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Environmental noise assessment of proposed wind farms using annual average L_{dn}

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Summary

One problem when performing environmental noise assessments for wind farm permitting is that there is no consideration of the frequency of occurrence of best or worst case propagation conditions. For example, it is intuitive to think that residents that are downwind of a wind farm for 5% of the year would be less annoyed than residents that are downwind for 50% of the year, everything else being equal. One approach to address this problem is to calculate the annual average L_{dn}, based on a distribution of noise emission and propagation classes using real weather statistics. In this example scenario, the annual average noise immission was calculated using one year of weather statistics and example wind turbine generator (WTG) sound power levels. Noise predictions were performed for 28 classes using the Harmonoise/IMAGINE approach to estimate the annual average L_{dn}. Prediction results were compared with conventional modelling best practices using ISO 9613. It was found that significant differences could exist depending on the approach and that further work should be performed to validate prediction methods and approaches for accurate wind turbine noise assessment.

1. Introduction

In British Columbia, environmental noise from proposed wind farms is currently evaluated based on assumed worst case conditions using ISO 9613 (ISO 1996). However, it is generally accepted that human annoyance due to environmental noise is based on long term conditions and that annual average noise levels are preferred to assess environmental noise (ANSI 2007, European Commission 2002, ISO 2003), including noise from wind farms (Janssen et al. 2010). Wind farm noise immission is highly variable due to time-varying noise emission and weather conditions (because of long propagation distances).

The real weather conditions from the below example scenario indicated that worst case conditions would only occur for about 3-4% of the year, prompting the audition of an approach that would take varying conditions into account. Some have proposed assessing wind farm noise using annual average levels based on varying noise emission (van den Berg 2010). Others have discussed incorporating varying propagation conditions for wind farms (Sorensen et al. 2009) and for other environmental noise sources (Eurasto 2006) to produce annual average levels. There is an ISO standard that describes a more detailed approach for statistical assessment of predicted noise levels in different propagation conditions (ISO 2009). Considerable efforts were made in this area by the European Harmonoise and IMAGINE workgroups (Nota et al. 2005, Beuving and Hemsworth 2007), with the development of a point-to-point Harmonoise propagation model (Van Maercke 2004) now implemented in commercial outdoor sound propagation software. The earlier developed Nord2000 prediction method has provided similar results to Harmonoise (Gunnar and Jacobsen 2008) and is also now commercially available for predicting noise in varying propagation conditions. Nord2000 has been validated for wind turbine scenarios under downwind and upwind conditions, over flat and non-flat terrain, with distances up to 1500 m (Plovsing and Sondergaard 2011).

This paper summarizes one case study investigating results produced by different available approaches with ISO 9613 and Harmonoise/IMAGINE predictions.

2. Emission and propagation classes

Time varying parameters that may significantly affect noise immission levels from wind farms include:

- WTG sound power
- Wind speed
- Wind shear
- Wind direction
- Solar radiation
- Cloud cover
- Turbulence
- Ground conditions (dry, wet, ice cover, snow cover, etc.)
- Temperature
- Relative humidity

Wind speed affects the strength of wind and temperature gradients and the sound power produced by the WTG's. These variables are related by wind shear since they are assessed at different heights; the wind speed at a height of 10 m can be used to rate the wind class (Beuving and Hemsworth 2007) and the wind speed at the wind turbine hub height is used to best determine the WTG operating condition. WTG sound power levels are rated according to a "derived" wind speed at a 10 m height, assuming a standardized roughness length (IEC 2012). Therefore, the actual wind speed at 10 m should be assumed to be different.

Adequate assessment of noise levels in each emission and propagation class combination would require thousands of predictions per source-receiver pair. Some have suggested that the evaluation of 9 or 25 propagation classes are necessary to obtain accurate results (Heimann and Salomons 2004, Plovsing 2007). Others have suggested that important variables such as turbulence are not being adequately assessed even with state-of-the-art engineering methods (Maijala 2011). The IMAGINE workgroup proposed that only four propagation classes would be required to obtain accurate predictions of annual average noise levels for strategic noise mapping according to the parameter *D/R*, the product of the propagation distance (*D*) and inverse ray curvature (*1/R*). Van Maercke outlined an approach to classify meteorological data into the four groups summarized in Table 1 (Van Maercke 2006a) and included a further adjustment for long range sound propagation mentioned in the release notes for version 2.012 of the Harmonoise P2P software (Van Maercke 2006b).

Table 1: IMAGINE propagation classes M1 to M4 using propagation distance (*D*) and ray curvature (*R*)

Propagation Class	*D/R* Range	*D/R* Representative Value	Description
M1	< -0.04	-0.08	Unfavourable
M2	-0.04 to 0.04	0.00	Neutral
M3	0.04 to 0.12	0.08	Favourable
M4	> 0.12	0.16	Very favourable

Three time varying inputs are required to estimate *D/R* in Van Maercke's approach: wind speed, wind direction and cloud cover. Solar radiation is assumed based on the cloud cover rating. Following this approach and ignoring the variation in turbulence, ground conditions, temperature and relative humidity, the number of required scenarios would then be the product of the four propagation classes and number of WTG emission classes. For the assessed example, sound power data was available for seven emission classes (at 10 m height derived wind speeds from 3 m/s to 9 m/s), corresponding to 28 unique classes per source-receiver pair.

3. Site specific conditions and proposed wind turbines

This example scenario includes two WTG's at the same theoretical coordinates, with hub height 84 m above the ground, and one receiver, at 4 m above the ground, separated by 1000 m of flat, soft ground.

The proposed A-weighted sound power levels at each measured source emission condition are shown in Table 2. It was assumed that the sound power would be zero at wind speeds below 2.5 m/s (the reported WTG cut-in speed was 3 m/s) and that it would be the same as the 9 m/s sound power at wind speeds above 9 m/s.

Table 2: Example WTG sound power level data (dBA) at different 10 m height derived wind speeds (m/s)

3	4	5	6	7	8	9	10
97.9	100.4	104.3	106.3	107.0	106.1	105.3	105.3

A one year period of meteorological data measured on site was analyzed to determine the day and night frequency of occurrence of different conditions. Data was collected in 10 minute intervals, including wind speeds, wind direction, temperature and relative humidity. Wind speeds were measured at two heights, one more than 60% of the proposed turbine hub height and the other more than 15 m below it, meeting UK Institute of Acoustics (IOA) best practice (IOA 2013). Actual wind speeds at a height of 10 m were calculated using the 10 minute wind shear value and 10 m height derived wind speeds were calculated based on the actual speed at hub height using the standard roughness length. Solar radiation and cloud cover were not measured. Therefore, (not simultaneous) monthly cloud cover data from a neighbouring city's weather station was used to estimate the occurrence of clear and cloudy skies on site. The data was split into day and night periods using 7:00 am and 10:00 pm cut-off times and not actual sunrise and sunset data.

A number of noise significant weather observations were made after analyzing the weather data:

1. With a cut-in speed of 3 m/s, the WTG's would not operate for 22-23% of the year, as shown in Figure 1.

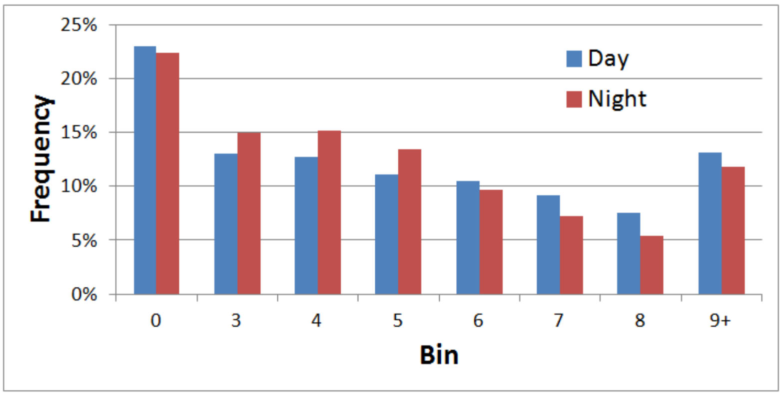

Figure 1: Histogram of 10 m height derived wind speed (m/s) corresponding to WTG operating conditions.

2. The wind farm site would normally operate directly upwind of the receiver, as illustrated by the statistics for wind direction and actual 10 m height wind speed downwind component (during conditions when the 10 m height derived wind speed was greater than 2.5 m/s) in Figure 2. There was a downwind component for 26% of the day and 24% of the night.

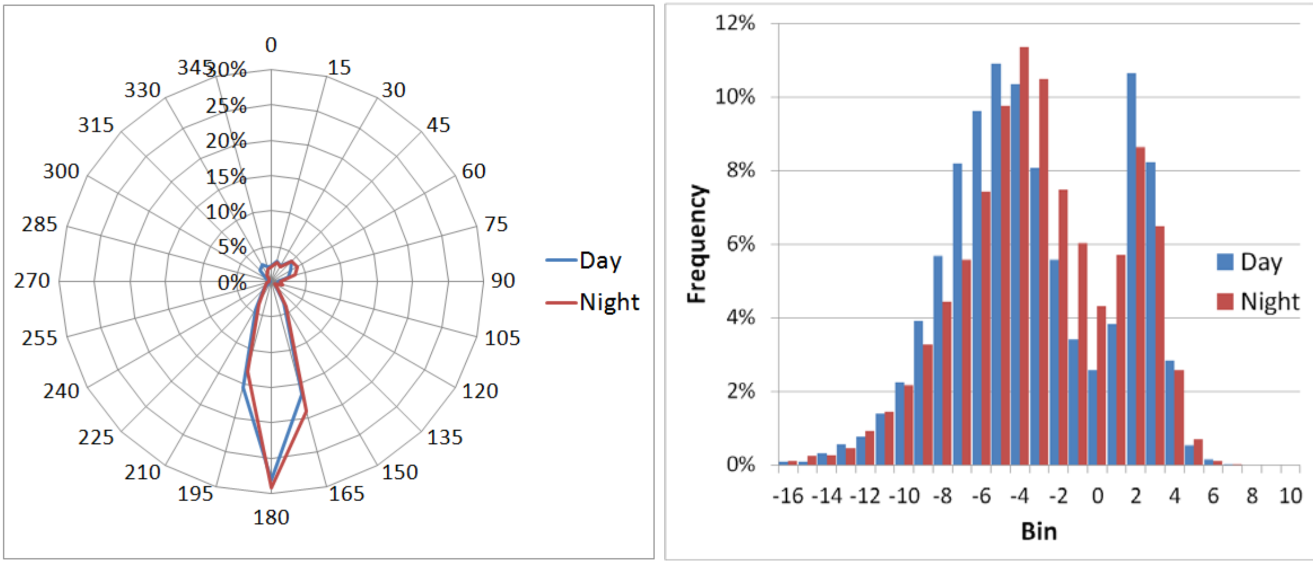

Figure 2: Wind rose and 10 m height actual wind speed component (m/s) histogram showing the lack of project site downwind conditions, with downwind conditions corresponding to a direction of 0° and a positive wind speed component.

3. Overcast conditions occurred for approximately half of the year, reducing the occurrence of favourable (during the night) and unfavourable (during the day) propagation conditions.

4. ISO 9613 results

ISO 9613 predictions were performed using Cadna/A software in 1/1 octave bands. The ground absorption was set to G=0.5 per the IOA wind turbine noise best practice guide (IOA 2013). Table 3 summarizes the predicted L_{eq} for each 10 m derived wind speed operating class.

Table 3: Predicted L_{eq} and day/night percentage occurrence per 10 m height derived wind speed (m/s) source emission class.

	3	4	5	6	7	8	9
L_{eq}	25 dBA	27 dBA	31 dBA	33 dBA	34 dBA	33 dBA	32 dBA
p,day	13%	13%	11%	11%	9%	7%	13%
p,night	15%	15%	13%	10%	7%	5%	12%

A worst case 24 hour period would consist of the WTG operating with a 10 m derived wind speed of 7 m/s for 24 hours continuously, resulting in day and night L_{eq} of 33.6 dBA and an L_{dn} of 40.0 dBA.

The annual average L_{eq}, based on the percentage occurrence of each emission class throughout the year of meteorological data, was calculated to be 29.9 dBA for the day period and 29.6 dBA for the night period, resulting in an annual average L_{dn} of 36.0 dBA.

5. Harmonoise/IMAGINE (H/I) results

The Harmonoise P2P software version 2.016 was used to calculate the excess attenuation for four propagation conditions in 1/3 octave bands, following Van Maercke's approach[1] and using the representative *D/R* values for each class from Table 1.The calculation results accounted for refraction, ground effect (80 kPA*s/m^2) and air absorption (15 °C and 70 % RH*)*. Additional corrections were made for distance and varying sound power using a spreadsheet. Tables 4 to 6 summarize the results per noise immission class and Figure 3 provides a histogram of predicted immission levels in 1 dB bins.

[1] The only deviation was that *cosφ* was not squared in the calculation of *B*

Table 4: Predicted L_{eq} (dBA) for varying 10 m height derived wind speed (m/s) source and propagation (*M1* to *M4*) classes.

	0	3	4	5	6	7	8	9
M1	0	23	26	30	32	33	32	31
M2	0	27	29	33	35	36	35	34
M3	0	27	29	33	35	36	35	34
M4	0	28	30	34	36	37	36	35

Table 5: Percentage occurrence of source (10 m height derived wind speed, m/s) and propagation (*M1* to *M4*) classes during the day.

	0	3	4	5	6	7	8	9	Sum
M1		5%	7%	8%	9%	8%	7%	13%	56%
M2		7%	5%	3%	2%	1%	0%	0%	18%
M3		1%	1%	0%	0%	0%	0%	0%	3%
M4		0%	0%	0%	0%	0%	0%	0%	0%
WTG OFF	23%								

Table 6: Percentage occurrence of source (10 m height derived wind speed, m/s) and propagation (*M1* to *M4*) classes during the night.

	0	3	4	5	6	7	8	9	Sum
M1		6%	9%	10%	8%	6%	5%	11%	55%
M2		1%	1%	0%	0%	0%	0%	0%	2%
M3		1%	1%	1%	0%	0%	0%	0%	2%
M4		7%	5%	3%	1%	1%	1%	1%	18%
WTG OFF	22%								

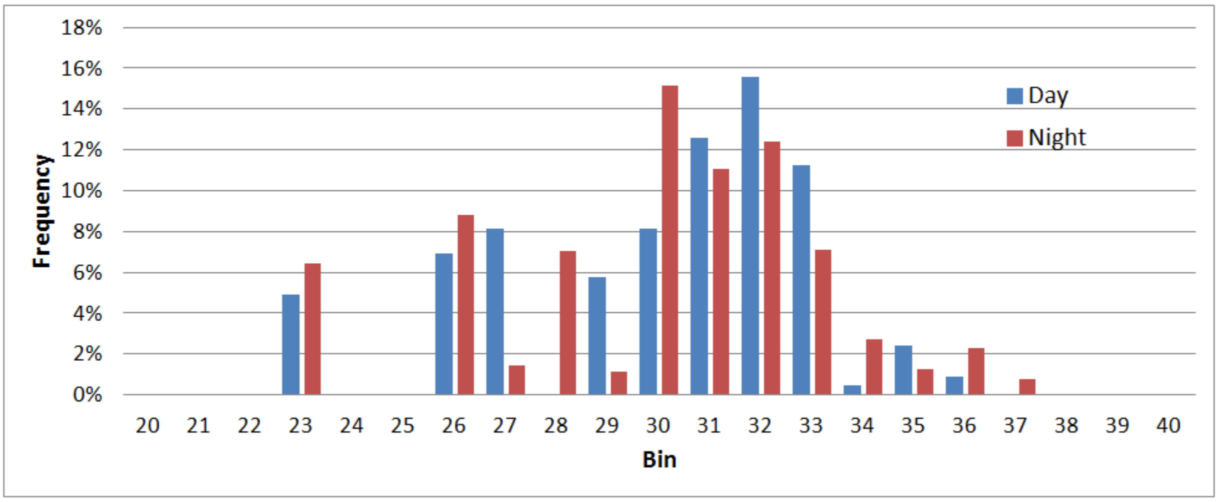

Figure 3: Histogram of predicted noise immission levels (dBA) based on the occurrence of source and propagation classes.

According to these results, "worst case conditions", let's say within 2 dBA of the maximum predicted level, i.e. 35-37 dBA, would occur for 3.3% of the day and 4.4% of the night. The annual average L_{eq} would be 29.9 dBA for the day period and 30.0 for the night period, giving an annual average L_{dn} of 36.4 dBA.

6. Discussion

The following observations were made after analyzing the results:

1. The "worst case result" was significantly higher using the H/I method (37 dBA) compared to the ISO method (34 dBA). Harmonoise is presumably accurate for wind turbine noise prediction (Plovsing and Sondergaard 2011) but detailed validation studies have not been performed, whereas numerous studies have been performed comparing

measurements to ISO 9613 predictions, with good overall agreement found (IOA 2013). It would make sense that Harmonoise would predict a more extreme worst case result since it is intended to cover a large range of propagation conditions. Whether that is useful for an environmental assessment or not depends on whether it is considered accurate and on the frequency of occurrence of extreme propagation conditions.

2. It is somewhat amusing to see that the ISO 9613 and Harmonoise/IMAGINE annual average results were identical, as summarized in Table 7. However, they were the same for different reasons. The ISO annual average results were controlled by the occurrence of different 10 m height derived wind speeds while the H/I annual average results were also significantly affected by the occurrence of *M1* propagation conditions. For example, it appears that the H/I results would have been 1 dB lower if a fifth propagation class for “very unfavourable” conditions was included (with *D/R* less than -0.12). Another way to look at it is to note that the H/I results would have been 2-3 dBA higher than the ISO 9613 annual average results if the wind directions were 180 degrees different, as summarized by the last column in Table 7. This comparison provides only one data point and is not predictive for other projects.

Table 7: Summary of annual average results using ISO 9613 and Harmonoise/IMAGINE (H/I) methods.

Metric	ISO 9613 worst case	ISO 9613 annual average	H/I annual average	H/I annual average (with opposite wind directions)
L_d	34	30	30	32
L_n	34	30	30	32
L_{dn}	40	36	36	39

3. That the H/I results for *M2* and *M3* were identical (and *M4* only 1 dBA different) may indicate a limitation in the usefulness of the *D/R* metric to delineate four unique propagation classes as originally intended by the IMAGINE project. Perhaps a correction for source/receiver height is also required in addition to the propagation distance to ensure that the four propagation conditions adequately cover the range of potential noise classes important for the production of annual average levels.

4. The analysis could be improved by:

    a. Using a greater number of propagation classes
    b. Using simultaneous cloud cover data
    c. Using actual sunrise and sunset times to separate day and night weather data
    d. Further examination of the calculation of the *A* and *B* (lin. and log.) propagation constants from meteorological data
    e. Comparing results with Nord2000 results
    f. Performing field measurements to validate predictions

5. The use of the method outlined in ISO 13474 to produce a cumulative distribution of (exceedance/percentile) noise levels may be desirable in cases where an operating wind turbine farm’s compliance is established using a statistical value. The environmental assessment would then be able to proactively estimate whether compliance would be likely or not with an “apples to apples” comparison. This would presumably require the assessment of more than four propagation classes, increasing the complexity of the study.

7. Conclusions

There appears to be a lot of scrutiny being placed on wind turbine environmental noise assessments these days (in North America at least), with perhaps much of it warranted. However, this author has seen regulatory bodies ask for a much higher level of detail than ever requested on other much noisier industrial and transportation projects. Assessing noise levels under different propagation conditions could help to address concerns or at least assist with establishing the sensitivity of the project with respect to noise. However, the Harmonoise propagation model doesn't currently have the industry acceptance of ISO 9613 and has not been validated with comprehensive field measurements addressing wind turbine noise relevant factors.

Prescribing annual average noise limits and performing sound emission annual averaging along with ISO 9613 noise predictions seems to be the logical next step in providing a more accurate picture of potential wind turbine noise impacts. It appears that incorporating varying propagation conditions into these assessments will require more field validation work before being considered industry best practice.

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