J.13.3 A PRELIMINARY REVIEW OF TORNADOES IMPACTING INTERSTATES: SERVICE AND SOCIETAL CONSIDERATIONS

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1. INTRODUCTION

Motorists traveling on the Interstate System inherently lack immediate access to a substantial shelter in the case of a tornado, such as an interior room away from windows, basement, or an underground storm shelter as is recommended by the National Weather Service (NWS) (NOAA 1992). Therefore, these individuals may not have the opportunity to take sufficient cover in the event of short-fused severe weather. Travelers are limited in their ability to obtain short-term convective weather forecasts, such as NWS tornado warnings, or are unaware of or unable to access the few existing mobile services that provide warning information. Also, drivers may have few opportunities to change their direction of travel or exit off the Interstate. Finally, motorists venturing away from home are likely unfamiliar with local towns, counties, and landmarks referenced in warnings, even if they have access to warning information. The enhanced risk faced by Interstate motorists encountering a tornado highlights the need to further assess their vulnerability by quantifying the occurrences of Interstate tornadoes and the associated tornado impacts to vehicles.

2. METHODOLOGY AND DATA

The domain for this study was defined within the central contiguous United States, specifically states bounded by the Continental Divide to the Mississippi River Valley region (Fig. 2). This region encompasses much of Tornado Alley, where tornadoes most frequently occur within the United States (Concannon et al. 2000; Brooks et al. 2003). The time interval for this study was set from 1 January 1990 through 31 December 2008. This period was selected to benefit from the increasing number of reports in the national tornado database. A multitude of reasons contributed to this reporting increase, including the implementation of well-trained storm spotter networks, storm chasers, advances in technology, and improved public awareness (Doswell et al. 1999; Brooks and Doswell 2002; Verbout et al. 2006). The existence of Weather Surveillance Radar 1988 Doppler (WSR-88D) network coincides with most of the study period, as does an increased emphasis on NWS warning verification and improved lead times, which has also contributed to the upward trend of tornado reports (Serafin and Wilson 2000; Simmons and Sutter 2005).

Figure 1: An EF4 tornado crossed Interstate 70 at mile marker 104 near Quinter, Kansas on 23 May 2008. Photo by Bill Hark.

The Interstate System holds a relatively constant stream of vehicles and therefore provides the potential for many eyewitnesses to observe severe weather phenomena. Varying densities of human population have been correlated in the

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spatial variability and inconsistency of the tornado record (Grazulis 1993; Ray et al. 2003; Anderson et al. 2007). Rural areas have typically suffered from an underreporting, whereas population centers, typically defined as urban regions, have a much more thorough tornado record. The authors theorize Interstate travel may offset some of the traditional underrepresentation of rural tornado events, due to the increased number of individuals on the roadways. This lends a higher confidence in the tornado record along the Interstates as opposed to other rural areas with lesser travel.

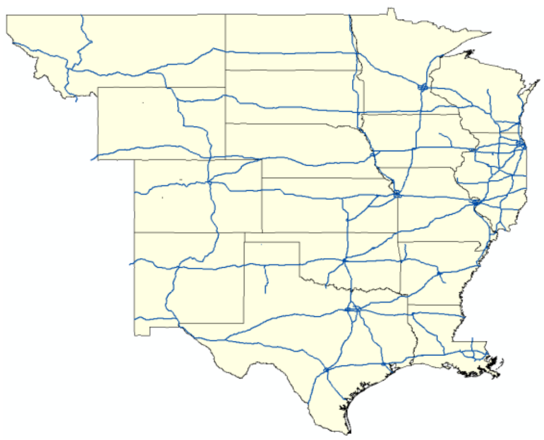

Figure 2: The domain and associated Interstates across the central contiguous United States used in this study.

2.1 *INTERSTATES*

Primary and Auxiliary Interstate roadways within the domain were used for the study. The definition of an Interstate was consistent with the standards set forth by the United States Department of Transportation Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) (*A Policy on Design Standards - Interstate System*). A comprehensive list of Interstates was compiled. The total mileage for each roadway and year of completion of individual road segments were recorded. Interstates and the associated tornado data were omitted during the initial construction phase since the roadway was incomplete and no travel occurred. Duplicate mileage was removed when two Interstates overlapped. An Interstate base map with a North American Datum of 1983 (NAD83) projection was created from a USGS National Atlas Interstate shapefile. All roadways on the Interstate base map were quality controlled for accurate placement.

2.2 *TORNADOES*

The National Climatic Data Center (NCDC) *Storm Data* was examined to identify all tornadoes that occurred within the spatial and temporal study domain. The beginning and ending points of each tornado were downloaded, plotted, and connected in a straight line in Environmental Systems Research Institute (ESRI) ArcMap 9.2 software. In cases where an individual tornado crossed multiple Interstates, the tornado was recognized as a singular event within the database.

Tornado paths were extensively reviewed to accurately determine whether a tornado crossed an Interstate. A query of tornado paths was first conducted to catalog all tornadoes that occurred within 5 miles of either side of an Interstate. This buffer mitigated tornado coordinate estimates or rounding inaccuracies found within *Storm Data*. A five-step quality control process was established to investigate all tornadoes within the 5-mile buffer to determine inclusion within the Interstate tornado database (Table 1). Additional resources were consulted to provide supplemental information not available in *Storm Data*. Specific damage information was compiled, and further tornado track information refined the initial database. These resources consisted of the following:

- *Significant Tornadoes 1680-1991* and *Significant Tornadoes Update 1992-1995* (Grazulis 1993, Grazulis 1997)
- NWS preliminary local storm reports, public information statements, and web page event summaries
- Online media and news articles
- Personal communications between county Emergency Managers, field office NWS Warning Coordination Meteorologists, and storm chasers

Direct tornado fatalities that occurred on an Interstate were compiled for the study period. The NWS specifies instructions for recording the location of fatalities in *Storm Data*, but provides no guidance for entering injury locations (NWS NDS 10-1605, 2005). Specific injuries from tornadoes that occurred on Interstates were frequently indistinguishable from other injury locations along the tornado path; therefore the study only investigated tornado fatalities.

Caveats to the national tornado record have been previously established (Doswell and Burgess 1988; Grazulis 1993; Marshall 2002; Verbout et al. 2006). These references evoke some concern with the reliability of the data, such as rating inconsistencies with the Enhanced Fujita Scale (EF-scale, F-scale prior to 2007) and questionable reports from untrained witnesses. Therefore, to mitigate potential erroneous tornado reports and estimated tornado locations, EF0 and EF1 tornadoes with path lengths one mile or less that resulted in no reported injuries or deaths, and no sources cited an Interstate crossing, were eliminated from the database. Additionally, tornadoes that crossed an Interstate either before the roadway was in operation, or before an official Interstate designation, were removed. Following these aforementioned quality control procedures, a final Interstate tornado database was compiled, re-plotted, and reviewed for any errors.

Table 1: Five-step quality control process applied to *Storm Data* for tornadoes within a 5 mile radius of an Interstate.

QC Steps	GIS Plotted Track Crossed	Narrative Confirmed Or Denied Crossing	Final Database Inclusion
1	Yes	Confirmed	Yes
2	Yes	N/A	Yes
3	Yes	Denied	No
4	No	Confirmed	Yes
5	No	N/A	No

3. RESULTS

3.1 *INTERSTATE TORNADOES*

A total of 144 Interstates comprising 18,169 miles of non-overlapping roadway fell within the defined domain. A total of 15,621 tornadoes occurred within the study area during the investigation period. This is approximately 822 events per year, or 68.5% of the average annual tornado count in the United States. This study identified 484 tornadoes that crossed one or more Interstates during the sample period, or 3.1% of all tornadoes within the defined domain. Tornadoes therefore crossed Interstates approximately 25 times in a given year within the selected domain. The Interstate-crossing tornado count for the years 1990, 1999, and 2008 featured the highest annual totals with 37, 39, and 43 events respectively.

Every state in the domain had one or more Interstate-crossing tornadoes, ranging from 1 in Montana to 74 in Texas. Fig. 3 shows the distribution of tornado paths intersecting Interstates, whereas Fig. 4 shows a distribution by state of normalized Interstate tornado crossings per 100 miles of roadway. The Rocky Mountain States had the fewest occurrences with a maximum region found across portions of the southern and central Great Plains into the Ozark Mountain region. This tornado distribution is similar to previously established climatologies, showing some of the most frequent occurrences of tornadoes in this portion of the United States (Concannon et al. 2000).

3.2 *EF-SCALE DISTRIBUTION*

The relative frequency of significant tornadoes (defined as EF2 to EF5) was higher for those that crossed Interstates than the entire United States tornado database for the 1990-2008 period (Fig. 5). Interstate-crossing significant tornadoes accounted for 43.2% of the total tornado number, while the national average of significant tornadoes was 11.1%. The aforementioned quality control procedure for weak tornadoes removed approximately 5% of EF0 and EF1 tornadoes from the

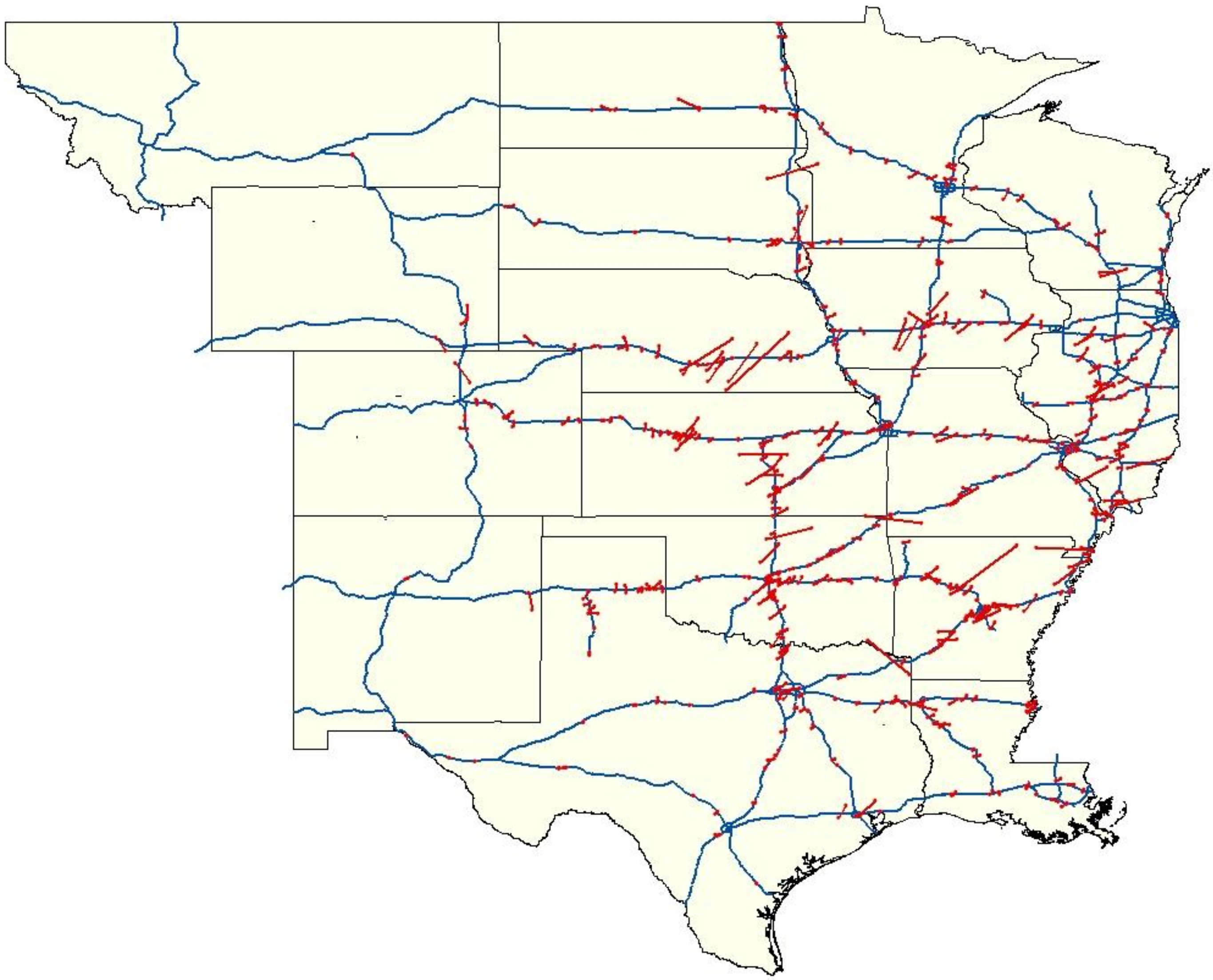

Figure 3: Tornadoes paths (red lines) crossing one or more Interstates (blue lines) from 1990 to 2008.

Interstate database, slightly increasing the percentage of significant Interstate tornado occurrences. It is worthy to mention the rating of a tornado is based on the greatest damage along its entire path, which may not necessarily be representative of the strength when a tornado crossed an Interstate. Regardless, it is suspected the higher number of significant Interstate tornadoes episodes may be attributed to additional damage indicators typically present along or near Interstate roadways, such as residential and commercial structures.

3.3 *VEHICLE IMPACT*

A database of tornadoes impacting vehicles on Interstates was compiled and analyzed. A vehicle impact tornado (VIT) was defined as any motor vehicle struck by a tornado on a primary or auxiliary Interstate. For the purpose of this analysis, the word *struck* designates an existing record of damage to the vehicle.

Damage consisted of any of the following: broken windows, body damage, vehicles shifted or blown off the road, or a vehicle rolled, overturned, tossed, or destroyed. A total of 92 VITs were recorded during the study period, accounting for approximately 19% of all Interstate tornadoes. VITs impacted 263 vehicles, 150 of which were semi-trailer trucks.

Significant Interstate VITs (defined as EF2 to EF5) accounted for 57.6% of all VITs, while again the national average for all significant tornadoes is 11.1%. It is hypothesized weaker tornadoes, such as those rated EF0 that contain winds less than 86 mph, may result in little to no apparent damage to vehicles, contributing to an underreporting of VITs in weaker circulations. This speculation is reinforced by the database in this study where EF0 tornadoes only account for 14.1% of VITs whereas the national EF0 distribution was 62.4%.

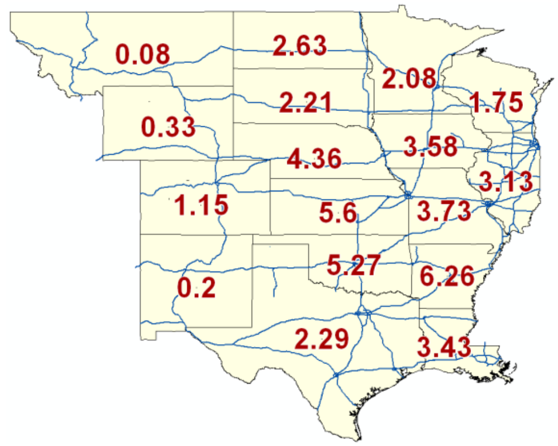

Figure 4: Normalized distribution of Interstate tornado crossings per 100 miles of roadway by state.

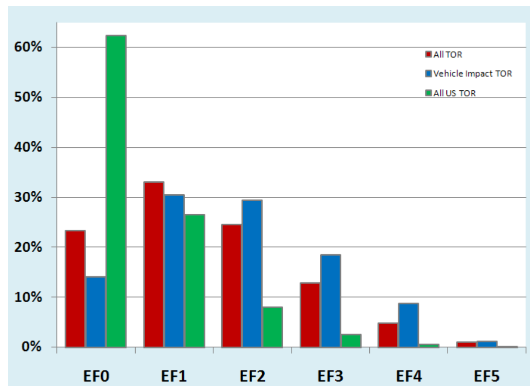

Figure 5: Distribution of all Interstate tornadoes (red), Interstate tornadoes resulting in an impact to a vehicle (blue), and all United States tornadoes (green) by EF-Scale from 1990 to 2008.

3.4 *TIME OF DAY*

The study categorized each Interstate tornado by the time of day relative to specific sunrise and sunset times (Fig. 6). Daytime tornadoes were defined to have occurred between sunrise and sunset, while nighttime tornadoes occurred between sunset and sunrise. Daytime Interstate tornadoes accounted for 66.5% of events while nighttime tornadoes totaled 33.5%. Volume analysis of hourly Interstate travel shows the lowest travel densities are found during the late evening hours through dawn (Barb Blue, personal communications). Compared to the relative frequency of all nighttime interstate tornadoes, there was a 9% increase for nighttime VITs. It is speculated that nighttime tornadoes elevate the vulnerability of Interstate motorists, regardless of the traditionally lower traffic volume on roadways.

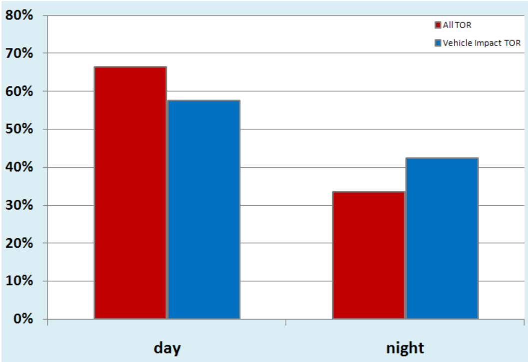

Figure 6: Time of day distribution of all Interstate tornadoes (red) and Interstate tornadoes resulting in an impact to a vehicle (blue) from 1990 to 2008.

3.5 *INTERSTATE TORNADO FATALITIES*

Interstate-crossing tornadoes resulted in 8 direct fatalities in 7 separate events. This is approximately 1.5% of the 484 Interstate tornadoes, and 7.6% of the 92 VITs. Table 2 displays the location, date, time of day, and EF-Scale rating of the killer tornadoes. Approximately 43% of killer tornadoes occurred during the day, whereas 57% of events occurred at night. All VITs resulting in a fatality were EF3 or greater intensity. This is similar to the national climatological record of tornado deaths, where significant tornadoes account for 98.8% of all tornado fatalities from 1950 to 2004 (Ashley 2007).

Of these deaths, two occurred outside of the vehicle under an overpass, which is a frequently discouraged option of last resort (Miller et al. 2000). Other fatalities occurred inside of vehicles, and it is unknown whether these deaths may have been mitigated with the use of a safety belt to minimize physical trauma or ejection from the vehicle upon rolling. Of the known 263 vehicles impacted by tornadoes, a small number of fatalities resulted. Unfortunately, it is largely unknown what percentage of occupants who survived tornado impacts remained inside a vehicle or abandoned it and sought shelter in other locations, such as a ditch. The authors suspect the majority of motorists remained inside a vehicle, especially in high-precipitation and nighttime cases when a tornado would have been difficult to observe.

Table 2: A list of tornadoes that resulted in a fatality on an Interstate from 1990 to 2008 within the study domain

Date	State	Time	F-Scale
27 August 1994	WI	Night	F3
19 April 1996	IL	Night	F3
1 March 1997	AR	Day	F4
3 May 1999	OK	Day	F5
3 May 1999	OK	Night	F4
1 June 1999	IL	Day	F3
27 November 2005	AR	Night	F3

4. SAFETY RECOMMENDATIONS

The American Red Cross (ARC), Federal Emergency Management Administration (FEMA), and NWS encourage motorists to seek a substantial shelter when a tornado threatens. Generally, a *safest shelter* is considered to be an underground shelter, basement, or safe room. If those locations are not available, then a small, windowless interior room or hallway on the lowest level of a sturdy building is the best alternative (NOAA 2009). However, these safe shelter options may not be available to motorists traveling on an Interstate, or time may not be sufficient to reach these shelters.

The NWS had recommended in preparedness training and Call-to-Action (CTA) statements that motorists and their passengers abandon their vehicles to lie flat in a nearby ditch or depression as a last-resort tornado shelter prior to June 2009 (NOAA 1992). Hammer and Schmidlin (2001) suggested this recommendation was written during a period when vehicle-related tornado deaths had been increasing and tragic events, such as the 1979 Wichita Falls, Texas tornado and the 1989 Huntsville, Alabama tornado, resulted in multiple fatalities in vehicles. Schmidlin and

King (1996) argued the guidelines that encouraged motorists to abandon their vehicles for nearby ditches were developed without research supporting the subject matter. Brenner and Noji (1993) also noted a lack of NWS guidance in situations where no ditch or depression was present to motorists. Previous research also questioned the assumption that remaining inside a vehicle would be a greater hazard during a tornado than being outdoors (Brenner and Noji 1993; Schmidlin and King 1996; Hammer and Schmidlin 2001, Schmidlin et al. 2002).

The ARC and NWS recently revisited the tornado safety recommendations and composed a joint statement containing several updates to tornado safety information, which included guidance to motorists with an absence of substantial shelter (NOAA 2009). Fig. 7 shows an example of a motorist using a vehicle as a last-resort option. A portion of this document is provided below:

- If flying debris occurs while you are driving, pull over and park. Now you have the following options as a last resort:

    Stay in the car with the seat belt on. Put your head down below the windows, covering with your hands and a blanket if possible.

    If you can safely get noticeably lower than the level of the roadway, exit your car and lie in that area, covering your head with your hands.

In addition, the NWS has formulated updated tornado call-to-action (CTA) statements that provide recommended actions to be included in tornado warnings and preparedness literature. The new CTA statement targeted for motorists with a lack of substantial shelter reads:

- Motorists should not take shelter under highway overpasses. As a last resort, either park your vehicle and stay put, or abandon your vehicle and lie down in a low lying area.

Figure 7: An example of a motorist remaining inside a vehicle as a last-resort option in a tornado.

The revised tornado safety recommendations force a paradigm shift from the suggestion to abandon one's vehicle, to encouraging motorists to remain inside one's vehicle. Carter et al. (1989), Hammer and Schmidlin (2001) and Schmidlin et al. (2002) made cases regarding the relative safety a vehicle offers its occupants, when compared to seeking shelter in an exposed outdoor environment. Currently, only anecdotal accounts exist for individuals surviving a tornado impact in a ditch. Golden (2002) noted several documented instances of unoccupied vehicles lofted considerable distances, flattened, and wrapped around trees during significant tornadoes, which would have likely resulted in injuries or fatalities. Despite this information, it should not be implied that seeking shelter outdoors in a ditch would produce a safer outcome in the event of a tornado. Motorists that choose to leave their vehicle to seek an outdoor shelter are exposed to other thunderstorm hazards such as large hail, lighting, high winds, or flash flooding. Other hazards during a tornado may include falling debris, unobstructed projectiles, and other vehicles forced off the roadway.

It is currently unknown whether a controlled research environment could accurately resolve the variables involved in distinguishing whether a motorist's *safest* options is remaining in or abandoning a vehicle. It is plausible that both last-resort options in the most violent tornadoes (EF4, EF5) may offer virtually no protection from a direct tornado strike and result in a high probability of injury or death. However during the sample period, weak and strong tornadoes (EF0-EF3) accounted for 99.4% of the national tornado count (NOAA 2009). The authors question whether future research on the safest last-resort tornado shelter option for motorists should focus more emphasis on the large majority of tornadoes (EF0-EF3) versus the rare occurrences of violent tornadoes. The ARC and NWS have made the initial steps by identifying two last-resort options to assist motorists making the best decision based on their individual circumstances. Additional research in this field will help to overcome the unknowns and challenges in recommending and promoting the *safest* last-resort option to motorists.

5. CONCLUSIONS

This study serves as the first quantitative review of tornadoes impacting motorists traveling along the Interstate system in the central United States. It was found that tornadoes crossed an Interstate within the domain approximately 25 times annually. All 17 states recorded one or more Interstate tornado occurrences since 1990. One in every five Interstate tornadoes impacted a motor vehicle. Only a small number of vehicle-related fatalities occurred, despite the known 263 vehicles impacted by tornadoes.

These findings encouraged a review of last-resort tornado safety recommendations and the degree of safety vehicles may offer if impacted by a tornado. A safe shelter is frequently a challenge for motorists to obtain when traveling on an Interstate. It is hoped additional research with regards to vehicle safety in tornadic winds will continue to refine the best last-resort safety options to motorists. NWS offices should also make a concerted effort with media and emergency planners to advocate the paradigm shift in tornado safety information to motorists and encourage developing a plan of action.

While this study focused on Interstates and tornadoes exclusively across the central United States, it is believed the findings and recommendations could be applied to other primary highways in other regions of the country, as well as other severe weather hazards. Ultimately, the best safety recommendations combined with emerging technologies suited to the motorists needs will lead to an improved situational awareness and overall safety enhancement to travelers when faced with hazardous weather on the roadway.

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