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Using Measured Sound Power Inputs for Comparison of Measured Immission Noise Levels and Sound Levels Predicted with ISO 9613-2 for Various Ground Factors.

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Summary

In order to minimize the risk of adverse effect from a proposed wind facility, predictive modelling is often used as a pre-construction assessment method. In Ontario and elsewhere in the world, ISO 9613-2 is used to predict the noise impact from industrial noise sources, including wind facilities.

ISO 9613-2 makes use of several modelling parameters which affect the predicted attenuation over distance. The ground factor, G, dictates the degree of attenuation provided by the interaction of the wave front and the ground between a source and a receiver. Values between 0 and 1, representing perfectly reflective and perfectly absorptive ground, respectively, have been applied in the context of industrial noise modelling. There remains a lack of consensus within the industry on the appropriate ground factor to be used during the modelling for the permitting process for a wind farm. Studies have been performed assessing the applicability of various ground factors by comparing the sound levels predicted with ISO 9613-2 and those measured on site.

This study seeks to add further context to the comparison of these levels by using the sound levels measured according to IEC 61400-11 for inputs as noise source power levels in the model and making predictions at five locations across four wind farms. The cumulative impact from all relevant turbines has been assessed at each of the five locations using ground factors between 0.0 and 0.8. These predicted sound levels are then compared to average measured sound pressure levels from high-quality datasets collected at the same locations. These noise measurements are conducted such that the worst-case impact from the wind facility is assessed.

Comparison of the measured and predicted sound levels across all sites shows a trend indicating that lower values of G, between G=0.2 and G=0.4, may be most appropriate to accurately predict the sound levels on site, providing that the actual turbine emission levels and spectra closely match those of the specification. To further reduce the degree of uncertainty in these calculations, additional work to expand the assessment dataset is planned. Additionally, steps will be taken to more accurately quantify the uncertainty inherent to the immission measurements.

1. Introduction

In order to minimize the risk of adverse effect from a proposed wind facility, predictive modelling is often used as a pre-construction assessment method. In Ontario, and elsewhere in the world, ISO 9613-2 [1] is used to predict the noise impact from industrial noise sources, including wind facilities.

Although it has been shown that more complex modelling methods such as Parametric Equation Modelling can make predictions with a higher accuracy, the ISO 9613-2 standard is still applied widely for the permitting of wind facilities. The applicability of the ISO 9613-2 standard for wind turbine noise propagation prediction has been the subject of much research. Many studies have compared sound levels measured from wind farms to predicted noise levels in modelling, and specifically to those employing ISO 9613-2 [2] [3] [4].

When applying ISO 9613-2 in this context, there has been some variation in the literature regarding the most appropriate ground factor ("G") to ensure that the noise modelling does not under-predict the noise impact from the facility.

Previous research that was conducted in order to determine the most appropriate ground factor to use have largely been based on comparing the result of a measurement campaign with the predicted level from the model. [2] [3] [4]. However, a major shortcoming of these studies is the assumption that the turbines were emitting sound levels and spectra equal to that of the specifications used in the model. From experience, the sound emission output of the turbines have an inherent variation based on the turbine model, and may be subject to differences when compared to the manufacturer specified maximum sound emission. Consequently, any conclusions from those previous studies may have been biased by whether the turbines in the study were louder or quieter than their manufacturer specification used in the model, as well as the associated differences in spectral levels.

As part of this study, far field measurement datasets have been identified where the signal-to-noise ratio is sufficiently high, and the sound emission levels have been measured in-situ at one or more turbine from the site. This is often the closest turbine to the measurement location.

To assess the most appropriate ground factor, a comparison has been made between the noise levels predicted using measured sound power levels according to ISO-9613 and the noise levels measured during immission measurements at the same locations.

2. Background

The following section describes the nature of the acoustical immission measurements as well as the selection criterion for which sites were assessed in the study. Further, additional context is provided regarding the ISO 9613-2 modelling parameters. Finally, the methodology for the comparison of the measured and predicted sound levels is described.

2.1 Immission Measurements

In Ontario, it is often a condition of the approval for a wind farm that audits of the noise impact be conducted at a selection of the worst-affected points of reception around the wind farm. The primary requisites for a receptor being classified as worst-case are as follows:

- High predicted noise impact
- Situated downwind of the farm in the prevailing wind direction

The regulatory framework [5] necessitates assessment of the worst-case impact, only allowing the assessment of data satisfying the following criteria:

- Nearest turbine is producing above 85% of its rated power output.
- All turbines within 1.5 km are operating according to the scenario:
  - Total Noise: All turbines are spinning and producing power
  - Background: All turbines are parked and not producing power
- Measurement location is downwind of nearest turbine – within +/- 45° of the nearest turbine's measured yaw angle.
- Significant transient contamination is not present.

Night-time (22:00 – 05:00) noise measurements are carried out in two phases, with one taking place in the fall/winter (typically September-December), and the other taking place in the spring (typically March-May). Measurement locations are often between 550m and 850m from the nearest turbine and are sufficiently far removed from any reflective surfaces or foliage. Using a microphone with a primary and secondary wind screen at a typical height of 4.5 meters, audio data is recorded in one-minute intervals between frequencies of 20Hz to 10,000Hz. The insertion loss of the wind screen has been tested and accounted for in the processing. One-minute LA_{eq} and L_{90} values are recorded for determination of average sound levels and for transient event filtering, respectively. Weather data including wind speed, direction as well as atmospheric conditions are recorded simultaneously at a height of 10 meters above ground level (10m-AGL). Measurement datasets from two of the assessed sites are included below and generally demonstrate the quality of the data being used in this assessment.

Figure 1: Site A Measurement Data - Spring Measurement Period

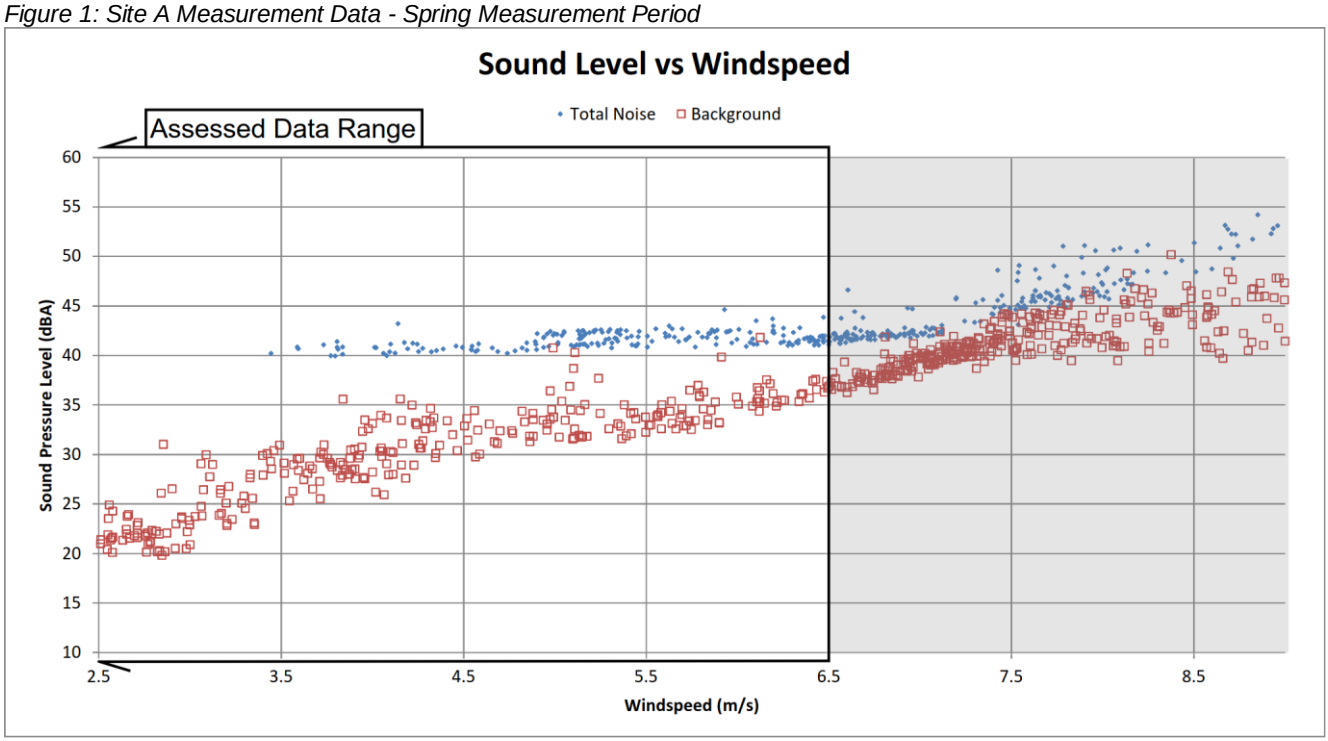
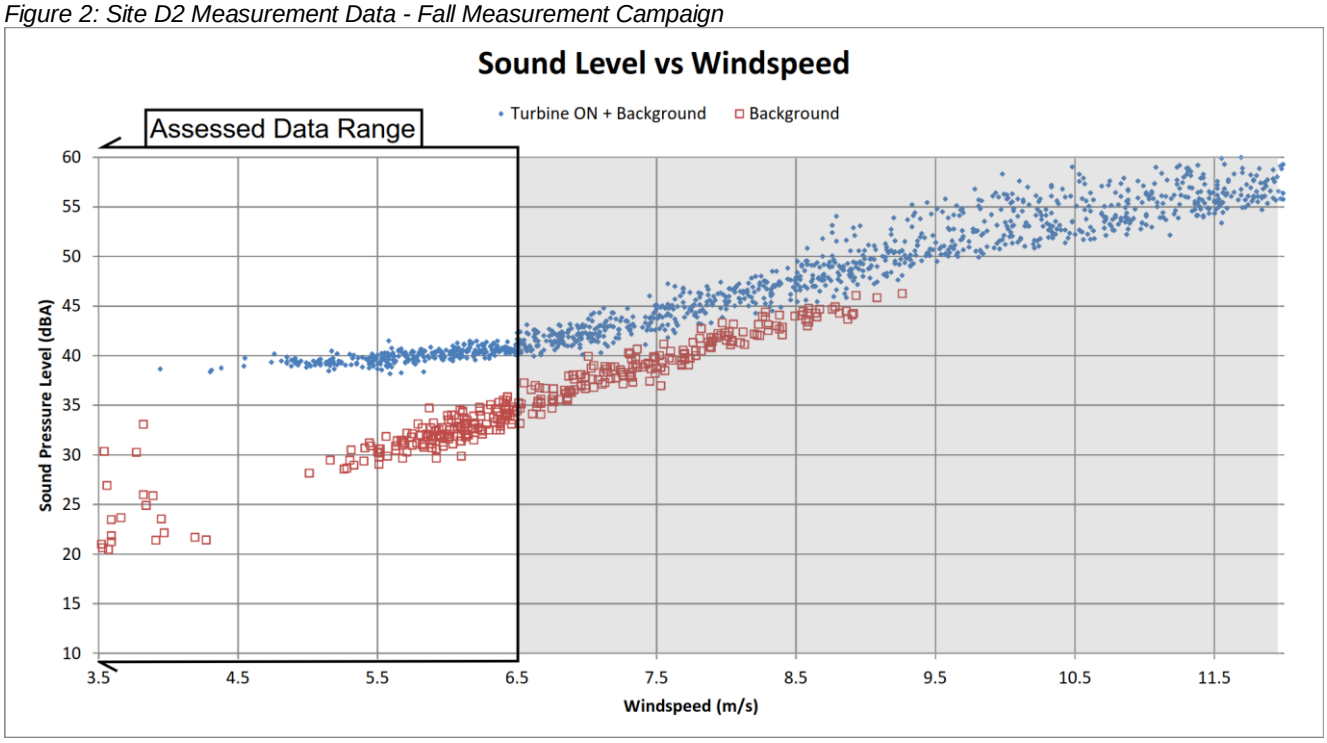


Figure 2: Site D2 Measurement Data - Fall Measurement Campaign



To account for the influence of wind speed on the acoustical measurements, data are sorted into integer wind speed bins ranging from 1-7 m/s (0.5-1.49 m/s, 1.5-2.49 m/s, etc).
The assessed project noise impact level is an average Turbine-Only sound level, which is taken to be the result of logarithmically subtracting the average measured Background sound level from the average measured Total Noise sound level, for each wind speed bin. The standard imposes data filtering to ensure representative conditions between these Total Noise and Background periods, such that the subtraction of windbin-averaged values for these periods results in the noise impact from the turbine operation only.

2.2 Sites Selected for Comparison

Aercoustics has conducted immission measurements at numerous sites across Ontario for which comparisons could be made. However, in order to remove as much uncertainty as possible from the noise level comparisons, the following considerations were made regarding the selection of sites for this study:

- Emission test data is available for turbines near the monitor; ideally the closest turbine.
- High data quality was demonstrated, demonstrating separation between the Total Noise and Background data across multiple wind speed bins.

Five measurement locations across four wind farms were selected for the assessment. For two of the sites, both a spring and a fall/winter dataset was assessed. For three of the sites, only a fall/winter measurement campaign was assessed.

All of the turbines in the study were pitch controlled and were uniformly in the 2 MW class with hub heights of approximately 100 meters. The assessed measurement locations are described in Table 1.

Table 1: Measurement Location Summary

Site			A	B	C	D1	D2
Measurement Period	Spring	Duration	Apr. 2017	Mar. – Apr. 2018	-	-	-
		# Days	8	58			
	Fall / Winter	Duration	Sept. – Nov. 2018	Oct. – Nov. 2018	Apr. – May. 2018	Nov. 2018 – Jan 2019	Nov. 2018 – Feb. 2019
		# Days	29	36	23	72	73
Wind Farm Size	Nameplate Capacity [MW]		10	8	8	>250	
Measurement Location Details	Distance from Nearest Turbine [m]		570	385	675	724	630
	Ground Cover between Turbine and Measurement Location		Crop / Grassland	Forest / Crop	Crop / Grassland	Crop	Crop
	Topography between Turbine and Measurement Location		Flat/Hilly, +/- 15m	Flat, +/- 10m	Flat, +/- 5m	Flat, +/- 5m	Flat, +/- 5m

2.3 Noise Level Prediction Using ISO 9613-2

Sound propagation according to ISO 9613-2 is calculated according to several attenuation parameters. In the context of a typical wind facility, the dominant factors are usually A_{div}, (geometric divergence), A_{gr} (ground effect), and A_{atm} (atmospheric absorption). The divergence term is based on spherical spreading of the wave front and varies solely with distance from the source. The ground attenuation term varies in frequency over distance and is dictated predominantly by the ground effect constant, G, which ranges between values of 0 and 1. These extremes are intended to represent perfectly reflective (G=0) and completely porous ground (G=1), with the value G=0.5 representing ground of 'mixed porosity'. The atmospheric term varies spectrally with the attenuation-per-distance depending on temperature and humidity values. The permitting guideline for Ontario [6] dictates that propagation be modelled accounting for a temperature of 10 degrees Celsius and a relative humidity value of 70%. Average meteorological values for each measurement campaign at each site are included in the table below. These values often shift throughout these measurement campaigns, however the average for the measurement periods generally agree with the modelled conditions.

In this data subset, five of the seven datasets were collected in the fall/winter months, and two of the seven were collected in the spring months.

Table 2: Measured Atmospheric Conditions at Each Measurement Location

Site	Period	Atmospheric Value	Relative Humidity [%]	Temperature [°C]
A	Spring	Average	44	8.9
		Maximum	66	17.8
		Minimum	25	4.6
	Fall	Average	85	16.0
		Maximum	96	20.9
		Minimum	62	2.2
B	Spring	Average	71	0.5
		Maximum	89	4.2
		Minimum	41	-4.8
	Fall	Average	70	2.6
		Maximum	89	9.9
		Minimum	62	-1.8

C	Fall	Average	60	1.5
		Maximum	96	9.4
		Minimum	44	-0.6
D1	Fall	Average	73	0.2
		Maximum	94	6.2
		Minimum	52	-12.4
D2	Fall	Average	73	-3.1
		Maximum	93	6.5
		Minimum	46	-15.8
Overall Average			**68**	**4**

The acoustical modelling software CadnaA, which utilizes ISO 9613-2, was used to make worst-case noise predictions at the five sites considered in the study. All wind turbines considered in the permitting of the wind farm were accounted for in the noise modelling, including those from adjacent facilities. Predictions of the cumulative noise impact from all relevant turbines were made at noise receptors corresponding to the real-world measurement locations at ground factors ranging from 0.0 - 0.8 in increments of 0.1.

Wind turbine noise sources were modelled as point sources at heights corresponding to the hub-height of the turbine. The worst-case sound power spectra measured according to IEC 61400-11 [7], [8] were used for each turbine where measurement data was available. Measurement data was available for some but not all turbines on a given site; for turbine noise sources that were not measured, turbine sound power spectra for were taken to be the energy-average of the tested values from other turbines on-site, for all turbines having the same model and rated sound output as those tested. Where no suitable test data was available for a given turbine model or rated sound power output, sound power spectra from the turbine specification were used. This was only the case for one model of turbine at Site D1/D2, and, at all sites, for the turbines from adjacent facilities. The table below compares the manufacturer specified sound power levels with those measured on site and provides context regarding the predicted acoustical contribution from measured sources compared to the overall predicted noise level.

Table 3: Measurement Location Noise Impact Comparison

Site	A	B	C	D1	D2
Nearest Turbine Rated Sound Power [dBA]	103.2	103.2	103.2	102.0	104.0
Measured Turbine Max IEC Sound Power [dBA]	102.6, 103.2	103.2, 103.2	102.9, 103.7	102.0	103.7
Predicted Sound Level[1] from All Noise Sources [dBA]	39.5	42.7	38.0	39.5	37.8
Predicted Sound Level[1] from Measured Noise Sources [dBA]	34.3	42.3	35.2	35.0	31.4

1 – Sound level Predicted at Measurement Location using Measured Values and G=0.7.

2.4 Comparison of Measured and Predicted Noise Levels

Data had been collected at a range of wind speeds at the sites mentioned above. A high-quality subset of this data was selected for assessment based on a number of criteria. Specifically, the windbin-average Turbine-Only sound pressure level for a given measurement location was only considered where:

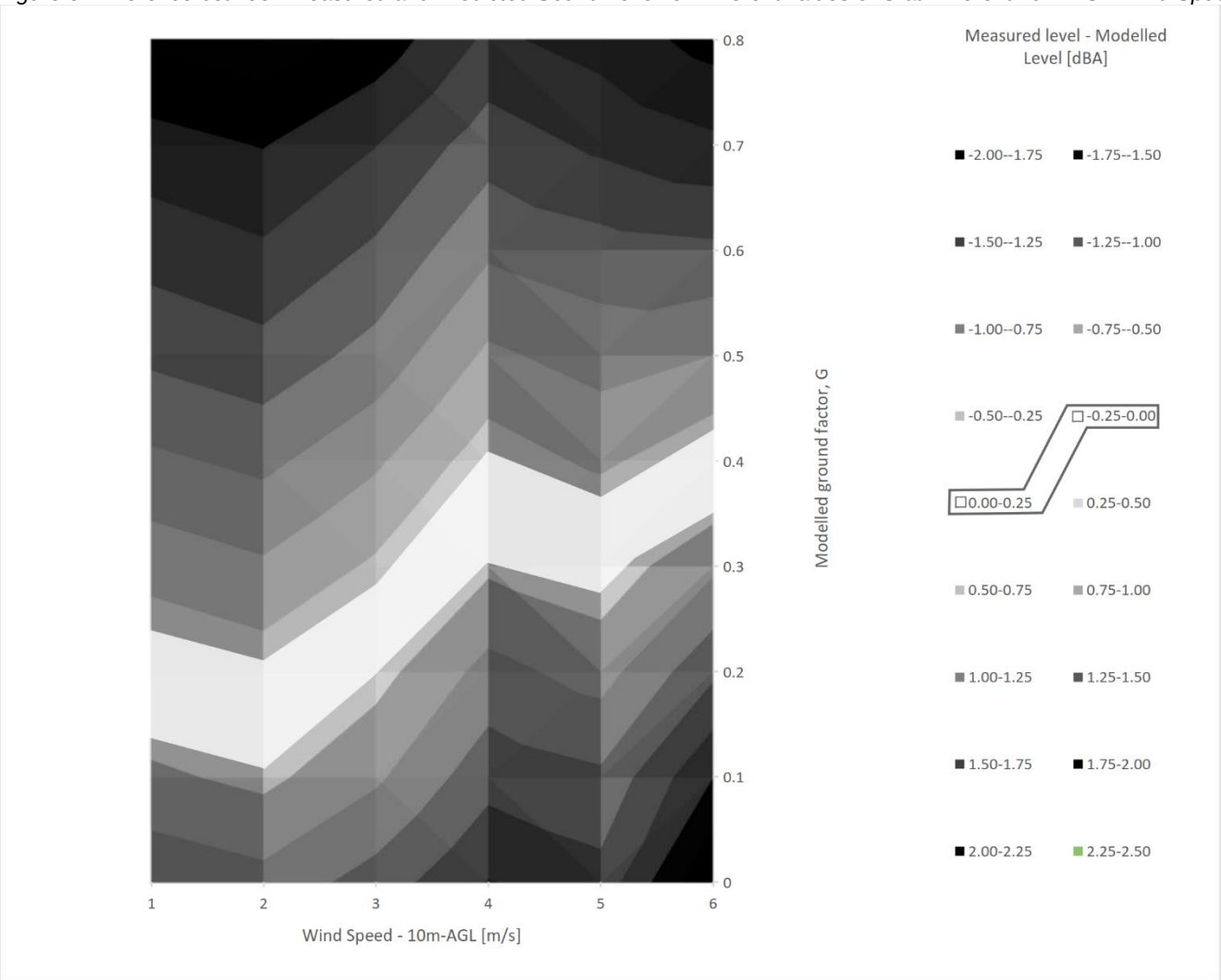
- A minimum 1-minute data count of 20 was achieved for both Total Noise and Background Noise intervals
- A minimum signal-to-noise ratio between average Total Noise and Background sound levels of 5 dBA was achieved
- The wind speed bin was below 7 m/s, in order to reduce the influence of wind-related noise on the measurement data.

Applying these filters resulted in a dataset with a population of N=16. By virtue of the signal-to-noise threshold, minimum turbine power threshold, and downwind criterion for all data, these final Turbine-Only average sound levels represent the most accurate assessment of a worst-case impact from the nearby wind farm in the far field.

3. Results

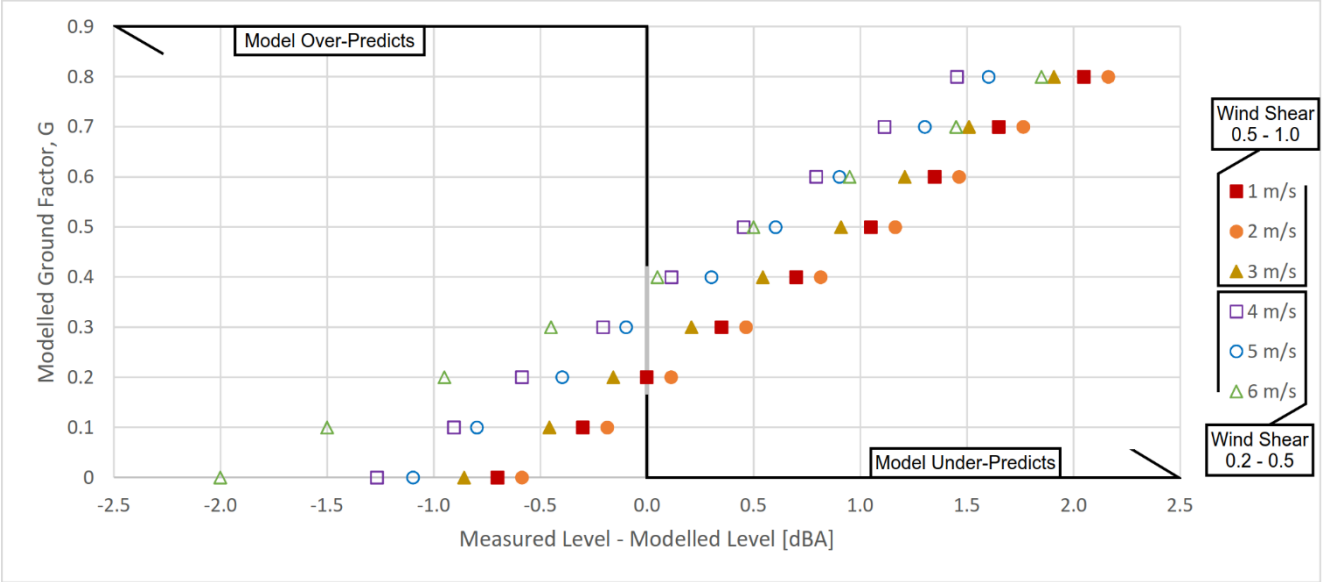
The filtered selection of data has been grouped into wind speed bins for assessment of the average difference between measured and predicted noise levels for different values of G across multiple sites. Figure 3 below shows, for various wind speeds, the difference between measured levels and modelled levels with different ground factors. The grading is in 0.25 dBA increments, and the white area represents deviations of -0.25 to +0.25 dBA, i.e. most accurately reflecting the measured levels. Areas below the 'white belt' represent conditions where the measurements were less than the modelled levels (i.e. the model overpredicted) while the area above the white line represents times where the measured levels where higher than the modelled level (i.e. the model underpredicted).

Figure 3: Difference between Measured and Predicted Sound Level for Different values of G at Different 10m-AGL Wind Speeds



This same data is also presented in a more granular format in **Error! Not a valid bookmark self-reference.**
Values falling around the y-axis represent those most accurately reflecting the measured levels.

Figure 4: Difference between Measured and Predicted Sound Level for Different values of G at Different 10m-AGL Wind Speeds



On average it was found that application of a ground factor of about G=0.3 was required in order to align the model with the measured value. This value is lower than findings from other studies [3]; potential reasons for these findings are presented in Section 5 of this study. These findings should be considered preliminary based on a limited sample size of 16. Further measurements and site locations are planned to be added to this data set in order to confirm the observed trends. Furthermore, the data was also analysed by the measured ground level wind speed. It should be noted that because the analysis only considers datapoints where the electrical power being generated is at least 85% of rated output, it would therefore necessitate that lower ground level wind speeds represent higher wind shear events, and higher wind speeds represent comparatively lower wind shear events.
That is, for the case of 10m-AGL wind speed of 1m/s, the hub height wind speed used in the analysis was still ~10m/s, making the wind shear coefficient approximately 1.00; for the case of 3m/s the wind shear coefficient would be approximately 0.5.

An interesting trend appears to be that at lower wind speeds (i.e. higher shear conditions) the ground factor to match the model to the measurements would have to be considerably lower than originally anticipated – roughly G=0.2. As the ground level wind speed increases and the associated wind shear decreases, the ground factor that best matches the measurements increases to G=0.4. This could be due to more extreme downward refraction conditions when the ground level wind speed is below 3m/s and the hub height wind speed is ~10m/s. However, the difference in measured level between extreme and moderate level shear was found to be relatively minor, in the order of 0.5 – 1 dBA.

4. Limitations of Study

Differences of fractional decibels are not practically relevant in terms of environmental acoustics but become important in the context of wind farm permitting. Even so, it is important to understand that the degree of uncertainty in this context often exceeds the magnitude of the value being assessed.

Compared to other studies regarding the applicability of various ground factors in wind turbine noise modelling, this study represents a lower degree of uncertainty in the results by virtue of using measured sound power levels combined with high quality immission data.

Regardless, there remain numerous sources of uncertainty involved in this assessment which arise from multiple sources. Specifically;

1. Wind Turbine Sound Emission Levels used for Modelling
    a. *IEC measurement uncertainty*
    b. *Variation in Turbine sound emission for turbines of the same model within a wind farm*
2. ISO-9613-2 Modelling Uncertainty
    a. *General uncertainty of model*
    b. *Downwind condition from <u>all</u> sources simultaneously*
3. Calculated Turbine-Only Sound Pressure Levels (Immission) - Unknown
    a. *Variation in environmental weather conditions across campaign*
    b. *Uncertainty related to the signal-to-noise ratio*
    c. *Uncertainty related to the measurement chain*

Items 1a, b, 2a, and 3a, b, c may bias values either above or below the real value, where item 2b is expected to have the effect of over-predicting the sound pressure level in situations where the receptor is surrounded by wind turbines and therefore cannot be downwind of all turbines simultaneously. This situation is most relevant at sites D1/D2, and less relevant at the other sites, where the measurement location was downwind of the majority of the closest turbines.

The uncertainty associated with the ISO 9613-2 methodology is stated to be +/- 3.0 dB in situations where the average height between source and receiver is below 30 meters, and where noise sources are within 1,000 meters of the receptor. In the context of most wind farms, this is not the case, and so the uncertainty may exceed the stated value.

Additionally, all of the measurement scenarios in this study generally correspond to flat ground. Variations with respect to hilly and complex terrain was not part of the scope of this study; the appropriateness of various values of G has been assessed to vary based on topography [4].

A detailed assessment of uncertainty was not possible at the time of this study. A simplified uncertainty for the results was calculated based on the various discrete uncertainties mentioned above, and was found to be in the order of at least +/- 1.6 dB
As mentioned previously, the results presented here represent a relatively small set of samples with high quality far-field data, and with field tested turbine emission data. Future work on this subject will include the addition of further sample sets in order to improve the quality of the conclusions.

5. Implications of Study - Appropriateness of G<0.5 Ground Factors

The results of the study indicate that a value of G=0.3 or lower is appropriate for conservatively and accurately predicting the sound level at a point of reception for a wind farm. Higher values of G, up to G=0.5, may be appropriate for lower-shear conditions, and may be valid for sites where high-shear conditions occur rarely. Conversely, for worst-case assessment of sites with a greater prevalence of high-shear conditions, values of G down to G=0.2 may be applicable. As stated earlier in this study, the applicability of these lower ground factor values is valid for situations where the sound power spectra used in modelling are known or expected to closely match the real-world turbine outputs.
For most wind facilities, the ISO 9613-2 methodology is inherently conservative in that it considers the point of reception to be down wind of all noise sources. This will not be the case for any receptor that is surrounding by turbines and therefore will only be down-wind of a selection of those. Conservatism can be added in different areas during the noise impact assessment,

including in the manufacturer's turbine noise specifications, in the selection of ground factors, and in the application of explicit safety factors on the noise output level.
Higher values of G may be applicable in situations where the representative or average noise impact of the facility is being assessed, rather than the absolute worst-case.
In consideration of the findings of this study, it is important to be sufficiently conservative in the modelling process for wind facilities, particularly so considering the limitations of the ISO 9613-2 methodology. Modelling using ground factors as high as G=0.7 has somewhat consistently resulted in compliant immission sound levels in Ontario, providing that the turbine sound power output is within specification; this effect may not be the result of the applicability of that ground factor and may be due to other factors regarding sound output spectrum of the turbine(s) in-situ as compared to the assumed values in the pre-construction noise studies. However, this should not be an indication of the validity of using ground factor of G=0.7 in the future.

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