Invited Paper

inter.noise 2010
noise and sustainability
13-16 June 2010 . Lisbon . Portugal
www.internoise2010.org

# WHY IS WIND TURBINE NOISE POORLY MASKED BY ROAD TRAFFIC NOISE?

**Eja Pedersen[1], Frits van den Berg[2]**

[1]Halmstad University and University of Gothenburg
{eja.pedersen@hh.se}
[2]GGD Amsterdam
{fvdberg@ggd.amsterdam.nl}

**Abstract**
The possibility of road traffic noise masking noise from wind turbines was explored among residents living close to wind turbines in the Netherlands (n = 725) with different levels of road traffic noise present. No general masking effect was found, except when levels of wind turbine sound were moderate (35 – 40 dB(A) Lden) and road traffic sound level exceeded that level with at least 20 dB(A). This low masking capacity may be due to the different time patterns of these noise sources, both on a small time scale (car passages/regular blade passing) and a larger time scale (diurnal and weekly patterns). Also, wind turbine sound is relatively easy audible and may be heard upwind more often than road traffic.

**Keywords:** Wind turbine noise, road traffic noise, masking, audibility, time patterns.

# 1 Introduction

Suitable sites for wind turbines can be difficult to find due to conflicting requirements. Placing wind farms close to the electric grid and existing roads (both are usually better available in populated areas) is favourable for investment costs, but it may increase the possibility that neighbours may be visually and aurally disturbed. It is therefore not uncommon that wind turbines are planned to be erected at distances from dwellings that are unacceptable by the local residents.

The individual appraisal of wind turbines planned close to one's home is not irrational but based on considerations such as the evaluation of the wind turbines' impact (scenic and otherwise) and feelings of equity and fairness [1]. The apprehension that for example the noise will be disturbing in an otherwise comparable quiet area has been confirmed by research: wind turbine noise may be louder and is apparently more annoying than was assumed before the growth in wind turbine numbers and power in the '90s [2, 3]. The recommended noise limits (different in different countries), and consequently a minimum distance depending on the number of wind turbines and their sound power levels, should therefore be kept or should even be more rigorous if the original level of noise protection is to be maintained.

To decrease the adverse impact it has been suggested that masking sounds could create a situation where the wind turbines could not be heard and therefore not annoying. Outdoor sounds that are potential maskers are natural sounds like wind induced sounds from trees or sound from sea waves, or manmade noise, of which road traffic appears to be the most common. Models have previously suggested that natural sounds are fairly good potential maskers for wind turbine noise due to, for example, similarities between the broadband noise of vegetation and wind turbine sound [4]. Experimental listening tests have however shown that the detection thresholds for wind turbine noise in the presence of natural sounds from trees or sea waves are in the range -8 to -12 dB S/N-ratio, implying that the ambient sound must have a considerably higher level in order to completely mask the wind turbine noise [5]. Loudness tests, in the same series of experiments, indicated on the other hand that introducing natural sounds, for example the rustling of trees, of the same level as the wind turbine sound, could reduce the perceived sound level of the wind turbine sound with up to 5 dB. This hypothesis is yet to be experienced in the field; it is not obvious that this would lead to decreased risk for noise annoyance.

The masking effect of road traffic on wind turbine noise has to our knowledge not been studied in listening tests. An epidemiological study carried out in the Netherlands 2007 [3] provided an opportunity to compare the perception of wind turbine noise at different levels of ambient noise, in this study mainly from road traffic. The results indicate that also for traffic noise the masking effect is low [6]. The objective of this paper is to discuss why road traffic does not decrease the risk for being annoyed by wind turbine sound.

# 2 Method

A field study was carried out in the Netherlands among residents in wind farm areas. A stratified sample of 1948 people living within different levels of wind turbine noise were approached with a questionnaire about environmental issues in their residential area; 725 responded satisfactory (37%; a non-response analysis showed no statistically significant differences between responders and non-responders). The questionnaire comprised two parallel parts measuring perception of sound and attitude towards the sound source; one part concerning road traffic sound and the other concerning wind turbine sound. The possibility to hear the sounds from the dwelling or the garden/balcony was measured binary with no/yes. Noise annoyance was measured with several items, referring both to outdoor and indoor situations. Two factor scores derived from five items (WT annoyance, Cronbach's alpha 0.89) and six items (RT annoyance; Cronbach's alpha 0.86), respectively, were used as dependent variables with mean = 0 and standard deviation = 1. Attitude towards the noise source's impact on landscape scenery were measured with a 5-point scale from "very positive" to "very negative". Noise sensitivity was measured on a 5-point scale. Stress was measured with 6 items and factorized (Stress; Cronbach's alpha 0.84).

The immission levels in dB(A) of wind turbine sound outside the dwelling of each respondent were calculated as recommended by the international ISO standard [7]. The levels correspond to a situation with a neutral atmosphere and a wind speed of 8 m/s at 10 m height. The immission levels were transformed into levels of day-evening-night values (Lden) by adding 4.7 dB [8]. Levels of road traffic sound were obtained from the Dutch National Institute for Public Health (RIVM) who supplied calculated Lden immission levels due to traffic in 5 dB intervals for a 25 by 25 m grid over the entire country. The levels approximate road traffic exposure as there was no railroad or airport close to any of the respondents. The respondents were divided into sub-samples due to the levels of road traffic sound exceeding the levels of wind turbine sound. This paper explores to what extent wind turbines were heard or were annoying when the sound levels of road traffic exceeded that of wind turbines with 5-10 dB (n = 79), 10-15 dB (n = 138), 15-20 dB (n = 108) or 20-25 dB (n = 67). Noise annoyance due to wind turbines is influenced by having an economical benefit from the wind turbines or not [3]. Only respondents that did not benefit were included when the impact of road traffic noise on annoyance with wind turbine noise was explored and the sample sizes were therefore somewhat reduced in Figure 2 (below): 5-10 dB (n = 70), 10-15 dB (n = 119), 15-20 dB (n = 102) or 20-25 dB (n = 66). For more detailed description of the research methods see [3] and [6].

# 3 Perception of wind turbine sound in different levels of road traffic sound

## 3.1 Possibility to hear wind turbine sound

The proportions of respondents that reported hearing wind turbine sound outside their dwelling increased from 0-23% at the interval 30-35 Lden to 59-69% at 40-45 Lden (Figure 1). Though there are differences between the groups these are not statistically significant, *i.e.* no masking effect was detected.

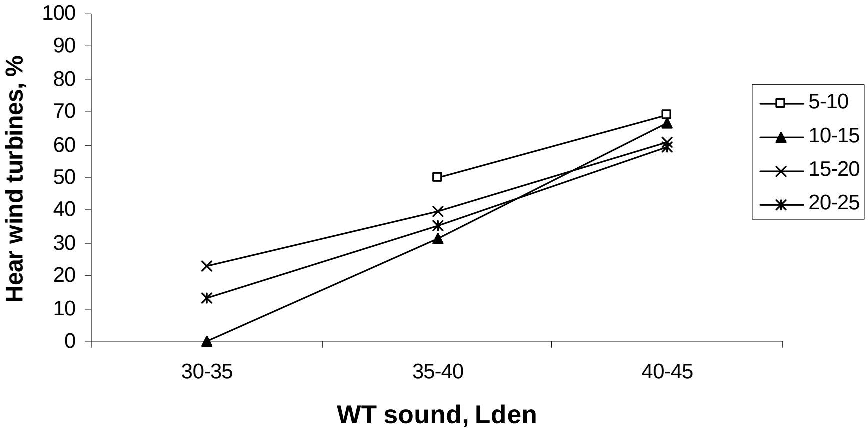


Figure 1. Proportion of respondents that could hear wind turbine sound outdoors at their dwelling or garden/balcony (%) related to levels of wind turbine sound (Lden) for four situations where road traffic sound levels exceeded wind turbine sound levels with 5-10, 10-15, 15-20 or 20-25 dB(A) Lden.

## 3.2 Annoyance due to wind turbine sound

The mean annoyance score increased from -0.6 - -0.5 at the interval 30-35 Lden to 0.1 – 0.8 at 40-45 Lden (Figure 2). When looking at the four RT-WT level difference groups, a reduction of annoyance was found, but only for respondents in the interval 35 – 40 Lden of wind turbine noise when the road traffic noise exceeded wind turbine noise with 20 – 25 dB. This difference was statistically significant (t = -0.69; p<0.05), other differences were not.

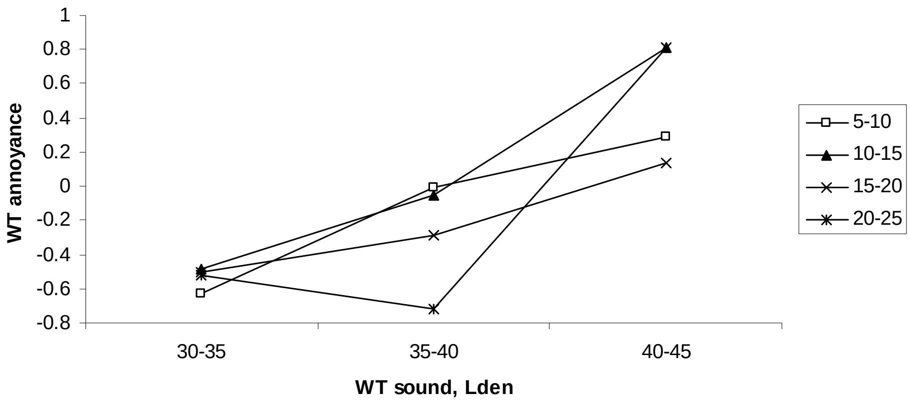


Figure 2. Mean annoyance score for wind turbine noise related to levels of wind turbine sound (Lden) for four situations where road traffic sound levels exceeded wind turbine sound levels with 5-10, 10-15, 15-20 or 20-25 dB(A) Lden.

Annoyance due to wind turbine noise was positively correlated to annoyance with road traffic noise (r = 0.26; p<0.001) suggesting that there was no masking effect but an increased risk for annoyance if both noises were present. This result was explored further in a multivariate general linear model with two dependent variables present simultaneous: annoyance with wind turbine noise and annoyance with road traffic noise (Figure 3).

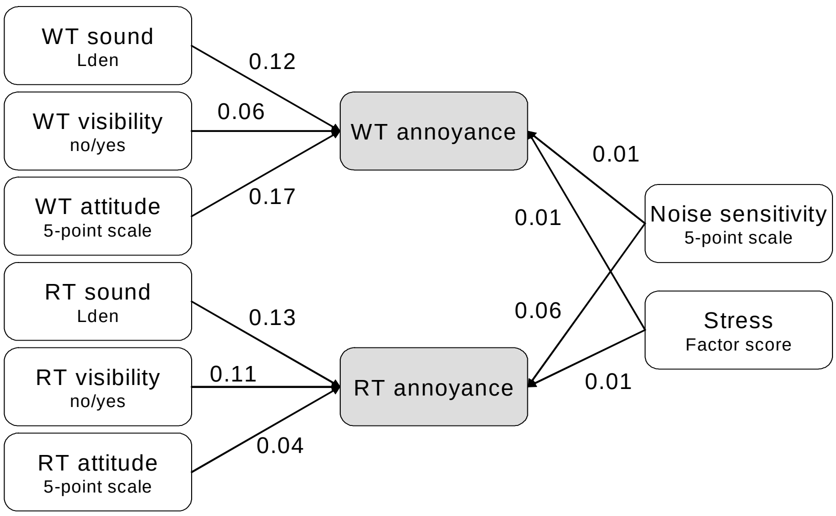


Figure 3. Conceptual figure of variables simultaneous explaining the variance of the two dependent variables annoyance with wind turbine noise (adj. R-square 0.43) and road traffic noise (adj. R-square 0.38), respectively. Result of multivariate general linear model. Adjusted for economical benefits from wind turbines. Partial eta-squared values; only statistically significant associations are shown.

Noise from wind turbines, together with visibility of wind turbines and attitude to their impact on the landscape, only explained the variance in annoyance due to wind turbines, but not the variance in annoyance due to road traffic. Similar, noise levels, visibility and attitude regarding road traffic were only associated to annoyance with road traffic noise. However, noise sensitivity and stress explained part of the variance of both annoyance score, which explains the correlation between them. The test indicates that there was no enhanced risk for annoyance due to double exposure: this risk is simply the sum of both separate risks.

### 3.3 Conditions influencing loudness of wind turbine sound

One of the questions in the WINDFARMperception study survey was about conditions when the wind farm sound was louder or less loud [10]. Figure 4 shows the results: more respondents thought the sound from the wind farm was louder when the wind blew from the wind farm towards the dwelling or when the wind was stronger. Unfortunately we do not know whether respondents were referring to the near-ground wind they were exposed to or the higher altitude wind that the blades were exposed to (which can be inferred from the rotational speed and the backwards bending of the blades). A minority of respondents (22%) thought the sound was less loud at night: 40% thought the sound was louder at night and another 38% saw no clear difference between night and day in this respect.

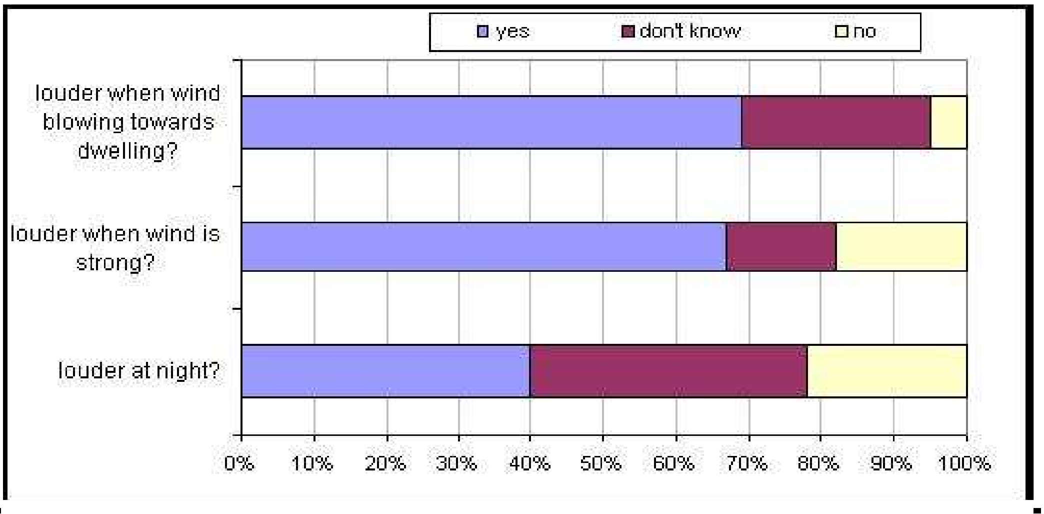


Figure 4. Opinions on conditions when wind farms are perceived as being louder or less loud (based on [10])

## 4 Possible acoustical explanations for the poor masking effect

In the text above WT and RT sound levels were compared based on their Lden at receiver locations. However, when the Lden values are equal this does not mean that both sounds are acoustically equal, nor that the levels are equal at all times or the sounds have the same perceptive quality–even when they are of the same level. The distributions over time and frequency, as well as the character of the sound and the altitude of the source, have an influence on their perception, and thus possibly on the annoyance they may cause. These influences will be discussed here.

### 4.1 Diurnal variations in level

Road traffic noise usually subsides at night and in early morning resumes to the morning rush hour level. Figure 5 shows the change in level for two situations: a busy motorway in the central part of the Netherlands and the city ring road of Amsterdam (figure taken from [9]). It also shows that the lowest night time levels Lmin are approximately 8 dB below the highest levels in day time for the motorway; for the ring road the difference is somewhat higher: 10 dB. When compared to Lden, the minimum levels are approximately 12 dB lower.

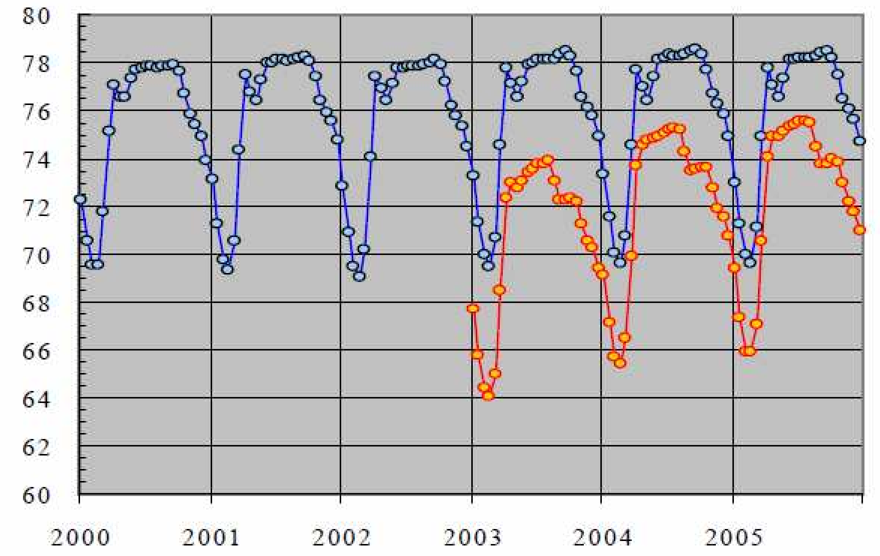


Figure 5. Hourly equivalent sound level (Leq) in dB(A) per average day in each of six years at a busy motorway (blue dots) and over three years at the Amsterdam ring road (orange dots).

The diurnal variation for an 80 m hub height wind turbine is rather different as figure 6 shows for an average day in one year, where wind speed data from 1987 have been used (figure taken from [10]).

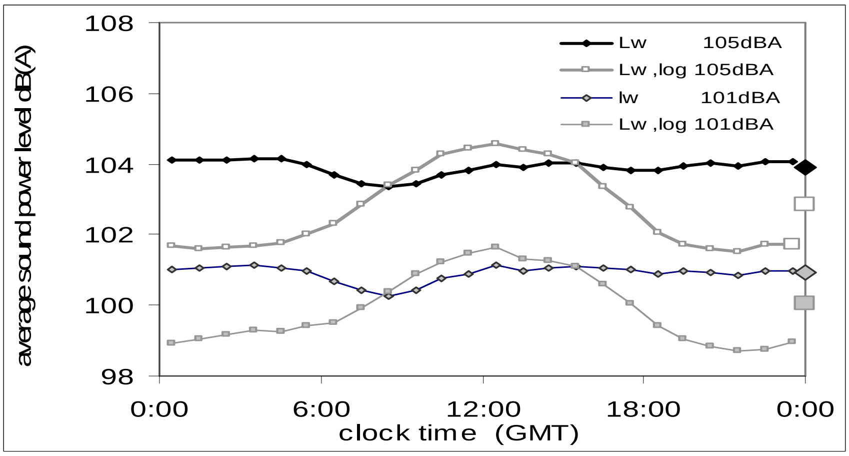


Figure 6. Hourly averaged real and estimated (log) sound power level of a Vestas V80-2MW at two power settings.

Here the night time level is on average higher than daytime levels, as in daytime the 80 m wind is slowed down by more intense coupling to lower altitude air due to vertical movements that are stronger when the sun is up. Here the night time level is approximately 6 dB lower than the Lden due to this wind turbine, the lowest (daytime) level is 7 dB lower than Lden. Hence, when road traffic and wind turbines produce the same Lden sound level, the RT level in the quietest hour of the night is 12 dB lower whereas the WT level at that time is 6 dB lower and thus, at that time, 6 dB higher than the RT sound level. In daytime this difference is smaller (3 dB).

## 4.2 Spectral differences

Road traffic sound as well as wind turbine sound is relatively broad band. In figure 7 the spectral distributions of the sounds are plotted as A-weighted octave band levels where each level is given relative to the total sound power. Expressed this way, the reference total sound power is equal (*viz.* 0 dB) for each source. The WT spectrum is the sound power spectrum of a Vestas V80-2MW, the RT spectra are those used for light, medium and heavy vehicles in the Dutch calculation model for road traffic noise, and the average spectrum for all traffic as measured at the city ring road (taken from [9]). The figure shows that wind turbine sound, when compared to road traffic sound, is relatively loud at low frequencies up to 500 Hz and then less loud (at higher levels the wind turbine is again louder, but such high frequencies are irrelevant at distances over several hundreds of meters, and even more so when indoors). Of course at some distance from the sources the spectrum will change due to frequency dependent attenuation, but that will affect the spectra in the same way and thus not change the relative contributions. If the WT and RT sound levels are equal at the receiver, the WT will be louder at frequencies below 500 Hz, and less loud above that frequency. All spectral levels of the wind turbine will be lower then the RT spectral levels (averaged over traffic types) when the wind turbine level is reduced by at least 8 dB. The other way around, all RT spectral levels will be lower than the (average) WT levels if the wind turbine is at least 4 dB louder.

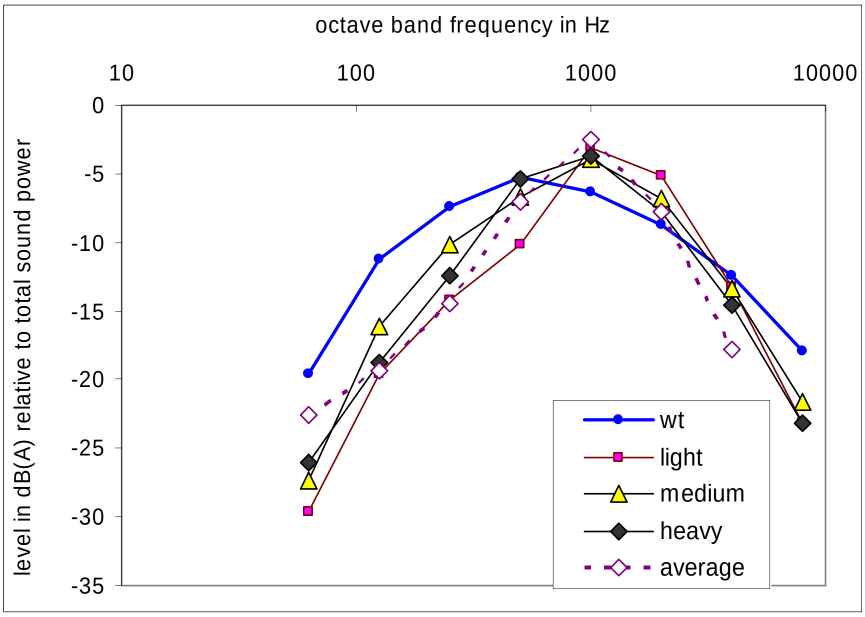


Figure 7. Octave band spectra (each level relative to total sound power level) of a wind turbine (wt) and of light, medium and heavy vehicles and the average as determined on the city ring road.

### 4.3 Sound character: swishing

Swishing is an important characteristic of wind turbine sound: 75% of the respondents of the WINDFARMperception study thought that swishing or lashing was the best description of the sound [10]. Reported swish levels (the level of the peaks occurring at blade passing frequency relative to the base level in between peaks) are up to approximately 5 dB, highest reported values are 9 dB [11]. Obviously the audible modulation attracts attention, just as the reverse gear beep on trucks or the signal of an alarm clock do. From various studies it follows that this modulation is equivalent in annoyance to the un-modulated sound at an approximately 5 dB higher level.

### 4.4 Sound shadow

Usually a sound source is louder downwind of the source than upwind in the sound shadow, where only reflected and turbulence scattered, but no direct sound rays can reach an observer. The distance between the sound source and its sound shadow depend on atmospheric conditions and on the height of the source. With a normal temperature profile (temperature decreasing with height) in a still atmosphere sound rays refract upward and the sound shadow is along a circle with the source in its center. When some wind is present, and it is when a wind turbine is in operation, the refraction due to wind is usually stronger and there is a sound shadow only in the upwind direction. The distance to the source depends on the wind speed and the height of the source: for a high source the sound shadow is further away than for a low source. In figure 8 the contours of the sound shadow related to a sound source at 95 m height are plotted, using night time atmospheric data from the Royal Netherlands Meteorological Institute and an algorithm provided by Makarewicz et al [12]. The contours are open as there is no sound shadow in the downwind direction. For a source at 95 m height the minimum and maximum distances to the sound shadow in the upwind direction at night are just over 500 m and just over 1 km (average over all days 650 m). For a road, the sound shadow is at least 130 m and at most 250 m (average: 160 m) from the road in the upwind direction. This means that for residents at several hundreds of meters from a road may often not hear the road when it is downwind, but they will often be able to hear wind turbines in that situation if these are alongside the road.

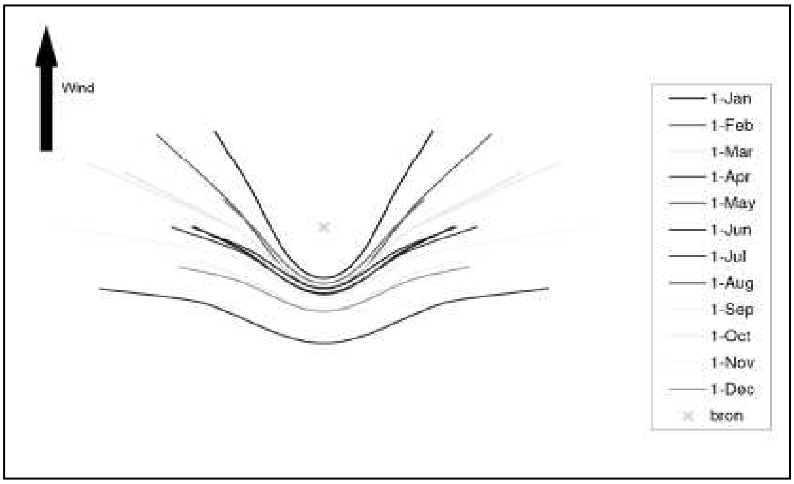


Figure 8. Contours of the sound shadow in twelve night over a year for a source (x) at 95 m height.

# 5 Discussion

Most respondents in the WINDFARMperception survey thought the sound from one or more modern, tall wind turbines at night is louder than or not very different from the sound in daytime, which is consistent with the actual average sound levels of these turbines. Also, most respondents thought the sound is louder in strong winds and when the wind is blowing towards their dwelling, which is consistent with the wind dependent sound power level and the directivity of the sound (higher at the downwind side).

Comparing equal Lden levels of road traffic and wind turbine sound gives no information on the levels or the relative audibility of each sound at specific times. In fact, at equal Lden values wind turbine sound levels will be higher at night than road traffic sound levels because of the different diurnal patterns, the different spectral distributions and the modulation present in wind turbine sound. It can be estimated that the Lden due to modern, tall wind turbines must be 6 dB (diurnal variation) + 8 dB (spectral differences) + 5 dB (amplitude modulation) = 19 dB lower then the Lden due to road traffic in order to obtain equal hourly levels at the least busiest traffic hours at night. If the road is a provincial road and not a very busy motorway, there may be shorter or longer periods of time, especially at night, when no road traffic at all can be heard. In that case the Lden due to that road traffic is in fact irrelevant when determining the audibility of a wind turbine.

It is not clear whether the greater distance of the sound shadow to a source is important in relation to annoyance. An upwind receiver may be in the sound shadow of a road but not in the sound shadow of a wind turbine along that road, but the receiver is in that case also at the front side of the turbine which emits less sound than the rear side.

### Acknowledgments

We thank our co-researcher Roel Bakker and Jelte Bouma at the Medical Center in Groningen, and the RIVM for providing the road traffic sound data.

### References

[1] Wolsink, A. Wind power implementation: The nature of public attitudes: Equity and fairness instead of 'backyard motives'. *Renewable & Sustainable Energy Reviews*, Vol 11, 2007, pp 1188-1207.

[2] Pedersen. E.; Persson Waye, K. Wind turbines—low levels noise sources interfering with restoration?, *Environmental Research Letters*, Vol 3, 2008, 5 pp.

[3] Pedersen. E.; van den Berg, F.; Bakker, R.; Bouma, J. Response to noise from modern wind farms in The Netherlands, *Journal of the Acoustical Society of America*, Vol 126 (2), 2009, pp 634-643.

[4] Bolin, K. *Masking of wind turbine noise by ambient noise*. Licentiate Thesis in Technical Acoustics. KTH, Stockholm, Sweden, 2006.

[5] Bolin, K.; Nilsson, M.E.; Khan, S. The potential of natural sounds to mask wind turbine noise, *Acta Acustica united with Acustica*. Vol. 96, 2010, pp 131-137.

[6] Pedersen. E.; van den Berg, F.; Bakker, R.; Bouma, J. Can road traffic mask sound from wind turbines? Response to wind turbine sound at different levels of road traffic sound, *Energy Policy*, Vol 38, 2010, pp 2520-2527.

[7] *Attenuation of sound during propagation outdoors. Part 2: general method of calculation*. ISO 9613-2, Geneva, Switzerland, 1996.

[8] Van den Berg, F. Criteria for wind farm noise: Lmax and Lden. *The 7th European Conference of Noise Control, Acoustics'08*, Paris, June 30 – July 4, 2008.

[9] Jabben J, Potma CJM. *Sound monitor 2005 – trend and validation measurements of environmental sound.* Report RIVM (in Dutch), Bilthoven, 2006

[10] Van den Berg F, Pedersen E, Bakker R, Bouma J. *Project WINDFARMperception – Visual and acoustic impact of wind turbine farms on residents.* University of Groningen, UMCG and University of Göteborg, 2008

[11] Van den Berg F. Why is wind turbine noise noisier than other noise? *Proceedings of Euronoise2009*, Edinburgh, October 26-28, 2009

[12] Makarewicz R, Wojciechowska H. Noise duration for a single overflight. *Journal of the Acoustical Society of America*, Vol. 114 (218), 2003, 218-224