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Evaluation of noise levels of two micro-wind turbines using a randomised experiment

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Abstract
One of the more contentious environmental concerns of wind turbines is the wind turbine noise. This study assesses the noise impacts of two micro-wind turbines on the environment by comparing the noise generated by these turbines to traditionally accepted surrounding sounds. The sound level data was collected using a randomised experiment and fitted using a general linear model (GLM). The GLM was used to determine the relationship between the sound level generated at a given site to the time of day, the wind speed, the wind direction and a fixed predetermined distance from the sound source.

Keywords: general linear model, micro-wind turbine sound levels, sound pressure levels.

1. Introduction

Energy is an important aspect of social and economic development in South Africa. The demand for electricity has increased over the years and the challenge is to promote renewable energy in South Africa (Winkler, 2005).

Eskom, the predominate supplier of electricity in South Africa, has implemented a number of price increases over the past few years, causing a growing concern in the country. In light of the current electricity shortage, there is a need to consider alternative energy sources. Solar, water, wind and nuclear power are generating interest as future sustainable sources of power.

One of the most developed and cost effective renewable energy source has been shown to be wind energy (Prospathopoulos and Voutsinas, 2007). Wind turbines are one of the cleanest energy production machines (Islam, 2010). Tommaso, Miceli and Rando (2010) refer to a study conducted by Greenpeace where it was estimated that in the year 2020, 12% of the world's energy will be by means of wind energy.

One of the biggest environmental concerns of wind turbines is the noise emission (Prospathopoulos and Voutsinas, 2007). Excessive exposure to noise has been shown to cause several health problems. The most common health problems are hearing loss, headaches, and fatigue (caused by sleep disturbance) (Alberts, 2006). Extremely high noise exposure may even cause constricted arteries and a weakened immune system (Alberts, 2006). This paper assesses the noise impacts of wind turbines on the environment by comparing the wind turbine noise to traditional accepted surrounding sounds.

Most studies conducted internationally on the noise emission of wind turbines have been survey type studies. These studies deal with the perception of noise and focus on large scale wind turbine farms near residential areas. At the time of the study, there were no operational wind turbine farms near residential areas in South Africa and thus a survey study was not possible. However, micro-wind turbines are a growing area of interest in the Port Elizabeth (PE) region. There has been an increase in the installation of micro-wind turbines and solar panels in households. As such, this paper evaluates actual noise measurements from operational micro-wind turbines in PE.

1.1 Noise and sound fundamentals

Sound is a travelling wave which is characterised by its frequency and magnitude. The loudness is related to a physically measurable quantity, namely the intensity of the wave. The intensity is defined as the energy transported by the wave per unit time across unit area and is proportional to the square of the wave amplitude. Sound in this paper was measured on a logarithmic scale, using the Sound Pressure Level (SPL) in units known as decibels (dB). SPL is defined as the instantaneous difference between the actual pressure created by the wave and the average pressure given at a point in space.

A-weighting, denoted by dBA, is a filter that is often related to SPL. It decreases or amplifies certain frequencies. This is in accordance with the international standards to approximate the frequency dependence of average human hearing. A-weighting readings are intended for measurements of low-level sounds (e.g. environmental noise and industrial noise) (Howe, Gastmeier and McCabe, 2007).

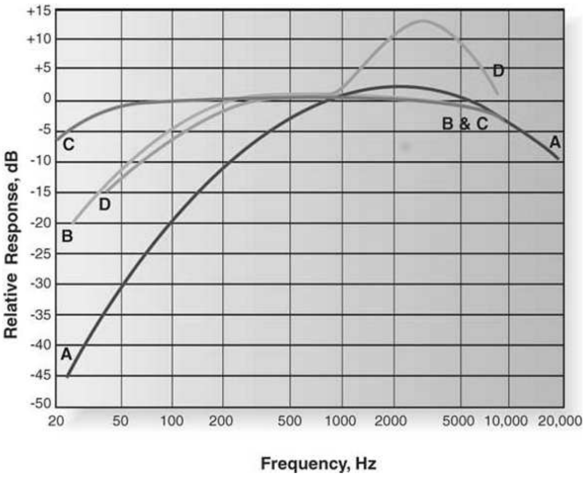

Figure 1: Acoustic weighting curve
Source: www.extron.com (Retrieved on 13 November 2011)

Noise is defined as unwanted sound and does not need to be excessively loud to cause annoyance. For sound to be perceived as noise it depends on the duration and amplitude of the sound (Kamperman and James, 2008). Noise annoyance is a feeling of displeasure that is created by noise. Noise annoyance is related to sound properties and as well as individual, situational and noise source related factors (Pederson and Waye, 2007).

1.1.1 Sounds from wind turbines

Sounds from wind turbines can be divided into two groups: mechanical sounds and aerodynamic sounds.

Mechanical sounds are described as sounds that are related to the interaction of wind turbine components. The source of this sound comes from the gearbox, generator, yaw drives, cooling fans and auxiliary equipment (Rogers *et al*, 2006). According to Rogers *et al.* (2006) small (or micro) wind turbines are more likely to produce more noticeable mechanical noise.

Aerodynamic sounds are generated by the interaction between the wind flow and the wind turbine components, namely the blades of the wind turbine and the wind turbine tower. Depending on the wind turbine and the wind speed, aerodynamic noise has been described as a buzzing, whooshing, pulsing and even a sizzling sound (Alberts, 2006). When the wind turbines blades are downwind of the tower, it is known to make a thumping sound as each blade passes the tower.

1.1.2 Previous studies

Other researchers (Pederson and Waye, 2007) claim that excessive noise associated with wind turbines may just be a perception. Factors that add to this perception are visibility, economic benefit from wind turbine farms and place of residence. Pederson and Waye (2007) showed that there is an increase in the irritability of noise when residents can see the wind turbines. Furthermore, Pederson and Waye (2007) showed that one in two respondents was positive towards wind turbines, but only one in every five was positive towards their impact on the landscape scenery. The conclusion of their study was that there was a significant decrease in noise annoyance when people benefitted economically from the wind turbines.

Bolin, Nilsson and Khan (2010) investigated whether natural sounds are able to mask wind turbine noise. Their results showed that there was a reduction in the perceived loudness of wind turbines due to the masking of natural sounds. Wind turbine farms are normally placed in rural areas with low ambient noise. This may contribute to the perception that wind turbines are noisy. The research of Bolin *et a*l. (2010) impacts this study as it provides evidence that placing a wind turbine in an environment with high ambient noise levels may have the ability to mask the wind turbine noise.

1.2 Objectives

This study has the following objectives:

- To design an experiment to collect sound level data from different sites in the Summerstrand, PE region.
- To propose a method for comparison of wind turbine noise to traditional surrounding sounds.
- To identify the factors influencing the sound levels of micro-wind turbines by comparing the sound levels at different sites.

2. Research methodology

A randomised experiment was designed to collect sound level data from several sites in the PE region. Sound level data was collected via an MT975 sound level meter. Readings were taken over a 70 day period. The site and time for each reading were selected randomly and four measurements were taken at each site and time. The reason that only four sets of measurements were taken at each site and time was due to the time constraint. The randomised selection process of each site and time was created in GNU R 2.11.1 (R Development Core Team, 2010).

The sites selected for the experiment are given in Table 1. The seventh site was the ambient measurement for the vertical axis micro-wind turbine. The ambient measurement for the horizontal micro-wind turbine was not possible as the horizontal wind turbine could not be switched off during the experiment.

Measurements were taken at 08h00, 12h00, 17h00 and 22h00. The reasons for these four times were that they were believed to include a typical day's activity. The 08h00 and 17h00 times represent periods of busy community activity, the 12h00 time represents a period of midday relaxation, while the 22h00 time represents a quiet period with little community activity.

For each treatment level two separate readings were taken. These recordings were related to the distance from the sound source. The first measurement was taken close to the sound source. The second measurement was taken approximately 10m from the source sound. This 10 m distance was chosen as it was believed to be the approximate distance that a micro-axis wind turbine would be between two residential households.

Sound measurements were recorded in decibels with an A-weighting over a period of two minutes. In the two minute period, decibel measurements were recorded every half a second making a sample size of 240. This was assumed to be a large enough sample to obtain an accurate decibel recording for each measurement. According to the IEC (International standards: Wind turbine generator systems Part 11: Acoustic noise measurement techniques) document at least 30 measurements are required in a one minute period to determine an accurate average sound level for a wind turbine evaluation. Once the sound data was collected the average decibel level over the 240 measurements was calculated in MS Excel 2007.

A WSD-100 Wind Speed and Direction Sensor was used to record the average wind speed in m/s and the average wind direction for each measurement. The WSD-100 Wind Speed and Direction Sensor was set up at the Centre of Energy Research (CER) on the Nelson Mandela Metropolitan University South Campus. It was assumed that the measurement recorded at the CER was an accurate average measurement for wind speed and direction for the Summerstrand region in PE, where all measurements were taken. Wind speeds and wind directions were logged instantaneously every 5 minutes. The average wind speed and wind direction were calculated over a 15 minute period during the time that the sound measurements were taken. The wind direction was defined as a qualitative variable and was grouped into four categories, North, South, East and West.

3. Results and discussion

The descriptive statistical analysis of the sound level data is given in Section 3.1 with results presented in tabular and graphical form followed by discussion. The fitted General Linear Model is given and discussed in Section 3.2.

3.1 Descriptive statistics

A basic descriptive analysis of the quantitative variables was done in STATISTICA v10. Presented in Table 2 are the descriptive analysis results of decibel measurements at the seven sites at the distance closest to the turbine. Similar results were observed for distance 10m away.

The data set had one missing observation. This is seen in Table 2, under the vertical axis wind turbine column. The missing sample measurement occurred at 08h00. The reason a measurement was not obtained was a malfunction of the vertical axis wind turbine.

The results in Table 2 indicate that the street had the highest average decibel reading of 66.0 dBA. The sound levels at the site were influenced by vehicles travelling in the vicinity and the change in vehicle speeds for traffic lights, hills and intersecting roads. This street is used by vehicles during the day and has a busy traffic intersection with traffic lights. These factors influence the average sound levels present at the site.

The horizontal axis wind turbine had an average decibel reading of 62.4 dBA. This was the second

Table 1: Site description

Site	*Location*	*Geographical co-ordinates*
Horizontal axis wind turbine e300[1] (1kW)	Hobie Beach, Port Elizabeth	33° 58.881'S, 25° 39.530'E
Vertical Axis Wind Turbine (1kW)	NMMU South Campus, Port Elizabeth	34° 0.523'S, 25° 39.908'E
Residential area	Cathcart Road, Port Elizabeth	33° 58.801'S, 25° 38.441'E
Beach front	Pollock Beach,Port Elizabeth	33° 59.065'S, 25° 40.279'E
Rural environment	NMMU South Campus, Port Elizabeth	34° 0.509'S, 25° 39.744'E
Street	Beach Road,Port Elizabeth	33° 58.607'S, 25° 38.870'E

Table 2: Descriptive statistics

	Street	*Horizontal wind turbine*	*Beach front*	*Residential area*	*Rural*	*Vertical wind turbine*	*Ambient site of the vertical turbine*
Mean (dBA)	66.0	62.4	60.5	51.0	48.4	46.1	43.8
Standard deviation (dBA)	3.8	4.2	5.1	4.2	7.8	6.0	4.8
Sample size (n)	16	16	16	16	16	15	16

highest average sound level found across the sites. Although the microphone was in close proximity to the wind turbine, the surrounding sounds of traffic, pedestrians and beach activity could have contributed to the readings. However it was noted that the wind turbine made sounds that can be described as a 'whoosing' and 'swishing' sound. This type of sound can be characterised as aerodynamic sounds produced by the interaction between the blades of the wind turbine and the air flow around the blades. These sounds would have also been captured when taking the measurements.

The lowest average decibel reading was the ambient sound level at the vertical axis wind turbine site. This result was surprising as the rural site was expected to have the lowest sound level readings. However, the rural site measurement position was situated near several trees and bushes. An increase in wind speeds could have increased the noise levels due to the moving of the leaves of the trees and bushes. Also the ambient measurement for the vertical axis wind turbine was situated at the CER which consists of buildings and other structures. These buildings and structures would have influenced noise propagation paths and most likely dampened the sound levels recorded.

The second lowest average decibel reading was found at the vertical axis wind turbine with an estimated sound level of 46.1 dBA. The vertical axis wind turbine mean estimate of 46.1 dBA indicates a 2.3 dBA increase in sound levels at this site.

For most of the sites, the standard deviation of the sound levels was fairly low. This indicates that the sounds levels did not vary much from their mean values. The exceptions to this were the rural and the vertical wind turbine sites, which had considerably higher standard deviations. This could be due to the low ambient noise levels at these sites.

Figure 2 is a graphical representation of the mean decibel recordings for the seven sites at the four different times. The graph indicates that the sound levels at the residential site, ambient site of the vertical axis wind turbine, the vertical axis wind turbine site and the rural environment are lower than the other three sites. Worth noting is that the average sound levels at the vertical axis wind turbine were lower than the residential area. This is a very interesting result. This indicates that the existing noise in the residential areas is sufficiently noisy to potentially mask noise created by the vertical axis wind turbine. This means installing a vertical axis wind turbine in a residential area may not increase the noise pollution, as is often argued.

As concluded by Bolin *et al* (2010), environments with high sound levels may have the ability to mask wind turbine noise. This masking may decrease the perception of noise irritability of wind turbines. The sites with the highest sound levels are the street and the beachfront. This suggests these sites are potential environments in which to place horizontal axis micro-wind turbines.

3.2 General linear model

To assess the noise level of wind turbines, a general linear model was used. The model compared the response variable, the average sound measurement

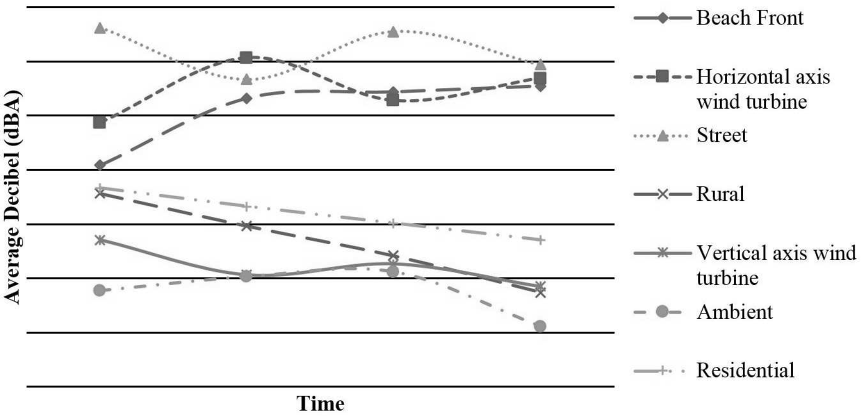

Figure 2: The average decibel recordings for each site across the four different times

at the different sites, and the results are interpreted as noise comparisons. The linear model was also used to identify which variables influence the sound levels.

The following model was fitted to the sound level data:

$$y=\beta_0+\underbrace{\beta_1 x_1}_{windspeed}+\underbrace{\beta_2 x_2+\ldots+\beta_7 x_7}_{site}$$
$$+\underbrace{\beta_8 x_8+\ldots+\beta_{10} x_{10}}_{time}+\underbrace{\beta_{11} x_{11}}_{distance}$$
$$+\underbrace{\beta_{12} x_{12}+\ldots+\beta_{14} x_{14}}_{direction}$$

where y, the response variable, is the average sound level (dBA). The independent variable, x_1 = wind speed (m/s) is quantitative, and the independent variables site, time, wind direction and distance, coded as binary response variables, are qualitative. The seven sites are coded as

$$x_2=\begin{cases}1 & if\ \ Beach\ Front\\ 0 & otherwise\end{cases},$$
$$x_3=\begin{cases}1 & if\ \ Horizontal\ \ axis\ \ wind\ \ turbine\\ 0 & otherwise\end{cases},$$
$$x_4=\begin{cases}1 & if\ \ Ambient\ site\\ 0 & otherwise\end{cases},$$
$$x_5=\begin{cases}1 & if\ \ Vertical\ \ axis\ \ wind\ \ turbine\\ 0 & otherwise\end{cases},$$
$$x_6=\begin{cases}1 & if\ \ Rural\ site\\ 0 & otherwise\end{cases}, \text{ and}$$
$$x_7=\begin{cases}1 & if\ \ Street\\ 0 & otherwise\end{cases}$$

with the residential site used as the base level.

The four time periods are coded as

$$x_8=\begin{cases}1 & if\ \ 08h00\\ 0 & otherwise\end{cases},\ x_9=\begin{cases}1 & if\ \ 12h00\\ 0 & otherwise\end{cases}, \text{ and}$$
$$x_{10}=\begin{cases}1 & if\ \ 17h00\\ 0 & otherwise\end{cases}$$

with 22h00 used as the base level.

The two distance measures are coded as

$$x_{11}=\begin{cases}1 & if\ \ Distance\ one\\ 0 & otherwise\end{cases}$$

with distance two used as the base level.

The four directions are coded as

$$x_{12}=\begin{cases}1 & if\ \ West\\ 0 & otherwise\end{cases},\ x_{13}=\begin{cases}1 & if\ \ North\\ 0 & otherwise\end{cases}, \text{ and}$$
$$x_{14}=\begin{cases}1 & if\ \ South\\ 0 & otherwise\end{cases}$$

with East used as the base level.

This model was fitted to 222 data points using the statistical software package STATISTICA 10. The goodness-of-fit measures of the model, as well as the significance level of the models' overall fit are presented in Table 3.

Table 3: Goodness-of-fit statistics for the GLM

Multiple R	*Multiple R^2*	*Adjusted R^2_a*	*p*
0.8707	0.7582	0.7418	0.0000

The coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a) are 0.8707, 0.7582 and 0.7418 respectively. These statistics all indicated a good fit for the model. The *F*-test to determine the utility of the model had a statistically significant *p*-value of 0.00. This small *p*-value indicated that the model was useful for predicting the average sound level based on the independent variables used.

The effects of the individual factors are shown in Table 4. The significance of the factor is indicated by the *p*-value in the table. Commonly used levels of significance are 1%, 5% and 10%. These are typically referred to as strongly significant, significant and weakly significant respectively. The results in Table 4 indicate that wind speed, site and wind direction are statistically significant at the 1% level, whilst time and distance at 10 m from the sound source are statistically insignificant at the 10% level.

Table 4: Effects of individual factors for the GLM

Effect	*p*
Intercept	0.0000
Wind speed (m/s)	0.0000
Site	0.0000
Time	0.2511
Distance	0.2145
Wind direction	0.0024

We use these results to reduce the size of the model by omitting the insignificant factors whilst simultaneously cautioning researchers to the fact that the model used did not contain interaction terms. Interaction terms can influence factor levels in such a way that a factor appears to be statistically significant yet it is the interaction between factors that creates the significance. Likewise it is also possible that a factor appears to be statistically insignificant yet it is an important predictor of a response variable. The reason for not including interaction terms at this stage is that the variable, wind direction is uncontrolled, which resulted in an incomplete data set hence estimation problems occurred.

The reduced model estimated for the 222 data points is given by the equation

$$y=\beta_0+\underbrace{\beta_1 x_1}_{windspeed}+\underbrace{\beta_2 x_2+\ldots+\beta_7 x_7}_{site}$$
$$+\underbrace{\beta_{12}x_{12}+\ldots+\beta_{14}x_{14}}_{direction},$$

with variables as previously defined.

In Table 5 is the summary of goodness-of-fit measures of the reduced model, as well as the significance level of the overall models' fit.

Table 5: Goodness-of-fit statistics for reduced model

Multiple R	*Multiple R^2*	*Adjusted R^2_a*	*p*
0.8669	0.7515	0.7398	0.0000

Although there was a slight decrease in the R, R^2 and R^2_a the model still had a good fit to the average sound level data. This decrease was due to the decrease in the number of variables used in the estimated model. The *F*-test had a statistically significant *p*-value of 0.00 which indicated a good fit for the model. This small *p*-value indicated that the model was useful in predicting the average sound level based on the independent variables used.

Table 6: Effects of individual factors for reduced model

Effect	*p*
Intercept	0.0000
Wind speed (m/s)	0.0000
Site	0.0000
Wind direction	0.0017

The effects of the individual factors are shown in Table 6. The results in Table 6 indicate that wind speed, site and wind direction are all statistically significant at the 1% level.

Given we have reduced our model to the most parsimonious case and that no outliers were detected it is important to consider the parameter estimation for each variable. The individual parameter estimates for the reduced model are given in Table 7.

Table 7: Parameters estimates for the reduced model

	Parameter estimates	*Std error*	*p*
Intercept	49.27	0.66	0.0000
x_1 Wind speed	1.21	0.15	0.0000
x_2 Beach front	7.45	0.79	0.0000
x_3 Horizontal axis wind turbine	7.39	0.79	0.0000
x_4 Ambient site	-8.18	0.79	0.0000
x_5 Vertical axis wind turbine	-7.45	0.81	0.0000
x_6 Rural site	-5.51	0.78	0.0000
x_7 Street	9.83	0.78	0.0000
x_{12} West	-1.55	0.53	0.0037
x_{13} North	1.26	0.667	*0.0607*
x_{14} South	-1.38	0.61	0.0254

The intercept represents the average sound level response for the base level variables. The estimated parameter for wind speed indicates that for every 1 m/s increase in wind speed there will be 1.21 increase in the average sound level if all other variables are fixed. To interpret the parameter estimates a single case is discussed.

The parameter estimate for variable is -8.18. This is the lowest value of all the parameter estimates. This estimate represents the difference between the estimated mean sound level for the ambient site and the mean base level when all other factors are fixed. The negative value indicates a site of low sound levels. This estimate (-8.18) is interpreted as follows: the mean sound level recording at the ambient site is 8.18 dBA less than the residential site when all other factors are fixed. This mean response for the ambient measurement for the vertical axis micro-wind turbine site confirms what has already been shown in section 3.1; that the site has very low sound levels compared to the other six sites.

The *p*-values for the parameter estimates indicated that all but one of the variables in the model are statistically significant at the 5% level. Variable has a *p*-value slightly higher than 0.05. However the overall factor contribution was statistically significant and wind direction was found to be a useful predictor.

The conclusion of the statistical analysis is that the reduced model is preferred to the complete model. The factors wind speed, site and wind direction were found to be significant predictors of the average sound level. Surprisingly, the factors time and distance were found to be statistically insignificant, however as discussed earlier this could be a result of interaction effects.

4. Conclusions and recommendations

The aim of the paper was to provide a comparison between wind turbine noise and traditionally accepted surrounding sounds. The collection of sound level data was done using a randomised experiment. Seven sites and four different times were selected. A GLM was used to determine the relationship between the noise generated at a given site and the time of day, wind speed, wind direction and distance.

The statistical analysis summary showed that the reduced model was preferred to the complete model. The reduced model fitted the data well according to the coefficient of correlation (R), coefficient of determination (R^2) and adjusted coefficient of determination (R^2_a). The factors wind speed, site and wind direction were found to be significant predictors of the average sound level. The factors time and distance of 10 m away from the sound source was found to be statistically insignificant. That being said, the model shows that several factors are important predictors of the response variable. As this study is the first attempt at investigating the noise of wind turbines, it provides a useful starting point for future evaluations.

Table 7 shows that when all other factors are fixed the horizontal axis micro-wind evaluated in this study turbine increases the sound level by 7.39 dBA when compared to the sound level of a typical residential area (the base site in this study).

Improvements into the study the model would be to increase the sample size and increase the distance at which the second measurement is taken from the sound source. Distance showed to be an insignificant predictor for the average sound level. Increasing the distance from the wind turbine may show the relationship between distance and average sound level in the model. Also, the inability to assess the ambient noise measurement of the horizontal axis micro-wind turbine can be addressed. This would add more information to the change in sound levels attributed to wind turbine noise.

Adding more variables such as rainfall, topography, height, ambient noise, temperature and other distance measures to the randomised experiment may allow for a more accurate and informative model to be developed. Increasing the number of micro-wind turbine models in the experiment may also provide more information about the wind turbine acoustics.

In conclusion, a methodology for collecting of sound level data was developed. This methodology allowed for accurate modelling of sound level data. Site, wind speed and wind direction were identified as factors influencing the sound levels in an environment. Investigation into this area has the potential for extensive future research, both in the field of wind turbine acoustics and experimental design

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