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Analysis of Induced Wind Speed along Embu-Nairobi Highway, Nairobi, Kenya

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ABSTRACT:
One potential source of wind energy that can be used to power highway lighting and telecommunication signalling is the turbulent airflow caused by vehicles moving along highways. To actualize this, a precise evaluation of wind speeds attributes is necessary in assessing the potential of wind energy. In this paper, we report on the wind potential alongEmbu-Nairobi highway at Juja by measuring the wind speed close to the highway. The wind speed data of the site at 1 m height was collected using Young wind sentry anemometer and vane, model 03002V and analysed on hourly time series data using Minitab Statistical Software. The Weibull distribution model gave a good fit for the recorded induced wind speed data. The model was then used to evaluate the Weibull distribution parameters, which were found to be k=3.0883 and c=4.689 m/s. The parameters were used to assess the wind power density along the highway, which was found to be 50.4 W/m^2 where maximum extractable power is 29.8 W/m^2.

***Key Word**: Vehicle-induced turbulence, Weibull distribution, induced wind speed, wind power density, renewable energy.*

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I. Introduction

Renewable energy is a rapidly growing field that involves the production of energy from sources that are replenished naturally and sustainably over time. Unlike fossil fuels, which are finite and contribute to climate change and the ongoing climate crisis, renewable energy sources like solar, wind, hydropower, geothermal, and biomass can provide clean, low-carbon energy that has minimal environmental impact [1].

Research done on wind potential in Kenya has shown that it has a good potential for wind energy, with some areas of the country experiencing strong and consistent winds[2]–[4]. It has a growing wind energy sector, with several wind farms currently in operation and more being developed. According to the Kenyan Ministry of Energy, wind energy currently accounts for about 7% of the country's total installed power generation capacity. The largest wind farm in Kenya is the Lake Turkana Wind Power project, which has a capacity of 310 MW and is located in Marsabit County [5]. Other notable wind farms in Kenya include the Kipeto Wind Power project (100 MW) in Kajiado County and the Ngong Wind Farm (25.5 MW) in Kajiado County.

There have been several studies on the potential for wind energy production along highways. These studies have typically focused on evaluating the wind resources at specific locations, analyzing the performance of wind turbines at those locations, and developing plans for implementing wind energy production.

One example of a study on wind energy assessment along highways is a project conducted in the United States by the Federal Highway Administration (FHWA). The FHWA conducted a wind resource assessment along selected stretches of interstate highway in several states, using wind monitoring towers and computer modeling to assess the potential for wind energy production[6]. The results of the study showed that there was significant potential for wind energy production along these highways, and the FHWA is now working to identify the most appropriate locations for wind turbines and develop plans for implementing wind energy production.

A study conducted on feasibility of highway energy harvesting using a vertical axis wind turbine along King Fahad Bin Abdul Aziz highway in Kuwait revealed that there is high potential along the highways. The average wind speed recorded was 4.4 m/s and the turbine designed extracted 48W with a 34.6% power coefficient [7] .

To assess the wind resource potential of a specific site, it is necessary to gather data on the wind speeds and patterns 3at that location. This can be done through the use of wind measurement towers, which are equipped with sensors to measure wind speed and direction at various heights above the ground. Once data has been collected on the wind resource potential of a site, the next step is to analyze the data in order to determine the feasibility of a wind energy project.

The Weibull distribution is a statistical distribution that is often used to model wind speeds and other meteorological data. It is characterized by two parameters: shape and scale. The shape parameter determines the distribution's overall shape and can be used to describe the skewness of the data [8]. The scale parameter determines the location of the distribution on the x-axis and is often used to describe the average wind speed or other characteristics of the data. It has a number of properties that make it useful for modelling wind speeds. It can be used to describe the frequency and intensity of wind gusts, as well as the distribution of wind speeds over different time periods. It is also often used in wind energy studies to estimate the power output of wind turbines and the economic feasibility of wind energy projects.

The two parameter Weibull probability distribution function and the cumulative function are given as

$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$……………………………………………………………….**Error! Bookmark not defined.**

$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right]$………………………………………………………………………**Error! Bookmark not defined.**

where v denotes the wind speed, k a dimensionless parameter and c has same dimension as that of v [9].

When $k = 2$, the Weibull distribution function turns into Rayleigh distribution function. Equations 3 and 4 describe the mean wind speed and power density respectively.

$V_m = c\Gamma\left(1 + \frac{1}{k}\right)$………………………………………………………………………………**Error! Bookmark not defined.**

$P_v = \frac{1}{2}\rho v^3$………………………………………………………………………………………**Error! Bookmark not defined.**

Where ρ is the air density which is a function of temperature and pressure that are specific to a site. [8]

Air density is one of the factors affecting power density of a given site. The density of dry air is calculated using equation 5:

$\rho = \frac{p}{R_{specific}\ T}$…………………………………………………………………………………..……**Error! Bookmark not defined.**

Where p is the absolute atmospheric pressure in Pa,$R_{specific}$ is the specific gas constant for dry air in J/kg , and T is the absolute temperature in Kelvin.

Weibull fit

Weibull parameters can be obtained using several numerical methods such as the maximum likelihood method (MLE), and standard deviation method [10]. MLE is the most commonly used method where the values of *k* and *c* can be evaluated using Newton Raphson Method, the Iterative method, or the modified iterative method [10]–[12].

Equations 6 and 7 are a simplification by Justus [13] and can be used to evaluate the *c* and *k*.

$k = \left(\frac{\sigma_v}{V_m}\right)^{-1.086}$ …………………………………………………………………………….……..***Error! Bookmark not defined.***

$c = V_m\left(0.568 + \frac{0.433}{k}\right)^{\frac{1}{k}}$…………………………………………………………………..……**Error! Bookmark not defined.**

Where V_m is the mean wind speed and σ_v is the standard deviation.

The wind power density can then evaluated using the Weibull scale and shape parameters obtained above using any of the method above using equation 8:

$P = \frac{1}{2}\rho c\Gamma(1 + \frac{3}{k})$……………………………………………………………………….**Error! Bookmark not defined.**

Many research studies have used the Weibull distribution to model wind speeds and other meteorological data. These studies have often focused on understanding the characteristics of wind patterns in different locations, assessing the potential of wind energy as a source of power, and developing wind energy prediction models. However, there is inadequate data in Kenya to characterize the highway wind regime making it hard to determine the wind potential and power density. Embu-Nairobi highway is a very active highway with a high volume of traffic using during the day as well as night. Vehicles move at different speeds depending on their body shape and size. The wind speed induced by these vehicles is proportional to the size of the vehicle [14]. This paper determines the shape and scale parameters of the Weibull distribution to estimate the wind power density and power that can be extracted along Embu-Nairobi highway.

II. Material And Methods

The wind data used for this study was collected along the Embu-Nairobi highway at Juja using Young wind sentry anemometer and vane, model 03002V that was mounted along the highway. Temperature data was collected using DS18B20 while pressure data was collected using BMP180. MCP30008 was used as an analog to digital converter to convert the analog signal from the anemometer to a digital signal. The sensors were placed at 1 meter height which had highest amount of vehicle induced turbulence [4]. The electrical circuit showing how these components were connected to raspberry pi 4 is shown in figure 1. The sensor collected and recorded the data at a 2 minutes interval. The data collected was then analyzed using the Weibull distribution to estimate the Weibull shape and scale parameters.

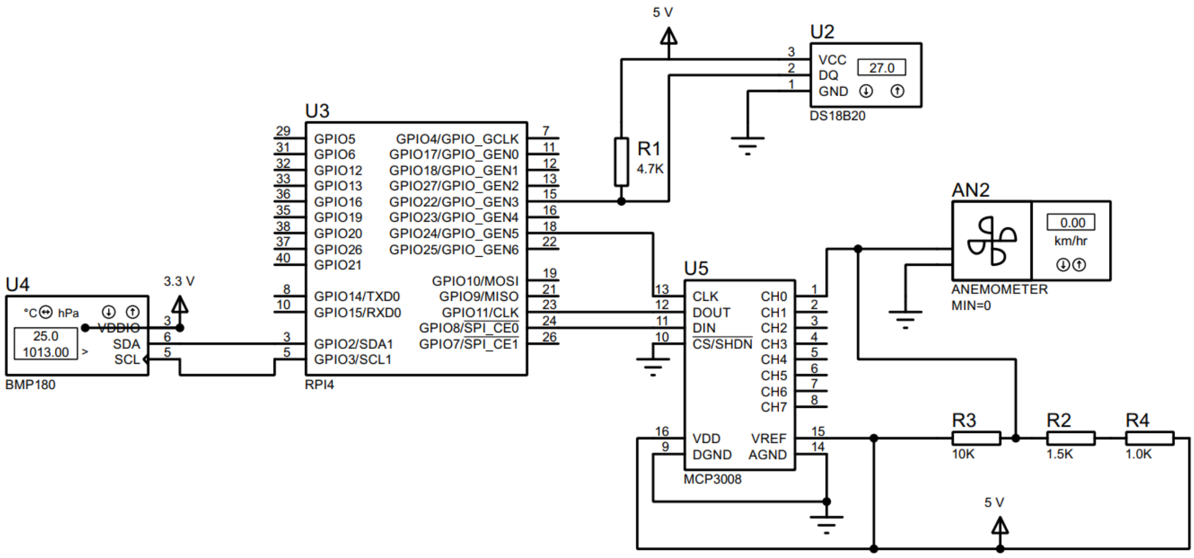

Figure 1: Electrical circuit configuration

III. Result and Discussion

Figure 1 shows that the lowest wind speed was recorded between 6-7 am.

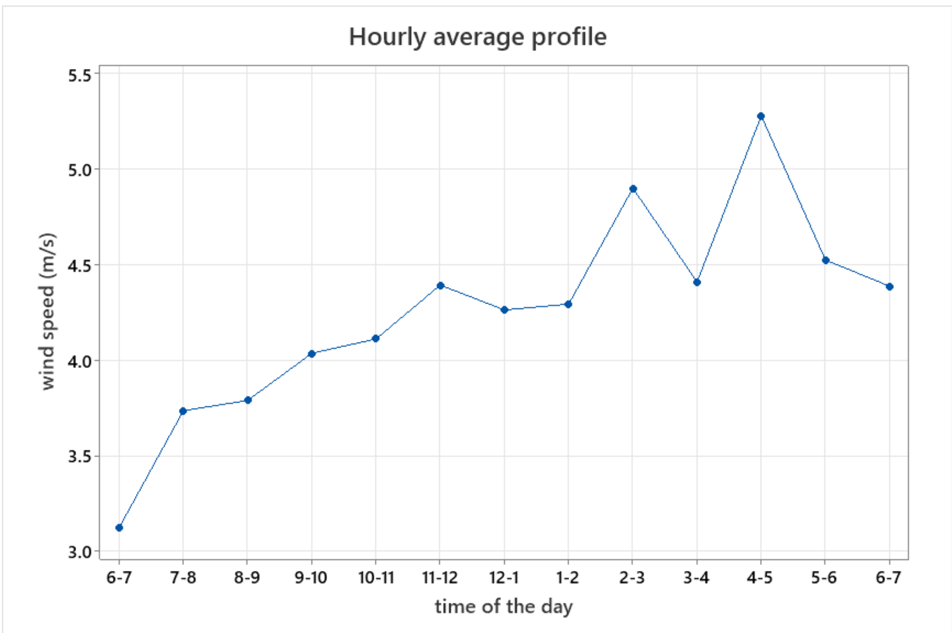

Figure2: Hourly average profile

This is expected because during that time of the day, there are not many vehicles using the highway. As the day goes by, it is evident that the wind speed increases as the number of vehicles increases. The highest wind speed is recorded between 4-5 pm at an average value of 5.27 m/s. This is also expected as during that time, the highway has a lot of vehicles. Thermal road induced turbulence resulting from the temperature difference between road surface and the environment also played a critical role in the high wind speed recorded between 4-5 pm. There is an increased ambient air temperature just above the road surface between 1 to 2 meters due to the high specific heat capacity of the road surface, typically 900 J/kgK12].
Temperature variations with time of day is as shown in Figure 2.

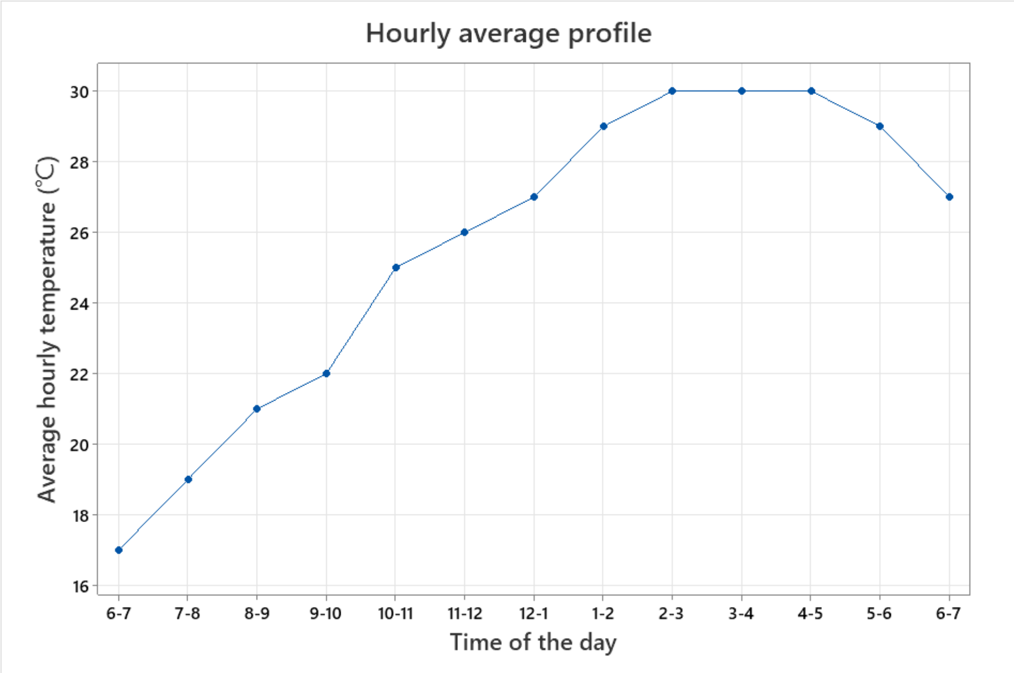

Figure ***Error! No text of specified style in document.****3: Hourly average temperature variation*

The average wind speed increases with an increase in temperature as the day goes by from 6am to 7 pm. During the day, the sun's radiation hits the earth, and some is absorbed while some is reflected back. Air at 1 m is heated through convention and radiation. The incoming sun radiation brings more energy than the earth is losing, hence, the air temperature at 1 m continues to rise up until 3 pm. At this time, then incoming solar radiation balances the outgoing infrared radiation from earth's surface and thus maximum temperature was attained. The incoming solar radiation remained the same which resulted in a constant temperature up until 6 pm. Past that, the incoming solar radiation was less than the outgoing radiation through convection, which resulted in a decrease in temperature.
Figure 3 shows there is an increase in wind speed as temperature increases.

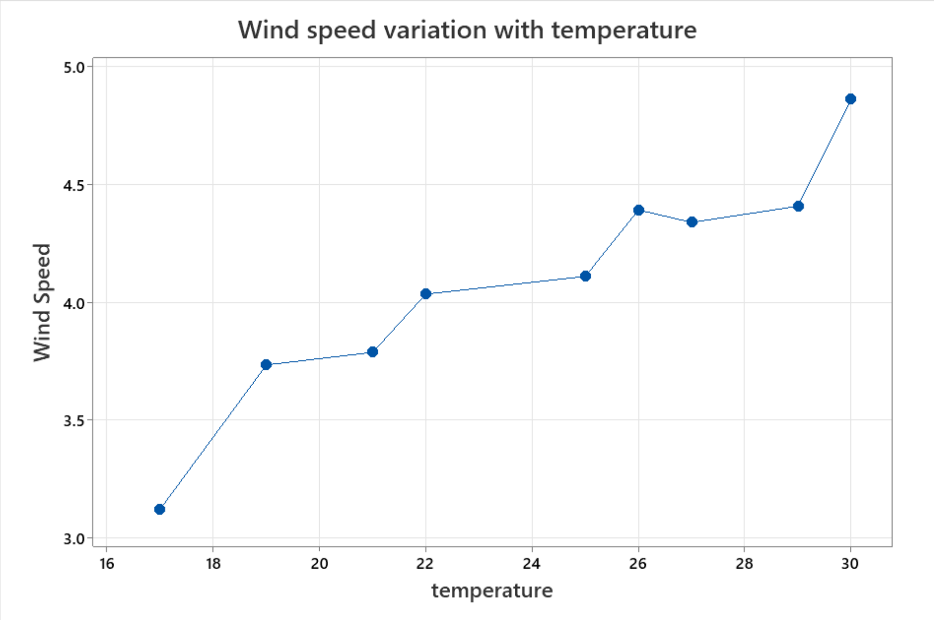

Figure 4: Wind speed variation with temperature

A rise in temperature increases the kinetic energy of air molecules causing them to move faster and eventually occupying a larger space. This increase in volume reduces the density of air at that point resulting in a corresponding decrease in pressure. Figure 4 shows the variation in pressure with time of day. Warm air moves upwards leaving a low-pressure region behind. Cold air is then forced to move into the low-pressure belt to replace the warm air. This air movement increases with an increase in temperature thus increasing the overall wind speed in the region.

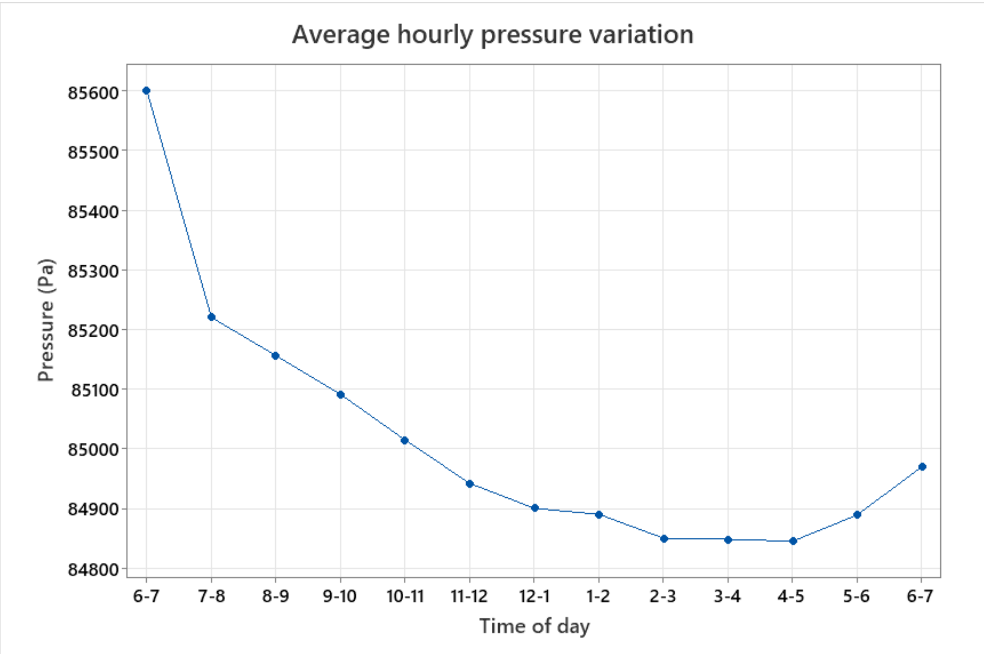

Figure5: Average hourly variation in pressure

The data was collected in March 2022. March is the hottest month in Juja with a daily average record high and low of 32.01℃ and 12.0℃ recorded [16]. The month of March has relatively low wind speeds with mean wind speeds of 2.81 m/s at 10 m and 3.36 m/s at 13 m height with a wind shear exponent of 0.16 [4]. Thus, the expected wind speed at 1 meter height at the highway where the data for this study was collected is

$$\frac{V}{2.81} = \left(\frac{1}{10}\right)^{0.16}$$

$$\frac{V}{2.81} = 0.6918$$
$$V = 1.944 \text{ m/s}$$

However, the average induced wind speed at this site was 4.1885 m/s. This means that the highway experiences more wind and turbulence than the normal environment in Juja. This can be attributed to the presence of vehicles moving along the highway contributing to vehicle induced turbulence and temperature variation of the boundary layer and the ambient air.

Turbulence intensity

Turbulence intensity (TI) is a measure of how much wind speed varies relative to its average value. It's calculated by taking the ratio of the standard deviation of wind velocity fluctuations to the mean wind speed. The TI along the highway for the period of that the data was collected is

$$TI = \frac{1.503}{4.1885} \times 100\% = 35.88\%$$

Turbulence at 1 m height from the earth's surface in the planetary boundary layer is caused by a variety of factors, including surface heating, surface roughness, and atmospheric instability. As the sun heats the Earth's surface, the air near the surface warms up and rises, creating an upward current of warm air. This warm air mixes with cooler air from higher altitudes, creating turbulence and causing the air to move in a chaotic manner. The turbulence at this point along the higher is further increased by movements in vehicles through the creation of wake vortices, which disturb the airflow and affect other vehicles and objects in their path [17]. The value obtained is elevated due to the high traffic volume experience on this highway.

While HAWTs have been the primary wind energy technology used, VAWTs may have an advantage over HAWTs in urban environments and especially along highways. VAWTs have the ability to work effectively in turbulent and non-traditional wind conditions and produce energy at lower speeds, which can be particularly useful in urban areas [18].

Weibull fit

The wind speed data was used to determine the Weibull shape and scale parameters and the wind power density were determined using standard deviation method and MLM.Minitab was used to determine the Weibull parameters as well as the probability density function for the wind data. Using the standard deviation method, the value of *k* can be evaluated as:

$$k = \left(\frac{1.4787}{4.1885}\right)^{-1.086} = 3.0883$$

$$c = 4.1885\left(0.568 + \frac{0.433}{3.0435}\right)^{\frac{1}{3.0883}} = 4.6835\ m/s$$

The Weibull shape and scale parameters from MLM are 3.045 and 4.689 m/s. Table 1 shows a comparison of the estimated parameters using the two methods.

Table 1: Weibull parameters

Method	c(m/s)	k
Standard deviation	4.6835	3.0883
MLM	4.689	3.045

The Weibull scale parameters estimated is almost equal while the shape parameter differs with a small range which validates the model used in this study. The shape parameter describes wind behavior based on its value; the wind speed is very low when the k value is small. On the other hand, the high value of *k* shows that the site has an equal number of high and low wind speeds.

Frequency distribution

The generated frequency distribution function is indicated in Figure 4. The plot shows the frequency against wind speeds. The graph shows how many instances there were for each wind speed.

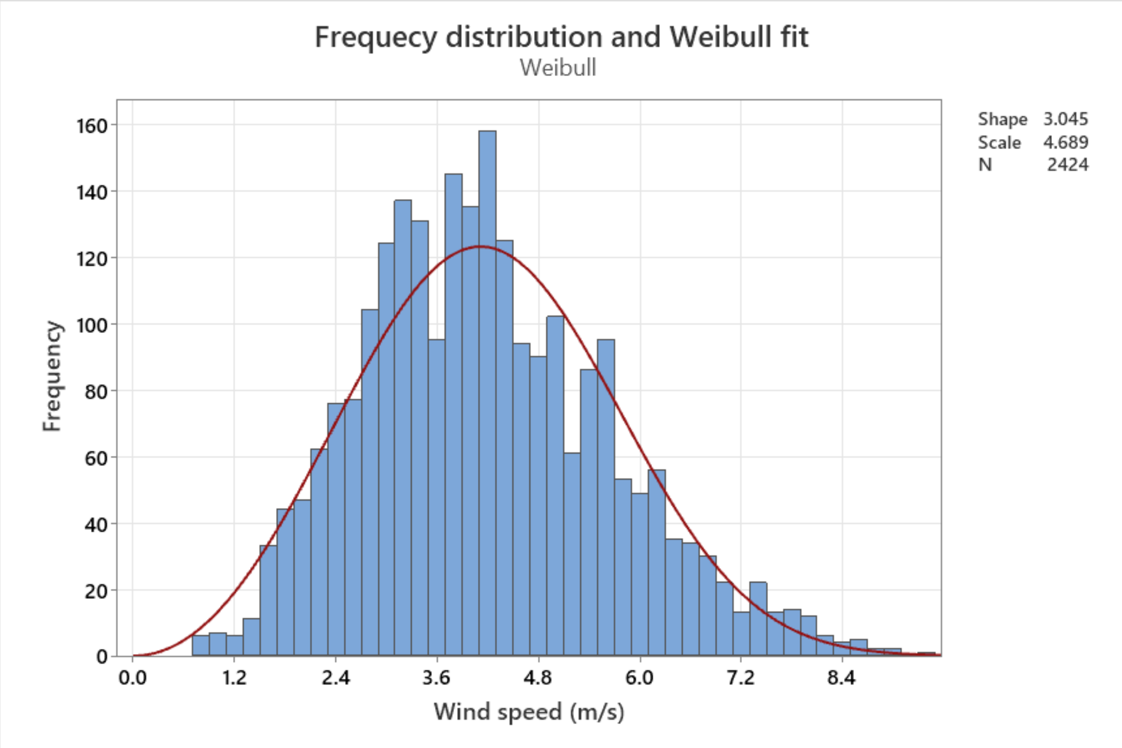

Figure 6: Frequency distribution graph with Weibull fit

The lowest wind speed recorded was 0.817 m/s, while the highest speed recorded was 9.39 m/s. These data values are in agreement with field measurements where wind speeds fluctuated between 1.4 m/s and 9.8 m/s [19] The mean wind speed, μ, was found to be 4.1885 m/s, and the standard deviation was found to be 1.4787. The mean wind speed recorded on the highway is less than the maximum wind speed of 4.5 m/s recorded at a road shoulder [20]. This is due decreased vortices behind and at the side of vehicles moving along the highway at 1.5m where the data collection senors were positioned.The The area under the Weibull fit curve in Figure 4 is equal to 1 since the probability of wind blowing at any speed including zero must be 100 percent. It can be seen the graph has a positive skewness implying that the probability of wind blowing with a wind speed below median is high. The modal wind speed is 4.27 m/s, which is greater than the mean wind speed recorded. The curve also picks at this modal speed meaning that these are the most probable wind speed along the highway.

Figure 6 shows the cumulative frequency curve which is essential in analyzing the percentage wind speed distribution at any site. The curve represents the probability that the wind speed is greater, equal to, or smaller than a given wind speed. It can be seen that more than 20% of the wind speed recorded at the highway is greater than 3 m/s.

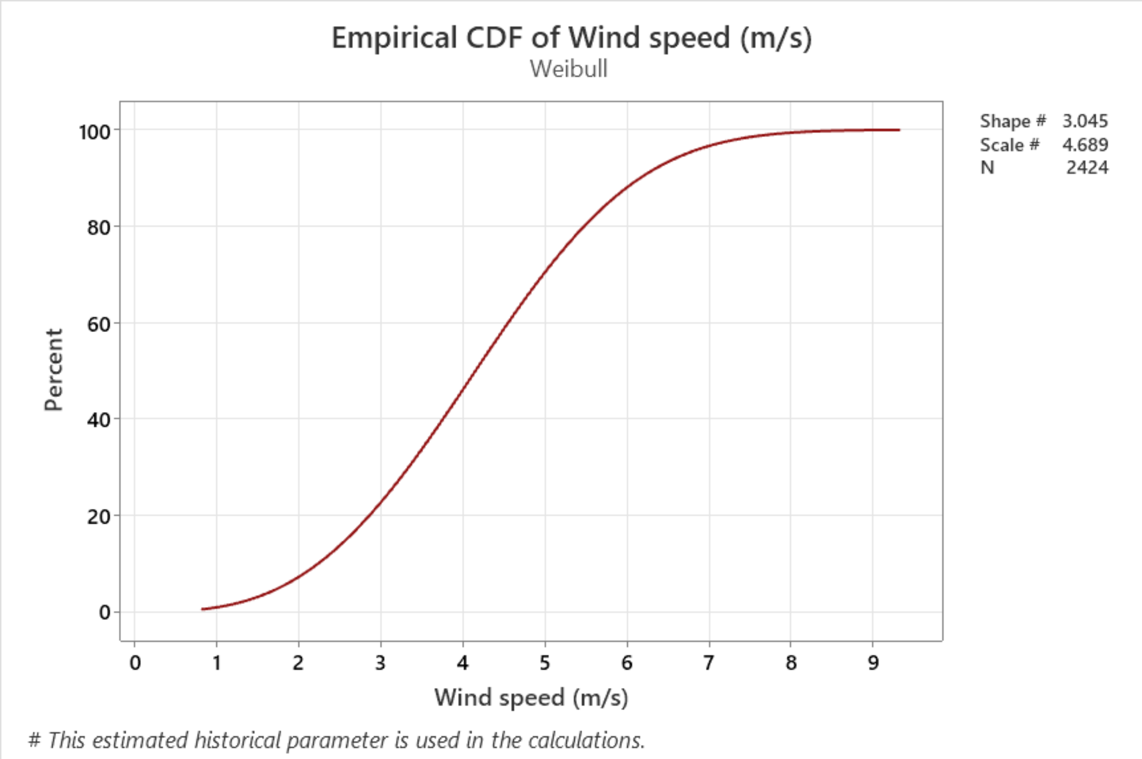

Figure7: Weibull cumulative frequency curve

The mean wind power density obtained due to the vehicle-induced wind speed using Weibull $k = 3.0883$ and $c = 4.689$ m/s and an average air density of 098967 kg/m^3 is 50.4 W/m^2. This power is 1.39 times higher than the power that would be recorded if the wind was blowing at a constant speed of 4.1883 m/s. This is because the wind power density takes into account the contribution from every wind speed with which the wind blows in every fluctuation. Taking Beltz limit into consideration that maximum power extractable from wind by a wind turbine is 59.3% of the theoretical power limit, then, for the highway, we can extract 29.8 W/m^2 of induced wind energy. The estimated wind speed at 10 meters height is 6.05m/s and thus the wind power density at this height is 109.39 W/m^2 which lies in the wind power density class 3 [21]

Recommended wind turbine

The highway has low wind speed and will require a turbine with a low cut-in speed. The recommended VAWT design of ETV 2.0 has characteristics indicated in table 1 (*Vertical Axis Wind Turbine*, n.d.).

Table 2: Recommended turbine specifications

Cut in speed	Cut out speed	Rated power	Rated wind speed	Survive wind speed	Blade length	Rotor diameter	Swept area	Number of blades
1 m/s	25 m/s	200 W	10 m/s	50 m/s	1.28 m	0.78 m	0.9 m^2	3

This turbine can generate and feed power to stand alone systems. This turbine can harness both low wind speeds induced by vehicles as well as gusts of up to 25 m/s. It can be observed from Figure 1 the wind speed is above the cut-in wind speed throughout the day; thus, the turbine will be generating power throughout the day. This power can be used in street lighting, and it can also feed a considerably good amount of power to the national grid.

IV. Conclusion

The following conclusions were made from the induced wind speed data collected along the Embu-Nairobi highway:

1. The average air density during the day was 0.9896 kg/m3, which is attributed to the thermal heating of the highway by the sun.
2. The Weibull shape parameter k was found to be 3.0883 while the scale parameter c was found to be 4.689 m/s with a mean wind speed of 4.1883 m/s which shows that the highway is windier than

surrounding environment which iscontributed by vehicles induced turbulence for harnessing by a VAWT.

3. The mean power density for the highway was 50.4 W/m2 where maximum extractable power from the highway was 29.8 W/m2.

References

[1] K. Kaygusuz, "Energy and environmental issues relating to greenhouse gas emissions for sustainable development in Turkey - ScienceDirect," *Elsevier*, vol. 13, no. 1, pp. 253–270, Jan. 2009.

[2] K. Muchiri, J. N. Kamau, D. W. Wekesa, C. O. Saoke, J. N. Mutuku, and J. K. Gathua, "Wind and solar resource complementarity and its viability in wind/PV hybrid energy systems in Machakos, Kenya," *Sci. Afr.*, vol. 20, p. e01599, Jul. 2023, doi: 10.1016/j.sciaf.2023.e01599.

[3] N. L. Ongaki, C. M. Maghanga, and J. Kerongo, "Evaluation of the Technical Wind Energy Potential of Kisii Region Based on the Weibull and Rayleigh Distribution Models," *J. Energy*, vol. 2021, p. e6627509, Jun. 2021, doi: 10.1155/2021/6627509.

[4] M. A. Wandia, K. J. Ngugi, and T. Nelson, "Wind Power Potential Analysis Based on Different Methods Fitted in Weibull and Rayleigh Models for Wind Patterns in Juja and Naivasha," vol. 5, no. 1, 2016.

[5] R. Janho, "Renewable energy in Kenya: An examination of the legal instruments and institutional changes that successfully attracted foreign investment," *Energy Central*, Nov. 18, 2020. https://energycentral.com/c/pip/renewable-energy-kenya-examination-legal-instruments-and-institutional-changes (accessed Feb. 11, 2023).

[6] FHWA, "Renewable Energy Generation in the Highway Right-of-Way." https://rosap.ntl.bts.gov/view/dot/49020/dot_49020_DS1.pdf? (accessed Jan. 08, 2023).

[7] E. H. Bani-Hani, A. Sedaghat, M. AL-Shemmary, A. Hussain, A. Alshaieb, and H. Kakoli, "Feasibility of Highway Energy Harvesting Using a Vertical Axis Wind Turbine," *Energy Eng.*, vol. 115, no. 2, pp. 61–74, Feb. 2018, doi: 10.1080/01998595.2018.11969276.

[8] S. K. Ghosh, M. H. Shawon, M. A. Rahman, and S. K. Nath, "Wind energy assessment using Weibull Distribution in coastal areas of Bangladesh," in *2014 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET)*, 2014, pp. 1–6.

[9] M. Shoaib, I. Siddiqui, Y. Amir, and S. Rehman, "Evaluation of wind power potential in Baburband (Pakistan) using Weibull distribution function," *Renew. Sustain. Energy Rev.*, pp. 1–9, 2016, doi: 10.1016.

[10] A. H. Shaban, A. K. Resen, and N. Bassil, "Weibull parameters evaluation by different methods for windmills farms," *Energy Rep.*, vol. 6, pp. 188–199, Feb. 2020, doi: 10.1016/j.egyr.2019.10.037.

[11] A. Ibraheem Al-Tmimi, "Graphical and Energy Pattern Factor Methods for Determination of the Weibull Parameters for Ali Algharbie Station, South East of Iraq," *Eng. Technol. J.*, vol. 31, no. Issue1A, pp. 98–106, Jan. 2013, doi: 10.30684/etj.2013.71251.

[12] T. P. Chang, "Estimation of wind energy potential using different probability density functions," *Appl. Energy*, vol. 88, no. 5, pp. 1848–1856, May 2011, doi: 10.1016/j.apenergy.2010.11.010.

[13] C. G. Justus, W. R. Hargraves, A. Mikhail, and D. Graber, "Methods for Estimating Wind Speed Frequency Distributions," *J. Appl. Meteorol. 1962-1982*, vol. 17, no. 3, pp. 350–353, 1978.

[14] Y. Kim, "Quantification of Vehicle-induced Turbulence on Roadways Using Computational Fluid Dynamics Simulation," University of Toronto, 2011. [Online]. Available: https://tspace.library.utoronto.ca/bitstream/1807/31283/1/Kim_Yesul_201111_MASc_thesis.pdf

[15] H. Li, J. T. Harvey, T. J. Holland, and M. Kayhanian, "The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management," *Environ. Res. Lett.*, vol. 8, no. 1, p. 015023, Feb. 2013, doi: 10.1088/1748-9326/8/1/015023.

[16] Weather and Climatea, "Juja, Kiambu, KE Climate Zone, Monthly Averages, Historical Weather Data." https://tcktcktck.org/kenya/kiambu/juja (accessed Feb. 16, 2023).

[17] D. Cogan, "The aerodynamic design and development of an urban concept vehicle through CFD analysis," Thesis, Cape Peninsula University of Technology, 2016. Accessed: Feb. 19, 2023. [Online]. Available: https://etd.cput.ac.za/handle/20.500.11838/2386

[18] A. R. Winslow, "Urban Wind Generation: Comparing Horizontal and Vertical Axis Wind Turbines at Clark University in Worcester, Massachusetts," Clark University in Worcester, Massachusetts, 2017.

[19] A. Raheem and W. Esmaeel, "Highway wind power energy assessment of Al-Durra highway street in Baghdad, Iraq," *Int. J. Power Electron. Drive Syst. IJPEDS*, vol. 11, p. 2055, Dec. 2020, doi: 10.11591/ijpeds.v11.i4.pp2055-2061.

[20] A. A. Al-Aqel, B. K. Lim, E. E. Mohd Noor, T. C. Yap, and S. A. Alkaff, "Potentiality of small wind turbines along highway in Malaysia," in *2016 International Conference on Robotics, Automation and Sciences (ICORAS)*, Nov. 2016, pp. 1–6. doi: 10.1109/ICORAS.2016.7872634.

[21] M. Z. Ibrahim, K. H. Yong, M. Ismail, and A. Albani, "Spatial Analysis of Wind Potential for Malaysia," *Int. J. Renew. ENERGY Res.*, vol. 5, pp. 201–209, Jan. 2015.

[22] "Vertical Axis Wind Turbine -." http://www.energtrade.com/vertical-axis-wind-turbine/ (accessed Feb. 22, 2023).

Jane Wanja Karanja, et. al. "Analysis of Induced Wind Speed along Embu-Nairobi Highway, Nairobi, Kenya."*IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT)*, 17(3), (2023): pp 12-20.