Looking for a wind turbine noise legislation paying attention to annoyance: which metric?

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ABSTRACT

Wind turbine noise (WTN) is perceived much more disturbing than the conventional noise sources of equivalent intensity. For this reason, in our previous work, we suggested a specific limit for WTN that consider the real annoyance perceived by population in relation with the type of the source. This was done extracting the number of highly annoyed (%HA) from Miedema's curves corresponding to the Italian limits for road traffic noise. The sound level for WTN corresponding to that percentage of %HA was determined from the most recent dose-response relationships. The result was in accordance with the Danish noise limits. With a deeper analysis we found that the international framework on WTN can be basically divided into two main category: the first based on long term noise measurements or simulations and the second on short term noise measurements during the worst conditions. The limit of the methodology based on indicators of long term noise (L_{DEN}) is that the population is generally not disturbed from long-term average exposure, especially for fluctuating sources. For this reason, the population is not satisfied by this type of limits for a source that feels strongly annoying only a few times in particular conditions and remembers those situations in time. The second methodology is very selective, and case, time and weather conditions depen$_{den}$t. The benefits and drawbacks of these approaches are analyzed aiming to propose solutions for a future legislation that must protect people needs and have a scientific basis.

1 INTRODUCTION

Wind energy is fast growing for several years and many plants are installed continuously even nowadays. One of the main reasons why a wind farm sometimes is not authorized is the noise impact, in particular the non-compliance with the immission limits at receptors surrounding the area in which it is designed. In some cases these plants actually harm the health of citizens, in others limits are not suitable to the complicated issue of wind turbine noise (WTN).

In this paper we analyzed the international framework on WTN, finding that it can be basically divided into two main categories: one based on long term noise measurements or simulations and the other on short term noise measurements during the worst conditions. The limit of the methodology based on long term noise indicators (L_{den}) is that the population is generally not disturbed from long-term average exposure, especially for WTN. WTN is indeed a highly fluctuating sources in the short period, for amplitude modulation, and in the long period, for the atmospheric phenomena. For this reason, the population is not satisfied by long term limits for a source that feels strongly annoying only few times in particular conditions and remembers those situations in time. The second methodology is very selective, and case, time and weather conditions dependent.

Looking at the differences between perception of WTN and road traffic noise (RTN), in our previous work (Licitra & Fredianelli 2013) we found a limit for wind turbine noise with a scientific basis. In this study we performed a deeper analysis of the method we used to obtain our limit for WTN and we fixed some criticism arose, particularly focusing on the conversion factor used to convert a short term noise indicator (L_{Aeq}) to a long term one (L_{den}).

2 INTERNATIONAL WIND TURBINE NOISE REGULATIONS

Noise limits are based on specific noise metrics to ensure the quality of life of the population. A deep analysis showed that the metrics used to regulate WTN is not uniform between countries. Disparities arise in the noise measurement duration, wind speed and statistical data collection. A study (Fowler et al. 2013) involving 39 countries shown that the L_{Aeq} indicator is the most common used for regulating wind farm noise: 16 on the 39 regulations examined. Five countries use a metric that is derived from the it, like L_{den}, but include a penalty for parts of day with increased sensitivity. L_{den} is defined in the EU Directive Environmental Noise 2002/49/EC (END 2002) and is the yearly averaged noise levels. L_{Aeq} is defined as the "equivalent sound level" and is based on a time-integrated measurement period which varies between countries and regulations. Authorities integrated time period range from a 1 hour to a 24 hour measurement (evaluation period). The noise threshold established for the L_{Aeq} shows to be an approximate 20 dB variation depending on the regulation. Most European countries, South Australia, New Zealand and a number of states and states in the USA, have a noise limit which depends on the type of area or the existing background noise levels. Exceptions are The Netherlands, Norway, the Belgian Region Wallonia, the Canadian province of Alberta and a number of states and counties in the USA, which all have fixed limit values. Countries like France, Swe_{den}, South Australia and New Zealand have more stringent noise limits for rural areas with relatively low background noise levels than for residential areas. On the contrary, the Belgian Region Flanders, Denmark and Germany in general allow higher noise levels at dwellings in a rural area than at residential areas. A few countries use statistical noise metrics (L_{90}, L_{50}, and L_{10}) , but more do not have any published noise regulations. In Italy the regulations require to calculate the difference between environmental noise and background noise in the same weather conditions. To get a measure of residual, therefore, it's necessary to turn off the wind farm or to find some alternative method (Gallo et al. 2014).

3 A LIMIT FOR WIND TURBINE NOISE WITH A SCIENTIFIC BASIS

A lack of a scientific basis for the choice of the limit value is common between all normative approaches. For this reason, in our previous work we suggested a specific limits for WTN that consider the real annoyance perceived by population in relation with the specific source. We determined a limit value for WTN starting from the Italian one for RTN during daytime and night-time, equal or similar to those of many European countries. The percentage of highly annoyed (%HA) corresponding to the limit for RTN, converted in L_{den}, have been extracted from Miedema's dose-response relationship for %HA (Miedema & Vos 1998). Then, the tolerance threshold for outdoor WTN levels have been taken from the WTN dose-response relationship (Janssen et al 2011), derived from data coming from three studies (Pedersen & Persson Waye 2004, Pedersen & Persson Waye 2007, Pedersen et al 2009), at the %HA identified for RTN. The result have been converted from L_{den} to L_{Aeq} using Italian period: day from 6:00 to 20:00, evening from 20:00 to 22:00, night from 22:00 to 6:00.

Thus, the curve is determined by calculating the noise at receiver and through propagation models in generic wind conditions (8 m/s wind speed at 10 m height). The logical process is summarized in Figure 1.

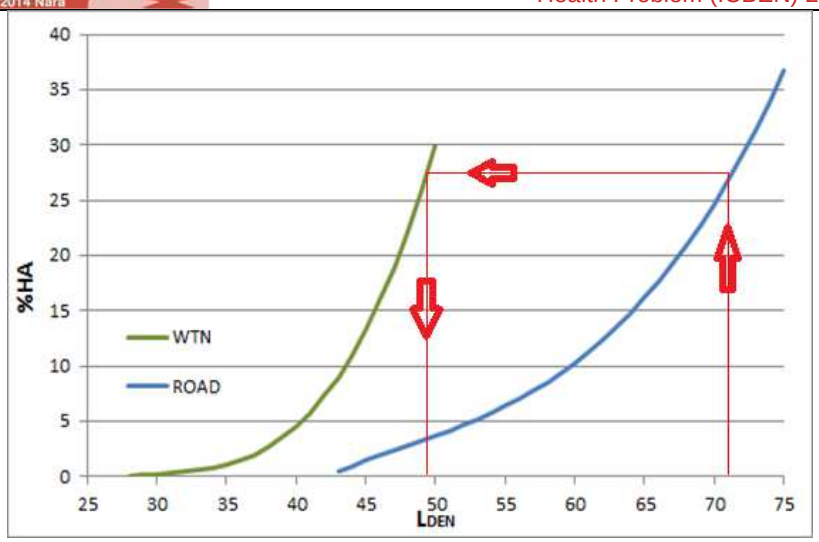

Figure1. Graphical summary of the process for the determination of the limit. Blue is Miedema's dose-response relationship for RTN, green is Janssen's for WTN.

The limit value obtained, calculated with negligible background noise, is 42.9 dB(A) of L_{Aeq} and is particularly comparable with the recent Danish standards (Statutory Order no. 1284 on Noise from Wind Turbines 2011).

4 THE DIFFERENCE IN DOSE-RESPONSE RELATIONSHIP FOR WIND TURBINE NOISE AND ROAD TRAFFIC NOISE

What makes so high the annoyance to WTN perceived by population is the sound character of wind turbine noise. Some of the factors contributing to this are here summarized. Noise comes from a level above the receiver, leading to an amplitude modulated sound. The constant change in amplitude modulation character increases attention and cognitive appraisal and reappraisal, inhibiting acclimatization of citizens to sound (Stigwood 2013). The sound power levels depend on the wind velocity, meaning that the immission levels also vary irregularly and unpredictably, is unpredictable and is often present at night (Doolan 2013). WTN may particularly be heard in otherwise quiet areas, where people do not expect to hear industrial noise. Furthermore, the mostly rural position of wind turbines may contribute to the heightened annoyance response. In addition to the ambient noise level, the expectations of a living environment supposedly influence an individual's appraisal of an uncontrollable sound. The special characteristics of omnipresence, periodic nature, random occurrence and low frequency content makes WTN a very annoying sound (von Hunerbein 2013).

The overall difference results in a different slope of the dose-response curves. Therefore, the transition from a curve to another one is not linear. At the same disturbance, then it is not possible to provide a simple conversion value between WTN and road noise. We have seen that this is very different as a function of noise exposure. For standard values of WTN exposure the difference between WTN and road noise varies from a minimum of 10 dB to a maximum of 25 dB.

In Figure 2 we drawn the difference of L_{den} between RTN and WTN with equal percentages of highly disturbed as a function of L_{den} of WTN. This means that for a given L_{den} of WTN is necessary to add the corresponding value given by the curve in

order to obtain the value of L_{den} for RTN that causes the same disturbance to the exposed population. The curve was obtained by subtracting for each %HA the inverse of the equation of Janssen's dose effect relation by the inverse of the Miedema's and reporting this difference as a function of L_{den} of WTN.

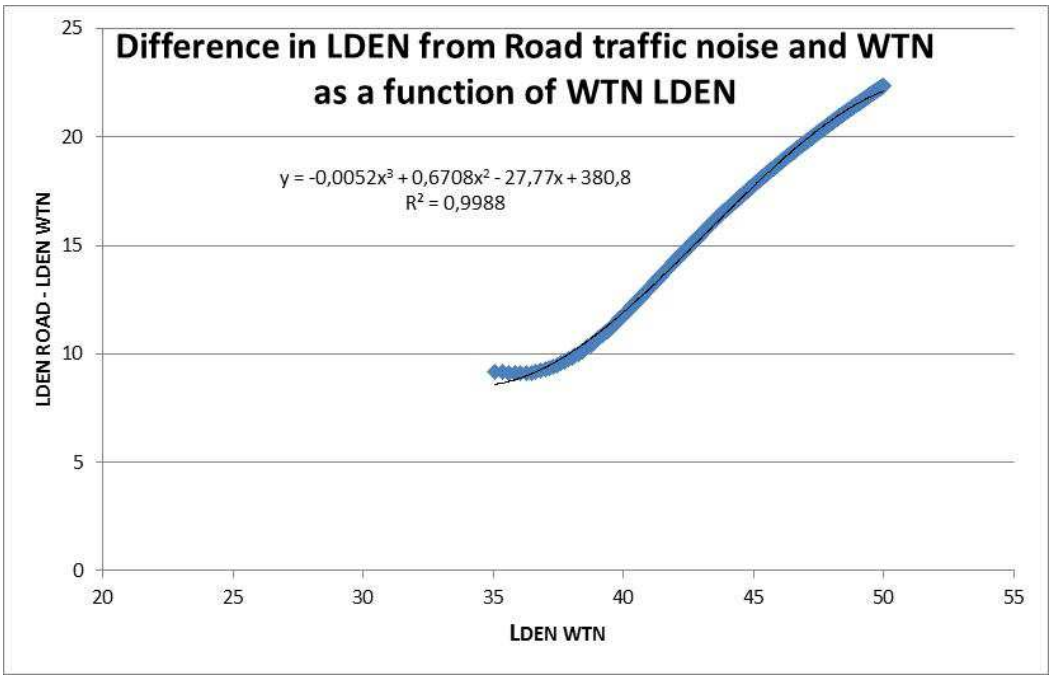

Figure 2. Difference of L_{den} between road traffic noise and WTN with equal percentages of highly disturbed as a function of L_{den} of WTN.

5 A DEEPER ANALYSIS

We used to convert L_{Aeq} to L_{den} and vice-versa, the definition:

$$L_{DEN} = 10log_{10}\left\{\frac{14}{24}\times 10^{0,1L_{day}} + \frac{2\cdot\sqrt{10}}{24}\times 10^{0,1L_{evening}} + \frac{8\cdot 10}{24}\times 10^{0,1L_{night}}\right\}$$

that does not take into account the variability of wind turbine operations and presumes the wind turbine is operating at its maximum sound level 100% of the time. Moreover, converting from L_{den} to the maximum hourly L_{Aeq} for wind turbines requires the evaluation of day/evening/night wind statistics. Our approach was correctly defined as conservative, but a +3 to +5 dB(A) adjustment to the hourly L_{Aeq} was expected.

The deeper analysis started from the noise levels used in Janssen's dose-response relationship. In this study annual day-evening-night A-weighted equivalent noise level (L_{den}) was calculated from the immission levels determined in the original studies. The outdoor A-weighted sound pressure levels from the nearest wind turbine(s) were determined with a neutral atmosphere at a constant wind velocity of 8 m/s at a height of 10 m in the direction towards the respondent. A correction of +4.7 dB(A) was applied to these data following the mean difference between L_{den} and the A-weighted sound pressure level calculated by van $_{den}$ Berg (2008).

The understanding of the origin of this conversion factor of 4.7 is of paramount importance. For this reason we summarize the steps which have led to it. The author started from the sound power level as a function of wind speed at hub height for two different Dutch wind farm, obtained by a 4th power polynomial fit of the noise data in

the range of 4-12 m/s of wind [van den Berg 2008]. The distribution of wind speed per diurnal period over 11 and 7 years were available at various height from meteorological towers. The distributions of wind speed at hub height directly yields the distribution of sound power levels and L_{day}, L_{night} and $L_{evening}$ were so calculated on annual basis through a wind class calculation. The L_{den} on annual basis have been obtained using the formula reported in END. This was calculated for various wind turbine height using the wind distribution at different height.

A generic constant sound power over time if subtracted to these values of L_{den} results in a difference of 6.4 dB, whereas the difference is 5.2 dB for a sound power mainly active during the night. Van $_{den}$ Berg found that the difference is variable with sound power (i.e. wind speed) when subtracting to the L_{den} the value of the sound power as a function of wind speed. In particular, he considered the cases of wind speed of 7 and 8 m/s at 10 meters of height, which are the most likely for the sites studied by him. The results were 5.2±2 dB of difference between L_{den} and noise power at 7 m/s of speed and 4.7±1.5 at 8 m/s, with uncertainties due to the height, location and type of turbine.

Returning to the epidemiological studies of Pedersen, Persson Waye, van den Berg et al. and Janssen, they all assign a noise levels to the receptors investigated by simulations with a wind speed of 8 m/s at 10 m in flat terrain. The number 4.7 previously shown was added to the L_{Aeq} at the receptors to transform them into L_{den} in order to construct the dose-effect curve related to L_{den}.

The conversion factor of 4.7±1.5 found by van der Berg was obtained using the sound power levels, so it would be absolutely plausible for short distances around the turbines. However, this has been hired as true in those epidemiological studies for the sound pressure levels at the receivers, although there is the possibility that during sound propagation this value does not remain constant. Nevertheless, without other information we assume this translation as true also for our work.

In paragraph 3 we found a tolerance threshold for outdoor WTN levels of 49.1 dB of L_{den}. The corresponding L_{Aeq} was calculated by subtracting 6.2 dB, simply inverting the formula for L_{den} and considering a constant noise throughout the day. The time periods used are the Italians day evening night (14 hours a day, 2 night, night 8). This is different than in the epidemiological studies, where the authors did not considered WTN flat on the day, but considered the distribution over time using the coefficient of van den Berg.

The aim of our work was to provide a limit for wind turbine noise. To do this, in fact, choosing

4.7 dB as the conversion factor from L_{den} to L_{Aeq} is not always the best choice, since this number was obtained only on two sites and is not always correct, but can vary with many parameters. So, considering a standard deviation for the value of 4.7 ± 1.5 we precisely obtain the value of 6.2 dB that we chose, at the edge of the uncertainty found in the work of van den Berg. With this new assumption in our case having turned L_{den} in L_{Aeq} subtracting 6.2 is not just having considered the source as uniform during the day, but it respects the studies in the field of meteorological variability. Our result has scientific bases, is in a precautionary manner respect to the variability of the difference between L_{den} and L_{Aeq} of WTN and now it does not neglect the fact that the emission can vary during the year.

6 A POSSIBLE APPROACH BASED ON MONTHLY MEASUREMENTS AT THE RECEPTOR

A criticism of the dose effect curves concerns the use of the indicator L_{den} on the annual period, because it is not sure that people suffer disturbance based on an annual average level. It is likely that they express their annoyance basing on the periods in which they are most disturbed. Probably L_{den} is not the right metric, but epidemiological studies are based on it and we followed this same path to get a limit for WTN. We want to propose an idea that considers short-term noise exposure on the basis of an equivalent level L_{Aeq}, but that is however linked to long-term noise exposure.

The method could consider noise levels obtained with a measurement campaign to the receiver, which lasts about a month in order to have a sufficient data. From the distribution of L_{Aeq} acquired every 10' a percentage of data could be discarded, which we consider at the moment of 10%. This is the percentage of eliminable transits by exceptional events accepted by the Italian D.M.16/3/98 (D.M. 16/3/98 1998)for the assessment of railway noise. In this way, we do not consider all possible random events that may occur during measurements.

Our idea is to consider the noise level exceeded in the 90% of the time (L_{10}), which is not a simulated value but it is effectively obtained at the receiver through measurements, and to find a correlation with L_{den}. In this way we could understand what level of annoyance the citizen has according to the dose-effect curves previously shown. To do this, however, there is the need of a new link to L_{den} and L10. This relation should be calculated according to the way in which van $_{den}$ Berg did for L_{den}-L_{Aeq}, but it will require long-term noise and meteorological data. The process would be possible whether the relationship between annual L_{den} and L10 on limited time would exists. This aspect should be investigated and we hope it will be a starting point for researchers having enough data.

We used the measures in our possession for further analysis, even if they have not an annual statistics. From 2010 to 2013 we performed 6 measurement campaigns of noise and wind near a receiver at 6 wind farms in various regions of Italy. The measures always lasted between 3 and 4 weeks. The topography of the sites varies from flat to hilly with rough vegetation or forest. In the analysis of noise data periods with rain or with wind speed at the receiver greater than 5 m/s (Fredianelli et al 2012) were removed, as well as noise events not directly related to the source or the sound of wind.

For each measurement site we took the L_{10} from the distributions of L_{Aeq} every 10' (as in Figure 3). This number have been compared to a L_{den}. That L_{den} was calculated taking the value exceeding in 90% of cases the distribution of the L_{den} s calculated on daily basis.

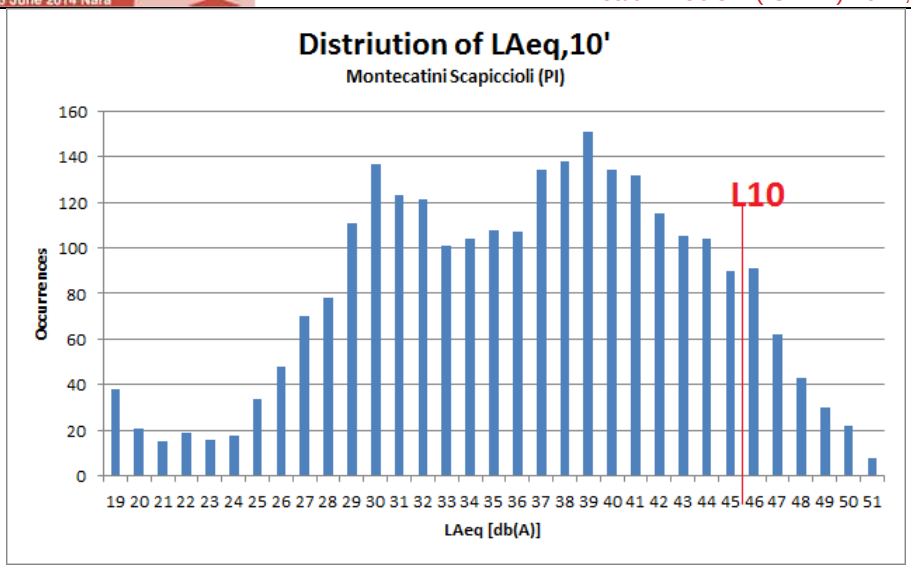

Figure 3. Distribution of L_{Aeq} every 10' measured at the site Montecatini Scapiccioli (PI).

Basically we took as a measure of the entire L_{den} the L10 of the daily L_{den}s. Results are reported in Table 1. The mean difference from L_{den} and L10 among the sites is 5.5 ± 1.4, a value similar to van $_{den}$ Berg's result for the difference between L_{den} and L_{Aeq}.

	L_{DEN}	# L_{DEN}	L_{10}	# L_{10}	Difference
San Giovanni in Lamis (FG)	51,1	26	48,1	2882	3
Montecatini Scapiccioli (PI)	51,7	22	45,4	2661	6,3
Montecatini Palareta (PI)	54,2	18	48,6	1776	5,6
Montecatini Provinca (PI)	46,8	18	41,9	1913	4,9
Scansano (GR)	57,6	18	51	2003	6,6
Lucera (FG)	53	30	46,2	2076	6,8

Table 1. L_{den} and L10 with their occurrences and difference between L_{den}, L10 for each measurement sites.

Following that first analysis, it appears that use the level L_{10} plus a correction or the method of L_{Aeq} plus a correction is not so different and obtains approximately the same uncertainty. Surely further analysis are necessary.

7 CONCLUSIONS

The international legislation and regulatory framework is not very homogeneous and there is often a lack of a scientific reason for the choice of the limit value. For this reason in our previous work we determined a limit value for WTN of 42.9 dB(A) of L_{Aeq}, that is comparable with the recent Danish regulations. In this study we went further, looking at the criticisms of our approach through a deeper analysis of the studies on which it is based on.

In this paper we showed that, due to their nature, the dose-response curves of WTN and RTN have different slope. We calculated and drawn the curve of the difference as a function of the L_{den} of WTN.

We also found that the conversion from L_{Aeq} to L_{den} and vice-versa takes into account the variability of wind turbine operations by means of the conversion factor of van $_{den}$ Berg and that our conversion factor is similar, but more precautionary. Our result has then scientific bases and is in a precautionary manner respect to the ±1.5 variability of the difference between L_{den} and L_{Aeq} of WTN experimented by van den Berg.

In order to take into account the variability of the source and its influence on people reactions, we propose a method for converting measurements on a limited period to an annual L_{den}, using one month data coming from 6 measurements campaign of noise and weather at 6 wind farms in various regions of Italy. We found that using the L_{10} plus a correction factor or the van den Berg's method of L_{Aeq} plus a correction is not so different and have approximately the same uncertainty. Further measurement data and analysis are necessary.

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