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A procedure for deriving wind turbine noise limits by taking into account annoyance

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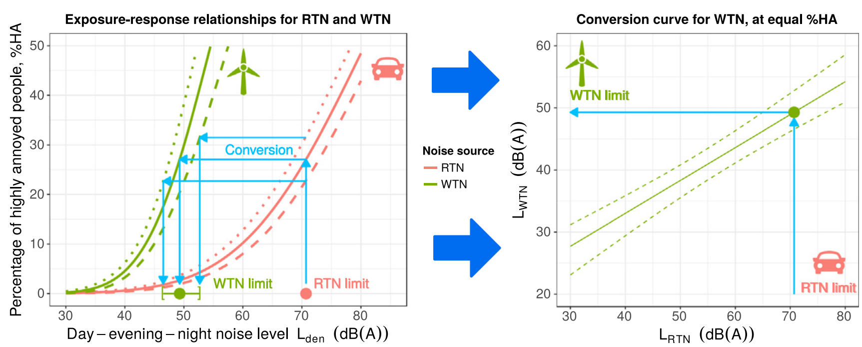
HIGHLIGHTS

- The importance to consider noise annoyance in legislation is discussed.
- Conversion curves for equally highly annoyed by different sources are presented.
- A wind turbine noise limit of 43.1 dB(A) is derived from the conversion curves.
- The limit is based on %HA and results are comparable with some international standards.

GRAPHICAL ABSTRACT



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ABSTRACT

With the increasing installation of wind farms, the attention of citizens towards wind turbine noise (WTN) has grown. Differently from some national legislations, the scientific community has promptly responded, increasing the studies and the social surveys in order to better understand the cause of disturbance and the indicators that relate to it. At first, the paper underlines the importance of low WTN levels for indirect health effects such as sleep disturbance and annoyance. The importance to consider noise annoyance in legislation is also discussed, as WTN is more disturbing than other most common noise sources. Then, conversion curves for equally highly annoyed are introduced considering the annoyance perceived by population in relation with the type of source. Finally, a specific limit value of 43 dB(A) for WTN is derived and suggested, comparable with British and Danish standards.

1. Introduction

In recent years, wind turbines are being installed around the world as a common practice to boost the production of non-fossil energy. Unfortunately, this quest for green energy is not always sufficiently followed by a careful analysis of the disturbance suffered by people. In

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the particular case of noise pollution, complaints by citizens living at a distance up to 1500 m from the farm are continuously growing (NHMRC, 2015). These are caused by a variety of factors, including that in some countries wind turbines are also planned in amazing and quiet areas (i.e. Mediterranean countries), where old dwellings are restored for touristic reasons and are chosen for their amenity and quietness as principal attractiveness. The disputes that follow the complaints often become legal actions, since the existing limit values are generic and not specifically designed for wind turbine noise (WTN), with exception for some Countries like U.K., Netherlands, New Zealand, Denmark, several Canadian provinces and Australian states.

Until the recent Canadian study (Michaud et al., 2013), the assessment of the health effects related to exposure to WTN has been limited to a few studies, mostly based on measurements of well-being or quality of life and on the extent to which noise alters various human activities (such as sleep). Self-reported health problems include, among others, nausea, dizziness, heart palpitations, stress, high blood pressure, sleep disorders and discomfort (Horner et al., 2013). Less attention has been paid to WTN because generally, noise disturbance in urban environments is more affected by road, railways and airports than wind farms. However, unwanted sounds out of the ordinary context are recognized as intrusive and more disturbing, thus they should be avoided (Cassina et al., 2017). Prolonged exposure to noise can directly or indirectly affect the health of individuals. Direct effects occur when the sound pressure levels are above 75 dB(A), potentially causing permanent hearing loss based on the duration of exposure and the sensitivity of the individual (Basner et al., 2014). Wind farms are usually placed in rural environments, where other noise sources are not significant and the general WTN exposure is far below the direct effect threshold (Michaud et al., 2013). A study (Salt and Kaltenbach, 2011) sentenced that actually no association between WTN and pain or stiffness, diabetes, high blood pressure, tinnitus, hearing impairment, cardiovascular diseases and headache have been found.

The issue of noise effects on health is complicated and the scientific community is discordant about the harmful effects of the low noise levels at the receivers produced by wind turbines, which usually vary between 35 and 50 dB(A). While some authors argue that these levels are not a problem for citizens (Kaldellis et al., 2012; Knopper and Ollson, 2011; Schmidt and Klokker, 2014), the WHO and other authors have an opposite opinion, supported by the actual complaints of the citizens. Nevertheless, the indirect effects on health are very important for prolonged exposure and WTN can be a source of real discomfort and adverse health effects (Timmerman, 2013). The most common indirect health effect for WTN is sleep disturbance with its long term complications, as found in some studies (Knopper and Ollson, 2011; Smith et al., 2017). Indirect effects on health cannot exclude annoyance, recognized as a psychological state that represents a degree of mental discomfort to noise (Berglund et al., 1999) and a specific dose-effect relation has been found for WTN annoyance, which will be analyzed in a specific chapter.

The exposure-response relationship for highly annoyed people by WTN (Janssen et al., 2011) shows a more pronounced slope compared to conventional noise sources (Miedema and Vos, 1998; Miedema and Oudshoorn, 2001), although, when properly installed, wind turbines are not related to adverse health effects (Knopper et al., 2014). Thus, the clear understanding of a minimum WTN value to be avoided at receivers is vital both in the design phase of new wind farms and for the existing ones, for which a proper noise assessment without interrupting the activities of the wind farm under investigation is feasible but more complex (Gallo et al., 2016; Fredianelli et al., 2017).

Section 2 will underline the importance of annoyance as a health effect even at low noise levels. Experience shows that the relevance of annoyance is not always recognized, especially in courts and legal contests, but on the contrary it should be considered as a starting point to assess environmental noise.

Section 3.1 describes the exposure-response curves (Miedema and Vos, 1998; Miedema and Oudshoorn, 2001) that allow to compare the level of annoyance for different sources, like wind turbine noise, road traffic noise (RTN), aircraft and railway.

In Section 3.2 the noise levels that produce the same percentages of highly annoyed people are calculated from the exposure-response curves in order to consider the same health effects for different sources,. In particular, linear relationships linking the exposure noise levels respective to different sources at equal percentages of highly annoyed people are obtained. These relations allow directly converting exposure noise levels from different sources, having the same effect on the population. For this reason, in this paper the linear relationships are addressed as conversion curves for equally highly annoyed people, simply called "conversion curves", whose confidence intervals are calculated in Section 3.3. The conversion curves could be useful to provide a simple way of comparing a given noise exposure to a source in terms of annoyance to RTN exposure, which is the most widespread and widely understood by people.

Finally, in Section 4 a specific limit for WTN is suggested, and discussed in Section 5, by using the obtained conversion curves to consider the %HA corresponding to the Italian limits for RTN. The method can be applied to any source and represents a useful tool to update national limits according to the source. In particular, the limit proposed can be used to guide national legislation in WTN.

2. Noise annoyance as a health effect

Depending on the type of the source, noise can be more or less disturbing, despite having the same energy. The percentage of annoyed people is a parameter used to measure the reaction to a specific source and it represents the degree of acceptability of a source, rather than the sound energy detected. Annoyance measured in psychoacoustics surveys is generally evaluated on a scale that ranges from 0 to 100 and is divided into intervals, defining the percentages of people little annoyed (%LA), annoyed (%A) or highly annoyed (%HA), with cutoff values of 28, 50, 72, respectively (Miedema and Oudshoorn, 2001). Therefore, %HA can be defined as the expected percentage of people reporting a level of annoyance greater than or equal to 72/100 in psychoacoustics surveys.

A high degree of annoyance deriving from noise exposure constitutes an adverse health effect and the role of the percentage of highly annoyed is one of the most important health endpoints for an environmental assessment (Michaud et al., 2008a), since health is defined as "a state of complete physical, mental and social well-being, and not merely the absence of disease or infirmity" and "the extent to which an individual or group is able, on the one hand, to realize aspirations and satisfy needs, and on the other, to change or cope with the environment" (WHO, 2009).

Low noise exposure has been already investigated in 1999 by WHO (Berglund et al., 1999), who suggested to avoid equivalent continuous sound pressure levels L_{Aeq} greater than 30 dB(A) inside homes, in order to reduce some of the effects produced by noise, such as sleep disturbance, annoyance and speech interference. Specifically, noise annoyance was identified as one of the effects of noise on health for which values were fixed (Fields et al., 1997), since it was found that:

- o a sound pressure level equal to 42 dB(A) measured at night outdoors interferes with the quality of sleep and produces self-reported disorders.
- o a sound pressure level equal to 40 dB(A), measured at night outdoors causes sufficient evidence of the use of sedatives and sleeping drugs.

Therefore, for the primary prevention of adverse albeit subclinical effects on health related to noise, the WHO recommends that the population should not be exposed to levels of external noise at night above 40 dB(A).

In 2008 a Canadian study (Michaud et al., 2008b) showed that %HA due to RTN is statistically related to the increase of the intensity of voice during a conversation outdoors and to interference with the ability to sleep, with the listening ability and with reading/writing skills.

In 2010, the appearance of health effects produced by annoyance and sleep disturbances due to outdoor L_{den} levels greater than 42 dB (A) has been confirmed (EEA, 2010).

In 2011, WHO (2011) stated yet again the importance of annoyance, suggesting to consider it as a basis for noise impact assessment on the population, on the grounds that people disturbed by noise can experience a variety of negative responses, such as anger, disappointment, dissatisfaction, helplessness, depression, anxiety, distraction, agitation or exhaustion (Fields et al., 1997, 2001). In addition, stress-related psychological symptoms, such as fatigue, stomach upset and stress itself are associated with exposure to noise and annoyance (Öhrström, 2004; Öhrström et al., 2006; Klæboe, 2011). A high level of self-reported annoyance among adults towards noise is also statistically associated and can be a serious risk factor for allergy, symptoms of arthritis, bronchitis, cardiovascular symptoms, depression, hypertension, migraine, respiratory symptoms (Niemann et al., 2006; Maschke and Niemann, 2007).

Outside Europe, the U.S. has recognized the %HA as a parameter that reflects a long-term response to exposure to noise levels, with the ability to interfere with daily activities, and %HA has been accepted by two federal agencies to assess the impact of noise (U.S.FTA, 1995; U.S.FRA, 2005; ANSI, 1996).

Specifically, for WTN, the Canadian study (Michaud et al., 2008b) reported a statistical relation between annoyance caused by WTN and several self-reported health effects such as blood pressure, migraines, tinnitus, dizziness and perceived stress and a relation with measured hair cortisol, systolic and diastolic blood pressure. In addition, annoyance and sleep disturbance are closely linked and can influence one another (Stansfeld and Matheson, 2003; Stansfeld and Clark, 2011); Janssen et al. (2008) also reported a relation between WTN, annoyance and self-reported disturbed sleep. Particularly WTN can be above the sleep disturbance threshold, since it occasionally shows an amplitude modulation that makes it disturbing especially when audible inside bedrooms. In fact, the high number of beats leads to a higher probability of sleep disturbance. On the contrary, recently Michaud et al. (2016), using the Pittsburgh Sleep Quality Index as a starting point, suggested that sleep was not influenced by exposure to WTN, thus leaving open the scientific debate on sleep disturbance at low noise exposure to WTN.

However, the presence of WTN is easily recognizable (Van Renterghem et al., 2013) and cause of high annoyance on the exposed people, as confirmed by the dose-effect relationships studies performed around the world and described in the following chapter.

3. Methods

3.1. Exposure-response relationships for WTN and other sources

Exposure-response relationships are obtained in studies relating citizens' self-reported annoyance trough questionnaire to their noise exposure level. The most important study was performed by Miedema and Oudshoorn (2001), which produced curves that were recommended by the European Commission and the World Health Organization (WHO, 2011) for calculation of Disability-Adjusted Life Years (DALYs) due to noise annoyance. At present, the theoretical framework is still valid and well tested, although some issues about prediction capabilities of these curves have been reported (Gille et al., 2016), highlighting the necessity to perform an update with new and more recent socio-acoustical studies.

Miedema's curves were produced only for the principal urban noise sources, thus omitting WTN. Since then, a certain number of socio-acoustical surveys concerning WTN have been carried out. At first a Danish study (Pedersen and Nielsen, 1994), two consecutive Swedish studies (Pedersen and Persson Waye, 2004; Pedersen and Persson Waye, 2007) and a European one carried out in Denmark, Netherlands and Germany (Pedersen et al., 2009). All the previous studies have been collected and analyzed together providing a cumulative curve that still represents the exposure-response relationships for WTN actually present in literature with the wider population for questionnaires (Janssen et al., 2011). Later, also a Canadian (Michaud et al., 2013), a Polish (Pawlaczyk-Luszczynska et al., 2014), and a Japanese study (Kageyama et al., 2016) have been performed, but still no cumulative analysis have been published in literature.

The noise indicator used to model annoyance is the day-evening-night noise level L_{den} reported in Eq. (1), which combines the levels L_{day}, $L_{evening}$, L_{night} weighting the different time period over a typical year.

$$L_{den} = 10\log_{10}\frac{1}{24}\left(12\times 10^{0.1\ L_{day}} + 4\times 10^{0.1\ (L_{evening}+5)} + 8\times 10^{0.1\ (L_{night}+10)}\right) \tag{1}$$

In Miedema's study (Miedema and Oudshoorn, 2001) annoyance is modeled using a multilevel regression of the annoyance reported in psychoacoustical surveys as a function of L_{den}. The model includes an error term, assumed to be normally distributed with total standard deviation σ, consisting of the within variance related to individual answer and the between study variance (Groothuis-Oudshoorn and Miedema, 2006). The percentage of people whose annoyance is greater than a value C is given by the statistical model reported in Eq. (2), representing the Miedema-Oudshoorn exposure-response curves. Often in literature these relationships are used by considering the fitted approximated polynomial curves (Miedema and Oudshoorn, 2001).

$$P_C(L_{den}) = 100\left(1-\phi\left(\frac{C-a-bL_{den}}{\sigma}\right)\right) \tag{2}$$

The function ϕ is the cumulative standard normal distribution: $\phi(x) = \int_{-\infty}^{x}\frac{e^{-0.5\ t^2}}{\sqrt{2\ \pi}}$. The parameters a and b are the linear regression coefficients, while C it is the cutoff value, which for highly annoyed people is 72: $\%HA = P_{C=72}(L_{den})$.

The confidence limits $CL_{\%HA}$ for the percentage of highly annoyed people associated to a certain value of L_{den} are given by Eq. (3) in agreement with (Groothuis-Oudshoorn and Miedema, 2006):

$$CL_{\%HA}(\alpha, L_{den}) = 100\cdot\left(1-\phi\left(\frac{C-CL_A}{\sigma}\right)\right) \tag{3}$$

with $CL_A = \boldsymbol{x^t y} \pm k(\alpha)\sqrt{\boldsymbol{x^t S x}}$, $\boldsymbol{x} = \begin{bmatrix}1\\ L_{den}\end{bmatrix}$, $\boldsymbol{y} = \begin{bmatrix}a\\ b\end{bmatrix}$, $\boldsymbol{S} = \begin{bmatrix}\sigma_a^2 & \sigma_{a,b}\\ \sigma_{a,b} & \sigma_b^2\end{bmatrix}$.

The confidence limits for %HA are computed by considering the confidence limits CL_A on the annoyance levels, modeled by the multilevel linear regression. The coverage factor $k(\alpha)$ defines the probability α for the confidence limits, while the covariance matrix $\boldsymbol{S}$ consists of the variances of the model coefficients and their respective covariance. The values of the coefficients of the statistical model for road, railway and aircraft from Miedema and for WTN from Janssen are reported in Table 1 together with the covariance matrix values.

The dose-effect relations depicted in Fig. 1 show that the WTN becomes highly disturbing at much lower levels compared to transportation noise, with a higher percentage of highly annoyed people at the same L_{den} level. This effect is mainly caused by the amplitude modulation typical of wind turbine generated sound and its intrusive character, present both day and night in a similar way, depending solely on the presence of wind. In particular, WTN resulted even more disturbing than the airport noise, known to be a very disturbing noise and widely studied for its high impact on population (Licitra et al., 2014).

Table 1
Linear regression coefficients (a, b), standard deviation (σ) and respective estimated variances and covariance, for the %HA statistical model for road, railway and aircraft (Miedema and Oudshoorn, 2001) and WTN (Janssen et al., 2011).

Parameter	Road	Aircraft	Railway	Wind turbine
a	−106.97	−91.42	−110.09	−226.88
b	2.22	2.17	2.10	5.48
σ	36.07	35.56	33.65	47.20
σ_a^2	15.3	10.88	40.04	369.09
σ_b^2	0.0023	0.0017	0.0071	0.21
$\sigma_{a,\,b}$	−0.146	−0.105	−0.478	−8.64

3.2. Conversion curves for equally highly annoyed exposed to different sources

As far as public health is regarded, the combination of different exposure curves in one relationship represents an important tool that could allow to consider people exposed to multiple sources and then directly compare the effects. Miedema (2004) and then Gille et al. (2016) tried to address the problem considering RTN as the reference source and then deriving equally annoying levels for aircraft and railway noise sources, obtaining a combined exposure-response relationship for transportation noise.

In the present paper the problem is addressed by obtaining a mathematical relation to directly convert noise exposure levels due to different sources, producing the same health effect on population which is measured by the percentage of highly annoyed people (%HA).

The approach used in this work treats the different sources separately, still using a common criterion for comparison. Instead of considering the noise levels at the same annoyance, as previous studies suggested, in this paper the relation between noise levels of different sources is achieved by considering equal percentages of highly annoyed people. Such a relationship would pave the way to the definition of noise law limits or indicators being homogeneous from a public health perspective.

The percentage of people annoyed by WTN is matched to the percentage annoyed by RTN, considered as the reference source, using the respective Miedema's statistical models:

$$P_C\,(L_{den,WTN}) = P_C\,(L_{den,RTN}) \tag{4}$$

The interpretation of Eq. (4) is straightforward, the exposure curves in Fig. 1 are compared at the same height (%HA), and the corresponding L_{den} values for different sources are therefore obtained. Eq. (4) provides a simple linear relation linking the noise levels for the two sources, dependent on the parameters of the two statistical model, including the standard deviations (σ):

$$L_{WTN}(L_{RTN}) = \frac{(\sigma_W\, a_R - \sigma_R a_W) + (\sigma_R - \sigma_W)\, C}{b_W\, \sigma_R} + \frac{b_R\, \sigma_W}{b_W\, \sigma_R} L_{RTN} \equiv A + B\, L_{RTN} \tag{5}$$

where W and R indicate here wind turbine noise or road traffic noise.

The linear relationship in Eq. (5) is defined as the conversion curves for equally highly annoyed exposed to different sources. The slope of the linear relation B depends on the slopes of the different annoyance models and on the standard deviations of the corresponding distributions, also conserving information on the variability of people's response to noise, in addition to the mean. The constant term A contains also the threshold C used to establish the category of annoyed people, %LA, %A, %HA.

The values of coefficients A and B are calculated using the parameters in Table 1 for highly annoyed people, and are reported in Table 2. The model described by Eq. (5) can also be used for Aircraft and Railway noise referring to RTN by selecting the correct parameters in Table 2. At the same time, also the reference source could be changed in order to compare a different couple of sources.

The conversion curves obtained for equally highly annoyed people exposed to different sources using RTN as reference noise are represented in Fig. 2. A slope of $B \simeq 1$, which occurs for aircraft and railway noises, means that the difference of perception between these sources and road noise remains constant while increasing noise levels. For WTN the difference increases evidently, since the parameter B for WTN is about the half of its value for both railway and aircraft noise.

For example, the noise levels at equal percentage of highly annoyed people respect to a road noise level of 60 dB(A) reported in Eq. (6) are obtained using the conversion curves in Eq. (5) with the parameters A and B in Table 2:

$$\begin{aligned} L_{den,WTN} &= A_{WTN} + B_{WTN}\, L_{den,Road} = 11.8 + 0.53 \times 60 = 43.6 \quad \text{dB(A)} \\ L_{den,Aircraft} &= A_{Aircraft} + B_{Aircraft}\, L_{den,Road} = -6 + 1.0086 \times 60 = 54.5 \quad \text{dB(A)} \\ L_{den,Railway} &= A_{Railway} + B_{Railway}\, L_{den,Road} = 7.2 + 0.986 \times 60 = 66.4 \quad \text{dB(A)} \end{aligned} \tag{6}$$

These exposure noise levels yield the same percentage of highly annoyed people, which can be calculated using the exposure-relationship in Eq. (2), obtaining a value %HA = 10.2%.

The converted noise levels should be considered valid only if lying within the range of applicability of their respective exposure curve. For transportation noise the Miedema's study includes data with L_{den} values between 42 and 75 dB(A), while for WTN Janssen considered data in a range of 39 ± 4.8 dB(A).

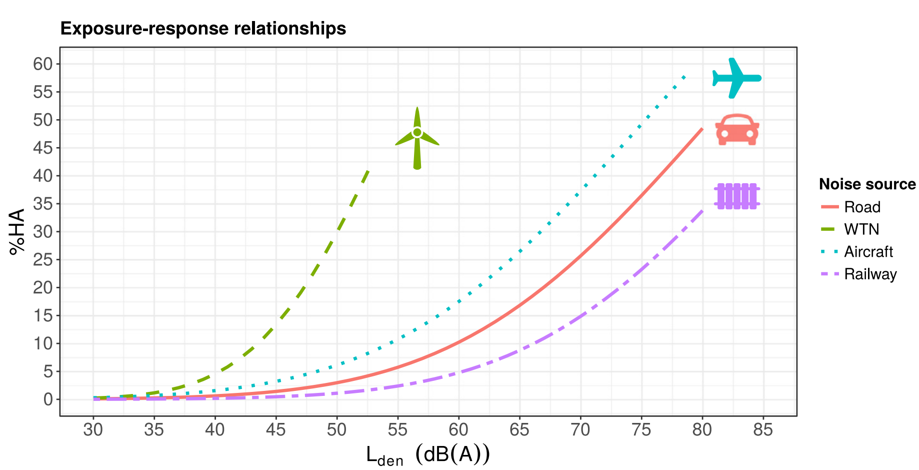

Fig. 1. Comparison of exposure-response relationships for people highly annoyed by road, railway, aircraft (Miedema and Oudshoorn, 2001) and WTN noise (Janssen et al., 2011).

Table 2
Conversion curves parameters A and B, calculated with Eq. (5) for road, railway, aircraft, wind turbines with RTN as a reference source.

Parameter	Road	Aircraft	Railway	Wind turbine
A [dB(A)]	0	−6.0	7.2	11.8
B [dB(A)]	1	1.0086	0.9863	0.530

Fig. 3 reports the differences between the conversion curves with RTN as a reference, that can be used to convert RTN levels into other sources ones having the same %HA or vice-versa. The conversion difference between exposure noise levels for railway and aircraft noise into an equivalent road noise level $D_{conv} = L_{source} - L_{road}$ is approximately constant. Therefore, railway noise results less disturbing than road noise, since a road noise level equal to 60 dB(A) is equivalent to $60 + 6.4 = 66.4$ dB(A); the difference D_{conv} varies within an interval equal to [6.1, 6.6] dB(A), which corresponds to a road noise range of [40, 80] dB(A).

For aircraft noise the conversion difference is −5.5 dB(A) at 60 dB (A) of road noise level, with the negative value indicating that the same percentage of highly annoyed people is reached at a lower noise level. The variation of the aircraft conversion difference is within an interval [−5.7, −5.3] dB(A) for a road noise range in [40, 80] dB(A).

For WTN the conversion difference shows its linear decreasing trend, which can be calculated with the conversion curves provided by Eq. (5), using the parameters A and B in Table 2, or equivalently, it is provided by Eq. (7).

$$\begin{aligned} D_{conv,WTN} &= A_{WTN} + B_{WTN}\, L_{den,Road} - L_{den,Road} \\ &= A_{WTN} + (B_{WTN} - 1) L_{den,Road} \end{aligned} \quad (7)$$

3.3. Confidence intervals for conversion curves

The confidence intervals for the conversion curves can be estimated using a similar approach to the methodology used to compute the conversion curves themselves. The approach is presented by comparing the reference source, traffic noise, with wind turbine noise, but the methodology can be applied to the other sources too. Given a certain level L_{RTN} for traffic noise, the confidence interval for the converted L_{WTN} level at the same %HA is estimated by considering both the confidence intervals for WTN and RTN. The confidence curves are directly compared instead of matching the %HA for the two sources as in Eq. (4). Unfortunately, the computations are more complex respect to the easiness observed for the conversion curves, an analytical computation is not feasible because of the non-linearity of the confidence curves. A numerical approach to calculate the intersections between them has then be used, as sketched in Fig. 4. The confidence limits for a L_{WTN} value are obtained by intersecting the upper confidence curves of RTN with the lower one for WTN, and vice-versa. The intersections are calculated by numerically computing the roots of Eq. (8) and repeating the procedure by variating the values of the %HA.

$$\begin{aligned} CL_{\%HA,WTN,Low}(L_{WTN}) &= CL_{\%HA,RTN,Up}(L_{RTN}) \rightarrow CL_{L_{WTN},Up}\ (L_{RTN}) \\ CL_{\%HA,WTN,Up}(L_{WTN}) &= CL_{\%HA,RTN,Low}(L_{RTN}) \rightarrow CL_{L_{WTN},Low}\ (L_{RTN}) \end{aligned} \quad (8)$$

The WTN conversion curve and the respective confidence intervals are reported in Fig. 5.

In order to provide an analytical expression for the estimated confidence curves for any value of L_{den}, the obtained numerical curves have been fitted by using the same standard functional form of the confidence intervals used for annoyance in Eq. (3) by Miedema, which is the confidence interval for a linear regression. In this way, also the coefficients of the covariance matrix S_W for the WTN conversion curve can be estimated. The differences between the numerical results and the fitted ones are negligible, in particular the upper analytical confidence curve perfectly overlaps the numerical one, while the lower analytical confidence curve results slightly more conservative respect to the numerical. Therefore, the confidence limits for a WTN converted noise level can be calculated with Eq. (9) by using the coefficients reported in Table 3.

$$\begin{aligned} CL_{L_{WTN},\alpha} &= \boldsymbol{X^t Y} \pm k(\alpha)\sqrt{\boldsymbol{X^t S_W X}} = A + B\, L_{RTN} \\ &\pm k(\alpha)\sqrt{\sigma_A^2 + 2\sigma_{A,B} L_{RTN} + \sigma_B^2 L_{RTN}^2} \end{aligned} \quad (9)$$

with $\boldsymbol{X} = \begin{bmatrix} 1 \\ L_{RTN} \end{bmatrix}$, $\boldsymbol{Y} = \begin{bmatrix} A \\ B \end{bmatrix}$, $\boldsymbol{S_W} = \begin{bmatrix} \sigma_A^2 & \sigma_{A,B} \\ \sigma_{A,B} & \sigma_B^2 \end{bmatrix}$.

For example, in order to estimate the 95% confidence limits of the WTN converted noise level equivalent to 60 dB(A) of RTN, Eq. (9) is computed with the values reported in Table 3:

$$L_{den,WTN} = A_{WTN} + B_{WTN}\, L_{den,Road} = 11.8 + 0.53 \times 60 = 43.6 \text{ dB(A)}$$

$$\begin{aligned} CL_{L_{WTN},95\%} &= 43.6 \pm 1.96\sqrt{\sigma_A^2 + 2\sigma_{A,B} L_{RTN} + \sigma_B^2 L_{RTN}^2} \\ &= (40.9, 46.3) \text{ dB(A)} \end{aligned}$$

4. Results: WTN limits derived by conversion curves

The conversion curves for equally highly annoyed people exposed to different sources offer a direct comparison between the noise level exposures to different sources. The comparison can be exploited to obtain

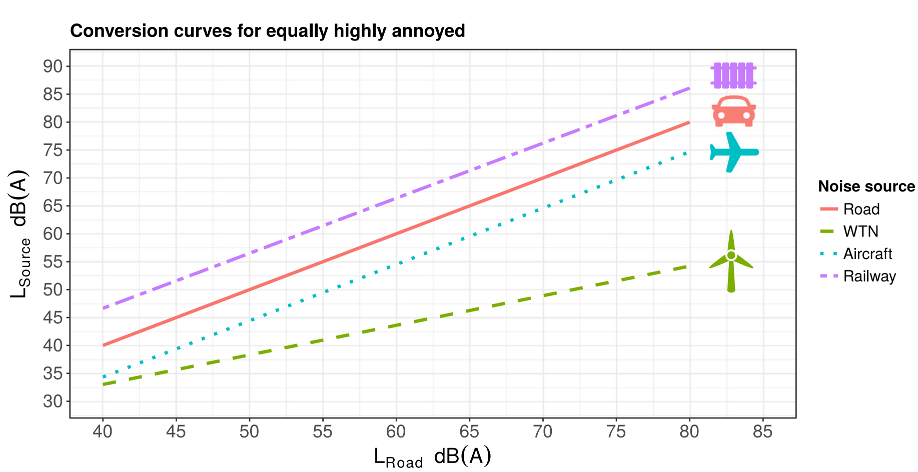

Fig. 2. Conversion curves, with RTN used as a reference.

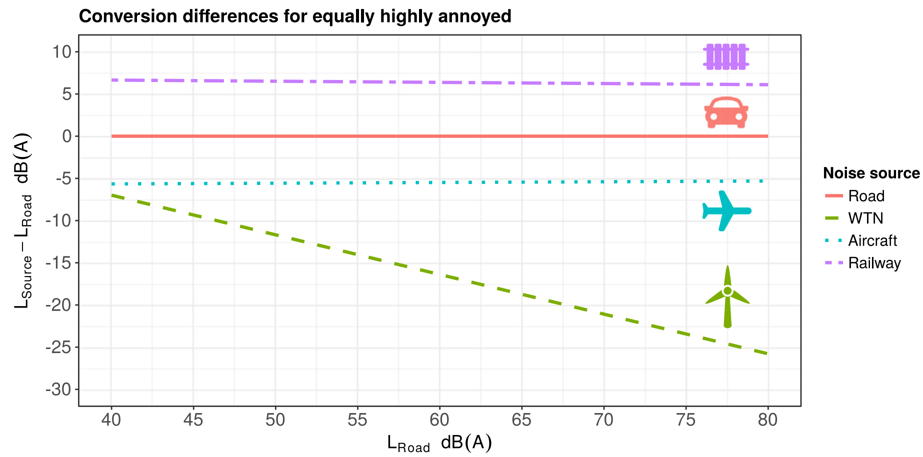

Fig. 3. Conversion differences for highly annoyed people, with RTN used as a reference.

homogeneous law limits considering the same response of the population to noise.

In particular, a WTN limit can be calculated, on the basis of the well-established limits for RTN. For this purpose, the Italian law limits for traffic noise during daytime and night-time are used, which are equal or similar to those of many European countries (Milieu Ltd., 2010).

The calculation is based on the assumption that the %HA correspondent to RTN is considered tolerable according to the generic Italian noise limits. This percentage should be the same for each type of source for a uniformity in the treatment of people exposed to noise, given that the specificity of the source is already considered in the diversity of the exposure-response relationship.

The limit is derived according to the following three steps, sketched in Fig. 4 and described in the following:

1. Conversion from L_{Aeq} to L_{den} of the Italian law limits for RTN;
2. Calculation of the equal highly annoying noise level for WTN;
3. Conversion back from $L_{den,\ WTN}$ to L_{Aeq} to establish the law limit.

4.1. Conversion from L_{Aeq} to L_{den} of the Italian RTN limits

The maximum noise level admitted in Italy (Italian Law 447, 1995) for outdoor RTN is 70 dB(A) during daytime (day and evening) and 60 dB(A) during night-time for a distance equal to 100 m from every type of road, except the very local ones. These limits are also almost the same as or similar to those in most European countries, including the Czech Republic, France, Germany, Netherlands, Spain, Sweden (Milieu Ltd., 2010).

The transformation of L_{Aeq} in L_{den} is performed using Eq. (10) (Makarewicz and Galuszka, 2011), derived by Eq. (1) and adapted according to the definition of L_{den} in Italy that considers only 2 h for evening period and 14 for the day period:

$$L_{den} = 10\log_{10}\left(\frac{14}{24}\times 10^{0.1\cdot L_{Day}} + \frac{2\cdot\sqrt{10}}{24}\times 10^{0.1\cdot L_{Evening}} + \frac{8\cdot 10}{24}\times 10^{0.1\cdot L_{Night}}\right) \tag{10}$$

Assuming a road where the noise is exactly equal to the limit, the L_{den} corresponding to the limits in Italy for roads is 70.7 dB(A).

4.2. Calculation of the equally highly annoying noise level for WTN

The equally highly annoying noise level for WTN reported in Eq. (11) is calculated using Eq. (5) with the values in Table 2.

$$L_{den,WTN} = A + B\,L_{den,Road} = 11.8 + 0.53\times 70.7 = 49.3\ \text{dB(A)} \tag{11}$$

Thus, the WTN level that causes the same %HA of the Italian limit for RTN, expressed in terms of L_{den} is 49.3 dB(A). The confidence interval for this value has been estimated using Eq. (9):

$$\begin{aligned} CL_{L_{den,WTN},95\%} &= 49.3 \pm 1.96\sqrt{\sigma_A^2 + 2\sigma_{A,B}L_{RTN} + \sigma_B^2 L_{RTN}^2} \\ &= (45.9, 52.7)\ \text{dB(A)} \end{aligned} \tag{12}$$

The 49.3 dB(A) converted noise level is close to the upper bound of applicability of the WTN exposure-response relationship, but can still

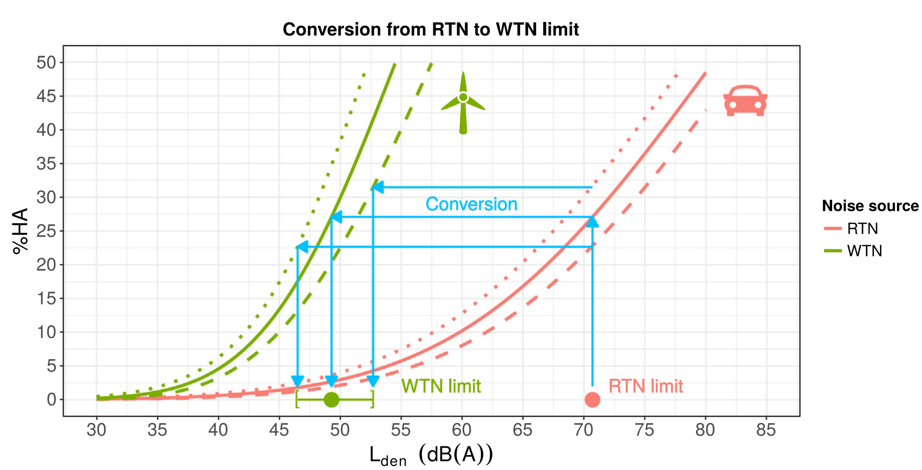

Fig. 4. Conversion from RTN limit to WTN, including 95% confidence intervals.

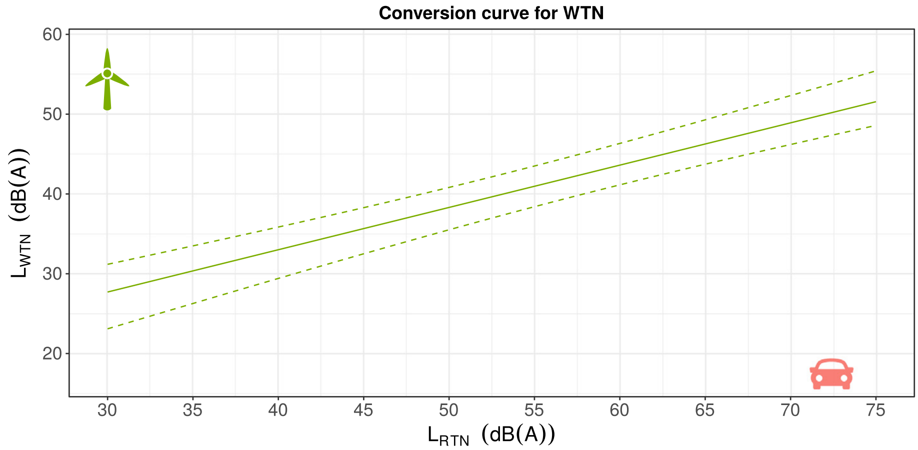

Fig. 5. Conversion curves for WTN with 95% confidence intervals, using RTN as reference.

be considered valid within the uncertainties. However, a national limit higher than the Italian one can eventually fall outside the validity ranges of the WTN exposure-response relationship.

4.3. Conversion from $L_{den,\ WTN}$ to L_{Aeq} to establish the limit

The L_{Aeq} value corresponding to the L_{den} previously estimated is calculated by inverting Eq. (10), which considers a constant noise throughout the day and the Italians day evening night periods (14 h a day, 2 evening, 8 night). The confidence limits are estimated with the same procedure, applied to the L_{den} confidence limits of Eq. (12), obtaining:

$$L_{Aeq,WTN\ limit} = 43.1\ \text{dB}(A),\quad \text{with}\ CL_{LAeq,WTN\ limit,95\%} = (\ 39.7, 46.5\ )\ \text{dB}(A) \tag{13}$$

The obtained 43.1 dB(A) noise level and its confidence interval could be considered for a proposal of a WTN limit for Italian legislation, but also for many other States having similar traffic noise limits. The confidence limits should be interpreted as a range of choice for policy makers to discuss the definition of WTN limits. A 40 dB(A) limit may represent a minimum limit value in a conservative approach to WTN. Instead, the upper confidence limit of about 46.5 dB(A) should be considered as a maximum threshold to not be exceeded in order to protect public health. The authors consider that a 43 dB(A) L_{Aeq} noise level it is a reasonable value for a balanced WTN limit proposal for Italian legislation.

By means of an analogous process it could be possible to calculate limits for any legislation, considering different traffic noise limits as a starting point.

5. Discussion

In the first parts of the paper a review of literature has been performed in order to quantify the threshold noise level that may already cause inconveniences to citizens. A lack of specific studies for WTN and its effects on health, especially at low noise levels has emerged quite clearly. Direct effects have not been reported yet in peer reviewed papers (Kurpas et al., 2013), and health problems referred to as "indirect" are often disregarded, although they represent the main negative effects of exposure to low noise levels. The result is that 40 dB(A) of WTN can be enough to cause a fair percentage of annoyance among citizens, as inferred from dose-effect curves based on the %HA. At this support, the effect of annoyance on human health has been reported. As also highlighted by the World Health Organization and by other scientists that recognize the key role of annoyance in health assessment, this noise level is already sufficient to negatively affect not only sleep, but outdoors social activities too, especially during summer. It is not by chance that the WHO has identified an annual average night-time noise level outdoor of 40 dB(A) as threshold to protect citizens' health from noise, the WHO recommended value is based on night-time road/rail/air traffic noise sources, but this value can be valid especially for the more disturbing wind turbines, as shown by the comparison of dose-effect relationships.

Table 3
Coefficients for the WTN conversion curve and its confidence limits.

A	B	σ_A^2	σ_B^2	$\sigma_{A,\ B}$
11.8	0.530	10.07	0.0034	−0.169

The particular acoustic characteristics of wind turbines are the cause of such a high annoyance perceived by population. In fact, noise comes from a height above the receiver and the sound that arrives to receivers is amplitude modulated with a constant change in its depth that increases attention and cognitive appraisal and reappraisal, inhibiting acclimatization to sound (Stigwood et al., 2013). The predominantly rural position of wind turbines may contribute to increase the annoyance response to WTN, where people do not expect to hear intrusive noise. In addition to the ambient noise level, the expectations of a living environment could influence an individual's appraisal of an uncontrollable sound. The special characteristics of omnipresence, periodic and amplitude modulated nature, random occurrence and low frequency content make WTN a very annoying sound (von Hunerbein, 2013; Lee et al., 2011), and are the cause of profound discomfort caused by WTN to the population even at low noise levels.

Unfortunately, WTN is a nearly constant noise and 40–45 dB(A) can be often achieved during the night for the typical distances at which the receivers are actually located in the quiet country areas, for which the U.K. suggested a noise limit between 37 and 44 dB(A) in the condition of low background noise, based on tranquillity surveys (Watts and Pheasant, 2015).

The conversion curves are obtained in Section 3.2 comparing the dose-response relationship for different sources at the same percentages of highly annoyed people, using the road traffic noise as reference values. These curves permit to directly compare the noise levels produced by different sources having the same annoyance on people, and can then be used to establish noise limits founded on a homogeneous public health effect.

The study is based on Miedema's (Miedema and Oudshoorn, 2001) and Janssen's study (Janssen et al., 2011). Some recent studies have found differences in people response to noise (Gille et al., 2016; Licitra et al., 2016) respect to Miedema's study but, given its large population, it can still represent the milestone of dose-effect relationship for noise annoyance to transport noise. At the same time, Janssen's study is the wider dose-effect relationship study but is only focused on north European Countries, whose habitants may have different noise tolerability respect to other areas. An updated version of both Miedema and Janssen's studies, with recent data and interview from a more Countries would be very welcomed by the scientific community. Especially for WTN, a study that combines Janssen's north Europe data with the other subsequent Japanese, Polish and Canadian ones would be useful.

The limit value of 43 dB(A) for the equivalent continuous sound pressure level L_{Aeq} derived for WTN has been determined using the conversion curves applied to the Italian limit for RTN during daytime and night-time, which are equal or similar to those of many European countries. A first conversion of RTN Italian limit in L_{Aeq} to the equivalent L_{den} and the WTN limit in L_{den} to L_{Aeq} have been performed by using the definition formula of L_{den}.

The obtained 95% confidence limits (39.7,46.5) dB(A) represents a reasonable interval for choosing a law limit for WTN and includes both the RTN and WTN 95% confidence intervals for the exposure-response relationships. In general, a confidence interval sets bounds for the average result by taking into account only the available data. In the present analysis, the studies by Janssen and Miedema are assumed as the reference and basis of the results. Therefore, further data collection could be useful in order to validate the obtained results and verify its applicability to populations different from those considered in these studies.

The conversion from L_{den} in L_{Aeq}, performed by inverting Eq. (10) resulted in the subtraction of a value of 6.2 dB from L_{den} with the assumption that noise throughout the day is constant. Furthermore, it does not take into account the variability of wind turbine operations and assumes that the wind turbine is operating at its maximum sound level 100% of the time. Such an assumption leads to a WTN limit that is more conservative for citizens than subtracting a lower value, which would have been by not assuming constant and maximum noise through the day. Even if in the epidemiological studies WTN is not considered constant during the day, but is simulated with noise model with a wind distribution over time as input, a difference of 6.2 dB is coherent with the few studies in the literature.

In fact, the outdoor A-weighted sound pressure levels used in Janssen's exposure-response relationship were simulated with a noise model considering the nearest wind turbine, in 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). In this study, sound levels were calculated in 2 different wind farms, where measured wind speed data were available for time spans of 11 and 7 years. Thus, with the distributions of wind speed were directly obtained the L_{day}, $L_{evening}$ and L_{night} at receivers on annual basis through a wind class calculation. The L_{den} on annual basis was then calculated using Eq. (1). Van den Berg found that the difference varies with sound power (i.e. wind speed) when subtracting to L_{den} the contribution to the sound power due to wind speed, which, for example, at 8 m/s corresponds to 4.7 ± 1.5 dB(A), with uncertainties due to the height, location and type of turbine. This delta value is exactly the value Janssen et al. used to convert L_{Aeq} at receivers into L_{den} in order to construct the dose-response curve.

The 6.2 dB(A) obtained in the present work is within the uncertainty boundaries of Van den Berg's coefficient, equal to 4.7 ± 1.5 dB(A). Thus, converting L_{den} in L_{Aeq} subtracting 6.2 dB(A) is an operation respecting the studies in the field of meteorological variability without neglecting the fact that the emission can vary during the year.

At last, the regulations typically establish limit values increasing with residual noise, and therefore with wind speed. The derivation of a limit value with general validity is complex, because residual noise levels depend exclusively on the environmental and weather conditions of the measurement site. The measuring procedure becomes determinant with respect to the results, which depend on many factors, such as wind, direction of sound propagation, the presence of any other source and distance from obstacles. Also the presence of vegetation, which varies seasonally, could influences the outcome of a measurement campaign which may result in exceeding the limit or not if carried out in winter rather than summer. Thus, in any legislation, the period and duration of residual noise measurement campaigns have to be chosen very carefully.

6. Conclusions

The promotion of the growth of wind energy has a strong impetus and is supported by many organizations around the world. However, citizens and installers require accurate information on the environmental impact that this fairly new technology causes, as well as any other possible source of pollutants, in order to improve the integration of wind farms in the territory and the control of environmental impact assessment for either existing or planned wind farms.

In this context, the paper suggested a limit value L_{Aeq} of 43 dB(A) for wind turbine noise (WTN), based on the assumption that the tolerated percentage of highly annoyed (%HA) correspondent to a certain noise limit for a source should be the same for each type of source for a uniformity in the treatment of people exposed to noise. Road traffic noise (RTN) has been chosen to be the reference because is the most diffused noise in modern society. According to many European Countries (such as Italy, Czech Republic, France, Germany, Netherlands, Spain, Sweden), and in particular according to Miedema's study (Miedema and Oudshoorn, 2001), the allowed %HA corresponding to RTN limits is 26.2%. The limit has been obtained using the newly introduced conversion curves for WTN and RTN. These curves have been obtained combining Janssen (Janssen et al., 2011) and Miedema's study and allow a direct comparison between the noise levels exposure to different sources.

A 95% confidence interval (39.7,46.5) dB(A) for the suggested 43 dB (A) limit has been estimated, representing a reasonable range for a WTN law limit choice. The policy makers have the final responsibility to address the problem of fixing law limits, but a conservative or loose approach to WTN protection should take into account the bounds of the estimated confidence interval. The authors consider that the suggested 43 dB(A) limit value could be appropriate for a balanced approach to WTN protection.

The conversion from L_{den} to L_{Aeq} agrees with the empirical conversion factor found by van den Berg. Thus, the methodology proposed is not only precautionary, since it considers the source as uniform during the day and night, but it is coherent with the experimental study on meteorological variability, without neglecting the variability of the emission during the year.

The obtained limit value of 43 dB(A) for L_{Aeq} results comparable with the British and Danish standards and is consistent with the analyzed health effects occurring at low noise levels. In fact, in literature it can be found that 40 dB(A) is a sufficient level to induce annoyance and sleep disorders, which are important effects that must be considered to ensure people's health.

The conversion curves for equally highly annoyed people exposed to different sources represent a useful tool that can be used to check the coherence, from a health point of view, between limits for different noise sources. The methodology is suitable to update limits for countries which still have no specific limits for wind turbine noise or other sources, as well as provide a scientific criterion to address the disputes between citizens and the wind farms operators.

Further and local socio acoustical studies would be useful in order to improve the local and up to date reliability of exposure-response relationship for each source.

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