# MODELING LIGHTNING FLASHES IN TRANSMISSION STRUCTURES

B. Ardila[1], E. Soto [2], J. Zamora [3]

[1] GISEL, Universidad Industrial de Santander, Colombia: Email: bardimur@correo.uis.edu.co
[2] GISEL, Universidad Industrial de Santander, Colombia: Email: easotor@uis.edu.co
[3] GISEL, Universidad Industrial de Santander, Colombia. Email: jzamoliz@correo.uis.edu.co

***Abstract*— In this work, the authors model the number of lightning flashes in transmission structures with Ground Flash Density, height tower, and elevation above sea level as variables. 333 transmission structures were located in the northeast of Colombia, where an influence radius of 150 meters was established for each one. Cloud-to-ground lightning strokes detected by the LINET network between 2014 and 2021 in the studied area were grouped into flashes and counted for each radius. Likewise, each structure was characterized by its height, elevation above sea level, and GFD of the area where it is located. In this way, a model that describes 75.66 % of flashes in transmission structures with a standard deviation of 0.32 flashes was built. It is concluded that there is a linear relationship between the dependent variable and all the independent variables.**

***Keywords*— Ground Flash Density (GFD), LINET Network, tall structures, transmission tower, lightning strikes, back-flashover rate BFR.**

## I. Introduction

ELEVATED structures are likelier to be struck by Cloud to Ground Lightning Flashes (CG) than their surroundings, lower towers, or natural objects [1]. This is because they respond with upward leaders that connect with downward-stepped leaders originating from thunderstorms, which propagate through the atmosphere by ionization processes. Once the attachment between leaders is established, one or several current peaks, known as return strokes, are recorded [2]. In turn, structures that exceed 100 meters can initiate upward leaders and trigger return strokes when they reach the thunderstorm charge structure [3].

The average number of lightning strikes in elevated structures (upward or downward flashes) was initially modeled in [4] through the expression:

$$N_s = 2.4\times10^{-5}H^{2,05} \qquad (1)$$

Where *Ns* corresponds to the average number of lightning strikes in the elevated structure per year for a Ground Flash Density *GFD =1* flash/km$^2$/year, and H is the structure height in meters. The above implies that the number of lightning strikes in elevated structures is directly proportional to the square of its height, as confirmed in [5]. Likewise, it was determined that the increase in lightning strikes in tall objects that exceed 100 meters of altitude was due to ascending leaders that start from the structure (upward flash).

In contrast, lower structures are struck only by downward leaders (downward flash) [6]. Subsequently, in [7] the proportion of upward flashes in elevated structures will be established according to its height as follows:

$$P_u = 52.8 \ln H - 230 \qquad (2)$$

Thus, the number of downward flashes in structures described by the expression (1) was finally obtained by:

$$N_d = 2.4\times10^{-5}H^{2,05} - 3.0\times10^{-9}H^{3,53} \qquad (3)$$

In addition, the concepts of equivalent attractive radius [7] and striking distance [8], were established, the latter widely used in lightning protection design of transmission lines. Finally, in [7], the average incidence of lightning strikes in transmission lines $N$ was determined and expressed in flashes/100km/year using the following expression:

$$N = N_g\left(b + 28\times H^{0,6}\right)\times10^{-1} \qquad (4)$$

Where b is the structure width. Subsequent studies introduced the effect of mountainous terrain on the number of negative lightning strikes in elevated structures, considering the impact of topography on the induced potential and the influence of the decrease in air density on the attachment process [9]. Moreover, the criteria for ascending lightning incidences arose. The hypothesis that electric fields on earth due to thunderstorms can significantly affect the radius of attraction to downward negative lightning flashes in elevated structures were established [10]. It was also determined that lightning strikes that struck tall objects had higher current peaks. Also, a more significant number of subsequent strokes compared to lightning strikes in the tower vicinity [11].

The electric and magnetic fields radiated by lightning flashes that struck elevated structures in the first return stroke and its subsequent ones were also analyzed. It was concluded that the presence of elevated objects tends to increase the peaks of those fields [12]. Other studies measured induced voltages in distribution lines due to negative lightning flashes in high structures [13]. Additionally, the physical processes that occur during the propagation of upward positive leaders in elevated structures were studied based on the bidirectional leader theory [14].

More recent studies determined wind turbines can initiate upward flashes much more quickly than static structures. This is because its blades' rotation and material cause a greater electrostatic induction, resulting in stronger electric fields that favor the initiation of upward flashes [15]. In addition, negative leaders that produced strikes on wind turbines were mapped through the Lightning Mapping Array LMA network [16][17]. The characteristics of thunderstorms favor ascending and descending lightning flashes to wind turbines were determined [18]. It was concluded that most lightning strikes impacting elevated structures correspond to negative flashes with current peaks above the average. Knowing the number of direct lightning flashes in transmission structures is crucial to determine the back-flashover rate (BFR), or in other words, to obtain the lightning performance of transmission lines. This work presents an expression to determine the number of lightning flashes in elevated structures as a function of the Ground Flash Density, the tower's height, and its elevation about sea level.

## II. Methodology

### *A. Study zone*

Fig 1. shows the study area corresponding to a 96×25 km area located in the northeast of Colombia in the department of Santander. The zone is crossed by a mountain range to the west and comprises a large plain to the east.

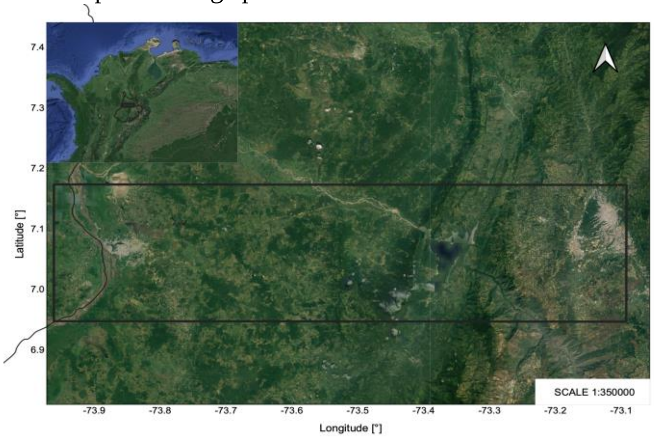


Fig. 1. Geographical location of the study area located in the northeast of Colombia in the department of Santander

### *B. Data*

Lightning information in this study corresponds to cloud-to-ground strokes detected between 2014 and 2021 by the Colombian Total Lightning Detection Network with LINET technology [19]–[22]. This "Total Lightning" network that operates in the very-low/low frequency (VLF/LF) ranges is made up of 19 sensors distributed throughout the country. These detect the magnetic field generated by the electromagnetic impulses of lightning through an arrangement of two loop antennas orthogonal to each other. The position of each event is determined through the Time of Arrival technique TOA. Considering that there are areas in the country where the minimum detectable amplitude of the peak discharge current is 10 kA [23], [24], impacts with currents lower than this value were not considered.

### *C. Elevated structures and radius of influence*

A total of 333 transmission structures whose heights vary between 40 and 140 meters were located in the study area. These structures are located at elevations between 65 and 1370 masl. Fig 2. presents the location of the transmission structures.

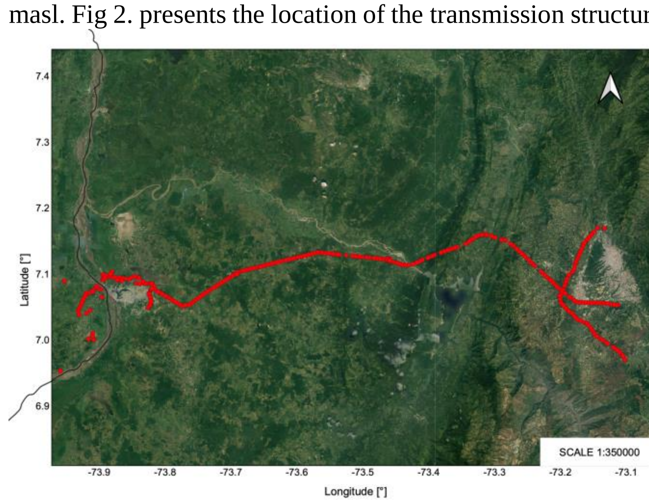


Fig. 2. Geographical location of the transmission structures in the study zone

In this work, we affirm that all flashes within the radius of influence of some elevated structure are direct. Therefore, impacts with significant errors must be discarded. In other words, flashes with minor errors must be considered to reduce the uncertainty of counting an impact as a direct one when it was not.

The detection error of each flash recorded in the study area was analyzed using percentiles to recalculate the radius of influence of elevated structures. The 75th percentile corresponds to 168 meters, which indicates that 75% of the located flashes have errors smaller than 168 m, so 25% of the data have substantial errors. Therefore, the probability of having impacted some transmission structure highly decreases. By the above, flashes with location errors greater than 168 m were discarded, and a radius of influence of 150 m supported by [25] was established for each elevated structure. So that each impact with a location error of less than 168 m and registered within some radius of influence of 150 m is considered direct.

Using the electrogeometric model and considering an average height of 40 m for the towers, flashes with currents greater than 10 kA safely impact an elevated structure if they are recorded at 45 m or less from it. The latter, if the network did not have a location error, but due to the average error calculated in the database of flashes and what was stated in [25], the location error criterion was used to define the radius of influence of each structure.

### *D. Determination of the Ground Flash Density*

A grid with 1 km$^2$ cells is established to calculate the Ground Flash Density GFD in the study area. The flashes are located as points in space, as shown in Fig. 3, where the obtained grid is also observed.

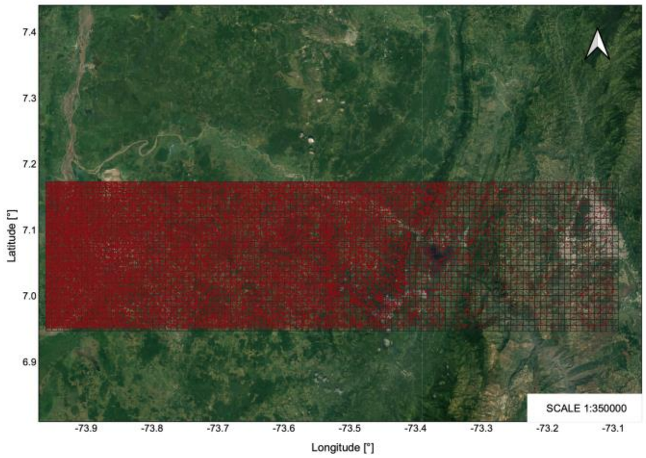


Fig. 3. Grid set for GFD calculation

Subsequently, all the flashes per cell were counted, and the result was divided into the number of years of the study that correspond to 8, in such a way that the GFD value is obtained in flashes/km$^2$/year.

Bearing that the position of an elevated structure within a cell may alter the calculation of the GFD, four additional grid movements were made to the one initially established. These movements correspond to 250 m to the right, left, and up and down, obtaining finally 5 grids. For each of them, the GFD was determined, and it was observed that there were no significant changes in the GFD values according to the position of the elevated structure in the cell. A study supports the preceding since hotspots were found in the study area [26], which do not necessarily coincide with elevated structures. Therefore, in this area, it is impossible to affirm that a high structure corresponds to a hotspot in all cases.

According to the above, the calculation of the GFD is not substantially altered by changing the grid position. However, the five grids were considered to assign a GFD value to each transmission structure. So, the average of the five GFD measurements corresponds to the GFD value assigned to each structure. Likewise, a second test was carried out, and it was to locate each elevated structure right in the center of a cell of 1 km on each side. The GFD was calculated for this cell, obtaining higher values than those obtained by averaging the five abovementioned measurements.

### *E. Correlation between Ground Flash Density and terrain elevation*

The first methodology [27]–[29] used to find a correlation between GFD and terrain elevation established 1 km$^2$ cells in the study terrain. Two average data characterized each cell: GFD(i,j) and height h(i,j) In this way, a mean value of GFD is calculated for each height interval, and therefore a correlation between GFD and *h* was achieved for all height values. Regions with the same height but different lightning activity are mixed with this method, and therefore distorted results can be obtained.

In [30], an improvement called the subarea decomposition method is proposed. A step that corresponds to dividing the study area into subareas with a relatively uniform average level of lightning activity is added. Then, the relation between GFD and *h* is calculated using the first method for each subarea. By adding this step, regions with the same altitude range and different lightning activity are separated. Fig 4 shows the sub-areas determined in the study area according to their average lightning activity for which the relation between the GFD and elevation was determined. The heights of the study area vary from 59 masl to 2068 masl.

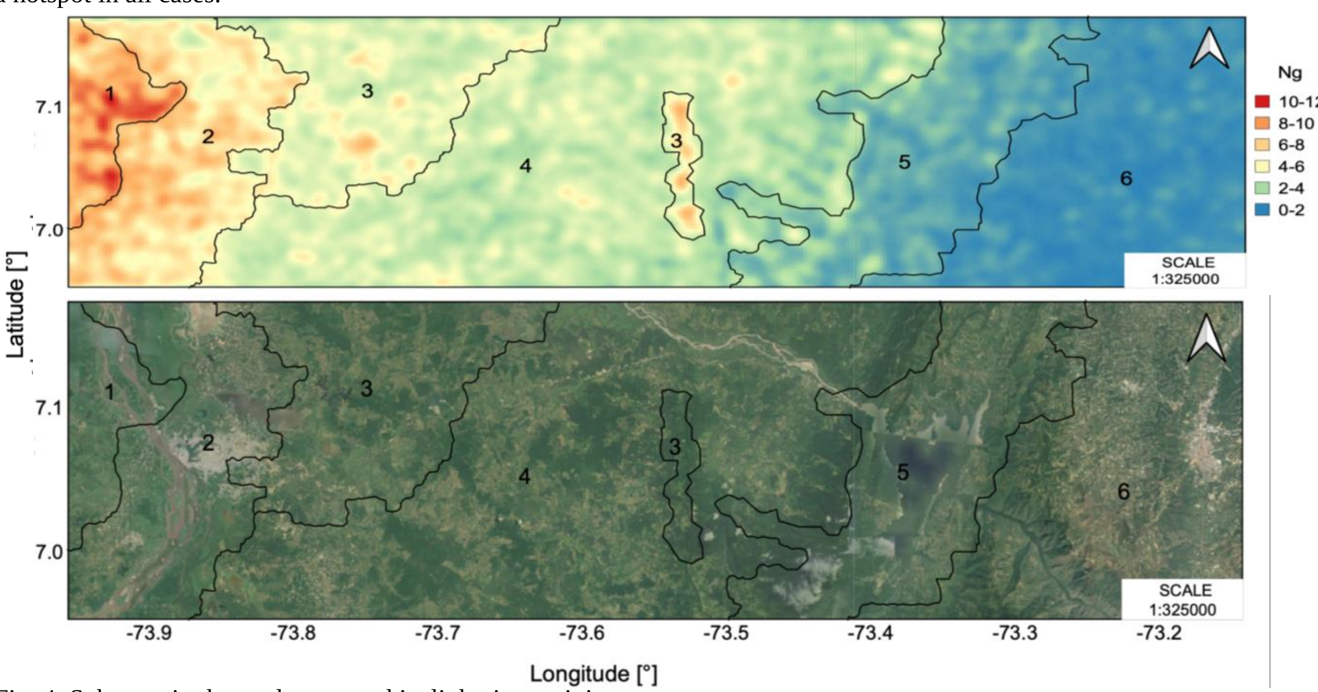


Fig. 4. Subareas in the study area and its lightning activity.

### F. Model construction

Taking the number of flashes on elevated structures as the dependent variable and the Ground Flash Density GFD, the structure height, and its elevation above sea level as independent variables, a multiple linear regression was performed, and the sensitivity of the dependent variable to each of the independent variables was analyzed.

## III. Results

### A. Flashes in transmission structures

Fig. 5 presents the variation in the number of flashes in transmission structures during the study period. It can be seen that the structures with the highest number of lightning flashes are located to the left of the graph on the banks of the Magdalena River and near the municipality of Barrancabermeja at elevations between 60 and 100 masl. The structures in yellow tones have moderate lightning flashes and are located at elevations between 100 and 600 meters above sea level. On the other hand, the structures less struck by lightning flashes are located to the right of the graph at heights that exceed 1000 meters above sea level, especially on mountain ranges.

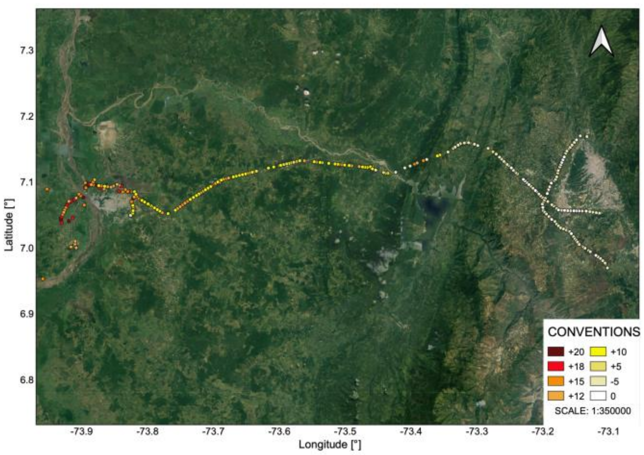


Fig. 5. Number of lightning flashes in transmission structures.

### B. Correlation between Ground Flash Density and terrain elevation

Fig 6 shows the variation of the GFD as a function of terrain elevation. From this, it can be concluded that the GFD increases with height in an area with uniform lightning activity (zone). Then, different GFD values can be obtained for the same height value according to the area where the structure is located. Based on the above, a structure located at less than 100 masl in a zone of high lightning activity (zone 1) may have a higher GFD than one located at more than 200 masl in a zone with lower activity (zone 3). Therefore, the statement that the GFD increases with height applies only to areas with uniform lightning activity.

The GFD values of the elevated structures are comparable but only for the structures that belong to the same area, in which case the structure with the highest elevation will have a higher GFD value and, therefore, a greater number of impacts. However, for structures that belong to different zones, the structure in an area with greater lightning activity will tend to register a greater number of lightning strikes, even if it is at a lower height. The above can be evidenced in the graphs presented.

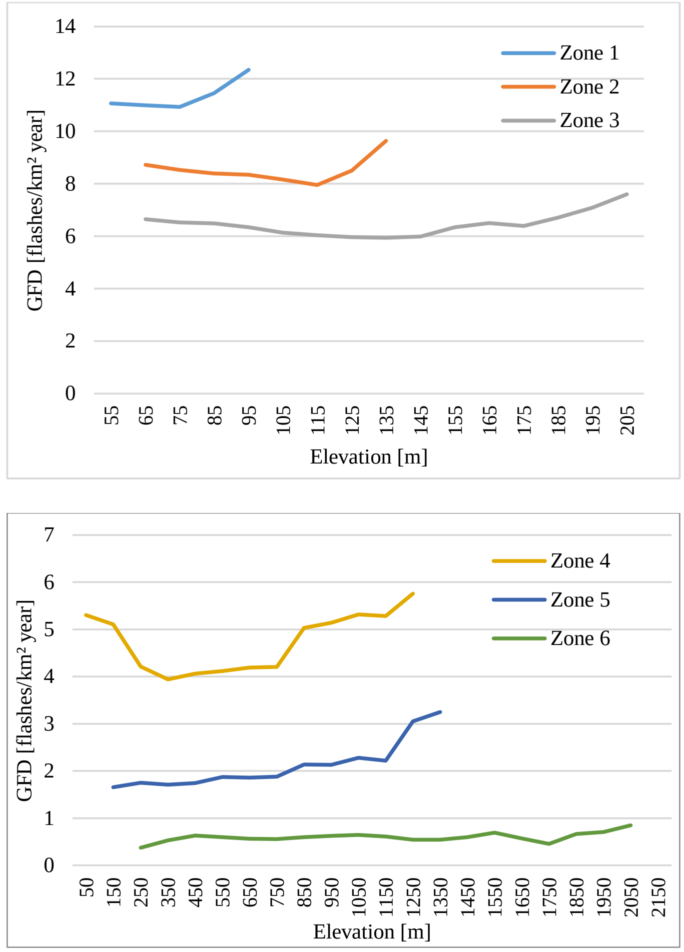


Fig. 6. Correlation between Ground Flash Density and terrain elevation in subareas 1 to 6.

### C. Formulation of the model

The following function models the number of flashes per transmission structure per year.

$$\mathrm{Fl} = 0.15438680\ \mathrm{GFD} + 0.00050055\ \mathrm{H} + 2.5948\times10^{-5}\mathrm{h} - 0.03755805 \quad (5)$$

Where:

Fl: Number of flashes per transmission structure per year
GFD: Ground Flash Density of the area where the elevated structure is located in flashes/km$^2$/year
H: Transmission structure's height in meters.
h: Height above sea level of the site where the elevated structure is located in meters

Equation (5) shows that keeping H and h constant, the number of flashes in transmission structures (Fl) will increase by 0.15 flashes (coefficient of GFD) for each increase of 1 flash/km$^2$/year in the GFD.

Likewise, the Fl value will increase by 0.00050 flashes (coefficient of H) for every 1-meter rise in H, keeping the GFD and h constant. Moreover, the Fl value will increase by $2.5948\times10^{-5}$ flashes (coefficient of h) for every 1-meter rise in h while the GFD and H are constant. Table I shows the multiple regression statistics obtained.

TABLE I
STATISTICS OF THE MULTIPLE REGRESSION

| Parameter | Value |
|---|---|
| Multiple correlation coefficient | 0.871 |
| Determination coefficient $R^2$ | 0.759 |
| $R^2$ tight | 0.757 |
| Typical error | 0.321 |
| Observations | 333 |

The association of the three independent variables with the dependent variable corresponds to 87.11%. Likewise, 75.88% of the variation in the number of lightning flashes on transmission structures is explained by the variation of the GFD, the height of the structure, and the elevation above sea level simultaneously. This results from dividing the sum of squares of the regression SSR (106.530) by the total sum of squares SST (140.389).

With the above, 24.12% of the variation in the number of lightning flashes on transmission structures is explained by other variables that will be the subject of subsequent studies. Among them are the topology of thunderstorms, which start the cloud-to-ground lightning flashes that strike high structures, the heights of their charge regions, and the polarity of leaders that cause these lightning strikes on elevated structures. Considering that including a new variable causes the loss of a degree of freedom is necessary verifying if the variable contributes sufficient explanatory power to the dependent variable.

The percentage of explanation of the number of lightning flashes in transmission structures carried out by the GFD, the height of the structure, and the elevation above sea level corresponds to 75.7%, considering the relationship between the number of transmission structures and dependent variables. Finally, the standard deviation of the model is 0.32 flashes, so ±0.64 flashes can approximate a prediction range for the number of lightning flashes in tall structures.

### *D. Diagnostic of the model*

The F test is performed to assess the overall significance of the found model. As a null hypothesis, there is no linear relationship between the dependent and independent variables.

As an alternative hypothesis, it is proposed that there is a linear relationship between the number of lightning flashes in elevated structures and at least one of the independent variables. The F test statistic is calculated as follows:

$$F = \frac{SSR/_k}{SSE/_{n-k-1}} = \frac{MSR}{MSE} \tag{6}$$

Where:
SSR: Sum of squares of the regression
SSE: Sum of squares of the residuals
k: Independent variables or degrees of freedom of the numerator
n: Number of transmission structures
n-k-1: Degrees of freedom of the numerator

$$F = \frac{106.530/_3}{33.859/_{329}} = 345.039 \tag{7}$$

With a significance level of 5% and 3 degrees of freedom for the numerator and 329 for the denominator, the critical value corresponding to the F distribution corresponds to 2.632. Then, starting from this value, it can define the rejection zone in which the test statistic is located, and therefore the null hypothesis is rejected. The above concludes that there is a linear relationship between the dependent variable and all the independent variables considered jointly. Therefore, there is sufficient evidence to show that the regression model explains part of the variation in the number of lightning flashes in elevated structures (at least one of the regression slopes is not zero).

The most significant variable of the model found is the Ground Flash Density GFD. Fig. 7 shows the variation in the number of lightning flashes in transmission structures as a function of the GFD, where the linear relationship is observed.

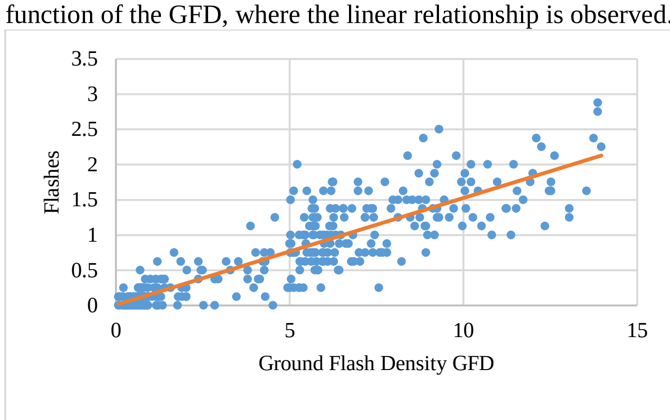


Fig. 7. Linear relationship between the GFD and the number of lightning flashes in transmission structures.

The t-test is performed to evaluate the significance of this variable, which shows if there is a linear relationship between the independent and dependent variables. The same hypotheses of the F test were used. For this case, the test statistic corresponds to 18.193. The critical value according to the t distribution with a degree of significance of 0,05 and 329 degrees of freedom corresponds to 1,967, from which it is delimited the rejection zone for positive and negative values. Due to the test statistic being located in the rejection zone, there is sufficient evidence to conclude that GFD significantly affects the number of impacts on tall structures.

## IV. Discussion

The parameter *N* indicates the number of lightning strikes in a 100 km section of a transmission line per year and is a fundamental part of calculating the back-flashover rate (BFR), which considers that, of all the impacts on the transmission line, 60% cause flashover and correspond to direct impacts on the transmission structure [31]. In this way, the BFR is described as:

$$\mathrm{BFR} = 0{,}6\ \mathrm{N}\ \mathrm{P(Ic)} \tag{9}$$

Where *N* is established in Equation (4) and P(Ic), the probability that the critical current Ic is exceeded.

For the calculation of *N*, an average height of the transmission structures is established along the 100 km of the line, and a GFD average value is also specified in this path. Understanding that the height of the transmission structures along the section depends on the terrain's topography, setting an average height value for the entire area may underestimate the number of lightning strikes on transmission structures. Similarly, considering the GFD variations with the relief and height above sea level in tropical zones [23], [32], it is complex to set an average value of this parameter over a 100 km journey that considers the count of these effects.

Therefore, in this work, it is proposed to find the number of direct lightning strikes in each transmission structure using Equation (5) and add these contributions along a 100 km stretch of a line as follows:

$$N_T = \sum_{1}^{n} Fl_i \tag{10}$$

Where i is the number of transmission structures in a 100 km section, Fl is the number of lightning flashes per structure, and $N_T$ is the total number of direct lightning flashes in transmission structures in the indicated area.

In this way, the BFR would be determined as follows:

$$\mathrm{BFR} = \mathrm{N_T}\ \mathrm{P(Ic)} \tag{11}$$

## V. Conclusions

With the data of 333 transmission structures located in the northeast of Colombia, a model to predict the number of direct lightning flashes in transmission structures was built. For this, three variables are used: The Ground Flash Density, the tower's height, and its elevation above sea level. Thus, 75.7 % of the variation in the number of impacts on elevated structures is explained by the variation of these three independent variables with a standard deviation of 0.32 flashes.

It was found that an increase in the Ground Flash Density GFD, the transmission structure's height, and the elevation above sea level of the tower causes an increase in the number of lightning flashes in transmission structures. It is established that the most significant variable in calculating direct lightning flashes on transmission structures is the Ground Flash Density GFD.

According to the diagnosis of the model, it is concluded that there is a linear relationship between the dependent variable and all the independent variables considered jointly. Therefore, there is sufficient evidence to show that the regression model explains part of the variation in the number of lightning flashes on transmission structures. It is essential to clarify that the proposed model applies to the specific conditions established in this work regarding the study area, lightning activity, the number of structures, and the lightning location network used.

For estimating the back-flashover rate (BFR), regarding the calculation of direct lightning flashes in a section of a transmission line, it is recommended to find the number of flashes for each transmission structure from the area and add these contributions along a stretch of 100 km of line. The above considering the variations of parameters such as the GFD and the tower's height with the terrain's topography.

## VI. Acknowledgment

The authors would like to thank the Keraunos Company, with its Colombian Total Lightning Detection Network with LINET technology, for providing us with the required data on lightning activity in the regions under study in this paper.

## VII. References

[1] Y. Baba, “Review of recent researches related to lightning to tall structures,” *IEEJ Transactions on Power and Energy*, vol. 130, no. 8. 2010. doi: 10.1541/ieejpes.130.769.

[2] J. He, V. Rakov, D. Wang, and P. K. Wang, “Lightning physics and effects,” *Atmospheric Research*. 2013. doi: 10.1016/j.atmosres.2013.05.005.

[3] K. Berger, “Novel observations on lightning discharges: Results of research on Mount San Salvatore,” *J Franklin Inst*, 1967, doi: 10.1016/0016-0032(67)90598-4.

[4] A. J. Eriksson, “LIGHTNING AND TALL STRUCTURES.,” *Trans S Afr Inst Electr Eng*, vol. 69, no. pt 8, 1978, doi: 10.1049/piee.1978.0084.

[5] R. H. Golde, “The Frequency of Occurrence and the Distribution of Lightning Flashes to Transmission Lines,” *Transactions of the American Institute of Electrical Engineers*, vol. 64, no. 12, 1945, doi: 10.1109/T-AIEE.1945.5059060.

[6] G. D. McCann, “The Measurement of Lightning Currents in Direct Strokes,” *Transactions of the American Institute of Electrical Engineers*, vol. 63, no. 12, 1944, doi: 10.1109/T-AIEE.1944.5058859.

[7] A. J. Eriksson, “The incidence of lightning strikes to power lines,” *IEEE Transactions on Power Delivery*,

vol. 2, no. 3, 1987, doi: 10.1109/TPWRD.1987.4308191.

[8] R. H. Golde, “The lightning conductor,” *J Franklin Inst*, vol. 283, no. 6, 1967, doi: 10.1016/0016-0032(67)90597-2.

[9] F. A. M. Rizk, “Modeling of Lightning Incidence to Tall Structures Part I: Theory,” *IEEE Transactions on Power Delivery*, vol. 9, no. 1, 1994, doi: 10.1109/61.277673.

[10] F. A. M. Rizk, “Modeling of Lightning Incidence to Tall Structures Part II: Application,” *IEEE Transactions on Power Delivery*, vol. 9, no. 1, 1994, doi: 10.1109/61.277690.

[11] G. Diendorfer and W. Schultz, “Lightning incidence to elevated objects on mountains,” *Proc. 24th Int. Conf. on Lightning Protection*, 1998.

[12] F. Rachidi *et al.*, “Current and electromagnetic field associated with lightning-return strokes to tall towers,” *IEEE Trans Electromagn Compat*, vol. 43, no. 3, 2001, doi: 10.1109/15.942607.

[13] K. Michishita, M. Ishii, A. Asakawa, S. Yokoyama, and K. Kami, “Voltage induced on a test distribution line by negative winter lightning strokes to a tall structure,” *IEEE Trans Electromagn Compat*, vol. 45, no. 1, 2003, doi: 10.1109/TEMC.2002.808044.

[14] V. Mazur and L. H. Ruhnke, “Physical processes during development of upward leaders from tall structures,” *J Electrostat*, 2011, doi: 10.1016/j.elstat.2011.01.003.

[15] J. Montanyà, O. van der Velde, and E. R. Williams, “Lightning discharges produced by wind turbines,” *J Geophys Res*, 2014, doi: 10.1002/2013JD020225.

[16] J. Montanyà, O. van der Velde, A. Domingo-Dalmau, N. Pineda, O. Argemí, and A. Salvador, “Lightning mapping observations of downward lightning flashes to wind turbines,” in *2016 33rd International Conference on Lightning Protection, ICLP 2016*, 2016. doi: 10.1109/ICLP.2016.7791449.

[17] A. Candela Garolera, K. L. Cummins, S. F. Madsen, J. Holboell, and J. D. Myers, “Multiple Lightning Discharges in Wind Turbines Associated with Nearby Cloud-to-Ground Lightning,” *IEEE Trans Sustain Energy*, 2015, doi: 10.1109/TSTE.2015.2391013.

[18] N. Pineda, J. Montanyà, A. Salvador, O. A. van der Velde, and J. A. López, “Thunderstorm characteristics favouring downward and upward lightning to wind turbines,” *Atmos Res*, 2018, doi: 10.1016/j.atmosres.2018.07.012.

[19] H. D. Betz, K. Schmidt, P. Oettinger, and M. Wirz, “Lightning detection with 3-D discrimination of intracloud and cloud-to-ground discharges,” *Geophys Res Lett*, 2004, doi: 10.1029/2004GL019821.

[20] H. Betz, K. Schmidt, B. Fuchs, W. Oettinger, and H. Höller, “Cloud Lightning: Detection and Utilization for Total Lightning Measured in the VLF/LF Regime,” *Journal of Lightning Research*, 2007.

[21] H. D. Betz *et al.*, “LINET-An international lightning detection network in Europe,” *Atmos Res*, 2009, doi: 10.1016/j.atmosres.2008.06.012.

[22] H. Ḧoller *et al.*, “Lightning characteristics observed by a VLF/LF lightning detection network (LINET) in Brazil, Australia, Africa and Germany,” *Atmos Chem Phys*, 2009, doi: 10.5194/acp-9-7795-2009.

[23] D. Aranguren, J. López, J. Inampués, H. Torres, and H. Betz, “Cloud-to-ground lightning activity in Colombia and the influence of topography,” *J Atmos Sol Terr Phys*, 2017, doi: 10.1016/j.jastp.2016.08.010.

[24] E. R. Williams, “The Electrification of Severe Storms,” *Meteorological Monographs*, 2001, doi: 10.1175/0065-9401-28.50.527.

[25] *Lightning: Principles, Instruments and Applications*. 2009. doi: 10.1007/978-1-4020-9079-0.

[26] B. S. Ardila Murillo y E. A. Soto Ríos, «Metodología para identificar zonas y estructuras elevadas con mayor cantidad de impactos de rayos en Barrancabermeja-Yondó», Tecnura, vol. 26, n.º 73, pp. 67–85, jul. 2022

[27] W. Schulz and G. Diendorfer, “Lightning characteristics as a function of altitude evaluated from lightning location network data,” in *SAE Technical Papers*, 1999. doi: 10.4271/1999-01-2310.

[28] O. Pinto *et al.*, “Cloud-to-ground lightning in southeastern Brazil in 1993 1. Geographical distribution,” *Journal of Geophysical Research Atmospheres*, vol. 104, no. D24, 1999, doi: 10.1029/1999JD900800.

[29] R. M. Reap, “Evaluation of cloud-to-ground lightning data from the western United States for the 1983-84 summer seasons.,” *Journal of Climate & Applied Meteorology*, vol. 25, no. 6, 1986, doi: 10.1175/1520-0450(1986)025<0785:EOCTGL>2.0.CO;2.

[30] A. Smorgonskiy, F. Rachidi, M. Rubinstein, and G. Diendorfer, “On the relation between lightning flash density and terrain elevation,” in *2013 International Symposium on Lightning Protection, SIPDA 2013*, 2013. doi: 10.1109/SIPDA.2013.6729216.

[31] CIGRE WG01 SC33, *Guide to procedures for estimating the lightning performance of transmission lines*, vol. 01, no. October. 1991.

[32] V. Bourscheidt, O. Pinto, K. P. Naccarato, and I. R. C. A. Pinto, “The influence of topography on the cloud-to-ground lightning density in South Brazil,” *Atmos Res*, 2009, doi: 10.1016/j.atmosres.2008.06.010.