Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

IMPROVED DETERMINATION OF TORNADO DAMAGE FREQUENCY

Thomas Riekert[1], Ronald Zinke[2]

[1] Head of Nuclear Safety, TÜV NORD EnSys GmbH&Co. KG, Hamburg, Germany (triekert@tuev-nord.de)
[2] Expert, TÜV NORD EnSys GmbH&Co. KG, Hanover, Germany (rzinke@tuev-nord.de)

ABSTRACT

In this paper, an improved generic model for the tornado damage zone sizes depending on tornado strength and the local damage distribution within the damage zone is developed. This model is based on U.S. data from a very comprehensive research project of the U.S. National Institute of Standards and Technology (NIST). The model is applied for two examples with regional tornado data from Switzerland and Germany to estimate the frequency with which a site is hit by a tornado with a specific local intensity. The results are conservative as the damage zone size model is predominantly based on data from the region with the most devastating tornados worldwide. Further research should be devoted to improving the statistical basis for tornado frequencies and analyzing tornado characteristics outside the USA.

INTRODUCTION

International safety regulations require the consideration of tornado impact on nuclear facilities. The guidelines IAEA (2011) and ENSI (2019) refer to data for damage size and wind speed ranges for tornados, ENSI (2019) also contains tornado occurrence frequencies. In past applications of the data, tornado hit frequencies were often calculated by multiplying the medium damage size with the expected occurrence frequency per area of a tornado of a specific class in the region of interest. As described in our contribution to SMiRT 27 Riekert (2024), this leads to an overestimation of the frequency of severe tornado damage, as the size of the damage zone of a tornado increases strongly with tornado intensity. However, this contradicts experience that stronger winds occur less frequently and neglects the fact that the most severe damage occurs only in a relatively small core of the damage zone of a tornado.

Based on these observations, in Riekert (2024) we developed a basic model for the description of the damage distribution within the zone affected by a tornado. Fig. 1 illustrates this basic model for a tornado rated EF3 on the Enhanced Fujita Scale, which we use in this paper for convenience and its wide application.

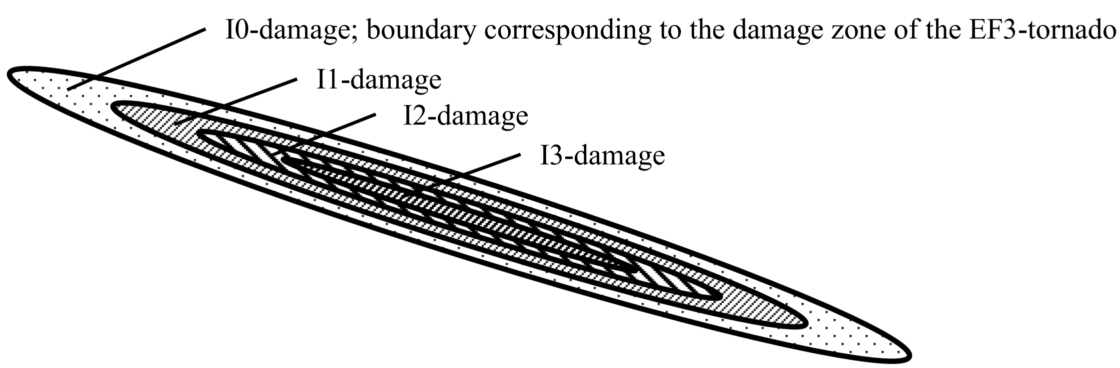

Figure 1. Damage zone of a tornado – schematic presentation for an EF3-tornado

To be able to distinguish between the overall rating of a tornado and the damage intensity within the damage zone, we will use the following denominations to describe tornados:

EF0-EF5:	Rating of a tornado according to the maximal damage observed
Damage zone:	Total area in which damage due to the tornado is observed
I0-I5:	Local damage intensity of the tornado within the damage zone, corresponding to damage equivalent to the respective tornado class

In this paper, we present the results of research performed to further develop this basic model. Based on recently published literature, we describe in the next chapter a generic size distribution model for tornados, i.e. the damage zone size for the different tornado classes and the distribution of the local damage intensities within the damage zone. Then, we demonstrate the application of the size distribution model for 2 examples with regional data for Europe. Finally, we summarize and discuss the results.

DEVELOPMENT OF A GENERIC SIZE DISTRIBUTION MODEL OF TORNADOS

General Aspects

Tornados are weather phenomena with very strong winds in a limited area, which occur in connection with strong storms and are observed in many regions all over the world. Hence, tornados have to be considered in the safety assessment of nuclear facilities. Tornados are categorized by the Fujita Scale into classes F0 to F5 or by the Enhanced Fujita Scale with classes EF0 to EF5 (descriptions are available e.g. at Wikipedia). The classification is based on the observed damage and gives a correlation to wind speed ranges. The scales differ in the wind speed ranges assigned to the tornado classes, which are determined by the observed damage. The Enhanced Fujita Scale, which gives lower wind speeds, is used especially in the USA and Canada, whereas the Fujita Scale is still often used in Europe. In recent years, an International Fujita Scale, with classes IF0 to IF5 in analogy to the F- and EF-scale, was developed (see Groenemeijer et al (2023)). This scale shall be internationally applicable for the classification of tornados by considering differences in building construction requirements when assessing tornado damage.

In this publication, we use predominantly the classification according to the Enhanced Fujita Scale, because most data exist with reference to this scale. The results are in principle applicable to data based on the Fujita or International Fujita Scale, as the basic characteristics of these classification systems are similar.

Literature Analysis

To further refine and substantiate the basic model developed in Riekert (2024), we analyzed available literature with a focus on the description of the tornado size distribution and the characteristics of the damage zone with local intensity distribution.

A good overview over tornado research can be found at the Wikipedia website "History of tornado research" Wikipedia (2025). The website summarizes tornado research with many references including recent publications until – currently – September 2024.

Hoverkamp et al. (2020) contains a comprehensive review of field measurements, lab simulations and computational fluid dynamics (CFD) analyses of tornados. The review is based on an extensive literature study. Several tornado events from the past are examined in detail and their characteristics presented. The study incorporates measurement data to derive e.g. the velocity distribution in the 3-dimensional wind field of a tornado. The results underline the great variety of tornados. E.g., tornados can occur as single cell tornados with radial inflow and uplift in the centre or as two cell tornados with uplift in a ring around a centre with downward stream of the air. Moreover, tornados can occur as clusters, i.e. multi-vortex tornados. This makes a general description and prediction of specific tornado characteristics impossible. The survey nevertheless shows that statistical descriptions based on the large number of observations can be derived. For example, Fig. 11 in Honerkamp et al. (2020) shows the distribution of the path width of tornados observed in the USA from 1950 to 2018. About 25 % of the tornados had a maximum path width of less than 10 m, i.e. they were very small. Only about 5 % of the tornados had a maximum path width of more than 500 m, demonstrating that large area tornados are quite seldom. The paper Honerkamp et al. (2020) is very useful to better understand the physical phenomena associated with tornados.

In 2023, the U.S. National Institute of Standards and Technology (NIST) published the results of a very large multi-year, interdisciplinary research project on tornados with the report Twisdale et al. (2023). The research project was initiated after an EF5-tornado had struck Joplin, Missouri in May 2011. It is regarded as the deadliest and costliest tornado that has struck the USA since the beginning of official records in 1950. According to our knowledge, Twisdale et al. (2023) contains the most complete assessment of tornado characteristics and associated risk published up to now. Tornado data bases and field measurements were analyzed to derive regions within the USA with distinct tornado characteristics. Not surprisingly, most observations stem from the centre of the USA (Region 4 in Fig. 2), often called Tornado Alley, where also the most severe tornados occur. In fact, in the USA tornados of the highest class EF5 have only been observed in that region. Another distinct region is the Southeast of the USA, where quite often tornados with lower intensity are observed in connection with hurricanes. The derived regions of the USA are depicted in Fig. 2.

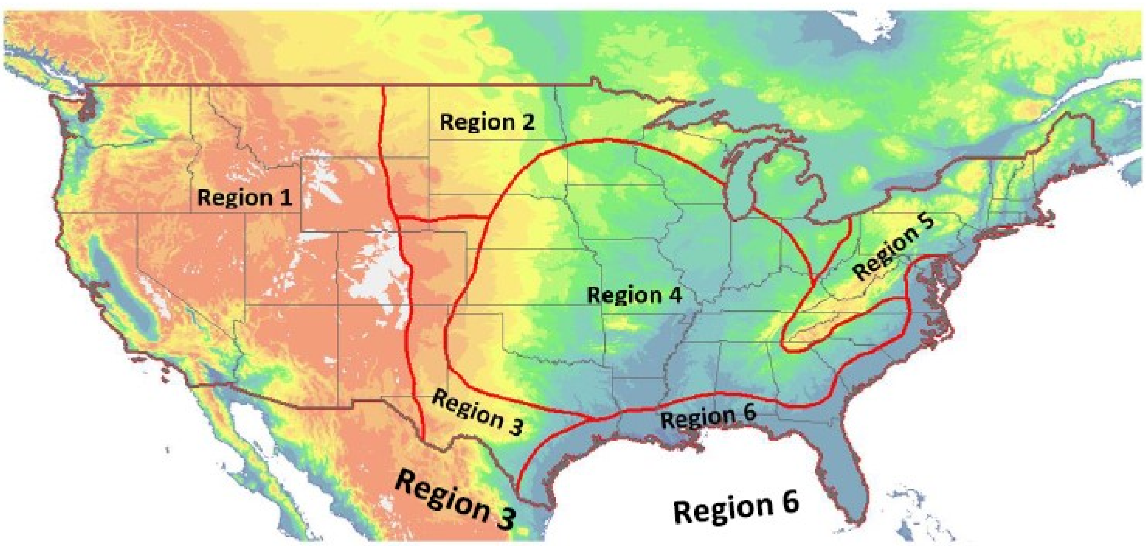

Figure 2. Regions used in Twisdale et al. (2023) for tornado characterization
Republished courtesy of the National Institute of Standards and Technology.

Based on the observations and theoretical analyses, many wind field simulations are performed for tornados with different characteristics. The results are used to derive tornado wind speed maps with occurrence frequencies of wind speeds for the different regions, covering the entire USA. The derived mean wind speeds are best estimates and can be used for engineering design and safety analyses.

Due consideration is given to uncertainties. Specifically, the authors underline that tornado damage observations depend on the population density of an area, as in sparsely populated areas fewer objects exist which can be damaged and be used to classify a tornado. This is an observation which should be kept in mind when analysing data from other regions.

With Twisdale et al. (2023) exists a well-founded und documented data base for tornado wind speed and frequency analyses in the USA. We do not know of a comparative research and data basis for other regions of the Earth. We use therefore the data and results from Twisdale et al. (2023) to derive a generic model for the damage zone and the distribution of local intensities within the damage zone for the different tornado classes.

Development Of The Generic Size Distribution Model Of Tornados

As described above, Twisdale et al. (2023) contains a great amount of data from the USA based on the documentation of numerous tornados. For our size distribution model, we start with the total number of observations. For the derivation of damage zone sizes, 11.809 tornados observed in the USA are taken into account in Twisdale et al. (2023). The tornados are distributed over the six considered U.S. regions as shown in Table 1.

Table 1: Counts of tornados of different classes per region (from Table 3-11 in Twisdale et al. (2023))

	Region of the USA					
Tornado class	R1	R2	R3	R4	R5	R6
EF0	240	674	655	3,889	229	1,019
EF1	49	291	96	2,537	207	496
EF2	13	83	37	759	40	111
EF3	1	15	7	242	14	25
EF4	0	7	0	58	2	4
EF5	0	0	0	9	0	0
Total	303	1,070	795	7,494	492	1,655

From the analyses of the observations in combination with the developed models to describe the tornado characteristics, the mean damage zone sizes are derived for the different regions (Table 3-15 in Twisdale et al. (2023)). The results are shown in Table 2, transformed into metric units.

Table 2: Mean damage zone sizes of tornados in km² for the different regions and tornado classes (derived from Table 3-15 in Twisdale et al. (2023))

	Region of the USA					
Tornado class	R1	R2	R3	R4	R5	R6
EF0	0.13	0.16	0.13	0.23	0.26	0.13
EF1	1.32	1.66	1.29	2.28	2.12	1.35
EF2	4.58	5.33	6.16	9.19	7.40	4.87
EF3	10.30	12.61	16.78	28.04	22.55	13.00
EF4	17.32	25.35	32.44	66.04	37.75	25.22
EF5	30.06	42.46	53.18	118.16	65.21	39.45

It should be noted that EF5 tornados have only been observed in region 4 and no EF4 tornados are documented for regions 1 and 3. However, Twisdale et al. (2023) point out that it cannot be concluded that EF4 and EF5 tornados are not possible in these regions, as the number of observations is lower than in region 6, and they derive sizes for these tornado classes in those regions from theoretical assumptions. The size distribution in different regions in Table 2 show similar characteristics, but the damage zone sizes are substantially larger in region 4 as compared to other regions. To derive a generic model, we combine the data for all regions by calculating weighted means with the actually observed number of tornados in each region and for each tornado class (resulting in the size of EF5-tornados being equal to the size in region 4). The result is given in Fig. 3.

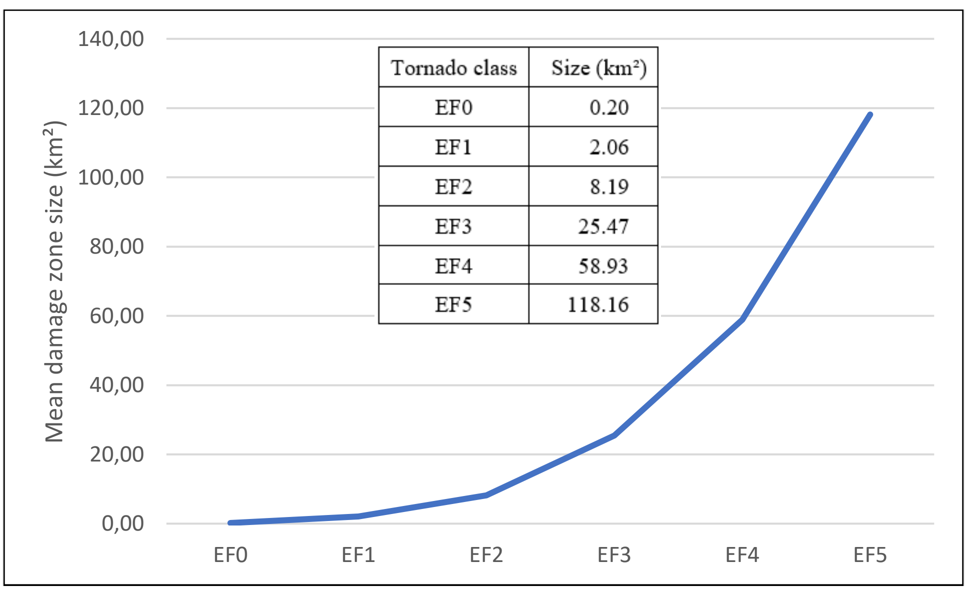

Figure 3. Tornado damage zone size depending on the tornado class

For an in-depth analysis for a specific region outside the USA, it might be reasonable to compare the meteorological and geographic characteristics of that region with the 6 U.S. regions considered in Twisdale et al. (2023). This might lead to a well-founded adaption of regional data. For the generic model, we believe that using the total data set is appropriate. As region 4, which dominates the results due to the high number of observed tornados, yields larger damage zones than the other regions and is the region on Earth known for the most devastating tornados, the approach results in a conservative estimation.

Having derived the damage zone size distributions, the distribution of tornado intensities within the damage zones is needed. Twisdale et al. (2023) contains data which can be used to this end:

- Table 3-19 in Twisdale et al. (2023) contains mean values for the relative length in which the tornado has a certain maximum intensity, called path length intensity variation. E.g. an EF3 tornado has a maximum intensity of I0 in 9.2 % of its length, intensity I1 in 26 %, intensity I2 in 31.5 % and intensity I3 in 33.3 %.

- Table 3-22 in Twisdale et al. (2023) gives the width of damage of a given intensity in relation to the maximum path width of the tornado.

Utilizing the data given in these tables and assuming a basic damage distribution as illustrated in Fig. 1, i.e. concentric damage intensity zones with decreasing damage intensity from the centre to the edge, the relative sizes of zones with a given intensity are calculated for the different tornado classes, see Table 3.

Table 3: Mean relative sizes of the zones with a given intensity for the different tornado classes

	Local intensity rating					
Tornado class	I0	I1	I2	I3	I4	I5
EF0	1.000					
EF1	0.682	0.318				
EF2	0.543	0.299	0.158			
EF3	0.500	0.253	0.154	0.094		
EF4	0.471	0.213	0.143	0.123	0.050	
EF5	0.352	0.246	0.218	0.110	0.050	0.024

With this distribution and the mean damage zone sizes given in Fig. 3, the mean sizes of the zones with a given local damage intensity can be estimated for the various tornado classes, see Table 4.

Table 4: Mean sizes of the zones with a given intensity for the different tornado classes in km²

	Local intensity rating					
Tornado class	I0	I1	I2	I3	I4	I5
EF0	0.20					
EF1	1.40	0.65				
EF2	4.44	2.45	1.29			
EF3	12.73	6.44	3.91	2.39		
EF4	27.75	12.58	8.41	7.24	2.95	
EF5	41.64	29.04	25.71	12.96	5.93	2.87

These estimates are derived from the huge amount of U.S. data thoroughly analysed in Twisdale et al. (2023), aggregated over the entire area of the USA. It has to be underlined that the result is a simplification to derive a generic model. The result can be further refined for an in-depth investigation for a specific region, utilizing the detailed information given in Twisdale et al. (2023) and comparable information for the region in question, if available. Nevertheless, the estimated damage zone sizes are conservative as they are mainly based on data from the region with the most devastating tornados. A transfer to other regions is possible as the physics of tornados are similar anywhere in the world. We will illustrate the application of the derived data in the following chapter.

SAMPLE APPLICATION OF THE SIZE DISTRIBUTION MODEL WITH REGIONAL DATA

Data From Switzerland

In the first example, the tornado frequency data given in the Swiss nuclear safety guideline ENSI (2019) are used. In Table 5 you find the occurrence frequencies per km² as well as the mean values for the length and the width of the damage zone depending on the strength according to the Enhanced Fujita Scale.

Table 5: Occurrence frequencies and damage zone sizes for tornado categories according to ENSI (2019), Appendix 7

Tornado category	Occurrence frequency [per year and km²] (Mean)	Length of damage zone [km] (Mean)	Width of damage zone [km] (Mean)
EF0	$1.23 \cdot 10^{-4}$	2.6	0.035
EF1	$5.53 \cdot 10^{-5}$	6.9	0.082
EF2	$1.59 \cdot 10^{-5}$	10.2	0.124
EF3	$4.65 \cdot 10^{-6}$	17.5	0.343
EF4	$1.04 \cdot 10^{-6}$	23.1	0.383
EF5	$1.00 \cdot 10^{-7}$	53.4	0.450

The damage zones given in Table 5 are smaller than the generic values derived from the U.S. data in Twisdale et al. (2023). We use the generic model as we think that the applied data is founded on a broader basis. However, it would be worthwhile to take a closer look into the meteorological and geographic conditions of the different U.S. regions considered in Twisdale et al. (2023) and of Switzerland, as the damage zone sizes derived for various of the U.S. regions are closer to the damage zone sizes which can be calculated from the data in ENSI (2019).

The frequency with which a tornado of a certain category hits a specific site can be calculated by multiplying the occurrence frequency of the tornado per year and km² with the area of the damage zone (see data in Fig. 3). From this, the frequency that the site is hit with a given local intensity is calculated by multiplying with the share of the area with this intensity in relation to the area of the damage zone for the tornado category (see Table 3). The value can be also calculated by directly multiplying the occurrence frequency of the tornado class with the mean size of the zone with the local intensity for this tornado class, i.e. the values in Table 4. To derive the total frequency with which this intensity occurs at the site the values for the different tornado classes have to be summarized. This is documented in Table 6, with the last column giving the resulting frequencies of the different intensities due to tornados at a site.

Table 6: Estimated frequencies for the occurrence of the different tornado intensities at a site, using tornado frequencies from ENSI (2019) and the developed generic size distribution model
Values for the different tornado classes and the resulting overall frequencies

	Frequency (1/yr)						
Intensity	EF0	EF1	EF2	EF3	EF4	EF5	Sum
I0	$2.4{\cdot}10^{-5}$	$7.8{\cdot}10^{-5}$	$7.1{\cdot}10^{-5}$	$5.9{\cdot}10^{-5}$	$2.9{\cdot}10^{-5}$	$4.1{\cdot}10^{-6}$	$2.7{\cdot}10^{-4}$
I1		$3.6{\cdot}10^{-5}$	$3.9{\cdot}10^{-5}$	$3.0{\cdot}10^{-5}$	$1.3{\cdot}10^{-5}$	$2.9{\cdot}10^{-6}$	$1.2{\cdot}10^{-4}$
I2			$2.1{\cdot}10^{-5}$	$1.8{\cdot}10^{-5}$	$8.8{\cdot}10^{-6}$	$2.6{\cdot}10^{-6}$	$5.0{\cdot}10^{-5}$
I3				$1.1{\cdot}10^{-5}$	$7.5{\cdot}10^{-6}$	$1.3{\cdot}10^{-6}$	$2.0{\cdot}10^{-5}$
I4					$3.1{\cdot}10^{-6}$	$5.9{\cdot}10^{-7}$	$3.7{\cdot}10^{-6}$
I5						$2.8{\cdot}10^{-7}$	$2.8{\cdot}10^{-7}$

The results are higher than given in Riekert (2024), which is due to the application of the generic data transferred from the USA.

Data From Germany

For the derivation of tornado frequencies in Germany, predominantly the well documented statistics of the European Severe Weather Database of the European Severe Storms Laboratory ESSL (2025) for the time period 1999 to 2024 were evaluated. In total, 851 tornados were registered in Germany in that time period. They were classified according to the Fujita Scale with 267 observations without classification, 132 F0, 210 F1, 84 F2 and 12 F3 tornados. No tornados of the highest classes F4 and F5 were observed in that time period. It can be assumed that the 267 tornados without classification caused low damage, because in the case of significant damage a classification would have been possible. The wind speeds must have been rather low. We add this number therefore to the counts of F0 tornados, although some of the tornados without classification might fall even below class 0.

With regard to F4 and F5 tornados, also historical data in ESSL (2025) were considered. Additionally the data base Tornadoliste Deutschland (Tornado List Germany) at Sävert (2025), which documents and classifies tornados in Germany from a private initiative including historic observations, was consulted. In these data bases, two historic F5 tornados are documented (years 1800 and 1764). Even acknowledging the uncertainties concerned with events having occurred so long ago, the observations indicate that F5 tornados are possible in Germany. This is in concurrence with the analysis in Twisdale et al. (2023), where the authors point out that EF5 tornados cannot be excluded in the regions of the USA where no such events have been recorded in the observation period. In the time period since 1750, ten F4 tornados are documented in Sävert (2025). Compared with this number, the share of F5 tornados seems rather high. Nevertheless, we use the documented F4 and F5 tornados from Sävert (2025) to estimate the frequency of such tornados.

Using the tornado counts and the related observation period (26 years or 275 years) in combination with the area of Germany (about 356,000 km²), we calculate the occurrence frequency of tornados per year and km² in Germany listed in Table 7. These values are lower than the data given in ENSI (2019).

Table 7: Estimated occurrence frequencies of tornados in Germany

Tornado category	Tornado counts	Observation period [years]	Occurrence frequency [per year and km²]
F0	399	26	$4.3 \cdot 10^{-5}$
F1	210	26	$2.3 \cdot 10^{-5}$
F2	84	26	$9.1 \cdot 10^{-6}$
F3	12	26	$1.3 \cdot 10^{-6}$
F4	10	275	$1.0 \cdot 10^{-7}$
F5	2	275	$2.0 \cdot 10^{-8}$

For our further deliberations, we neglect the differences between the Fujita and Enhanced Fujita Scale. The transfer of data would necessitate more analyses, as discussed for example in Twisdale et al. (2023). For a first estimation we regard the similarities as sufficient to use the values for damage zone sizes for the Enhanced Fujita Scale from Fig. 3 and the local intensity distribution given in Table 3 to calculate the frequency of occurrence for the different intensities. The result after summarizing over all tornado classes is given in Table 8.

Table 8: Estimated frequencies for the occurrence of the different tornado intensities at a site in Germany

Intensity	Frequency (1/yr)
I0	$1.1 \cdot 10^{-4}$
I1	$4.7 \cdot 10^{-5}$
I2	$1.8 \cdot 10^{-5}$
I3	$4.1 \cdot 10^{-6}$
I4	$4.2 \cdot 10^{-7}$
I5	$5.9 \cdot 10^{-8}$

CONCLUSIONS AND DISCUSSION

In this publication, we have further developed the approach presented in Riekert (2024) to determine the frequency with which a site is hit by a tornado with a given local intensity. The great amount of data documented from the very comprehensive U.S. research effort documented by the NIST in Twisdale et al. (2023) was analyzed to derive a generic damage zone size model for the different tornado classes and for the distribution of local intensities within the damage zone. This model can be regarded as conservative, as it is predominantly based on data from the U.S. region with the most devastating tornados worldwide. It has to be kept in mind that the derived occurrence frequencies are the result of a simplification. We see this simplification as justified because the physical mechanisms are the same for tornados anywhere. What is different in different regions of the Earth is the occurrence frequency of tornados. We then used the developed model for two sample applications, the first with data from the Swiss nuclear safety guideline ENSI (2019), the second with publicly available data on tornado observations in Germany. These data might need further review to improve the validity.

We think that further research should be devoted to improving the statistical basis for tornado frequencies and analyzing tornado characteristics outside the USA. This could lead to the adoption of U.S. regional data, which might reflect better the characteristics in other region of the Earth than the generic model, which we calculated by aggregating the U.S. data. The U.S. regional data show distinct differences, hence a well-founded transfer to other regions could improve the estimations. In a further step, the correlation between tornado classification and wind speeds would need attention to derive reliable wind speed estimations, depending on the occurrence frequency. To this end, a comparison of the data derived with our model with general wind speed distributions could be beneficial. With such an approach, a frequency distribution of wind speeds due to tornados might be developed, which would be based on general meteorological conditions of a region and would be less dependent on a reliable regional tornado data base.

REFERENCES

ENSI – Swiss Federal Nuclear Inspectorate (2019). *Probabilistic Safety Analysis (PSA): Quality and Scope, Guideline for Swiss Nuclear Installations*, ENSI – A05/e.

European Severe Storms Laboratory (ESSL) e.V. (2025), *European Severe Weather Database,* https://eswd.eu (last visited March 6, 2025)

Groenemeijer, P., Holzer, A. M., Kühne, T., and Púčik, T. (2023). "The International Fujita Scale and its implementation", *11th European Conference on Severe Storms*, Bucharest, Romania, ECSS2023-151

Honerkamp, R., Yan, G. and Snyder J. C. (2020). "A Review of the Characteristics of Tornadic Wind Fields through Observations and Simulations", *Journal of Wind Engineering and Industrial Aerodynamics*, Volume 202

IAEA – International Atomic Energy Agency (2011). *Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations*, Specific Safety Guide No. SSG-18.

Riekert, T. (2024). "Considerations on Tornado Frequency Determination", *Trans. Structural Mechanics in Reactor Technology (SMiRT) 27*, Yokohama Japan

Sävert, T. (2025). *Tornadoliste Deutschland*, https://tornadoliste.de (last visited March 20, 2025)

Twisdale, L. A. Jr., Banik, S. S., Mudd, L., Hardy, M. B., Quayyum, S., Liu, F., Faletra, M. K., Vickery, P. J., Levitan, M. L. and Phan, L. (2023). *Tornado Wind Speed Maps for Building Design: Research and Development of Tornado Risk Assessment Methodology*, National Institute of Standards and Technology (NIST), Gaithersburg, MD, Technical Note (TN) NIST TN 2242

Wikipedia (2025). *History of tornado research*, https://en.wikipedia.org/wiki/History_of_tornado_research (last visited March 24, 2025)