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# PREDICTING ANNOYANCE BY WIND TURBINE NOISE

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**Abstract**
While wind turbines have beneficial effects for the environment, they inevitably generate environmental noise. In order to protect residents against unacceptable levels of noise, exposure-response relationships are needed to predict the expected percentage of people annoyed or highly annoyed at a given level of wind turbine noise. Exposure-response relationships for wind turbine noise were derived on the basis of available data, using the same method that was previously used to derive relationships for transportation noise and industrial noise. Data from surveys in Sweden and the Netherlands were used to achieve relationships between $L_{den}$ and annoyance, both indoors and outdoors at the dwelling. It is shown that a given percentage of annoyance by wind turbine noise is expected at much lower levels of $L_{den}$ than the same percentage of annoyance by for instance road traffic noise. Results were used to guide new noise regulation for wind turbines in the Netherlands.

**Keywords:** Wind turbine noise, Annoyance, Exposure-response, Noise regulation

## 1 Introduction

Wind turbines have beneficial effects for the environment since they offer a clean substitute for fossil fuels. However, an inevitable side-effect is that they generate environmental noise. In order to protect residents against unacceptable levels of noise and guide noise regulation, it is important to be able to predict the expected percentage of people annoyed or highly annoyed at a given level of wind turbine noise. 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 [1-3]. 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 [2,4]. The annoyance also appears to be high in comparison to exposure-response relationships for stationary sources, suggesting that wind turbines should be treated as a new type of source in noise regulation. However, the relationship between exposure and annoyance was previously not investigated using noise exposure measures that correspond to international standards for assessing the impact of community noise ($L_{den}$ or $L_{dn}$). Furthermore, relationships were based on annoyance perceived outdoors at the dwelling, while established exposure-response relationships for other noise sources typically do not distinguish between annoyance indoors or outdoors. In the present study, exposure-response relationships between the exposure metric $L_{den}$ and self-reported annoyance indoors as well as outdoors due to wind turbines were derived using the method previously used to derive the exposure-response relationships for transportation and industrial noise. The analysis was done on available data that were collected during previous studies in Sweden and the Netherlands.

# 2 Methods

## 2.1 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 characterized primarily by agriculture in an overall flat, even landscape. The 2005 Swedish study was conducted in areas characterized by different types of terrain (i.e. even/flat vs. complex) and varying degrees of urbanization (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 study in the Netherlands 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.

## 2.2 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 [5] 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. Figure 1 shows the distribution of the noise exposure levels in $L_{den}$ within each of the three studies. The highest wind turbine noise exposure levels ($L_{den}$) were encountered in the study in the Netherlands. The majority of Swedish respondents were exposed to levels between $L_{den}$ 35 – 40 dB(A), while a relatively large proportion of respondents in the Netherlands were exposed to levels below $L_{den}$ 35 dB(A) and levels over 45 dB(A). This may partly be attributed to differences in study design: in the Netherlands the stratification was based on noise exposure levels, whereas in Sweden locations were selected mainly on the basis of geographical areas.

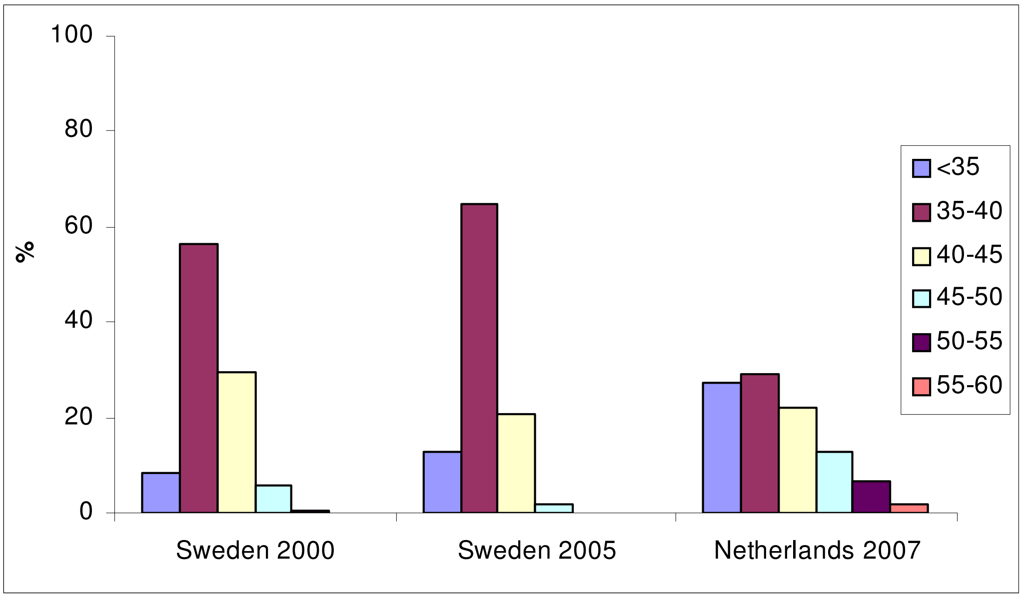


Figure 1 - Distribution of wind turbine noise exposure levels ($L_{den}$) within the three studies.

## 2.3 Questionnaire

In all three studies, annoyance due to wind turbines and other environmental stressors were assessed with the following question: “The list below summarizes 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. 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. In the present study, data of the 5-point annoyance scale were recoded and assessed as an index of self-reported annoyance indoors and outdoors. 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 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*).

### 2.4 Statistical model

The statistical model applied previously for predicting community annoyance response to other sources [6,7] was employed here to derive a model for both indoor and outdoor annoyance due to wind turbine noise. An exposure-response relationship between annoyance and $L_{den}$ was derived based on the combined data from Sweden and the Netherlands. 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. Since respondents with economical benefit hardly reported any annoyance despite living primarily in the highest exposure categories, including this relatively small number of residents was expected to contaminate the relationship over the total range of exposure.

## 3 Results

At a given exposure level, the expected percentage of annoyed persons indoors by wind turbine noise is higher than that due to other stationary sources of industrial noise, and also increases faster with increasing noise levels. Furthermore, the expected percentage of annoyed or highly annoyed persons due to wind turbine noise across the exposure range is higher than the expected percentages due to each of the three modes of transportation noise at the same exposure levels. Although the comparison may be hampered by differences between sources in exposure range, and the confidence intervals at the high end of the wind turbine noise range are large, the results indicate that a given percentage of annoyance by wind turbine noise is expected at much lower levels of $L_{den}$ than the same percentage of annoyance by for instance road traffic noise (see Figure 2).

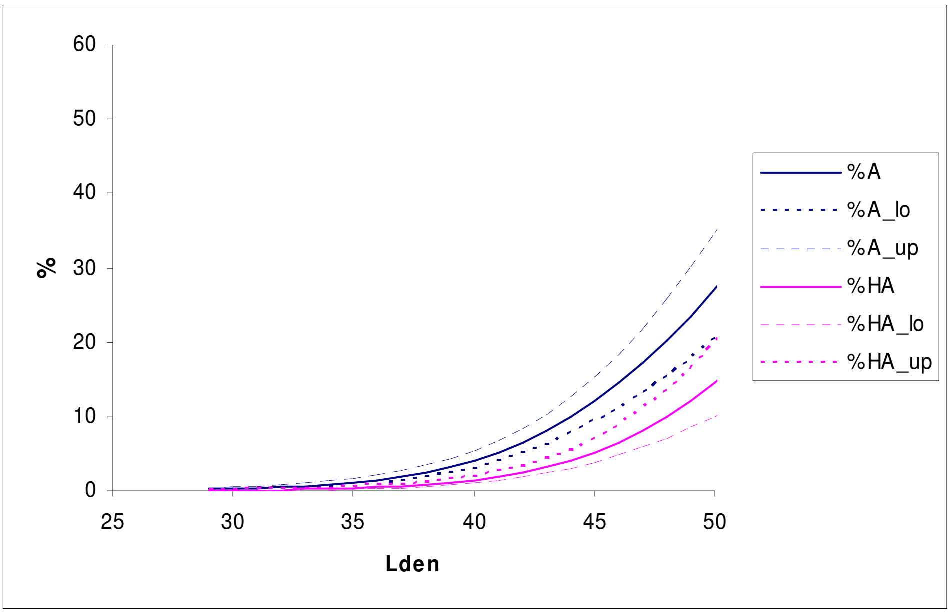


Figure 2 – Expected percentages annoyed (*%A*) and highly annoyed (*%HA*) indoors by wind turbine noise, with 95% confidence intervals.

# 4 Conclusions

In comparison to other sources of noise, annoyance due to wind turbine noise is found at relatively low noise exposure levels. The proposed exposure-response relationships for annoyance by wind turbine noise are only based on three studies and more studies are undeniably needed. Still, they may already serve as indicative for suitable regulations, or for the evaluation of existing legislation. However, it should be noted that situational factors, as well as possible cultural differences, may lead to considerable deviation from the curve in specific cases.

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