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MAPPING TORNADO HOTSPOTS IN THE U.S.: SPATIAL AND TEMPORAL ANALYSIS ACROSS THE U.S.

Seong Nam Hwang[1], Shishir Kumar Das[2], Mohammad Moniruzzaman[3], Eshmi Rai[4], Mosharef Hossain[5]

[1]*Professor, Department of Biology, Environmental Science Program; Southeast Missouri State University, Cape Girardeau, MO, USA*
Email: shwang@semo.edu

[2]*Graduate Assistant, Department of Biology, Environmental Science Program; Southeast Missouri State University, Cape Girardeau, MO, USA*
Email: shishir.semo@gmail.com

[3]*Master in Development Studies; Dhaka University, Dhaka, Bangladesh*
Email: monirnstu0321@gmail.com

[4]*Department of Biology, Environmental Science Program; Southeast Missouri State University; Cape Girardeau, USA*
Email: esmiraee01@gmail.com

[5] *Master of Environmental Science; Southeast Missouri State University, USA*
Email: mosharefhossain379@gmail.com

ABSTRACT

Tornadoes rank among the most damaging weather events in the US. They put lives at risk, wreck infrastructure, and upset economic systems. This study examines data from 1950 to 2022 using Geographic Information Systems (GIS) to uncover tornado hotspots, pinpoint high-risk areas, and grasp why some regions face bigger threats. States such as Texas, Alabama, and Oklahoma proved to be risk zones due to high tornado activity, which leads to major damage, deaths, and money losses. Texas tops the list as the state tornadoes hit hardest, with the most recorded events and severe economic blows. Season patterns show tornadoes strike most in late spring and early summer creating a pressing need to get ready during these months. The research also sheds light on the toll on key infrastructure, such as U.S. interstate highways. These results offer key insights to steer disaster management and mitigate risks for the most exposed areas.

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1 Introduction

Tornadoes are among the most disastrous weather events in the United States, leading to gigantic risks against life, habitation, and infrastructure (Ashley et al., 2014). The dangers have already taken a massive toll in life and have led communities heavily into economic distress. Past records testify to the fact that tornadoes have caused billions of dollars in damage every year; thus, there is an increasingly justified need for intensified and systematic studies towards improving the understanding and minimization of such risks (Brooks & Doswell, 2001). From annual statistics, NOAA (2024) estimates the United States to have the highest total average number of reported tornadoes in the world: more than 1,200 in a calendar year. These typically occur between central and southeastern areas of the country where certain weather conditions create room for tornado development.

In recent years, increasing frequencies and strengths of tornadoes in these affected areas have raised demands for reassessing high-risk areas and enhancing disaster readiness and resilience programs (Coleman et al., 2024). The literature highlights that tornado activity is geographically and seasonally dependent. Some states, depending on the geography of the region and the seasonal aspects, include Texas, Oklahoma, and Alabama, which have been defined as most susceptible (Corey et al., 2024; Corey and Senkbeil, 2023; Cusack, 2014). This study focuses on dynamical geospatial analysis in order to model the tornado density and distribution from 1950 to 2022 and explore some explanatory factors of tornado risk. Some valuable insights into tornado risks covering both spatial and temporal distribution could support focused investing in mitigation strategies and build disaster readiness and resilience for at-risk communities through better anticipation and designing of resources towards their effective use in sheltering infrastructures as well as resilience efforts.

2 Literature Review

2.1 Tornado Vulnerabilities and Impacts

The tornadoes produce massive destruction, causing widespread damage to properties and significant economic losses, aside from being a difficult factor to include in environmental planning and recovery efforts for the United States (Anderson et al., 2022; Ashley et al., 2014; Daneshvaran & Morden, 2007). Among some of the deadliest natural disasters across the whole country, tornadoes affect a mix of demographic and socioeconomic groups (Foglietti et al., 2020; Kelnosky et al., 2018; Senkbeil et al., 2022). In recent years, their increasing incidence and intensity have highlighted the need for a better understanding of their societal impact and their connection to climate change, which exacerbates extreme weather events (Farney & Dixon, 2014; Long et al., 2018).

Recent studies have shed light on tornado vulnerabilities and impacts in the United States, strengthening the argument that nocturnal tornadoes are associated with higher risks. The increased casualty rates during nighttime may be attributed to diminished public awareness and preparedness, as well as reduced warning times. A special warning-issuance mechanism appears unavoidable to keep this in check. The focus remains on residents, and as Strader and his coauthors (2022) note, as tornado risk shifts, another problem arises. Vulnerability becomes trouble as an increase in risk translates to more losses. Thus, there is a need for effective adaptive strategies for disaster preparedness. Ansari, Borrero, and Gonzalez (2023) propose a two-stage robust optimization model to target community resilience by applying the resource to retrofitting buildings to reduce population displacement and enhance resilience vis-à-vis tornado hazards. Thus, the one who is at the local level is exploring tornado vulnerability metrics using tornado incidence data and societal exposure metrics in Tennessee. Another work by Strader and his colleagues (2018), a fine-scale assessment of mobile home tornado vulnerability in central and southeastern United States, stresses the notion that the residents of this particular housing type are at heightened risk because of its personal vulnerability to tornadoes in that region. By far, this trifecta of studies opens the door into the complex nature of tornado risk and how, hence, differently prepared communities put themselves at the receiving end.

Tornadoes are described scientifically as violent vertical columns of air that spin clockwise and anticlockwise and extend from thunderstorms to the surface (NOAA, 2024; Masoomi & van de Lindt, 2017;

Pîrloagă et al., 2021). A closed atmospheric circuit produces wind shear, instability, and moisture; thus, central parts of the United States are described as hotspots for the birth of the tornadoes (Coleman & Dixon, 2014; Fuhrmann et al., 2014). It now appears that tornado activity is on the rise in southeastern states such as Alabama and Mississippi, suggesting that climate change may be driving a shift in tornado patterns (Masoomi & van de Lindt, 2017). Such shifts require risk assessments and adaptive actions to manage changing tornado activity.

Vulnerable populations bear disproportionate impacts of tornado disasters. These are, due to currently existing systems of the constructed world, among the most affected by tornado disasters. For this reason, Masoomi and van de Lindt (2017) stress the need for resilient infrastructure so that economic losses in low-income communities, which disproportionably suffer from tornadoes, can be minimized (Structure and Infrastructure Engineering). Likewise, Ashley et al. (2014) have highlighted the "bull's-eye effect," in which urbanization into high-risk areas raises the population's exposure to tornado hazards and increases vulnerabilities. Moore (2019) explains that low-income communities suffer a tough time in recovering from tornado destruction because they mostly lack resources, optimizing the socioeconomic tax of such events. Also, Boruff et al. (2003) show that socioeconomic factors are important determinants of a community's resilience: inequities of housing quality and emergency preparedness aggravate the risks and recovery times associated with tornado disasters. In general, those studies rank as equal in emphasizing the need for specific disaster management interventions which focus on the vulnerabilities facing at-risk populations.

Income and the position in the community makes certain groups vulnerable: it is mostly the low income due to various factors like low-quality housing and limited access to emergency services (Corey & Senkbeil, 2023; Moore, 2019). Survivors must cope with the long-term torturous stress that follows them as a result of the trauma of the event (Ashley et al., 2014). Addressing these vulnerabilities requires dissimilar strategies for disaster management according to specific needs of afflicted populations (Markert et al., 2019; Masoomi & van de Lindt, 2017).

2.2 GIS and Spatial Analysis in Tornado Studies

In combining the methodological abilities of exploitative mapping, geospatial analysis serves to unravel the ambiguities concerning tornado risks by providing revelations of spatial patterns, drawing attention to the highest risks. Geoprocessing, including kernel density estimation and hot spot analyses, serves to mark the tornado-prone areas (Dixon et al., 2011; Foglietti et al., 2020). These methods yield valuable information to disaster management agencies through highlighting the areas where tornadoes are most likely to occur (Istiak & Hwang, 2024).

The use of GIS tools not only increases the accuracy of risk assessments but also assists in demonstrating vulnerabilities in critical infrastructure. For example, mapping tornado activity along major highways and interstates allows for the assessment of how infrastructure interruptions due to tornadoes affect responses and recovery efforts much wider still (Farney & Dixon, 2014; Frazier et al., 2019; Fricker & Friesenhahn, 2022). Such analyses are required for the impacts of tornadoes to be reduced on the transportation networks and urban areas.

Another dimension to GIS based tornado research concerns seasonality. Research has pointed out that tornado activity is seen to ramp up in relation to a few months, especially, late spring and early summer months (Fuhrmann et al., 2014; Kelnosky et al., 2018; Markert et al., 2019). Historical data indicates that pronounced late spring peaks in a zone generally between May and June trends are enterable throughout the year for tornadoes (Long et al., 2018). The researchers use this analysis of seasonality trends to improve forecasting models so that disaster preparedness strategies can turn up more fruitful (Istiak et al., 2023). These models are critical to empower futures and a user with action steps to limit tornado risk.

GIS applications have also been introduced in the assessment of tornado impacts on critical infrastructure by transportation networks. Tornadoes may damage roads and highways to levels that impair movement of goods and emergency services (Fan & Pang, 2019; Foglietti et al., 2020; Fuhrmann et al., 2014). Maps recording historical tornado impacts on infrastructures highlight areas where new interventions are needed to improve resilience. GIS studies stress the need to protect vulnerable communities and mitigate potential losses by addressing tornado risk situated in a spatial aspect.

This study is part of an emerging body of literature

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emphasizing the need to include geospatial analysis in disaster risk reduction strategies. GIS is highly relevant to assessing the distribution, seasonality, and infrastructure vulnerability of tornadoes and thus provides tangible input for improving preparedness and resilience in tornado-prone areas (Coleman et al., 2024; Hatzis et al., 2018; Farney & Dixon, 2014).

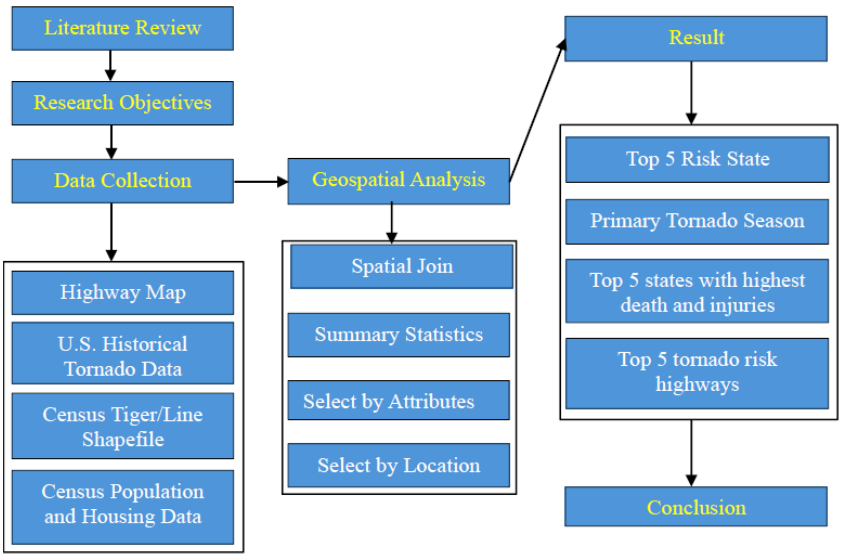
3 Research Objectives

Though tornadoes have been reported in many places of the world, they are usually concentrated within the United States, most severely, in the Midwest, Southeast, and Southwest regions. A total of 68,701 tornadoes are officially registered in the United States over the period from 1950 to 2022, since which nearly 6135 deaths and 97,454 injuries were recorded (SPC, 2024). This research aims to achieve several objectives: to conduct a detailed analysis of historical tornado data with an emphasis on their frequency, distribution, and intensity; to analyze tornado occurrences by state to identify those with the most tornado activity; to study the seasonal distribution of tornadoes to determine peak activity times; to examine tornadoes in terms of fatalities, injuries, and property losses to identify the five most affected states in each category; and finally, to explore the impact of tornadoes on interstates and major roads within states to gain a better understanding of these effects.

4 Methodology

The following illustration depicts the workflow, methodology, and processes of the research. For this research project, GIS data, historical tornado data in the United States, Census Tiger/Line shapefiles, and census-population data in 2020 were gathered following research objectives. U.S. historical tornado data were point data from 1950 to 2022 developed and administered by the Storm Prediction Center. Census Tiger/Line Shapefiles and U.S. state population data are developed and maintained by the Bureau of the Census. Importing the datasets into ArcGIS Pro allows for numerous spatial analyses utilizing various geoprocessing tools, such as Spatial Join, Select by Location, and Summary Statistics.

Figure 1: Methodological Flowchart

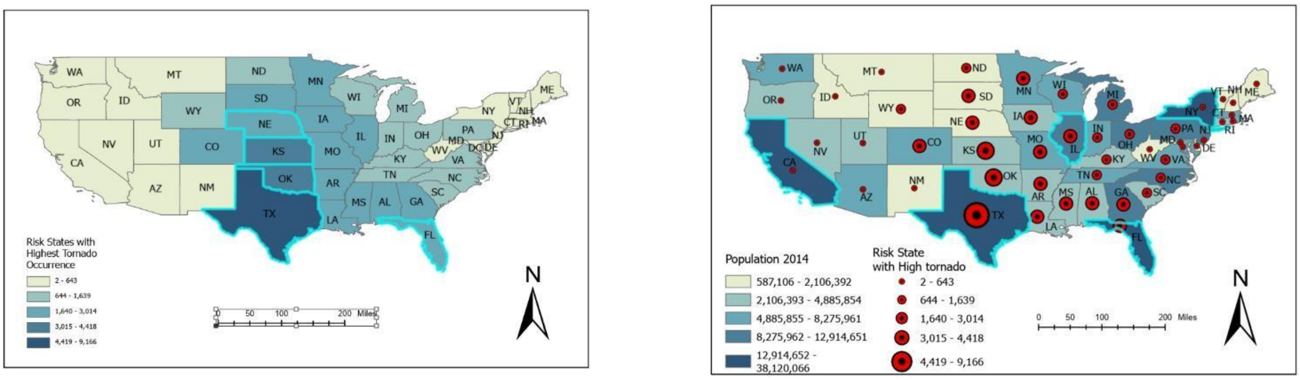


5 Results

5.1 Top Five Tornado-risk States in the USA

The analysis uses data on tornado occurrences from 1950 to 2022. The geoprocessing tool spatial join was used to combine two datasets: states and tornado occurrences. This operation allowed for identifying the number of tornadoes that occurred in a specific state during that time period. The result lists the top five states for tornadoes: Texas (9,166 occurrences), Kansas (4,418 occurrences), Oklahoma (4,165 occurrences), Nebraska (3,014 occurrences), and Florida (1,982 occurrences). The central United States region is generally termed "Tornado Alley", as it concentrates tornado occurrences, particularly Texas, Oklahoma, and Kansas. Further, another map was created to compare tornado occurrences with 2014 population distribution across the United States. This map indicated that while Texas had a very high population and a high number of tornado occurrences, other densely populated states such as California, New York, and Florida have very few tornadoes. On the contrary, states like Oklahoma, Kansas, and Nebraska showed high counts of tornadoes despite having moderate populations compared to the densely populated states. This analysis demonstrates that there are regions which have moderate populations but still encounter frequent tornadoes, owing to some features of the geography and climate. These results provide a proper overview of the distributions of tornado activities and their frequency.

Figure 2: Map of Risk States with the Highest Tornado Occurrence and Population 2014

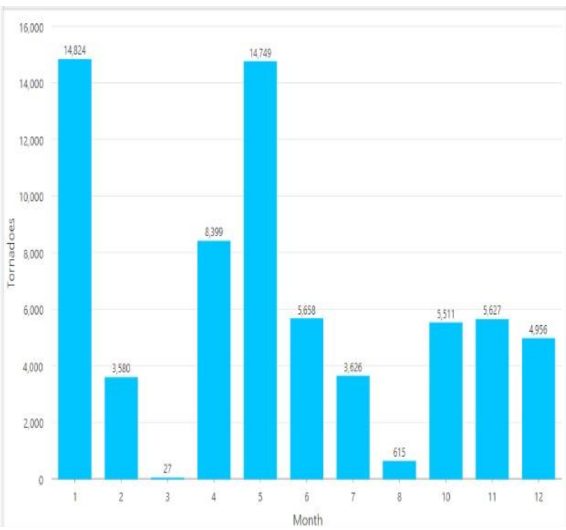


Source: Prepared by authors, September 1, 2024.

5.2 5.2. Top Five Tornado Months in the USA

This piece of analysis provides the top five months from 1950 to 2022 in terms of tornado frequencies per month. Data was analyzed using the geoprocessing tools of the "Dissolve" and "Summary Statistics" types. The "Dissolve" tool was applied to the attribute table of the U.S. tornadoes database, which aggregates this information by month. The procedure was completed using the "Summary Statistics" tool, which subsequently outputted a new table recording how many tornado occurrences were there for each month, with relevant statistics thereafter. The results demonstrate that the five top tornado months are: January (14,824 occurrences), April (8,399 occurrences), May (14,749 occurrences), June (5,658 occurrences), and October

Figure 3: Top Five Tornado Months in the USA



Tornado Season

	OBJECTID *	Month	Coun_Month
1	1	1	14824
2	2	2	3580
3	3	3	27
4	4	4	8399
5	5	5	14749
6	6	6	5658
7	7	7	3626
8	8	8	615
9	9	10	5511
10	10	11	5627
11	11	12	4956

11 of 11 selected Filter

Source: Prepared by authors, September 1, 2024.

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(5,627 occurrences). These months represent the periods of peak tornado activity and indicate the seasonal trends associated with tornado occurrences in the United States.

This analysis comprehensively captures the monthly tornado activities, showing seasonal trends for disaster preparedness and resource allocation. By identifying months of very active tornadoes, the study stresses enhanced preparedness focusing on peak times to minimize any potential risks and consequences thereafter.

5.3 Analyzing the Top Five States with Tornado Induced Injuries, Fatalities, and Property Damage:

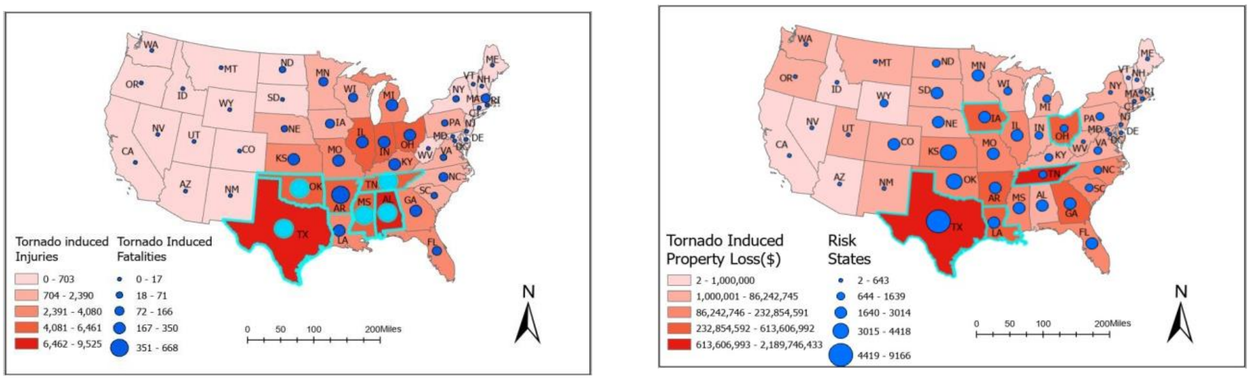
The analysis aimed to identify the top five states from 1950 to 2022 with the highest levels of fatalities, injuries, and property losses due to tornado impact. This would be implemented with a number of geoprocessing tools, such as “Selection by Attribute,” “Spatial Join,” and “Summary Statistics.” For the aggregation of fatalities and injuries caused by tornadoes by state, the “Summary Statistics” tool was used. Then, with this aggregated data joined to the states layer, a “Spatial Join” was executed. Finally, the joined layer was symbolized to give a visual representation of the spatial distribution of tornado fatalities, injuries, and property losses.

The obtained results identified the top five states with the following characteristics:

- Fatalities: Alabama (668), Texas (593), Mississippi (476), Oklahoma (439), and Tennessee (407).
- Injuries: Texas (9,475), Alabama (8,669), Mississippi (6,446), Oklahoma (5,999), and Arkansas (5,420).
- Property Loss: Texas ($2,189,746,433), Tennessee ($1,662,404,251), Ohio ($613,606,991), Iowa ($576,905,776), and Louisiana ($570,491,875).

This analysis provides an important view of the states hardest hit by tornadoes and provides tremendous insight into spatial patterns of tornado fatalities, injuries, and economic damage. It provides vital information for effective disaster management strategies, for prioritizing resource allocation, and for infrastructure planning. By visualizing the data, the study demonstrates the spatial concentration of tornado impacts and the ensuing need for targeted measures for mitigation of the situation in these high-risk states.

Figure 4: Map of Top Five States with Tornado Induced Injuries, Fatalities, and Property Damage



Source: Prepared by authors, September 1, 2024.

5.4 Tornado-Prone Highways and Roads

The analysis scrutinized tornado-prone highways and roads in the United States based on tornado occurrences from 1950 until 2022. A series of geoprocessing tools such as “Dissolve”, “Summary Statistics”, “Select by Attributes”, and “Spatial Join” were used to identify and visualize which highways and roads experienced the most tornado activity. To determine the top five interstates and major roads affected by tornado occurrences, two separate spatial join operations were made between the Tornadoes dataset and Interstates/Major Roads datasets. Another geographical operation of the States and Tornadoes datasets was made to examine the spatial distribution of tornadoes. The derived table was sorted to identify the highways and states most affected.

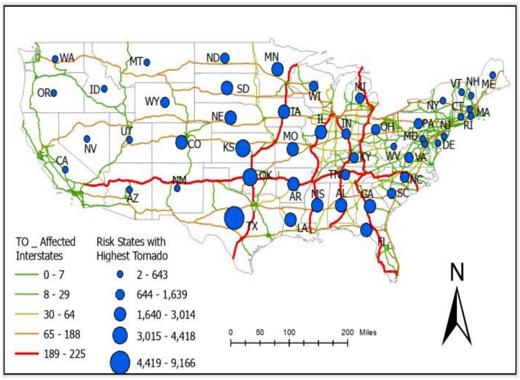
The top five interstates and major roads affected by tornadoes are:

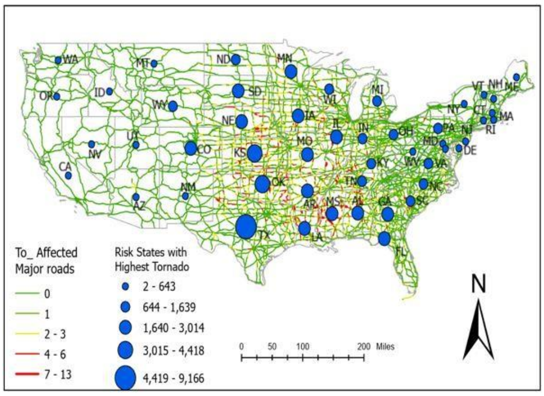
- Interstates: I40 (225 occurrences), I75 (204 occurrences), I65 (197 occurrences), I35 (191 occurrences), and I55 (189 occurrences).
- Major Roads: U231, U34, U49, U283, and U49.

This analysis provides useful information about highways and arterial roads frequent tornadoes. Vulnerability insights into the critical infrastructure are used for these findings to orient transportation planning and work for disaster preparedness by stopping the need for a mitigation plan for the highways during times of storm risk. It is only through an understanding of how tornadoes impact highways that we can begin to prioritize resource allocation on some basis. These must go into enhancing resilience or, at the very least, minimizing disruptions caused by tornadoes.

vulnerability of regions to hazards that may be posed by

Figure 5: Map of Top Five States with the Tornado Affected Interstates and Major Roads





Source: Prepared by authors, September 1, 2024.

6 Conclusion

This research provides an investigation of tornado risk in the United States with the aid of spatial tools and historical data from 1950 to 2022. The results identify locations and months of highest activity with respect to tornadoes. The analysis offers insight into regions experiencing the highest level of tornado-induced deaths and injuries, property damage, and passage blockage on major highways. The observations further highlight the intricacy of tornado risk built on the compound nature of geography and climatic factors producing different patterns of frequency and severity of tornadoes in different states. There are glaring differences in the way tornado risks are manifested. While a state like Texas has very high tornado counts with equally huge human and economic impacts, others, such as Oklahoma and Kansas, have a high number of tornadoes, producing relatively lower consequences in terms of property loss or fatalities. In contrast, states such as Alabama and Mississippi, though experiencing fewer tornadoes, bear a heavy cuddle in human life lost and persons injured, signifying the differentiated tornadoes. Meanwhile, the risk of tornadoes is highly seasonal, as during the span of 1950 to 2022, May and January were peak tornado months, recording above 14,000 tornadoes each. Because of these seasonal trends, there are periods when it is even more important to enhance preparedness. The analysis of property losses indicates that although "Tornado Alley" states—the likes of Texas, Oklahoma, and Kansas—bear the brunt of economic losses, signs show that these assets are also highly threatened in Tennessee and Ohio, albeit there are fewer tornadoes recorded per year. The investigation also studied the interaction between major transportation corridors and tornado paths. Highways and arterial roads, especially interstates such as I-40, I-75, and I-65, commonly intersect tornado paths and are thus exceptionally vulnerable. This vulnerability indicates fragility within the transportation network, and they call therefore for urgent intervention aimed at improving the resilience of the infrastructure to hold down disruptions.

The findings provide spatial assessment data that can be used by urban planners and emergency managers in gaining insight into and comparing hypothetical risks

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with actual tornado impacts. These findings are directly correlated to region-specific preparedness, brought about by a mixture of tornado frequency and intensity. By addressing these factors, customized solutions that reduce tornado risks attentively in high-frequency and high-impact states can follow, resulting in fair and strategic risk management across the United States.

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