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Tornadoes Impacting Interstates: Service and Societal Considerations

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ABSTRACT

Motorists traveling on Interstate highways are likely to have an increased vulnerability to weather hazards due to their unfamiliarity with nearby towns, limited methods to receive short-term weather information, and a general deficiency of a suitable shelter. To assess the threat, a database of 678 tornadoes, crossing primary and auxiliary Interstates across portions of the central and southeastern contiguous United States, was compiled for the period of 1990 to 2008. Approximately 17% of Interstate-crossing tornadoes impacted vehicles. Factors such as time of the day, EF-Scale rating, and travel density were examined to assess potential association with the probability of a tornado impact. This paper discusses current warning and preparedness activities in the operational meteorological community and state transportation departments, and recommends future actions and new technology to mitigate the loss of life and property from tornadoes that cross Interstate highways.

1. Introduction

Tornadoes are among the most destructive and deadly of all natural disasters in the United States. Approximately 1200 tornadoes occur per year and cause an average of 60 fatalities and 1500 injuries (NOAA 2009a). Moreover, travel on the Dwight D. Eisenhower National System of Interstate and Defense Highways has increased steadily across the United States during the past twenty years (U. S. Department of Transportation 2007). A 59.3% growth rate in Interstate highway travel occurred since 1990 across the central and southeast contiguous United States, with a 3.3% annual increase (Fig. 1). Ashley (2007) calculated that nearly 10% of all tornado-related deaths occurred in vehicles from 1985–2005. Previous studies investigated vehicles in severe winds, and posed various recommendations for taking shelter while on the road (Schmidlin and King 1996; Hammer and Schmidlin 2001; Schmidlin et al. 2002). Other research has examined specific tornado fatality and injury occurrences within vehicles including the Wichita Falls, TX (Glass et al. 1980), Marion, IL (Duclos and Ing 1989), Ontario, Canada (Carter et al. 1989), and Oklahoma City, OK (Brown et al. 2002) tornadoes. However, little research has been done to evaluate the vulnerability of motorists on Interstates due to short-fused severe weather hazards, specifically tornadoes.

Motorists traveling on the Interstate System inherently lack immediate access to a substantial shelter, such as an interior room away from windows, a basement, or an underground storm shelter as is recommended by the National Weather Service (NWS) (NOAA 2009b), and may not have the opportunity to take sufficient cover during severe weather. Travelers are limited in their ability to obtain short-term convective weather forecasts, such as NWS tornado warnings, and are unaware of or are unable to access the few existing mobile services that provide warning information. Also, drivers may have few opportunities to take evasive action while traveling on an Interstate highway.

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This is especially true with Interstate turnpikes, where limited access to exits is controlled by toll plazas. 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 tornadoes that cross Interstates and the associated tornado impacts to vehicles.

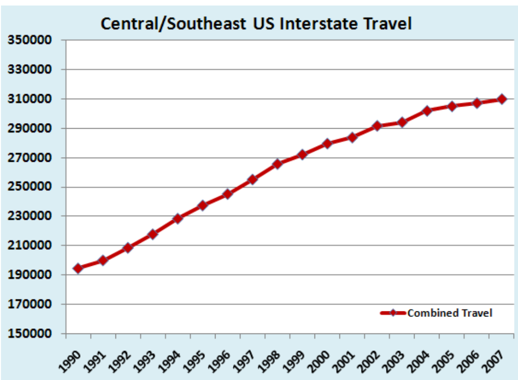

Figure 1: Annual vehicle miles of Interstate travel within the defined study domain from 1990 to 2007 (U. S. Department of Transportation 1990-2007). *Click image to enlarge.*

The coincident intersection of an Interstate roadway and tornado path serves as a focal point for this study (Fig. 2). This paper quantifies the number of Interstate-crossing tornadoes, event distribution, vehicles impacted, and subsequent fatalities over a 19-year period. An overview of the methods used to create an Interstate tornado database is provided in Section 2. The results are presented in Section 3 with a review of tornado spatial distribution and vehicle impacts. Section 4 explores safety recommendations, NWS warning information, and new technologies geared for disseminating severe weather information to Interstate travelers. The paper concludes with a summary of the findings and future recommendations in Section 5.

2. Methodology and data

The domain for this study was defined within portions of the central and southeast contiguous United States, generally states east of the Continental Divide and west of the Appalachian Mountains region. This area encompasses much of "tornado alley," where tornadoes most frequently occur within the United States, and the lower Mississippi Valley where the highest number of tornado fatalities are found (Concannon et al. 2000; Brooks et al. 2003; Ashley 2007). 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 the 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, both of which contributed to the upward trend of tornado reports (Serafin and Wilson 2000; Simmons and Sutter 2005).

Figure 2: An EF4 tornado crossed Interstate 70 at mile marker 104 near Quinter, KS, on 23 May 2008. Photo by Bill Hark. *Click image to enlarge.*

The Interstate System holds a relatively constant stream of vehicles and therefore provides the potential for many eyewitnesses to observe severe weather phenomena. Variations in population density have been shown to be correlated with spatial variability and inconsistency in the tornado record (Grazulis 1993; Ray et al. 2003; Anderson et al. 2007). Tornadoes historically have been undercounted in rural areas, whereas the tornado record in urban areas is believed to be more complete. The authors believe Interstate travel may offset some of the traditional undercounting of rural tornado events, due to the increased potential for observers on the roadways. This lends a higher confidence in the tornado record along the Interstates as opposed to other, less-traveled rural areas.

a. 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 (2005) Federal Highway Administration and the American Association of State Highway and Transportation Officials. 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 of the highway, 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 projection, was created from a USGS National Atlas Interstate shapefile. All roadways on the Interstate base map were quality controlled for accurate placement using 2009 DeLorme Street Atlas software.

b. Tornadoes

The Storm Prediction Center tornado database compiled from National Climatic Data Center (NCDC) publication *Storm Data* (NCDC 1990–2008) 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 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 reviewed extensively to determine whether a tornado crossed an Interstate. First, a query of tornado paths was conducted to catalog all tornadoes within 5 mi (8 km) 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-mi (8-km) buffer to determine inclusion within the Interstate tornado database (Table 1). Additional resources listed below 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 (NOAA 2007). Specific injuries from tornadoes that occurred on Interstates frequently were indistinguishable from other injury locations along the tornado path; therefore the study only investigated tornado fatalities.

Caveats regarding the national tornado record have been established previously (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 (F-scale prior to 1 February 2007, which is hereafter inferred) and questionable reports from untrained witnesses. Therefore, to lessen 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 for which 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 being designated an official Interstate, were removed. Following these aforementioned quality control procedures, a final database of tornadoes that crossed Interstates 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	Neither	Yes
3	Yes	Denied	No
4	No	Confirmed	Yes
5	No	Neither	No

3. Results

a. Interstate tornadoes

A total of 115 Interstate highways comprising 24,009 miles of non-overlapping roadway fell within the defined domain. A total of 19,069 tornadoes occurred within the study area during the investigation period. This sample accounts for approximately 1,004 events per year, or 83% of the average annual tornado count in the United States. We identified 678 tornadoes that crossed one or more Interstates during the sample period, or 3.6% of all tornadoes within the defined domain. Tornadoes therefore crossed Interstates approximately 36 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 46, 43, and 74 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 study domain and 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 of Interstate-crossing tornadoes. A maximum occurrence of events was found across portions of the central Great Plains extending into the Lower Mississippi Valley 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; Ashley 2007, Fig. 6b).

b. EF-Scale distribution

The relative frequency of significant tornadoes (defined as EF2 to EF5) was higher for those that crossed Interstates than for the entire United States tornado database in the 1990–2008 period (Fig. 5). Of all tornadoes that crossed Interstates, 43.7% were rated as significant, while the national proportion of significant tornadoes was 11.1%. The aforementioned quality control procedure for EF0 and EF1 tornadoes removed approximately 5% of weak tornadoes from the Interstate database, slightly increasing the percentage of significant Interstate tornado occurrences. It is important to note 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 tornado episodes may be attributed to additional damage indicators typically present along or near Interstate roadways, such as residential and commercial structures.

c. 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 from a tornado.

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 113 VITs were recorded during the study period, accounting for approximately 17% of all Interstate tornadoes. VITs impacted 311 vehicles, 181 of which were semi-trailer trucks.

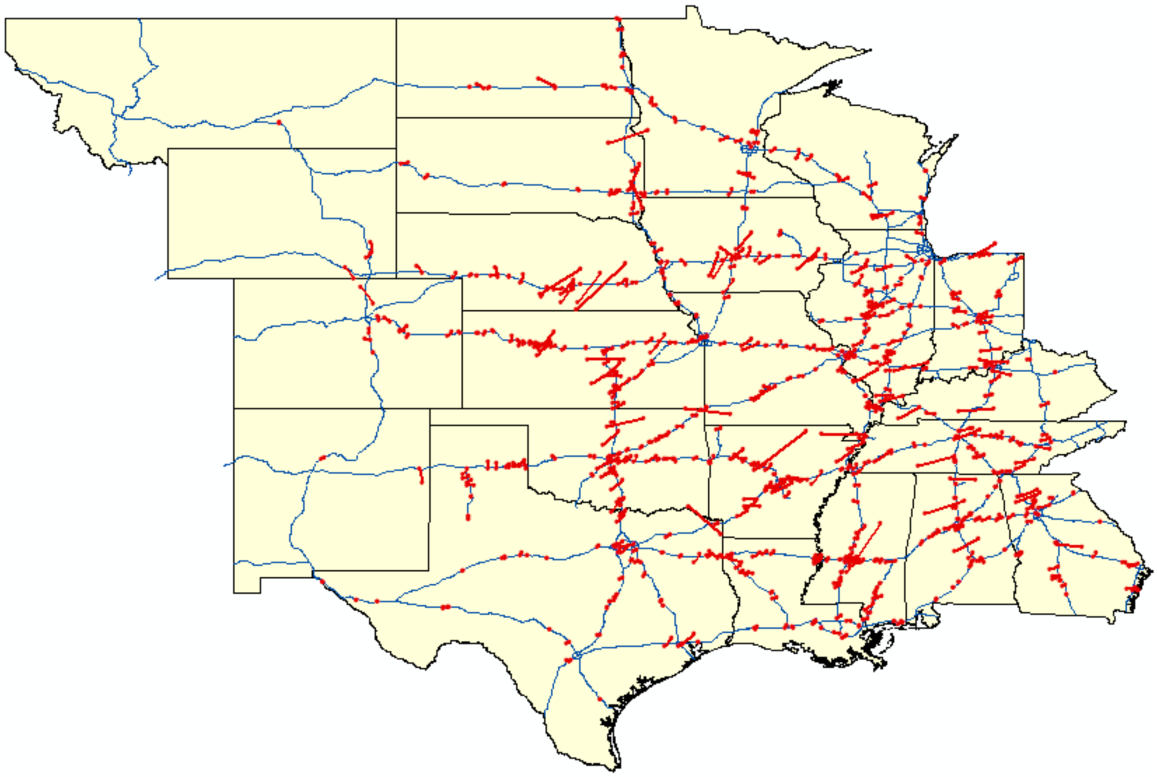

Figure 3: Study domain with tornado paths (red lines) crossing one or more Interstates (blue lines) from 1990 to 2008. Click image to enlarge.

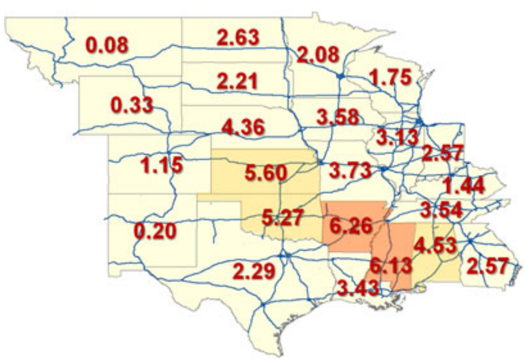

Figure 4: Normalized distribution of Interstate tornado crossings per 100 miles of roadway by state; shaded states 1.5 times above the domain average (gold) and 2 times above the domain average (orange) of 2.99. *Click image to enlarge.*

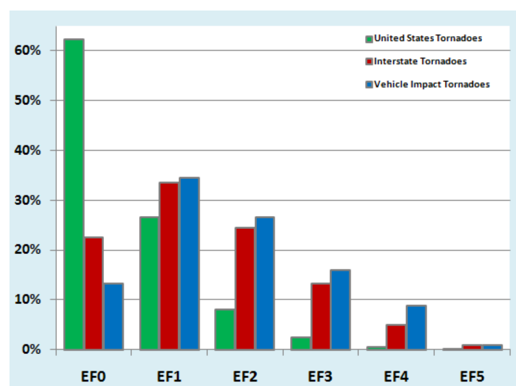

Figure 5: EF-Scale distributions of all United States tornadoes (green), Interstate tornadoes (red), and Interstate tornadoes resulting in an impact to a vehicle (blue) from 1990 to 2008. *Click image to enlarge.*

Significant Interstate VITs (defined as EF2 to EF5) accounted for 52.2% of all VITs, well above the national average for all significant tornadoes of 11.1%. Weaker tornadoes, such as those rated EF0 (winds less than 86 mph), may result in little to no apparent damage to many vehicles, which would contribute to an under-reporting of VITs in weaker circulations. This speculation is reinforced in this study where EF0 tornadoes only account for 13.2% of VITs whereas the national EF0 tornado proportion was 62.4%.

d. Time of day

An hourly distribution of Interstate tornadoes and VITs were examined for the study period (Fig 6a). Additionally, each event was categorized by the time of day relative to specific sunrise and sunset times (Fig. 6b). Daytime tornadoes were defined to have occurred between sunrise and sunset, while nighttime tornadoes occurred between sunset and sunrise. It was found that 54.2% of Interstate tornadoes occurred within a 5 hour window between the hours of 3 pm CST (2100 UTC) and 8 pm CST (0200 UTC). This maximum period encompasses most of the traditional afternoon and evening "rush hour" traffic, potentially increasing the probability of a motorist being impacted by a tornado. Daytime Interstate tornadoes accounted for 64.5% of events while nighttime tornadoes totaled 35.5%. Volume analysis of hourly Interstate travel shows that the lowest travel densities are found during the late evening hours through dawn (B. Blue, 2009, personal communications). Compared to the relative frequency of all nighttime Interstate tornadoes, there was a 9% increase for nighttime VITs. It is speculated that motorists are more vulnerable to nighttime tornadoes, regardless of the traditionally lower traffic volume on the roadways.

e. Interstate tornado fatalities

Interstate-crossing tornadoes resulted in 9 direct fatalities in 8 separate events. This is approximately 1.2% of the 678 Interstate tornadoes, and 7.1% of the 113 VITs. Table 2 displays the location, date, time of day, and EF-Scale rating of the killer tornadoes. Approximately 37.5% of killer tornadoes occurred during the day, whereas 62.5% of events occurred at night. Approximately 88% of VITs that resulted in a fatality were EF3 or greater intensity. The sample size is small but still 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).

Table 3 summarizes specific tornado fatality locations. Of these deaths, two occurred outside of the vehicle under an overpass. Seeking shelter under an overpass is a discouraged option of last resort (Miller et al. 1999). Nearly all other fatalities occurred within vehicles. 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 311 vehicles impacted by tornadoes, a small number of fatalities resulted. Unfortunately, with mostly anecdotal evidence, 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.

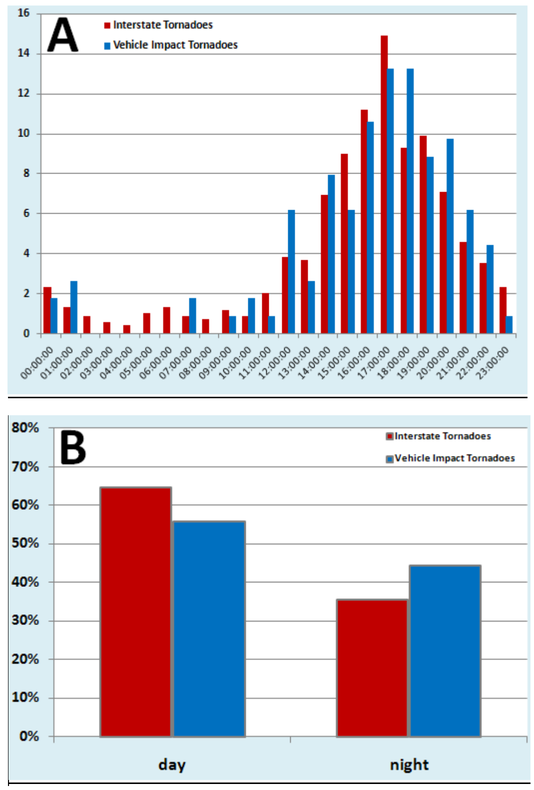

Figure 6: a) Hourly and b) time of day distributions (%) of all Interstate tornadoes (red) and Interstate tornadoes resulting in an impact to a vehicle (blue) from 1990 to 2008. Time is CST (UTC – 6 h). *Click image to enlarge.*

4. Safety, service, and new technologies

a. Recommended safety actions

The American Red Cross (ARC), Federal Emergency Management Administration, 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 2009b). However, these safe shelter options, or the necessary time to reach a safe shelter may not be available to motorists traveling on an Interstate.

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	Rating
27 Aug 1994	WI	Night	F3
19 Apr 1996	IL	Night	F3
1 Mar 1997	AR	Day	F4
3 May 1999	OK	Day	F5
3 May 1999	OK	Night	F4
1 Jun 1999	IL	Day	F3
27 Nov 2005	AR	Night	F3
15 Dec 2007	GA	Night	EF1

Table 3: Tornado fatality locations along an Interstate from 1990 to 2008 within the study domain.

Deaths	***Location***
2	**Overpass**
2	**Debris projectile inside vehicle**
1	**Semi at rest area on Interstate**
1	**Sleeper portion of a semi**
1	**Person ejected**
1	**Vehicle thrown upside down**
1	**Semi rolled down 15 m embankment**

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 in response to a period when vehicle-related tornado deaths had been increasing and tragic events, such as the 1979 Wichita Falls, TX tornado and the 1989 Huntsville, AL 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, Hammer and Schmidlin 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 2009a). 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.

Your choice should be driven by your specific circumstances.

In addition, the NWS has formulated updated tornado 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. *Click image to enlarge.*

The revised tornado safety recommendations force a paradigm shift from the sole suggestion to abandon one's vehicle, to either remain inside a vehicle or exit a vehicle for a ditch based on an individual's specific circumstances. Carter et al. (1989), Hammer and Schmidlin (2001), and Hammer and Schmidlin (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 encounter in a ditch. Golden (2002) noted several documented instances of unoccupied vehicles lofted considerable distances, flattened, and wrapped around trees during significant tornadoes, which likely would have 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 accurately could resolve the variables involved in distinguishing whether a motorist's *safest* option 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 1990-2008). The authors question whether future research on the safest last-resort tornado shelter option for motorists should focus on the majority of tornadoes (EF0 to EF3) instead of rare 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. The authors also question if combining the current last-resort protective measures, recommending a motorist remain in his/her vehicle and drive into a low depression, may yield the safest option. Additional research in this area will help develop a best recommendation for the *safest* last-resort option.

b. NWS warning operations

NWS meteorologists have the capability to include Interstate information within the body of text in convective warnings. The specific Interstate and associated mile markers located within the warning polygon can be included automatically as a location in the path of severe weather (Speheger 2004). An example of an Interstate tornado in Dickinson County, KS on 11 June 2008 shows the use of Interstate locations within a tornado warning:

- LOCATIONS IMPACTED INCLUDE… ABILENE...ENTERPRISE...MOONLIGHT ...WOODBINE…CHAPMAN.
- THIS INCLUDES INTERSTATE 70 BETWEEN MILE MARKERS 267 AND 289.

We investigated the use of Interstate information in NWS tornado warnings for each Interstate tornado event from 2005 to 2008. Subsequent warning statements were not reviewed as these are not disseminated through the Emergency Alert System (EAS). A total of 161 Interstate-crossing tornadoes occurred during this sample period. Of the total, 145 tornado events occurred within a tornado warning polygon, while 16 of the tornadoes had no associated tornado warning in effect. Of the 145 tornado warnings issued, 114 contained no mention of Interstates or Interstate mile markers within the text. Mile markers were included in 22 separate warnings, and specific Interstate locations were mentioned in another 9 warnings.

This equates to only 21% of tornado warnings in this sample that mentioned the impacted Interstate or mile markers within the warning text.

All states in the study domain use mileage-based Interstate exit numbers to coincide with nearby mile markers (U. S. Department of Transportation 2003). This provides an opportunity for NWS warnings to alert motorists using mile markers as specific landmarks. It is generally believed that Interstates are some of the most recognizable geographic features to residents and motorists. The authors suggest that the use of Interstates and mile markers within warning products serve as useful reference points to both travelers and local residents on or near an Interstate roadway. This language may help improve a motorist's familiarity with local towns and counties by citing a specific Interstate location. It is feasible that future NWS procedures and products could be enhanced to provide motorists, not only with the impacted Interstate locations, but also the nearest exit number where a substantial shelter may be available.

c. Technologies

Tornado warning information could be distributed to motorists in a variety of ways. The NWS Storm Prediction Center, in conjunction with local NWS offices, typically issues severe thunderstorm or tornado watches several hours ahead of severe convective events. Therefore, both short-fuse (less than one hour) and longer term (greater than one hour) information also should be made available to motorists, the former to encourage quick action in the event of severe weather, and the latter to help guide travel decision making and preparedness. Motorists within a warning would be encouraged to seek a suitable shelter and follow the previously mentioned guidance outlined by the ARC and NWS, enhanced by specific wording, such as mile markers or exit numbers included within the NWS warning text. All proposed means of dissemination should be accomplished with safety in mind, and with minimal distraction to vehicle operation, both before and potentially during a severe weather event.

There are several new potential avenues for the distribution of watch and warning information to motorists. Dynamic Message Signs (DMS) are electronic boards typically located along Interstates that can be updated almost instantaneously to display a brief amount of text (B. Blue, 2009, personal communications). State departments of transportation (DOT) within the domain were queried to determine the ability of DMS to disseminate watch and warning information. State DOTs could display watch information remotely to motorists, effectively notifying them of potentially hazardous weather several hours in advance. Additionally, warning information could be displayed on nearby DMS, based upon the inclusion of mile markers within the text of the tornado warning. In order for this to be an effective tool to warn Interstate motorists, the responsible NWS office would need to include mile marker information in the text of the tornado warning. Fig. 8 depicts a hypothetical example of a DMS that displays tornado warning information and the affected mile markers within a warning polygon. DMS have been used to broadcast both winter weather and fire weather information to motorists. It is therefore reasonable to believe that severe weather watch and warning information could be made available to Interstate travelers through DMS.

Figure 8: An example of a tornado warning disseminated through Dynamic Message Signs. *Click image to enlarge.*

Other avenues for the distribution of severe weather information to motorists within the existing infrastructure are also available, but not fully utilized. Approximately 70% of states within the domain have 511 Service to motorists (U. S. Department of Transportation 2005). The 511 Service is a standardized transportation and traffic information hotline available at no cost to the caller. The hotline currently provides updated road construction and winter weather-related road conditions. It is suggested that short-fused severe weather information could be incorporated into this system by a brief message alerting travelers of hazardous weather through the user-selected route option. Currently some states provide lobby radar displays and NOAA Weather Radio broadcasts at rest areas and state welcome centers. Expansion of these capabilities to other states may help prepare and warn travelers of severe weather threats. These centers could also offer safety and preparedness literature to motorists to assist them in making informed decisions in the event of a severe weather situation. Local AM/FM radio stations will broadcast severe weather warnings within their coverage area as part of the EAS. It is possible state DOTs also could record warning information relevant for Interstate motorists through the DOT AM radio broadcasts.

Mobile electronic devices increasingly are equipped to receive real-time watch and warning information. Although use of mobile electronic devices is discouraged while operating a motor vehicle, an audible alert triggered by a cell phone, GPS device, in-car navigation service, or other satellite-based communication system may alert the motorist. Multiple means of communicating weather information to motorists will help them to make the safest decision prior to or at the time of a severe weather event.

5. Conclusions

This study serves as the first quantitative review of tornadoes impacting motorists traveling along the Interstate System in the central and southeast United States. It was found that tornadoes crossed an Interstate within the domain approximately 36 times annually. All 23 states included in this study recorded one or more Interstate tornado occurrences since 1990. Nearly one in every five Interstate tornadoes impacted a motor vehicle. Only a small number of vehicle-related fatalities occurred, despite the known 311 vehicles impacted by tornadoes.

These findings encourage a review of last-resort tornado safety recommendations and the degree of safety vehicles may offer if impacted by a tornado. Finding safe shelter is a challenge to Interstate motorists. We hope additional research on vehicle safety in tornadic winds will help 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. We believe Interstates and mile markers within warning products serve as useful reference points to travelers and residents. Over 98% of NWS offices within the domain issue severe weather warnings that encompass one or more Interstates. We encourage NWS offices to include Interstate information in convective warnings. In the near future, this Interstate-related warning information may be utilized in technologies from both internal and external agencies to alert motorists of impending hazardous weather.

While this study focused on Interstates and tornadoes in the central and southeast 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 to 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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REVIEWER COMMENTS

[Authors' responses in *blue italics.*]

REVIEWER A (Stephen F. Corfidi):

Initial Review:

Recommendation: Accept pending (mainly) minor revision

General Comments: This paper addresses the risk posed by tornadoes that cross Interstate highways in the central United States between 1990 and 2008. In addition to documenting the nature and relative frequency of the risk, the paper describes current warning and preparedness activities, and suggests actions and technological changes that could be made to lessen loss of life and property damage in the future. To my knowledge, no paper to date has focused on some of these topics. Therefore, the manuscript fills a unique niche and should be of interest both within and outside the meteorological community.

The paper is generally well-written and well-organized. A consistent and well-reasoned approach appears to have been taken in identifying the cases used in the study. I did make numerous comments and suggestions (inserted directly in the original manuscript) regarding exposition. The suggested changes, I think, will make for an improved presentation. Many of the suggestions involve use of the word "Interstate," while others refer to the references. Suggestions of a more general nature are given in the following paragraphs.

We have corrected these errors and capitalized "interstate" when used as a proper noun.

In the section "EF-Scale Distribution" (page 4), and in the discussion regarding Figure 6, the EF scale is used to refer to tornado damage that occurred prior to 2007 (year that the EF scale replaced the legacy F-scale). In contrast, in Table 2, all of the tornadoes are listed with "F" ratings. The inconsistencies noted will have to be corrected prior to publication.

Earlier in the paper in section 2b (page 4), the EF-scale is introduced by "Enhanced Fujita Scale (F-scale prior to 2007, EF-scale hereafter)." We are comfortable in discussing this scale with the current "EF" nomenclature, with the exception of tornadoes mentioned in Table 2 when the specific damage rating scale can be listed.

I would consider extending the domain of the study into the eastern and southern states. No reason is given for confining the study to the central states. Considering population density, limitations on visual range posed by trees, and the fact that tornadoes over the eastern and southern United States do not exhibit as marked a diurnal tendency as do those in the Plains, I see no reason to exclude the substantial number of potentially significant events that occur in the eastern and southern states. I realize that this would require considerable effort. But, in the end, the effort would be well worthwhile.

We expanded the domain to include six additional states (IN, KY, TN, MS, AL, and GA) across portions of the east and southeast United States. The study domain now encompasses over 80% of the annual number of tornadoes in the United States, including the regions with the most frequent tornado activity and the highest number of tornado fatalities. Due to the large sample size, we believe the findings herein can be applied to other areas of the country outside of the study domain with similar results.

Because statistical data are, by nature, somewhat boring, and because this paper will be of interest to those outside the "hard science" community, the authors should consider adding discussion of one or two particular Interstate-crossing tornado events from a "human interest" point of view. For example, details might be presented on tornadoes that crossed (or moved closely parallel to) Interstate routes, and how such emergencies were handled by public safety officials.

Firsthand accounts from motorists faced with a tornado on an Interstate would be beneficial for identifying their decision-making process, actions that kept them safe (or not), and if mobile weather information was available. Such interview questions would need to be carefully crafted as to not lead the interviewee in a particular direction. Additionally, in order to gain a statistically significant dataset of responses, OMB approval would need to be obtained, which would take several months to a year. We believe that by adding only a few personal accounts from motorists to the current manuscript might inaccurately portray the larger spectrum of situations encountered by the general public, mislead the reader based on these 'results', and may detract from the focus of the paper. This type of information could serve as a valuable contribution to the social science meteorology literature and we would welcome any future collaboration, but at this time believe this research is beyond the scope of this paper.

Finally, but perhaps most importantly, the small number of Interstate-crossing tornado fatalities presented (Table 2) might lead a casual reader to conclude that tornadoes don't pose much of a threat to Interstate travelers. But the raw statistics do not reflect the true magnitude of such events. What about close calls? What about tornadoes that move parallel to Interstates for considerable distances, requiring rapid and astute decision making on the part of public safety officials? Such aspects need to be mentioned to better communicate the true nature of the Interstate tornado threat. I would think that police records in, say, Kansas, Oklahoma or any of the southern states would provide fertile material for inclusion here --- even if the event involved occurred prior to 1990. Mention might also be made of the particular hazard posed by Interstate *turnpikes*, wherein one is forced to stop to pay a toll and/or may be forced to go toward an approaching tornado as the Interstate is exited.

This study focused solely on Interstate-crossing tornadoes, which accounts for only a small subset of all vehicle-tornado fatalities in the United States. We do believe the findings contained within the paper can be generalized to other primary and secondary roadways.

Interstate-crossing tornado fatality statistics can be accurately counted due to the numerous sources outlined in section 2b. We cannot quantify the "true magnitude of such events" with any degree of certainty or accuracy, especially over such a large domain. Individual case studies or communication with local police departments may serve as a method to obtain "close call" information, but this sort of analysis is beyond the scope of this paper. Similarly, we can speculate on the impact of "close call" scenarios, but we do not believe such an analysis would add value to this paper. We would encourage others to pursue such questions, using this paper as a background to support their research.

We agree the fatality numbers presented herein do not, and cannot, directly reflect potential threats or close calls. This remains true to virtually any tornado scenario (e.g. thousands of people attending a sports event or a tornado narrowly missing a large mobile home park at night). There are obvious situations when the probability of Interstate-crossing tornado fatalities increases (i.e. rush hour traffic in urban areas; tornado paralleling along a roadway), but it's not feasible to account for each of these possibilities. Therefore, special attention was given in discussing the best protective actions motorists can make if faced with a tornado while on the roadway.

In short, I think the contribution by Blair and Lunde as it now stands is a good one. But I think that the paper could be substantially improved were its scope somewhat broadened in the manner discussed above.

Thank you.

[Minor comments omitted...]

Second review:

Recommendation: Accept with minor revisions

The authors expanded, as suggested, the domain of their study to include parts of the east central and southeastern United States. Broadening the geographical scope to include the nocturnal tornado belt of the lower Mississippi Valley, in particular, strengthens the relevance of their study.

The authors make a reasonable point regarding the inclusion of personal accounts of Interstate tornado encounters; such an addition would indeed be beyond the scope of the paper. I do, however, feel that a passing mention of the particular hazard posed by Interstate turnpikes would be worthwhile to highlight the enhanced potential for death or injury due to the presence of toll booths at points of exit.

The annotated revised manuscript contains just a few technical-type suggestions.

Blair and Lunde's paper appears nearly ready for publication; it will be a valuable contribution on the subject.

All the suggestions were incorporated. The size of the images was corrected/double-checked and the old Fig 3 was removed based on [Editor's] suggestion.

[Minor comments omitted...]

REVIEWER B (Kevin Scharfenberg):

Initial Review:

Reviewer recommendation: Accept with minor revisions

General Comments: This paper is a good fit for EJSSM. It may contribute to a better understanding of human vulnerability to tornadoes and may be an important contribution to work in creating a more effective warning system for travelers on the road. I recommend accepting this paper, conditional upon one major change (below) and several minor comments.

My main concerns with the paper regard parts of sections 3e and 4a. Specifically, the authors first state in the last part of section 3e that the sample size of fatalities associated with tornadoes striking vehicles on Interstates is very small and there is no information available about what protective actions were taken by the victims (leaving or staying with the vehicle). This is followed by:

> "The authors suspect the majority of motorists remained inside a vehicle, especially high-precipitation and nighttime cases when a tornado would have been difficult to observe."

Due to the caveats the authors mention, this can only be based on speculation which does not add value to the purpose of the paper: a climatology of tornado Interstate crossings and human vulnerability. I suggest the authors should retain the mention that motorists' protective action data are not available, but leave this speculative statement out.

It's reasonable to imagine a scenario in which Interstate motorists do not abandon a vehicle if they do not, or cannot, observe a tornado or rotation. This would arise at night or in high-precipitation storms when a tornado is difficult to observe. This scenario would likely be compounded when short-fused severe weather information is unavailable to motorists. With no visual or supplemental warning information to make an educated decision to leave a vehicle, it seems probable no action would be taken and the motorist would either continue driving or pull off the roadway if hazardous driving conditions were present. However, only anecdotal evidence of any type of human behavior with regards to Interstate-crossing tornadoes exists, and likewise we agree with the reviewer that the statement is speculative and will remove it from the revised product.

Section 4a appears to go off on a tangent regarding the unsettled debate about whether motorists should stay with their vehicle or leave it when threatened by a tornado. Because the authors do not provide any new data on motorists' protective actions, nor anything new about what happens when vehicles and people are exposed to extreme winds and flying debris, this literature review does not add anything new to the debate, and may even detract from the main purpose of the paper.

I suggest significantly shortening section 4a to just briefly acknowledge the debate from a **neutral** standpoint, note the change in ARC guidance and NWS call-to-action statements, and perhaps advocate that more data be collected on motorists' tornado encounters so later studies can better quantify what actions are actually being taken.

We do not believe the discussion in Section 4a is tangential because it is presented as a literature review of the topic, and leads into an examination of the new safety recommendations. A review is necessary because we have reason to believe that a movement geared toward public education on these new safety guidelines is in order, similar to what was accomplished after the overpass fatalities on 3 May 1999 in central Oklahoma. At the time of this writing, 13 states within the study domain have provided tornado safety information during their respective 2010 Severe Weather Awareness Weeks. Of those states, seven continued to recommend "Get out of automobiles and lie flat in a ditch. Do not try to outrun a tornado in your car" without mentioning the option to remain inside the vehicle. Another two states provided no safety information to motorists when faced with a tornado. This paper highlights the need to provide the best available information to citizens for decision making purposes, specifically to those driving. Therefore, we encourage use of the new last-resort safety guidance, as it hasn't been fully incorporated into NWS outreach as of yet.

We revised wording to reflect a neutral standpoint, but highly encourage additional research be done.

Several other more minor comments are embedded within my markup of the document. Thank you for the opportunity to review this paper. Hopefully these comments will help improve the final version of the paper; the authors are welcome to contact me for further discussion or clarification. I would be happy to look at a later version at the editor's discretion.

Thank you.

[Minor comments omitted...]

Second review:

Reviewer recommendation: Accept with minor revision.

General Comments: The authors should be commended for excellent improvements from the first round of the manuscript. I have only a few minor recommendations for further improvements.

[Minor comments omitted...]

Thank you for the opportunity to review this manuscript. I do not need to see any further revisions unless major changes are made.

REVIEWER C (Nikolai Dotzek):

Initial Review:

Recommendation: Accept with minor revision.

General Comments: The paper is well-written, clear, concise, interesting and relevant. I suggest to accept it with minor revisions. These are included in the file already, together with a few comments.

The list of references should be checked again for completeness and consistency with the citations in the text