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Hazardous weather conditions and multiple-vehicle chain-reaction crashes in the United States

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ABSTRACT: Motor vehicle crashes are a significant cause of death and injury worldwide, and adverse weather conditions are often a primary or underlying cause of crashes. This study focuses specifically on how weather contributes to multi-vehicle 'chain-reaction' crashes. Such crashes occur when a single crash halts traffic on a roadway and triggers a series of additional crashes due to motorists being unable to stop in time. Weather often contributes to such crashes by limiting visibility or making a roadway slick. By using data from the Fatality Analysis Reporting System (FARS) of the United States National Highway Traffic Safety Administration (NHTSA), this study found that more than 100 such crashes occurred between 2001 and 2012, and weather conditions were a factor in more than half of them. Radar, observations and satellite imagery were analysed for both 1 h before and 1 h after the crash to see if any diagnostic patterns were observed. Radar and observations were most useful for snow-related crashes. Dramatic increases in snow intensity and corresponding decreases in visibility were observed before most crashes. Dust-related crashes also show substantial decreases in visibility just before the crash. Satellite imagery sometimes showed plumes of dust in these cases. Meteorologists, law enforcement officials and others may find the results helpful in recognizing situations that could lead to multi-vehicle chain-reaction crashes, allowing them to take preventative action to reduce the risk of such crashes.

KEY WORDS driving hazards; transportation; multi-vehicle crashes; visibility; precipitation; winter weather

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1. Introduction

Motor vehicle crashes are a significant hazard, with more than 1.2 million people killed worldwide in 2010 (World Health Organization (WHO), 2013). In the United States, the National Highway Traffic Safety Administration (NHTSA) reported 32 675 deaths and estimated that more than 2.3 million people were injured in automobile crashes in 2014. Overall, the NHTSA estimated that more than 6.1 million crashes occurred in that year, an increase of 6.6% from 2013 (NHTSA, 2016a). While crashes can be caused by a variety of factors, such as alcohol, around one-quarter of crashes involve adverse weather conditions (Atmospheric Policy Program, 2004).

Multi-vehicle crashes involving a series of collisions, also referred to as 'chain-reaction' crashes, occur when a primary crash occurs and then additional crashes occur behind the primary crash. Such crashes can stretch over dozens of kilometres and involve hundreds of vehicles, leading to long highway closures and great inconvenience, in addition to potential loss of life and property damage. For example, more than 60 vehicles were involved in a series of crashes on Interstate Highway 78 in Lebanon County, Pennsylvania, on 13 February 2016. Three people were killed, more than 50 others were taken to local hospitals and the road itself was closed for 22.5 h (Marroni, 2016). Between 2001 and 2012, the present authors found that more than 100 fatal crashes of this type occurred in the United States alone. In at least half of such instances, adverse weather was a factor; in the specific example mentioned previously, the cause was sudden intense snow. Besides snow, torrential rain, blowing dust, fog and other weather-related hazards can also lead to such chain-reaction crashes.

Researchers in both North America and Europe have examined the relationship between weather and vehicle crashes. The most thorough treatise on the subject is the edited volume *Highway Meteorology* (Perry and Symons, 1991), a wide-ranging book that examines the role of climate in highway planning, methods for dealing with snow and ice and hazards such as fog and blowing dust, and the role of weather in crashes. The specific chapter on weather and crashes (Palutikof, 1991) found that moderate weather increased the crash potential in Britain; however, particularly severe conditions were found to reduce overall travel volumes and crashes. Multi-vehicle crashes were not considered separately from single-vehicle crashes.

Researchers have also examined specific hazards with respect to crashes. Visibility hazards were examined by Abdel-Aty *et al.* (2011), who looked at the impacts of fog and smoke on crashes in Florida, finding these to be most prevalent during the morning hours in winter (December–February). Ashley *et al.* (2015) also looked at visibility hazards, compiling a large dataset of crash information and making a strong case that such hazards are responsible for a non-trivial number of fatal crashes. Mills *et al.* (2011) studied how precipitation of all types influences crash rates in Winnipeg, Manitoba, Canada. Andrey (2010) also examined precipitation-related hazards in Canada, finding that while rainfall-related crashes have become less common, the number of snowfall-related crashes has held steady. Khattak and Knapp

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(2001) looked at how snow affects crash rates in Iowa. Black and Mote (2015b) examined the relationship between snow and crashes more broadly in a study of winter weather and crashes in the United States. Their most notable finding was that evening is the time of day with the greatest risk of crashing during winter weather events. In their closely related paper examining fatal crashes, they found that most winter-related crash deaths occur during daylight, and that fatalities are higher than expected in the Northeast and Great Lakes regions (Black and Mote, 2015a).

Meteorologists have also studied multi-vehicle chain-reaction crashes through case studies of specific events. Croft *et al.* (1997) examined the meteorology behind dense fog that caused a multi-car pileup in Mobile, Alabama. Croft also assisted in developing algorithms to improve dense fog forecasting (Garmon *et al.,* 1996). Buckley and Hunter (2011) considered the role of fog and smoke in causing a chain-reaction crash in South Carolina. Other researchers have evaluated high-intensity but short-duration snow events, finding that these can be particularly hazardous (DeVoir, 2004; Call, 2005; Milrad *et al.,* 2011). Finally, Pauley *et al.* (1996) studied a dust event on 29 November 1991 that caused more than 33 collisions along Interstate Highway 5 in California. They examined the meteorological causes of the dust event with the goal of improving forecasting.

In summary, researchers in transportation, geography and meteorology have considered the role that weather plays in traffic crashes. However, there are several gaps in the literature. First, while there is ample insight into how specific types of weather affect all crashes, outside the aforementioned case studies it is unknown what types of weather are most likely to lead to larger multi-vehicle multi-crash events. Second, once the weather types are identified, can meteorological tools such as Doppler radar be used to anticipate such crashes? Such knowledge could allow meteorologists, emergency managers, local law enforcement personnel and others to recognize potentially dangerous situations sooner and take actions to reduce the number and severity of chain-reaction crashes.

2. Data and methods

A list of multi-vehicle chain-reaction crashes was obtained from the NHTSA Fatality Analysis Reporting System (FARS) database. The database has been available online since 1994 (http://www.nhtsa.gov/FARS). Any crash with 10 or more 'vehicle forms' (reports of damage) was considered a multi-vehicle chain-reaction crash and included in this study. This criterion was not perfect, as the number of vehicle forms often vastly understates the actual number of vehicles involved. For example, a chain-reaction crash on Interstate Highway 94 near Fargo, North Dakota, on 30 December 2010 had 15 forms in the FARS database. However, contemporary media reports indicated that 'about 30' vehicles were actually involved in crashes with 'about 100' involved in the overall pileup (Martinez 2010). In examining a sample of other crashes, the authors found that FARS consistently noted fewer vehicle forms than the number of vehicles listed in news reports, despite the NHTSA's claim that the number is accurate to within two vehicles (NHTSA, 2016b). The FARS does not provide an explanation or support for this claim, unfortunately. Perhaps in a case with multiple crashes, only the vehicles involved in the fatal crash itself are included. Thus, a non-fatal crash 0.5 km behind the fatal crash may not be included in the vehicle form count. Perhaps the discrepancy in numbers could simply reflect the fact that news reports typically provide the total number of vehicles present at the scene, even if many were not actually damaged. Regardless, accurately counting vehicles in difficult weather conditions and over an area that could stretch for tens of kilometres is not an easy task. Since this study is not attempting to catalogue all crashes or the total number of vehicles involved, using 10 vehicle forms as a minimal criterion generated a sample of 109 crashes within the study period. These may not necessarily be the 'worst' of all crashes, but if a crash is listed in the FARS database, it must result in at least one fatality, a serious circumstance regardless of the true number of vehicles involved.

The FARS database also includes weather information associated with each crash. The weather information is categorical (e.g. clear, cloudy, rain). Over time, the number of category choices expanded, and in later years an option was added for multiple weather conditions. Because not all states had ways for the police to report adverse weather conditions (see Ashley *et al.*, 2015, for a further discussion), weather conditions for crashes with 'no adverse weather' reported were double-checked using both weather observations nearest the site and radar data to be sure that no adverse weather had actually occurred. Generally, there was less detail for earlier crash events, especially for visibility-related ones. As thoroughly discussed by Ashley *et al.* (2015), the database itself and methods used to code fields have changed over time, leading to discontinuities in the reporting of primarily visibility-related atmospheric hazards. The FARS database is simply a compendium of police crash reports, and the level of detail in these varies considerably from state to state; some states' accident forms did not even have a category for noting weather until recently (Ashley *et al.*, 2015). Finally, like many other databases, there is a lag in terms of how quickly new data are added to the database. Thus, the period of study for this research began with 2001 and ended with 2012, the most recent year with available data at the time of analysis.

For crashes with adverse weather, Doppler radar imagery was obtained. Specifically, base reflectivity data associated with a radar angle of 0.5° above the horizontal were obtained from the closest radar site. In cases where the crash occurred within 8 km of a radar site, composite reflectivity data, which include the greatest bin value from all scans, were used instead. This choice was made because it was found that base reflectivity data were often contaminated with ground clutter and/or other noise when viewing locations in close proximity to radar.

Radar data were collected for the period beginning 1 h before the crash through to 1 h after the crash. Depending on the mode in which the radar was operating, this meant that there were at least 12 scans ('clear air mode') up to as many as 20 scans ('precipitation mode') available for analysis. All this assumes that the radar was operating normally (that is, no data were missing). For each radar scan, the reflectivity for the pixel containing the crash location was recorded for further analysis. This pixel was determined by the latitude and longitude co-ordinates of the crash.

Raw meteorological observations, or METARs, were also collected in connection with each crash. The METARs from the closest regular hourly reporting station were obtained. At minimum there were at least three observations: the one nearest in time to the crash time, and ones 1 h before and 1 h after the crash time. In some cases, additional observations were available at a shorter time interval. Observations were examined in a more qualitative manner as there were significant differences in distance. In some cases, the nearest observing site was just a few kilometres away, while in the most extreme case no site was within 80 km of the crash.

Finally, a minimum of three to four satellite images were observed for each crash. Satellite images from at least 1 h before a crash to the first available time after the crash were viewed. When possible, the use of visible satellite imagery was favoured over infrared (IR) satellite imagery in order to identify best low-level, visibility-related weather conditions such as fog, blowing constituents (such as dust, sand and smoke), and blowing snow. (These weather phenomena are not as easily detected by the IR satellite since they are low level and, therefore, likely to be similar in temperature to the surface just beneath.) However, for crashes occurring during the night-time hours, IR imagery was used since visible imagery was unavailable. Each crash was assigned an indicator of whether or not the observed satellite imagery matched the conditions indicated by the FARS database ('yes', 'no' or 'unable to determine') and additional descriptive information was then recorded about the observed satellite conditions for each crash site.

3. Results

A total of 109 crashes met the basic criteria for inclusion in the study (at least one fatality and at least 10 vehicle forms) for the period 2001–2012. These crashes occurred in 35 US states and in nearly all regions of the country, as shown in Figure 1. The fewest crashes occurred in the far northeast (New England) and in the northwestern areas of the country, with one occurring in each region, respectively. Elsewhere, no region stood out as particularly crash prone. Just under 80% of all crashes occurred on interstate or other limited-access divided highways. This makes sense insofar as limited-access divided highways typically have faster traffic, thus making it more difficult for vehicles to stop in time to avoid chain-reaction crashes.

Just over half (59 of 109, or 54%) of crashes happened during adverse weather conditions. As shown in Figure 2, weather-related crashes occurred in more than 25 states and were located throughout the country, except for the aforementioned regions with few to no crashes. Further underscoring the national character of the problem, three widely separated states experienced the most crashes. Colorado (located slightly west of the middle of the United States) recorded six, followed closely by California (in the southwest) and Pennsylvania (in the northeast) with five crashes each. Nearly all weather-related crashes (93%) occurred on interstate or other limited-access divided highways compared with 62% of crashes not associated with adverse weather. This difference is statistically significant ($p = 0.0000$), underscoring how hazardous weather conditions such as reduced visibility and slick roadways contribute to chain-reaction crashes on high-speed, heavily travelled highways.

3.1. Winter weather conditions and crashes

Approximately 25% (or 15 of 59) crashes occurred under conditions of 'snow/blowing snow'. Two additional crashes occurred with 'blowing snow', and three more crashes were associated with 'sleet (hail)'. (Weather observations at the time of the crash indicated that the 'sleet (hail)' crashes were associated with winter weather, not hail from thunderstorms.) All crashes occurred north of the 35th parallel (generally, very little snow falls south of that latitude), but not necessarily in areas prone to lots of snow. New England and other snowy areas (such as the Sierra Nevada in California) did not experience any crashes. Pennsylvania and Colorado both experienced three crashes of this type, with the remainder scattered about various other states (Figure 2). Most of these occurred between December and March, with each month having a similar number of incidents. Two other crashes occurred on the edges of the winter: the last week of November and the first week of April.

Winter weather crashes involved more vehicles than others, with an average of 26 vehicle forms. Despite the large numbers of vehicles involved, winter incidents were not particularly deadly: 80% of crashes resulted in just one or two fatalities.

Radar signatures associated with winter crashes showed a pattern before the crashes. As shown in Figure 3, the intensity of snowfall often increased rapidly within the 1 h before the crash. Unfortunately, this finding is of limited utility as there were many exceptions, as also shown in Figure 3. These could have arisen due to distant radars not adequately sampling the lowest layer of the atmosphere due to the Earth's curvature, non-meteorological factors such as driver error that would have resulted in a crash regardless of the weather (e.g. someone falling asleep while driving), or other hazardous road conditions, such as a construction zone.

In contrast to radar, observations almost always were associated with either very low visibility or a rapid decrease in visibility before the crash. Several cases were not analysed because the closest METAR station was more than 50 km distant or data were unavailable, but in nearly 64% (7 of 11) of cases analysed, visibility decreased by more than 50% in the 1 h before the crash. Three others showed no change, and one actually had an increase in visibility (though at this site, visibilities varied considerably from hour to hour, suggesting a convective nature to the event, which radar confirmed). Both the radar and the observation findings are similar to those of Call (2005) and Black and Mote (2015b), who observed that overall crash risk was much greater during intense snowstorms.

3.2. Rain and crashes

Nine crashes occurred under conditions of 'rain'. Unfortunately, the vagueness of this term meant that crashes may have occurred with radar reflectivities as high as 50 dBZ or as low as 'no returns' from the pixel where the crash happened. One crash had no rain whatsoever on radar or in the observations, so it was disregarded. These crashes occurred in seven unique states (most commonly in the southern United States), generally only had one or two fatalities, and an average of 15 vehicle forms were filed (though when one crash with 34 forms was not included, the average dropped to 13). Opposite of snow/sleet, these crashes occurred most frequently between April and November.

In terms of observations, only one case showed a significant decrease in visibility before the crash. In this instance, a rapid onset of heavy rain reduced visibility from 16 to 2.8 km in the 10 min before the crash. Following the crash, visibility rapidly increased (within 30 min) to 10 km with light rain and mist also reported.

3.3. Non-precipitation events and crashes

Restricted visibility is associated with many crashes, and this may be caused by various non-precipitation events. In the FARS database, crashes within the 'fog, smog, smoke' or 'blowing sand, soil, dirt' categories were combined for analysis, providing a total of 23 crashes for evaluation, accounting for nearly 40% of crashes. The location of these crashes (Figure 2) generally corresponded with areas prone to reduced visibility (for a map, see Ashley *et al.*, 2015, fig. 4). These crashes often involved many vehicles and had an average of 23 forms filed, nearly as many as those associated with winter weather.

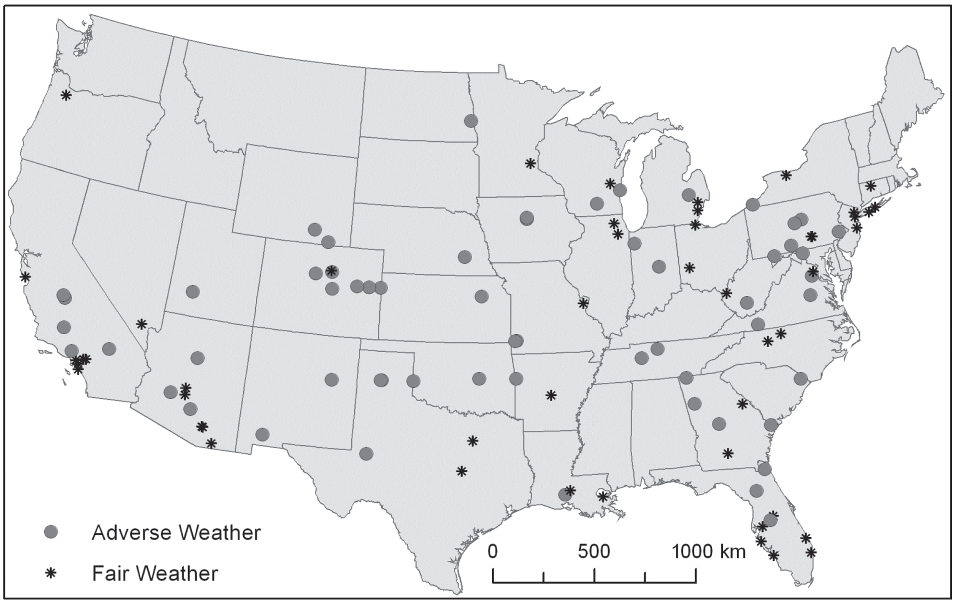

Figure 1. Locations of multi-vehicle chain-reaction crashes, 2001–2012. (No multi-vehicle chain-reaction crashes occurred in the states of Alaska or Hawaii.) Just under 80% of crashes occurred on interstate or other limited-access divided highways.

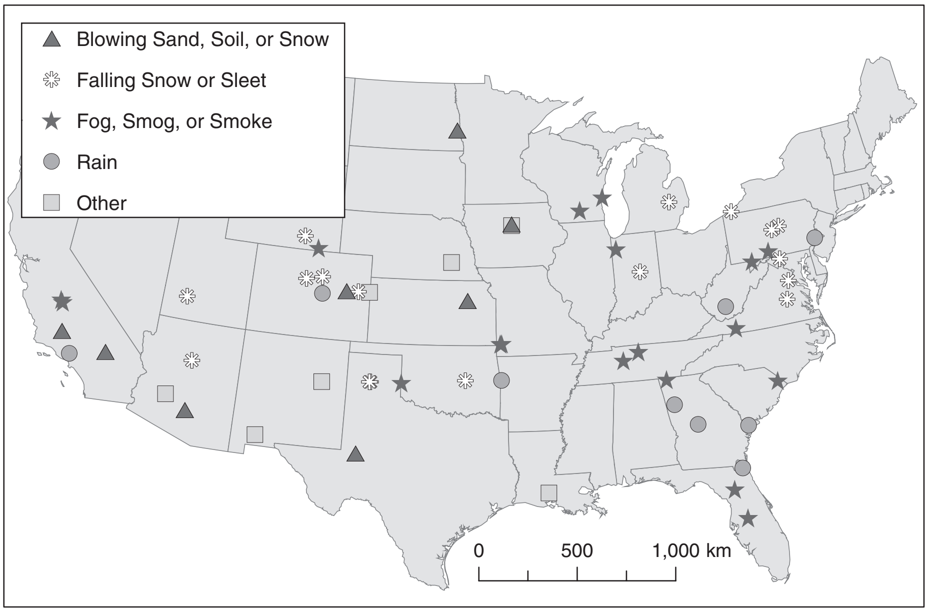

Figure 2. Locations of weather-related multi-vehicle chain-reaction crashes, 2001–2012. Symbols represent the type of inclement weather conditions reported with the crash. Around 93% of crashes occurred on interstate or other limited-access divided highways.

Crashes with no precipitation occurred in nearly all months of the year. They were most common during the cool season (October–March), when 17 of the 23 events occurred. This finding agrees with Ashley *et al.* (2015), who found a similar seasonality.

Radar data were of little utility in these crashes since precipitation is not actually falling during such events. When crashes occurred far from the radar, it was not unusual for nothing to be observed because the radar pulse overshot (was above) the cause of the crash, such as a fog bank. Reflectivity information that did appear in association with such crashes showed no pattern and was often noisy. The noise often resulted from the radar being operated in 'clear air mode', which increases radar sensitivity and also noise.

Observations associated with crashes which did not involve precipitation were more informative. Many of the fog, smog or smoke related crashes were associated with extremely low visibility. Ten of 17 cases analysed, or nearly 59%, were associated with visibility of 3.2 km or less at the time of the crash, and in four of those cases the visibility was at or below 0.4 km. For almost all the other cases, no METAR station was available within 25 km of the crash site, so while the reported visibility was greater, it may not reflect the local conditions at the site itself. Unlike the snow or rain events, visibility generally did not fluctuate around the time of the crash. Three cases did show a slight decrease (e.g. from 0.4 to 0.2 km), but in the remaining cases, the visibility was steady. Sand and dust events had a different pattern, with three of five events

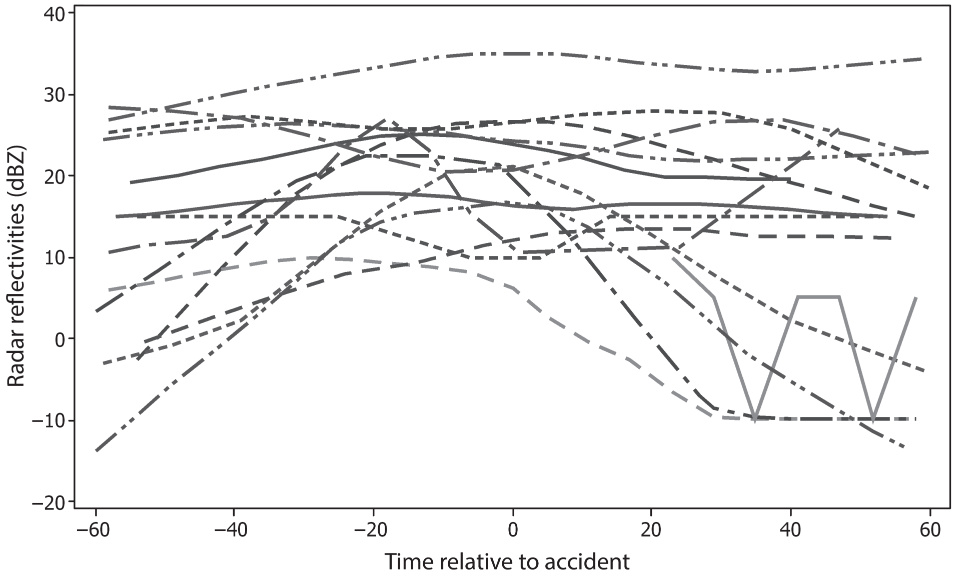

Figure 3. Radar reflectivities (dBZ) within 1 h of each snow-related crash showing that, on average, precipitation intensity increased before the crash.

(60%) showing a rapid decrease in visibility in 1 h before the crash.

Satellite observations were also examined for these types of crashes, since radar was of little use. Satellite imagery proved most helpful for blowing sand, soil and dirt-induced crashes. In half the cases, high-resolution visible imagery showed thick areas of debris blowing across the crash sites around the times of the crashes. (In the other cases, clouds obstructed the view of the surface.) Satellite proved less helpful in fog, smog and smoke cases. Some of these occurred at night, and IR imagery did not show anything distinguishable around the crash sites. In the remaining cases, low levels were obstructed by other clouds or the conditions at the crash site showed no apparent change over time.

4. Conclusions

This study examined the locations, pattern and weather conditions associated with fatal multi-vehicle chain-reaction crashes in the United States between 2001 and 2012. During this period, at least 100 such crashes occurred, killing some 236 people. It is likely that this understates the number of crashes and deaths since such crashes are often comprised of multiple crashes and can be difficult to identify in the FARS database; nonetheless, the sample was large enough to provide several findings of interest.

First, nearly all regions of the country, except the Northwest and New England areas, regularly experience such crashes. Most visibility-related crashes occurred in places more at risk of dense fog or other visibility obstructions. Winter weather-related crashes show less of a relationship with overall snowfall amounts, but are rare in areas that do not get much snow.

Second, radar, weather observations and satellite imagery have limited use as diagnostic features to predict such crashes. Radar is useful as a tool to diagnose snow-related crashes. In many cases, snow intensity rapidly increased shortly before the crash. However, for other types of events, radar had little utility. As with radar, weather observations were not useful in many cases. Nonetheless, they were helpful in diagnosing the causes of snow and sand-related crashes as rapid, sudden decreases in visibility were observed in connection with most of these events. Satellite imagery can be used to diagnose unfavourable conditions for driving due to blowing sand, soil or dirt, if the view of the ground is not obstructed by clouds. However, it was not helpful in other weather situations.

Future research should examine more closely how consistent the relationships are between increases in snowfall intensity and chain-reaction crashes by including a larger sample of crashes, perhaps gathered from news and other reports in addition to those listed in the FARS database. Indeed, during the winter while this paper was being written (2016), several such crashes occurred on roadways in the Midwestern United States, but because there were no fatalities such crashes are not listed in the FARS database. Ideally, further research in this area could lead to using radar and/or observations as objective predictive tools to prevent such crashes.

In conclusion, sudden increases in precipitation intensity and decreases in visibility in connection with snowstorms seem to be a triggering factor for multi-vehicle chain-reaction crashes. It would seem prudent when such a situation occurs that forecasters, the authorities and highway managers inform the public of the heightened risk. Such actions may make such crashes less widespread, less intense and, ultimately, save lives.

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