[2,3]. However, there are several reasons why the observed relationships between wind turbine noise and annoyance cannot be compared directly to the earlier established exposure-response relationships for transportation noise[4,5], or for industrial noise from stationary sources[6]. First, exposure-response relationships for wind turbine noise were derived using noise exposure measures that do not correspond to international standards (L_{den} or L_{dn}). Second, exposure-response relationships for wind turbine noise were derived for annoyance perceived outdoors, while established exposure-response relationships for other noise sources typically do not distinguish between annoyance indoors or outdoors. Third, different methods have been used to quantify the exposure-response relationships.

In the present study, exposure-response relationships between the exposure measure L_{den} and self-reported annoyance indoors due to wind turbines were derived using the method previously used to derive the exposure-response relationships for transportation and industrial noise. In addition, the influence of several individual and situational factors was assessed, such as age, noise sensitivity, economical benefit and visibility of the wind turbine. Data used here were collected during previous studies in Sweden and the Netherlands. A comparison was made of the newly derived relationship to earlier established exposure-response relationships for industrial noise from stationary sources.

2. METHODS

A. Study design and sample

Data from two studies conducted in Sweden[1] (2000 and 2005) and one study in the Netherlands[2] (2007) were used. Both Swedish studies were conducted during the summer and had cross-sectional designs with a sample of respondents who were exposed to varying levels of wind turbine noise. The 2000 study was conducted in the south of Sweden in an area characterised primarily by agriculture in an overall flat, even landscape. The 2005 Swedish study was conducted in areas characterised by different types of terrain (i.e. even/flat vs. complex) and varying degrees of urbanisation (i.e. rural vs. built-up). In both studies questionnaires were used. Of the 513 questionnaires sent to residents in the 2000 study, 351 (68%) usable questionnaires were returned. In the 2005 study 1309 questionnaires were sent to residents, of which 754 (58%) usable questionnaires were returned.

The Dutch study included a sample of the population living within a 2.5 km radius of a wind turbine, stratified according to: 1) wind turbine immission levels (25-30, 30-35, 35-40, 40-45 dB(A)), 2) environment type (A. Rural, quiet, B. Rural with main roads, C. Built-up). At a response rate of at least 30%, a minimum of 50 respondents per stratum (4 x 3 = 12 strata) was envisaged. A postal questionnaire, based on the Swedish questionnaire, was sent during April 2007. Of the 1948 questionnaire posted, 725 (37%) usable questionnaires were returned. All respondents received a gift voucher. A non-response analysis found no significant difference in the reported annoyance due to wind turbines between respondents and non-respondents.

B. Noise exposure

Annual day-evening-night A-weighted equivalent noise level (L_{den}) was defined in accordance with EU environmental noise guidelines. L_{den} was calculated from the immission levels determined in the original studies[1,2]. For each respondent, outdoor A-weighted sound power levels from the nearest wind turbine(s) were determined for a neutral atmosphere at a constant wind velocity of 8 m/s at a height of 10 meters in the direction towards the respondent, which is the reference wind velocity by convention (e.g. Swedish Environmental Protection Agency, 2001). To these data, a correction of +4.7 dB(A) was applied, calculated by van den Berg[7] as the mean difference between L_{den} and the immission level at a wind velocity of 8 m/s. While in principle the correction depends on the wind velocity distribution at a specific location, the type of wind turbine and the hub height, statistical wind velocity data was not available for all study locations. Furthermore, using a variable correction factor for the situation in the Netherlands did not provide a better prediction of annoyance in comparison to L_{den} calculated with the fixed correction factor.

C. Questionnaire

In all three studies, annoyance due to wind turbines and other environmental stressors were assessed with the following question: “The list below summarises a number of aspects that you may be aware of and/or be annoyed by when inside your home. Please indicate for each aspect whether you are aware of it and whether it annoys you?” The response to each aspect was registered on a 5-point scale: 1 = “Do not notice”, 2 = “Notice, but not annoyed”, 3 = “Slightly annoyed”, 4 = “Rather annoyed” and 5 = “Very annoyed”. The same question was repeated for annoyance outside the home. Visibility of the wind turbine from within the home was assessed by the question: “Is a wind turbine visible from within your home/garden/balcony?”, to which the response “Yes” or “No” was possible. To assess whether respondents benefitted economically from wind turbines, the question “Do you (partly) own one or more wind turbines?” was present in the questionnaire, to which the answers “Yes” or “No” could be given. Noise sensitivity was assessed along a 4-point scale, from 1 “Not sensitive” to 4 “Very sensitive”, except for the Dutch study, in which noise sensitivity was assessed along a 5-point scale, ranging from 1 = “Not sensitive” to 5 = “Extremely sensitive”. Furthermore, the questionnaire contained questions concerning demographic characteristics, health and the attitude regarding wind turbines.

In the present study, Swedish and Dutch data of the 5-point annoyance scale were recoded and assessed as an index of self-reported annoyance indoors. The 5-point scale was recoded to a 4-point scale: categories 1 and 2 were combined to obtain a new category 1 = “Not annoyed”. Subsequently, the annoyance and noise sensitivity response categories were converted into scales ranging from 0 to 100. This conversion is based on the assumption that a set of categories divides the range of 0 to 100 in equally spaced intervals. The general rule that gives the position of an inner category boundary on the scale of 0 to 100 is: $\text{score}_{\text{boundary } i} = 100 \cdot i/m$, where i is the rank number of the category boundary, starting from 1 for the upper boundary of the lowest category, and m is the number of categories. The percentage of responses exceeding a certain cut-off point on the scale may be reported. Following convention, if the cut-off is 72 on a 0-100 scale, the result is called the percentage of “highly annoyed” persons (%*HA*). Likewise, a cut-off of 50 indicates the percentage of “annoyed” persons (%*A*).

D. Statistical model

An earlier developed statistical model[5,8] was employed here. By applying this statistical model, a basic model of self-reported annoyance was derived for the combined Swedish and Dutch data. Data from the Swedish studies were distinguished from the Dutch data (i.e. the reference) by separate dummy variables. The gradient of the effect of L_{den} on annoyance was assumed to be constant between studies. Next, the following extra variables were added to the basic model: *Age* and Age^2 (age squared added since annoyance and age have previously been found to show an inverse U-shaped relationship), *Gender*, *Noise sensitivity*, *Economic benefit*, *Visibility*, *Degree of urbanisation* (i.e. rural vs. built-up: 1) in the Dutch situation defined on the basis of the environmental address density; 2) in the Swedish situation as defined during the original studies), and *Terrain* (i.e. even/flat vs. complex). Using a stepwise backward elimination procedure, at each step the variable with the least significant contribution (i.e. highest *p*-value) was removed, until all variables contributed with $p \leq .05$. Lastly, a new model without any extra variables or dummy variables was set up, resulting in a single exposure-response relationship for annoyance and L_{den} for the three studies combined.

3. RESULTS

A. General

Categories 1 and 2 of the 5-point annoyance scale were combined (i.e. “Not annoyed”) to give a converted 4-point annoyance scale. The mid-points of this converted scale along a 100-point scale are 12.5, 37.5, 62.5 and 87.5. Table 1 provides an overview of the individual and situational characteristics, plus the annoyance indoors scores along the 100-point scale, for each of the three studies and in total.

Table 1*: Individual and situational characteristics, plus annoyance indoors and outdoors, per study and in total.*

	Sweden 2000		**Sweden 2005**		**Netherlands 2007**		**Total**	
	n = 341		*n* = 754		*n* = 754		*N* = 1820	
	Mean or %	SD	Mean or %	SD	Mean or %	SD	Mean or %	SD
Lden	39.3	3.2	38.1	3.1	39.8	6.4	39.0	4.8
Lnight	33.0	3.2	31.8	3.1	33.5	6.4	32.7	4.8
Age	47.2	14.0	50.9	15.0	54.3	15.0	51.5	15.0
Noise sensitivity	51.0	20.9	50.7	22.3	46.1	23.8	48.9	22.7
Female (%)	58.5		55.6		49.2		53.6	
Economic benefit (%)	3.0		2.7		14.3		7.6	
Visible (%)	94.4		70.6		67.8		74.0	
Rural (%)	40.2		24.5		70.5		45.8	
Flat terrain (%)	100.0		50.3		100.0		79.4	
Annoyance	indoors	outdoors	indoors	outdoors	indoors	outdoors	indoors	outdoors
12.5 (%)	88.5	66.9	96.4	88.6	86.4	76.7	91.0	79.8
37.5 (%)	4.1	17.6	2.4	7.3	7.7	13.0	4.8	11.5
62.5 (%)	4.1	6.5	1.1	2.3	3.0	6.2	2.4	4.6
87.5 (%)	3.2	9.1	0.1	1.9	2.9	4.1	1.8	4.1

The highest wind turbine noise exposure levels (L_{den}) were encountered in the Dutch study; see Figure 1 (below). The majority of Swedish respondents were exposed to levels between

35 – 40 dB(A), while a relatively large proportion of Dutch respondents were exposed to levels below 35 dB(A).This may partly be attributed to differences in study design: in the Dutch study stratification was based on noise exposure levels, whereas in the Swedish studies locations were selected mainly on the basis of geographical areas.

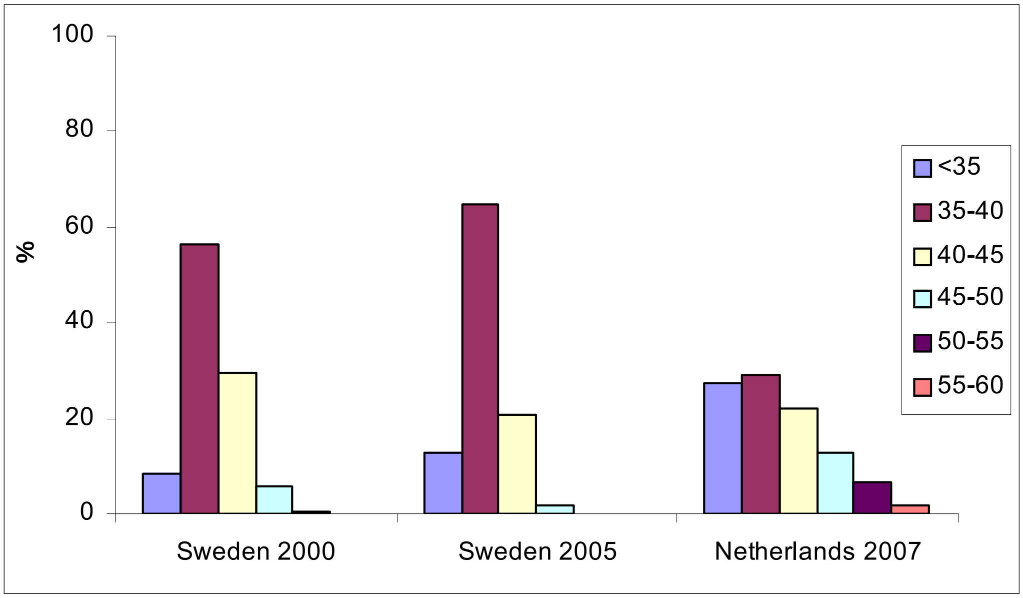

Figure 1: Distribution of the wind turbine noise exposure levels (L_{den}) within each of the three studies.

B. Study differences and the role of individual and situational characteristics

Annoyance indoors was found to be lower in the 2005 Swedish study (and slightly in the 2000 study) than in the Dutch study, even more so when adjusted for several individual and situational variables. Annoyance outdoors was found to be lower in the 2005 Swedish study than in the Dutch study, while there was no significant difference between the 2000 Swedish study and the Dutch study when adjusted for individual and situational variables. Of these, particularly *Age*, *Noise sensitivity*, *Economical benefit* and *Visibility* were found to influence annoyance. In all models, L_{den} was positively related to annoyance.

C. Exposure-response relationship: comparison to industrial noise

In line with van den Berg et al.[2], exposure-response relationships were derived only for respondents who did not benefit economically from wind turbines, because of the large attenuating effect of *Economic benefit* and the relatively small number of individuals in the present sample who benefitted economically from the use of wind turbines. Figure 2 provides a comparison of the exposure-response relationships for the percentage annoyed (*%A*) and highly annoyed (*%HA*) persons indoors derived in the present study to the exposure-response relationships for industrial noise[6].

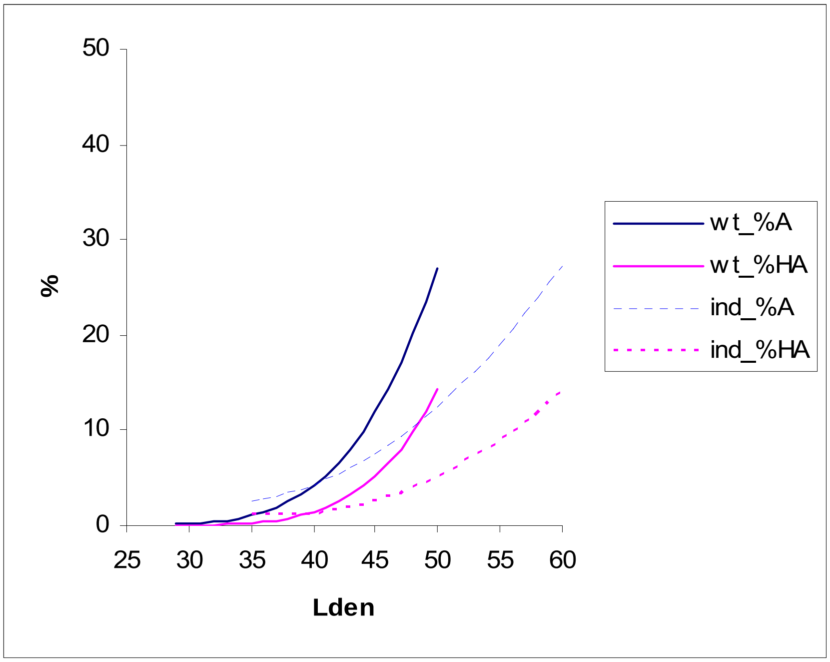

Figure 2: Comparison of the percentage (highly) annoyed persons indoors ($\%A_{indoors}$ and $\%HA_{indoors}$) due to wind turbine noise (wt) and industrial noise (ind).

4. CONCLUSIONS

Noise emitted by wind turbines is perceived as annoying by a proportion of the residents living in the vicinity of wind turbines. At exposure levels higher than 40 dB(A), the expected percentage of annoyed persons indoors due to wind turbine noise is higher than due to industrial noise from stationary sources at the same exposure level. Besides noise exposure, various individual and situational characteristics were found to influence the level of annoyance. Having economic benefit from the use of wind turbines, or being able to see one or more wind turbines from within the home are two particularly influential situational factors; both of which have been reported to affect annoyance due to wind turbine noise before[1,2,9]. The economic benefit factor is reminiscent of earlier findings that being employed at the noise source (e.g. airport or industry) attenuates the annoyance reported[6,10]. Also, visibility from the home (e.g. living room, bedroom) has been reported earlier to affect annoyance from stationary sources[6]. In addition, noise sensitivity and age had similar effects on annoyance to those found in research on annoyance by other sources.

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