Weather Conditions and Messaging Associated with Fatal Winter-Weather-Related Motor-Vehicle Crashes

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ABSTRACT: Winter-weather conditions pose an extreme hazard to motorists, resulting in approximately 1000 fatalities annually on U.S. roadways. Minimizing adverse impacts of winter weather requires (i) the identification of hazardous weather conditions leading up to and at the time of fatal crashes, and (ii) effective, targeted messaging of those hazards to motorists. The first objective is addressed by matching motor-vehicle-related fatalities from 2008 to 2019 to nearby weather reports to determine how precipitation types and other observable weather conditions (i.e., precipitation intensity, obscurations, and visibility) change leading up to crashes. One-half of fatalities occur in snow, with 75% occurring in ongoing snowfall. Of fatalities during freezing precipitation, 41% occur near the onset of freezing precipitation. In addition, 42% of fatalities have deteriorating weather conditions prior to the crash, primarily visibility reductions of ≥25%. The second objective is addressed by examining language currently used in National Weather Service Winter Weather Warning, Watch, or Advisory (WSW) issuances for fatal crashes. Only one-third of fatalities have a WSW. These WSWs both identify a road hazard (e.g., "roads will become slick") and provide an action item for motorists (e.g., "slow down and use caution while driving") but do not clearly convey tiered road-hazard ratings. Examination of non-weather-related attributes of fatal crashes suggest that variable-message signs along highways may be useful to communicate road hazards, and that future messaging should urge motorists to leave additional space around their vehicles, slow down, prepare for rapidly deteriorating conditions, and teach strategies to regain control of their vehicle.

SIGNIFICANCE STATEMENT: We find that approximately 1000 fatalities occur each year on U.S. roadways during winter weather. To inform how to reduce fatalities in the future, we identify weather conditions leading up to and at the time of fatal crashes and determine whether road hazards were publicly messaged alongside weather warnings and advisories. Ongoing snowfall, the onset of freezing precipitation, and visibility reductions were prominent factors found in many fatal crashes, suggesting that these may be important factors to address in future safety studies. Winter-weather warnings and advisories often contain language cautioning road hazards, yet only one-third of fatalities occur during conditions with such official statements. However, these statements do not clearly indicate how hazardous roads will be.

KEYWORDS: Snow; Societal impacts; Surface observations; Winter/cool season

1. Introduction

Motor-vehicle crashes on roads during inclement weather cause an average of 5000 deaths and 418 000 injuries each year in the United States (Road Weather Management Program 2020). This number is an order of magnitude larger than all other weather-related fatalities combined (Black and Mote 2015a). Among the various forms of weather that are hazardous for motorists, winter precipitation is associated with the greatest risk of crashes and injuries (e.g., Andrey et al. 2003; Qiu and Nixon 2008; Strong et al. 2010; Theofilatos and Yannis 2014). The aim of this research is to investigate motor-vehicle-related fatalities associated with winter precipitation to identify the typical weather conditions leading up to and at the time of fatal crashes, to analyze public messaging provided by meteorologists, and to add contextual information about these crashes that may be useful for future messaging.

There have been numerous investigations of traffic crashes associated with winter precipitation. Several investigators demonstrated that crash rates increase with increasing precipitation rates (e.g., Andrey et al. 2003; Qiu and Nixon 2008; Strong et al. 2010; Theofilatos and Yannis 2014). There is also evidence that precipitation type can influence crash risk, yet an exact hierarchy of risk based on precipitation type remains uncertain (cf. Andrey 1989; Suggett 1999; Black and Mote 2015b; Mills et al. 2019; Tobin et al. 2021). Reduced visibility—such as may result from fog or blowing/falling snow—also affects winter road safety and leads to increased crash risk and injury severity (Theofilatos and Yannis 2014 and references therein; Mills et al. 2019). Andrey and Yagar (1993) suggest that even if a driver is able to overcome slick roadway conditions, crash risk is still heightened when visibility is reduced.

Most studies relating traffic crashes to weather only consider weather conditions *at the time of the crash* using information in crash records and/or nearby meteorological observations (e.g., Eisenberg 2004; Eisenberg and Warner 2005; Black and Mote 2015b; Saha et al. 2016; Tobin et al. 2019). However, there is evidence that changes in weather conditions in the hours prior to a crash may be equally, if not more, important. Call et al. (2018) investigated this for several multiple-vehicle "chain

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TABLE 1. Winter-weather-related fatalities in each U.S. climate region (Karl and Koss 1984; Fig. 1) from 2008 to 2019 with ASOS-reported precipitation during the precrash or crash period, and the percentage of those fatalities within each precipitation-type category. Precipitation-type categories are abbreviated following section 2b.

Region	Fatalities	SN	RA	MX	FZ	NP
CONUS	5317	46.2%	5.0%	29.8%	9.3%	7.9%
Northeast	1136	38.0%	5.9%	35.8%	11.9%	7.1%
Central	1411	47.7%	4.5%	30.3%	9.14%	7.0%
East-north-central	1365	59.6%	3.0%	24.4%	4.0%	7.0%
West-north-central	255	49.8%	1.6%	31.0%	4.7%	9.8%
Northwest	244	34.8%	5.7%	34.0%	8.2%	15.2%
West	47	40.4%	8.5%	31.9%	0.0%	14.9%
Southwest	270	48.9%	5.2%	31.1%	14.4%	7.8%
South	322	23.0%	5.6%	26.7%	31.1%	11.8%
Southeast	267	37.5%	14.6%	27.0%	12.4%	7.1%

reaction" fatal crashes and found that 64% of them had at least a 50% reduction in visibility in the hour leading up to the crash, suggesting that rapidly deteriorating weather may heighten crash risk. But, this has yet to be demonstrated for other fatal crashes, particularly those that involve fewer vehicles.

Another key point of interest that has not been studied extensively is public messaging during winter weather. Barjenbruch et al. (2016) found that the general public does respond to messaging from both government and private-sector agencies by changing their travel schedules or avoiding travel altogether. This indicates that messaging plays a crucial role in driver awareness and behavior. Variable-message signs are also useful to alert motorists of adverse weather conditions (Minnesota Department of Transportation 2019). However, we are unaware of any studies that have analyzed the specific language of the messaging—let alone its impact on motorists—during winter weather that poses a threat to road safety. Research on messaging for other weather hazards such as tropical cyclones has shown that messaging is effective and can play an important role in protective decision-making; however, the specific language used in messaging can elicit varying responses from different people, thus it is ultimately beneficial to understand how people receive, interpret, and use weather-related messaging (e.g., Morss and Hayden 2010; Morss et al. 2016).

Herein, we investigate motor-vehicle-related fatalities associated with winter precipitation to address weather conditions both during and preceding these crashes, and to examine public messaging provided by the National Weather Service (NWS) for deadly winter events. We analyze fatalities as this is the only publicly available source of information about motor-vehicle crashes for the conterminous United States (CONUS). While motorists may have had access to messaging from other sources, we focus on NWS products as they are the only archived information available for the entire CONUS. We also investigate some key attributes of the fatal crashes that are not weather-related (e.g., location, number of vehicles involved) to uncover potentially useful information that may aid in crafting more targeted and effective messaging going forward.

2. Weather conditions associated with winter-weather-related fatalities

a. Winter-weather-related fatality records

Fatal crash data from 2008 to 2019 are obtained from the Fatality Analysis Reporting System (FARS) database maintained by the National Highway Traffic Safety Administration (NHTSA). FARS is a census dating back to 1975 of all fatal motor-vehicle crashes that occur on U.S. public roadways and result in a fatality within 30 days of the crash (NHTSA 2022). As the emphasis here is on winter precipitation, the dataset is thinned to include only fatal crashes within the CONUS that occur between October and April. We define winter-weather-related fatalities as those with (i) roadway surface conditions of ice, snow, or slush; or (ii) atmospheric conditions of snow, sleet, or freezing precipitation, as indicated in the FARS database. There are 11 966 such fatalities, located primarily within the Central, East-North-Central, and Northeast climate regions (Table 1; Figs. 1 and 2). This spatial distribution is related to population density, location of major roadways, and where winter weather most frequently occurs.

b. Precipitation types during and preceding fatal crashes

To examine weather conditions during and preceding the crashes, we define both a crash and precrash period: the crash period is the two hours centered on each fatal crash time, and the precrash period is the two hours preceding the crash

FIG. 1. CONUS climate regions (Karl and Koss 1984).

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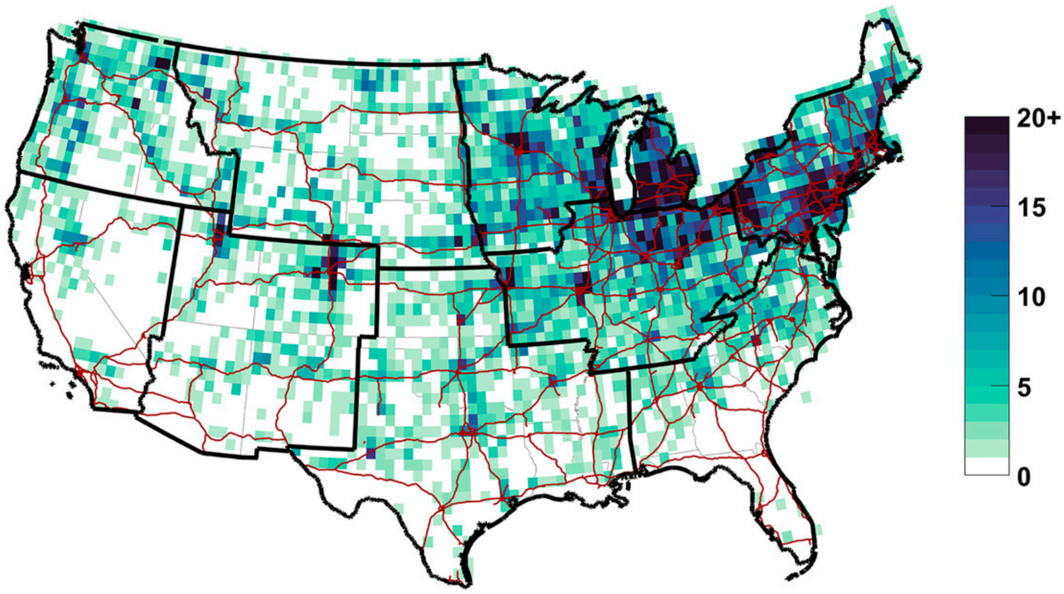

FIG. 2. Heat map of winter-weather-related fatalities in the CONUS for the 2008–19 period at 0.5° latitude by 0.5° longitude resolution, with fatality counts shaded according to the color bar. U.S. climate regions (black lines; Fig. 1) and major U.S. roadways (red lines) are also plotted.

period. We limit fatalities to only those with nearby (see below) Automated Surface Observing System (ASOS) reports of precipitation during either the precrash or crash periods, to focus on *recent* or *current* winter precipitation. There are 5317 fatalities meeting these criteria.

To identify precipitation types around the time of fatal crashes, each crash is matched to all ASOS sites within 32.2 km (20 mi). This distance is consistent with what previous investigations have used (Chung et al. 2018; Tobin et al. 2019). The 2-h crash-period time window is chosen to ensure observations both before and after a crash are included, as ASOS often only reports hourly. This window also accounts for the potential spatiotemporal offset of small-scale weather features (e.g., snow squalls) between the crash and ASOS reports. Precipitation types are categorized as snow (SN), rain or drizzle (RA), ice pellets or mixtures that do not include freezing precipitation (MX), freezing precipitation or freezing precipitation mixtures (FZ), and no precipitation (NP). These categories are based on all ASOS reports during the crash period and within the 32.2-km radius; thus, we do not distinguish between concurrent precipitation types (e.g., rain/snow mixtures) and transitions in precipitation type (e.g., rain-to-snow transitions). ASOS can only report ice pellets, drizzle, freezing drizzle, and precipitation-type mixtures if a human observer is there to augment the report (e.g., NOAA 1998; Reeves 2016; Landolt et al. 2019), so these categories are chosen to reflect the precipitation-type reports that ASOS can automate: snow, rain, and freezing rain. Reports of unknown precipitation are ignored for the purposes of categorization.

Precipitation types at the time of fatal crashes has been examined previously (e.g., Tobin et al. 2019), but not for individual climate regions. In all climate regions, except for the South, the largest percent of fatalities occur in SN (Table 1). In contrast, only a small fraction of fatalities occurs in RA. However, nearly 60% of the RA fatalities are reported as having either icy roads or freezing precipitation in the FARS (not shown), indicating that many of these fatalities are perhaps better classified as FZ, as found in Tobin et al. (2019). Most climate regions—again, except for the South—have the second-highest percentages occurring in MX, and even smaller percentages in FZ and NP. These results are consistent with expectations, as SN is more frequently observed than MX or FZ in ASOS-based climatologies (Reeves 2016; Landolt et al. 2019). However, the ratio of fatalities in MX and FZ relative to SN exceeds what one would expect based on the relative frequency of these phases in those climatologies, suggesting that precipitation-type mixtures, transitions, and freezing precipitation may constitute a higher threat to road safety than pure snow, which is consistent with implications in Tobin et al. (2021) of a hierarchy of risk with precipitation type. In the South climate region, FZ fatalities represent the largest fraction, followed by MX and SN. This is consistent with previous work showing that the ratio of SN to FZ ASOS reports in the South is smaller than in other climate regions (Landolt et al. 2019).

We now consider changes in precipitation type in the hours leading up to fatal crashes. Figure 3 shows the distribution of the precrash precipitation type binned by the crash-period type. The majority of SN fatalities (75%) also have SN in the precrash period, suggesting that these fatalities are related to ongoing snowfall. The majority of RA, MX, and FZ fatalities also have consistent precrash and crash precipitation types (~60%), suggesting ongoing and consistent precipitation. Approximately 15% of fatalities in each of these categories have NP in the precrash period, suggesting that precipitation began within an hour of these crashes. For FZ fatalities, 41% have

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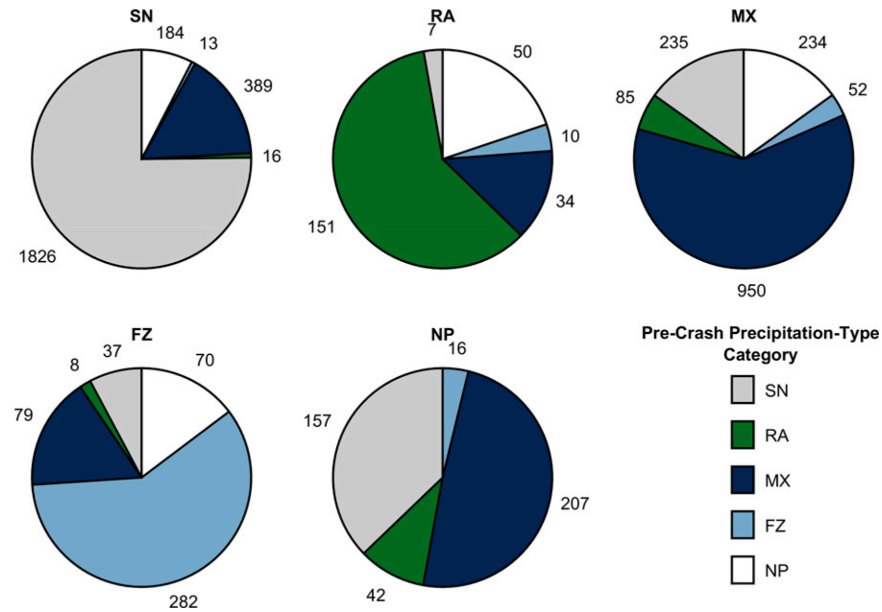

FIG. 3. For each crash-period precipitation-type category (labeled above their respective charts), segments represent the total number of fatalities across the CONUS with the designated precrash-period precipitation-type category (colored according to the legend and labeled with total fatalities). For example, the NP precrash category segment (white) in the SN crash category chart at top left indicates that 184 SN fatalities had NP during the precrash period. Precipitation-type categories are abbreviated in accordance with section 2b.

no freezing precipitation reported in the precrash period, suggesting that motorists first encounter freezing precipitation near the time of these crashes, and that the onset of freezing precipitation may have played a role in these crashes. The majority of NP fatalities (86%) have either SN or MX during the precrash period. These fatalities highlight the lingering risk that precipitation and snow accumulations on roadways pose to motorists in the hours after precipitation ends.

c. Other changes in weather conditions

In addition to changes in precipitation type, we examine changes in other weather observations, namely precipitation intensity (i.e., light, moderate, and heavy), visibility, and obscurations (i.e., haze, mist, fog, and freezing fog). These observations are primarily related to visibility, as ASOS obscurations and precipitation-intensity algorithms require input from visibility sensors (NOAA 1998). We focus on these visibility-related weather observations because drivers are nearly equally affected by visibility changes. Wind, for example, disproportionately affects higher-profile vehicles (e.g., Strong et al. 2010), and its effect on visibility (e.g., blowing snow; Burow and Cantrell 2021) is indirectly accounted for in visibility observations. Rapidly falling temperatures that can cause roadway surfaces to fall below freezing also affect road safety, but we ignore these influences because we do not want to conflate temperature changes with other factors (e.g., cloud cover and time of day).

Weather conditions between the precrash and crash periods for the 5317 fatalities in section 2b are classified as deteriorating, improving, or consistent. We emphasize that these classifications refer to observable weather conditions, and do not necessarily correspond with changes in road or driving conditions. We declare deteriorating weather conditions when any of the following occur between the precrash and crash periods: (i) precipitation begins, (ii) obscurations begin, (iii) precipitation intensity increases, (iv) obscurations worsen,[1] or (v) visibility decreases of ≥25%. Improving weather conditions are declared for the opposite: precipitation or obscurations end, precipitation intensity decreases, obscurations improve, or visibility increases ≥25%. This category is further disaggregated by whether conditions have improved to "fair" weather conditions. Here, fair refers to no precipitation, no obscurations, and visibility greater than 8.0 km (5 mi). Crashes meeting both deteriorating and improving criteria are not classified. Remaining crashes with precipitation reported during both the precrash and crash periods, and with visibility changes within 25%, are classified as having "consistent" weather conditions. In computing crash-period visibility, we employ temporal and spatial inverse weighting techniques to favor ASOS reports closest to the crash in both time and space and obtain the best-guess estimate for visibility at the time of the crash. Visibility for the precrash period is simply the mean of reports to obtain an estimate of the general precrash visibility.

The largest fraction (42%; Table 2) of fatalities is associated with deteriorating weather conditions, suggesting that adverse changes in weather may play a role in a large number of fatalities. The second largest fraction (26%) has improving weather

[1] Obscurations reported by ASOS are, in ascending severity: haze, mist, fog, and freezing fog.

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TABLE 2. Percentage of winter-weather-related fatalities categorized with deteriorating, improving (but not to fair), improving to fair, and consistent weather conditions between the precrash and crash periods. Percentages in each row may not sum to 100% because some fatalities were unable to be categorized.

Region	Fatalities	Deteriorating	Improving (not fair)	Improving (fair)	Consistent
CONUS	5317	42.3%	26.3%	6.6%	18.9%
Northeast	1136	48.3%	21.7%	6.0%	17.5%
Central	1411	40.0%	27.5%	5.5%	21.8%
East-north-central	1365	40.7%	29.2%	5.9%	18.5%
West-north-central	255	42.4%	23.5%	8.6%	18.0%
Northwest	244	40.6%	27.9%	12.7%	15.2%
West	47	44.7%	23.4%	12.8%	6.4%
Southwest	270	40.0%	30.0%	7.0%	15.2%
South	322	39.8%	25.8%	10.2%	17.7%
Southeast	267	43.8%	24.0%	4.5%	22.5%

conditions that have not improved to fair weather, implying that driving conditions are still not ideal, despite some improvement. Consistent weather conditions are present for 19% of fatalities, implying no drastic weather condition changes leading up to the crash. Last, <7% of fatalities have weather conditions that have improved to fair conditions, again highlighting the lingering risk of icy, snowy, or slushy roadways even during fair weather. These percentages have minimal regional variability (Table 2), so the rest of this discussion will focus on these categorized fatalities as a whole across the CONUS.

We wish to analyze the role that visibility has in these classifications. Nearly 80% of fatalities in both the deteriorating and improving weather conditions are tied to decreases and increases in visibility, respectively (Table 3). Further, nearly half of fatalities categorized as deteriorating or improving based on the beginning or ending of precipitation, and 70%–80% of fatalities classified based on changes in obscurations or precipitation intensity also have visibility changes of ≥25%. We also examine our threshold of visibility changes of at least 25%. This suggests that the majority of fatalities classified with deteriorating or improving weather conditions have significant visibility changes greater than the threshold of 25%. Although our methods differ from those in Call et al. (2018), our results in the context of their results suggest that rapid and significant reductions in visibility are more prevalent for large, fatal pileups than they are for fatal crashes in general. One reason could be that weather might play a larger role in fatal pileups than for fatal crashes in general.

With visibility changes highly correlated with changing weather conditions, we focus now on visibilities during precrash, crash, and postcrash periods (i.e., the 2-h period after the crash period), disaggregated by changing weather-condition category (Fig. 4). Crash period visibilities for all fatalities are slightly—but not statistically significantly—lower than those in both the precrash and postcrash periods (Fig. 4a). Visibilities in each weather condition category range from <0.4 to 16.1 km (<0.25–10 mi), indicating that fatalities occur at all visibilities reportable by ASOS. The most significant differences between precrash and crash visibilities are seen for fatalities with deteriorating and improving weather conditions (Figs. 4b,c), which is not surprising given that the majority of fatalities in these categories have at least a 75% change in visibility between these

TABLE 3. Percentages of fatalities categorized with deteriorating and improving weather conditions based on precipitation and obscuration changes that also have corresponding visibility changes. Percentages for visibility changes of 50% and 75% or more are only computed for all fatalities categorized with deteriorating and improving weather conditions, and those categorized with visibility changes of ≥25%.

Changing weather category	Classification basis	Fatalities	≥25% visibility change	≥50% visibility change	≥75% visibility change
Deteriorating	All	2249	80.5%	59.0%	46.9%
	Visibility decreases	1810	100%	73.4%	58.2%
	Precipitation begins	526	53.4%	—	—
	Obscurations begin	524	80.0%	—	—
	Precipitation intensity increases	517	77.8%	—	—
	Obscurations worsen	250	81.6%	—	—
Improving	All	1751	77.1%	77.1%	64.4%
	Visibility increases	1350	100%	83.6%	72.9%
	Precipitation ends	400	45.3%	—	—
	Obscurations end	314	75.5%	—	—
	Precipitation intensity decreases	371	69.8%	—	—
	Obscurations improve	190	75.8%	—	—

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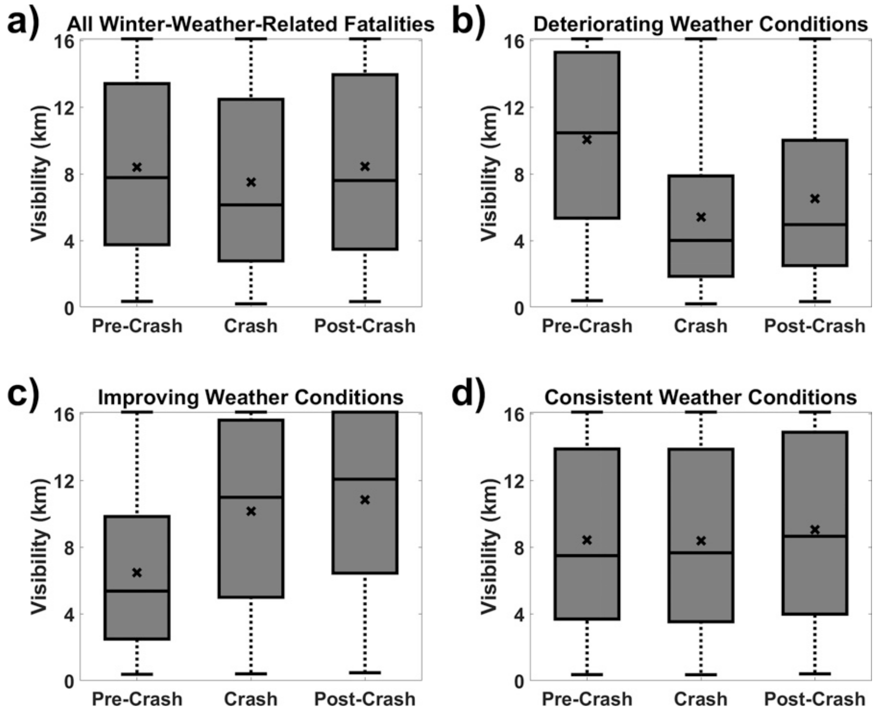

FIG. 4. Precrash, crash, and postcrash visibilities (km) for (a) all winter-weather-related fatalities and winter-weather-related fatalities categorized with (b) deteriorating weather conditions, (c) improving weather conditions, and (d) consistent weather conditions as defined in section 2c. Bars represent the interquartile range of visibilities, the middle line indicates the median, and the cross indicates the mean. Capped dashed lines represent the 95% confidence interval.

periods. However, there is significant overlap in these charts of visibilities between the crash and postcrash periods, suggesting that the primary changes in visibility occur leading up to these fatal crashes. For fatalities with consistent weather conditions, 75% have visibilities >3.2 km (2 mi) during the precrash–postcrash periods (Fig. 4d).

3. Winter-weather messaging

Minimizing the adverse impacts of winter weather on motor-vehicle safety requires not only the identification of hazardous weather conditions, but also effective communication of those hazards to motorists. Because a part of the mission of the NWS is to provide weather warnings for the protection of life and property, it is desirable to know whether a Winter Weather Warning, Watch, or Advisory (WSW; e.g., winter storm warning, blizzard warning, ice storm warning, winter-weather advisory, or snow squall warning) was in effect for fatal winter crashes, and whether the messaging specifically mention road hazards. We note that the NWS considers winter weather to be an "indirect" cause of vehicle-related fatalities (NOAA 2021), so the issuance of a WSW is not specifically intended to apply to the protection of life and property on roadways.

We obtain WSW issuances to determine if any were in effect for the exact date, time, and location of each fatal winter-weather-related crash. Across the CONUS, only 33% of the 11 966 fatalities (section 2a) have a corresponding WSW (Table 4). We note that only 6% of fatalities (18% of fatalities with a WSW) are associated with a warning as opposed to an advisory (not shown). Most climate regions have 22%–36% of fatalities with a WSW; however, >50% of fatalities in both the South and Southeast climate regions had WSWs. This is not surprising because NWS weather forecast offices (WFOs) in these regions typically have lower thresholds for issuing a WSW (NOAA 2020).

a. Road hazards messaging

The issuance of a WSW itself does not inherently convey a hazard to motorists; however, the NWS has increasingly migrated to impact-based messaging within WSWs and other NWS products. We now wish to examine standard NWS text products to see if road hazards are specifically mentioned. Although the NWS has increasingly utilized social media platforms (e.g., Facebook and Twitter) to communicate road hazards, we focus only on the standard text products, which include WSWs, Special Weather Statements (SPSs), and Area Forecast Discussions (AFDs). Our analysis focuses primarily on WSWs, while the inclusion of SPSs allow us to examine road hazards messaging in instances where WSWs are not issued, but forecasters still acknowledge a threat and wish to

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TABLE 4. Percentage of all winter-weather-related fatalities with a valid WSW. Corresponding to the analysis in section 3a, also shown are the threshold for the number of separate fatal crashes that must occur within a 12-h period to be considered for analysis of road hazards messaging in WSW issuances, the total number of events with 12-h periods that meet or exceeding that threshold, and the total number of fatalities during those events.

Region	Fatalities	Fatalities with WSW	Fatal crash threshold	No. of events	Fatalities during events
CONUS	11 966	33.2%	—	87	830
Central	2843	33.0%	10	15	231
East-north-central	2820	25.9%	8	12	116
Northeast	2262	35.5%	8	12	141
Southwest	722	32.7%	5	9	54
Southeast	523	50.9%	6	10	89
West-north-central	1006	27.7%	4	7	32
Northwest	755	22.9%	4	9	45
West	176	31.8%	3	2	9
South	859	56.6%	7	11	113

message accordingly. For AFDs, we wish to determine if any road-hazard messaging or specific context for such messaging are embedded within these often-lengthier text products.

To make this manual analysis of NWS text products manageable, we analyze only a subset of the total 11 966 fatalities (section 2a), namely those that occur during particularly deadly periods of winter weather in which an unusually large number of *separate* fatal crashes occur. For each climate region, we define this threshold as the mean number of fatal crashes that occur on days with at least one fatal crash, plus three standard deviations. Only 12-h periods with fatal crash counts that meet or exceed this threshold are considered (Table 4). This analysis includes 830 fatalities. For each of these fatalities, we obtain all standard NWS text products issued between 6 h prior to the crash and 1 h after the crash from the WFO responsible for issuing forecasts and warnings for the crash location.

Of the 830 fatalities, 63% occurred within a WSW. This nearly twofold increase from our earlier analysis of the entire fatality dataset is not surprising, given that the dataset has been thinned to only periods with multiple fatal crashes. We perform an inductive investigation of qualitatively examining the language used in WSWs by manually finding messaging related to road hazards and precautions for motorists. We synthesize our findings of the dominant types of messaging and include several examples. All WSWs that we examined include messaging that both (i) identifies a road hazard (e.g., "this will make travel very hazardous or impossible," "be prepared for slippery roads and limited visibilities," "roads will become slick and hazardous"), and (ii) offers a precautionary action item for motorists (e.g., "slow down and use caution while driving," "avoid travel if at all possible"). We find many of these messages, however, to be repetitive. This repetitiveness can be attributed to the WSW formatter that each WFO uses to generate a baseline draft of the text product based on gridded forecast data (NOAA 2020; D. Baumgardt, NWS La Crosse, 2021, personal communication). We also find that some WSWs were more detailed than others by including additional information for motorists to be more proactive in their safety while traveling. For example, some WSWs also urge motorists to remain informed of current and forecasted weather conditions, or to check the latest road conditions, often including resources such as phone numbers to call or websites to visit. Another example is WSWs urging motorists to keep a flashlight, food, water, extra clothing, tire chains, fully charged cell phones, or other items in their vehicles in case of emergencies or delays. However, we attribute these additional details to the text formatter, as they were also repetitive for WSWs issued by the same WFO.

We note limited variability in the connotation of the road-hazard messaging in WSWs that would otherwise be used to convey a tiered impacts or hazards rating based on weather conditions. For example, descriptors like "very hazardous," "extremely hazardous," and "extremely dangerous" all express similar sentiments and provide little additional information over simply "hazardous" or "dangerous" in relation to road hazards. One could argue that the use of specific language or phrases does in fact suggest a higher impact or hazard rating (e.g., "extremely hazardous" vs "hazardous"), yet there is nothing in the WSWs that indicates what those different impact levels are. Further, one WFO's or forecaster's use of the word "extreme," for example, may be different from another, such that there is no universal understanding for what "extremely hazardous driving conditions" are and what those impacts mean for an individual driver.

Some WSWs have messaging specific to an anticipated hazard or compounding risk factor. For example, rapidly changing weather conditions are specifically mentioned with wording such as "be prepared for rapid changes in road and visibility conditions" or "travel conditions will deteriorate rapidly." If freezing precipitation is anticipated, emphasis is placed on specific hazards associated with bridges, overpasses, higher elevations, parking lots, sidewalks, and untreated surfaces. Similar messaging is also included for snow events, but not as frequently. Messaging related to rush hours or commutes expresses additional concern for when winter weather overlaps these critical travel times. Although messaging of weather-related road hazards is often not included in AFDs, and instead contained primarily within WSWs or SPSs, AFDs tend to echo similar messaging of rush hours or commutes when timing is a critical factor in issuing the WSW. Another instance where AFDs and WSWs may both include road hazards is if black ice is

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TABLE 5. Percentage of all winter-weather-related fatalities occurring on highways, those involving one (1), two (2), or three or more (3+) vehicles, those involving a truck, and fatalities involving a speeding driver.

Region	Fatalities	Highways	1 vehicle	2 vehicles	3+ vehicles	Truck involved	Speeding
CONUS	11 966	66.9%	48.7%	43.5%	7.8%	18.54%	56.28%
Central	2843	66.2%	50.2%	42.5%	7.4%	18.26%	50.65%
East-north-central	2820	54.4%	42.3%	50.3%	7.4%	16.77%	49.26%
Northeast	2262	67.5%	50.6%	42.7%	6.6%	16.98%	57.65%
Southwest	722	81.9%	48.6%	39.6%	11.8%	20.36%	70.78%
Southeast	523	61.6%	59.5%	34.2%	6.3%	14.15%	52.39%
West-north-central	1006	79.9%	46.0%	46.3%	7.7%	27.63%	60.54%
Northwest	755	72.6%	49.9%	40.9%	9.1%	18.15%	67.28%
West	176	76.7%	58.0%	35.8%	6.3%	16.48%	72.16%
South	859	77.4%	43.7%	35.7%	10.6%	20.72%	66.71%

anticipated, in which case a brief meteorological justification is provided, such as “with overnight temperatures dropping well below freezing, black ice should form for most locations.” WSWs or AFDs occasionally mention reports of accidents or bridges iced over, suggesting that forecasters are aware of road hazards, and that some text products may be issued because of these reports. Interestingly, some messaging of road hazards is messaged in association with WSW cancelations. For example, one AFD says “note that the cancelation of the advisory does not diminish the threat for ‘black ice’ across the region.” Further, some WSW cancelations themselves include messaging of continued road hazards, such as “motorists should continue to exercise caution this morning” and “roads may remain icy if left untreated, use caution if traveling this afternoon.” These types of messaging indicate that forecasters recognize the lingering risk posed to motorists, despite weather conditions improving sufficiently to cancel the WSW.

Considering that all fatalities with WSWs have messaging related to road hazards, we now wish to assess whether fatalities without WSWs have road-hazard messaging in other standard NWS text products around the time of the crash. Out of the 309 fatalities with no valid WSW at the time and location of the crash, 71% had messaging of road hazards within AFDs, SPSs, or other WSWs valid for other nearby locations or times. Thus, of the 830 total fatalities considered for this analysis, 89% had road-hazard messaging issued by the corresponding WFO. This indicates that the NWS issues text products with road-hazard messaging in the majority of cases where an exceedingly large number of separate fatalities occur. Although we expect this percentage to be lower for all winter-weather-related fatalities, it is nonetheless encouraging to know that the NWS includes such road hazards messaging on high-impact winter-weather days.

b. Messaging considerations based on crash attributes

We now investigate non-weather-related attributes of the total 11 966 winter-weather-related fatalities (section 2a) to see if there is any useful information that can be used for messaging in the future. To determine whether other crash attributes are correlated with winter-weather-related fatalities, we compute odds ratios (ORs) and 95% confidence intervals (CIs; see the appendix for more information) of select additional attributes of interest occurring during (i) winter-weather versus nonadverse conditions and (ii) winter-weather conditions with versus without an associated WSW. These ORs represent the odds of a fatality having the attribute of interest (e.g., on a highway) during a weather condition of interest [i.e., (i) winter-weather conditions, or (ii) winter-weather conditions with a WSW] relative to the odds of the attribute during the comparison weather condition [i.e., (i) nonadverse conditions, or (ii) winter-weather conditions without a WSW]. An OR of 1.0 indicates that the odds of the fatality having the attribute of interest are equivalent during both the weather condition of interest and the comparison weather condition. If the 95% CI includes 1.0, the difference in odds between the two weather conditions is not statistically significant. For ORs with 95% CIs greater than 1.0, the odds of fatalities having the attribute of interest during the weather condition of interest is statistically significantly greater than the odds during the comparison weather condition. Conversely, for ORs with 95% CIs less than 1.0, the odds of fatalities having the attribute of interest during the weather condition of interest is statistically significantly less than the odds during the comparison weather condition. We stress that these ORs should *not* be interpreted as crash risk estimates. For example, ORs with 95% CIs $>$1.0 do not necessarily mean that crash risk is elevated.

This analysis of ORs allows us to ascertain whether there are any attributes statistically significantly correlated with fatal crashes that, if incorporated into messaging of winter weather, may help to mitigate risk for motorists. The two sets of ORs (winter-weather vs nonadverse conditions, and winter-weather conditions with vs without a WSW) will help inform whether messaging should be used in general for winter-weather conditions, or if the messaging is particularly pertinent to include in WSW messaging.

1) HIGHWAYS

Approximately two-thirds (67%) of winter-weather-related fatalities occur on highways[2] (Table 5). The odds of a fatal crash occurring on a highway during winter-weather conditions is statistically significantly greater than those during

[2] Highways include interstates, federal highways, and state highways.

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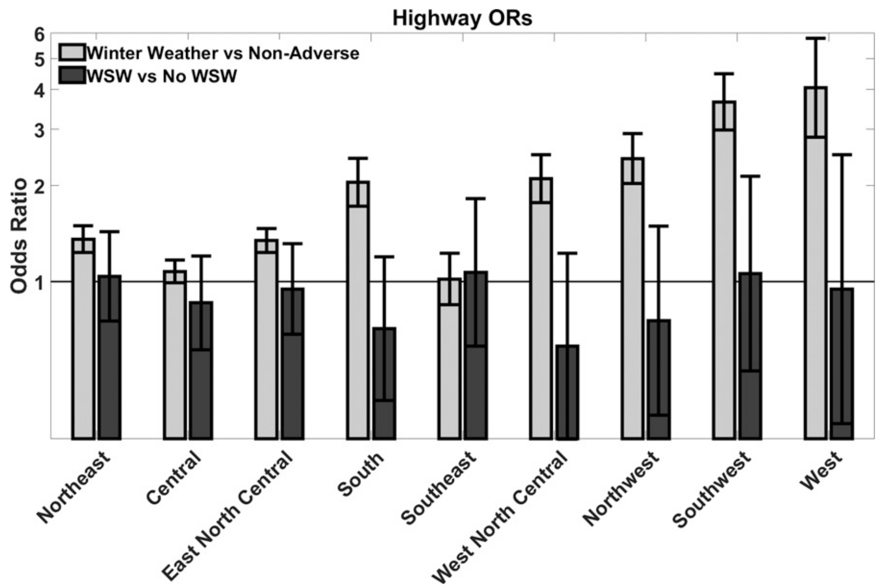

FIG. 5. Mean (bars) and 95% confidence interval (black lines) of the odds ratio of fatalities occurring on highways in winter vs nonadverse conditions (light gray), and in winter weather with a WSW vs no WSW (dark gray).

nonadverse conditions in all climate regions, except the Southeast where results are not statistically significant (Fig. 5). This result is consistent with similar odds ratios in Saha et al. (2016). Andrey et al. (2013) found that crash relative risk during winter precipitation is higher on roads with higher posted speeds, so it is unsurprising that comparatively more fatalities occur on highways during winter weather because of this increased risk. However, ORs of highway fatalities during winter-weather conditions with a WSW versus no WSW indicate no statistically significant difference (Fig. 5).

These results suggest that highway variable-message signs can be useful to communicate winter-weather hazards to motorists. The use of variable-message signs on highways in response to weather conditions has been strongly recommended for years (Atmospheric Policy Program 2004), and continued and expanded use of these systems for the purposes of messaging the hazards of winter weather to motorists should be encouraged. The fact that there is no statistically significant difference in highway fatalities for winter-weather conditions with versus without a WSW suggests that the use of such systems *should not* be limited only to conditions with an active WSW. Instead, these systems should be used more broadly to alert motorists of snow, ice, and other hazardous winter conditions, regardless of WSW status. For example, lower winter-weather thresholds than those typically used for WSWs may be appropriate for triggering the use of highway variable-message signs.

2) NUMBER AND TYPE OF VEHICLES INVOLVED

Nearly one-half (49%) of all winter-weather-related fatalities across the CONUS involve only a single vehicle (Table 5). A slightly smaller fraction of fatalities (44%) involves two vehicles, and <8% of fatalities involve three or more vehicles. We disaggregate fatalities by number of vehicles involved (one, two, three, or more), and by roadway (any roadway, highway, and nonhighway) to compute ORs (Fig. 6). The odds of a fatality resulting from single-vehicle crashes on highways are statistically significantly lower during winter weather than during nonadverse conditions, indicating that fatal winter-weather-related crashes on highways are less likely to involve only a single vehicle than fatal highway crashes during nonadverse conditions. Conversely, the odds of fatalities from double-vehicle crashes on all roadways are statistically significantly greater during winter weather, indicating that fatal winter-weather-related crashes in general are more likely to involve two vehicles. Interestingly, fatalities resulting from crashes involving three or more vehicles are less likely to occur during winter weather on nonhighways, but no more or less likely on highways.

ORs computed for winter-weather conditions with versus without a WSW produce similar results for single- and double-vehicle crashes (Fig. 6). Fewer fatalities from single-vehicle crashes on all roadways occur during weather conditions with WSWs, suggesting that fatal winter-weather-related crashes are *even less likely* to involve only one vehicle when they occur during the more-extreme conditions generally associated with a WSW. However, fatalities from double-vehicle crashes are *even more likely* to occur during such weather conditions. On highways, fatalities from multiple-vehicle crashes are more likely to occur, suggesting the involvement of more vehicles during winter conditions with WSWs.

The general shift in fatalities to involve more than one vehicle during winter-weather conditions—and even more so for conditions with WSWs—suggests that drivers are not giving themselves adequate additional space from other vehicles around them or are unable to maintain their lane while driving. Such additional space is required to account for poor

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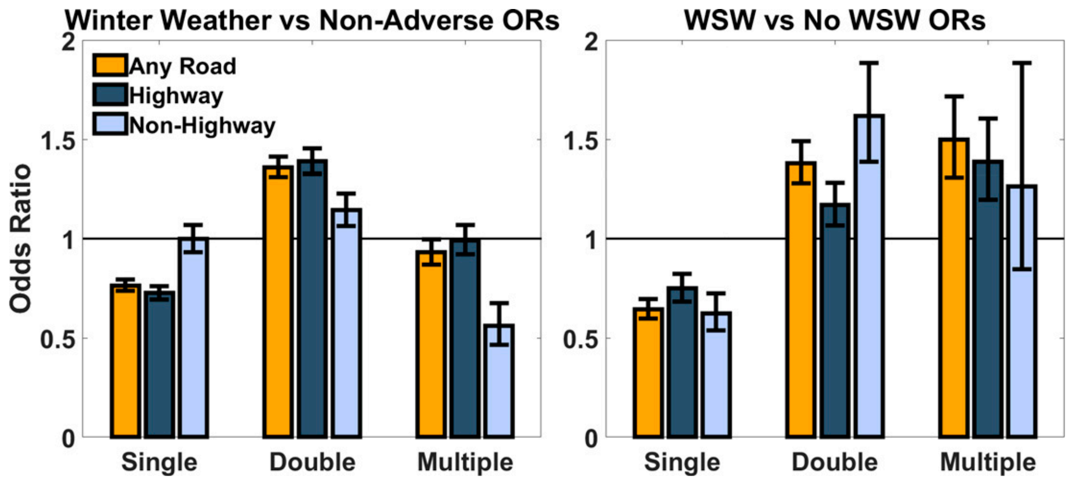

FIG. 6. Mean (bars) and 95% confidence interval (black lines) of the odds ratio of fatalities occurring from single-, double-, and multiple-vehicle crashes on any road (orange), highways (dark blue), and nonhighways (light blue) in (left) winter vs nonadverse conditions and (right) winter weather with a WSW vs no WSW.

visibility and increased stopping distances owing to slippery roads, and a motorist failing to maintain their lane can be a hazard to vehicles in other lanes or trafficways. Additional desired messaging for winter-weather conditions—both in general and within WSWs—may include language to the effect of urging motorists to budget for *even more space* around their vehicles, and to slow down to help maintain control of their vehicles on slippery surfaces. It may also be beneficial to inform drivers of proper strategies for regaining control of their vehicles if they begin to lose traction. For example, motorists should remain calm, take their foot off the accelerator, not slam on their brakes, and gently steer in the intended direction of travel until control is regained.

Considering that nearly one-half of all winter-weather-related fatalities *still only involve a single vehicle*, it is important to emphasize that individual drivers are responsible for their own safety in most scenarios. Andrey and Knapper (2003) found that motorists typically only make minor adjustments to weather hazards, and that more should be done to teach proper avoidance strategies in adverse weather and driving conditions. Thus, repeated and consistent messaging addressing how motorists should alter their driving behaviors in winter-weather conditions may be one avenue for improving safety.

We wish to briefly examine the involvement of trucks (e.g., tractor-trailers and class-3-and-higher trucks and vans). Nearly 20% of winter-weather-related fatalities involve a truck (Table 5). The involvement of a truck in a fatal crash on any roadway is statistically significantly more likely to occur in winter-weather conditions, both in general (OR 1.72; 95% CI 1.64–1.81) and with a WSW (OR 1.58; 95% CI 1.43–1.73). As opposed to this result implying "fault" with truck drivers, the increased involvement of trucks is more likely in relation to the fact that the ratio of truck to passenger-car traffic increases during snowstorms (Call 2011). However, nearly 90% of all fatalities involving a truck also involved more than one vehicle, as compared with only ~42% of passenger-car-only fatalities involving more than one vehicle (not shown). Trucks have much larger dimensions and inertia than passenger cars, which can make it easier to involve additional vehicles in a crash, particularly if the truck or trailer slides across the roadway or cannot stop quickly. Although many states' departments of transportation (DOTs) impose commercial-vehicle restrictions on some roadways during winter weather in an effort to minimize crashes (e.g., Pennsylvania Department of Transportation 2021), effective messaging may be beneficial to prevent truck crashes involving additional vehicles in other scenarios where trucks and passenger cars share the road. For example, motorists should be encouraged to allow *even more space* between themselves and large trucks, and to remain out of their blind spots.

3) SPEEDING

More than one-half (56%) of winter-weather-related fatalities involve speeding (Table 5), meaning that at least one driver involved in the crash was driving above the posted speed limit, or driving too fast for conditions, as indicated by law enforcement (NHTSA 2022). ORs indicate that speeding is a statistically significant factor in winter-weather-related fatalities on all roadways, but particularly on highways where speeding is 5–6 times as likely to be indicated than for fatalities during nonadverse conditions (Fig. 7). We contrast this result to that of Saha et al. (2016), who found that speeding—strictly in the sense of vehicles traveling faster than the speed limit—is *less likely* to occur concurrently with adverse weather. Survey results presented in Andrey and Knapper (2003) show that motorists typically only make minor adjustments to their driving behavior during adverse weather, with the most common adjustment being to reduce their speed. Indeed, other studies demonstrate that motorists typically drive at lower speeds during adverse weather (e.g., Kilpeläinen and Summala 2007; Jägerbrand and Sjöbergh 2016). Our results

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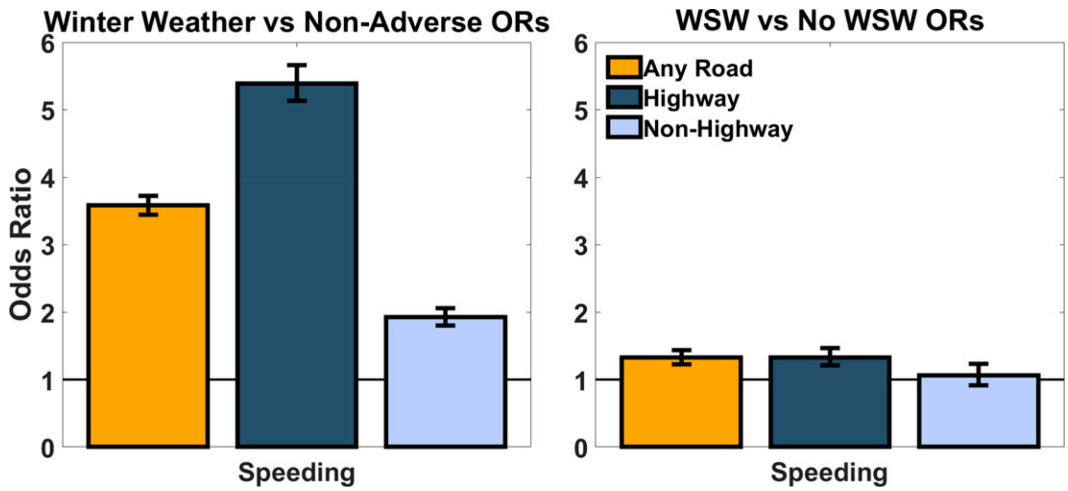

FIG. 7. As in Fig. 6, but for winter-weather-related fatalities involving a speeding driver.

suggest that although drivers in these fatal crashes are often driving *below* the speed limit, their speeds are *still too fast* for conditions. This finding is consistent with that of Call et al. (2019) for adverse-weather crashes. From these results, it is suggested that messaging during winter weather in general should strongly encourage motorists to reduce their traveling speeds, particularly on highways. Specifically, this messaging should encourage motorists to slow down *even more* than they typically would.

The odds of a motorist speeding prior to a fatal crash is statistically significantly greater during winter weather with a WSW versus without on highways, but there is no statistically significant difference on nonhighways (Fig. 7). This result suggests that WSWs should continue to reiterate the messaging for motorists to slow down. Further, this messaging should be targeted specifically to motorists on highways through the use of variable-message signs.

4) Deteriorating weather conditions

Because more than 2 of every 5 winter-weather-related fatalities are associated with deteriorating weather conditions [section 2c(2)], it is worth assessing whether these fatalities are more or less likely to occur on highways, and whether these fatalities are more likely to have associated WSWs.

Results indicate that the odds of a fatality with deteriorating weather to occur on a highway are greater than those with nondeteriorating conditions (OR 1.23; 95% CI 1.09–1.38). This suggests that deteriorating weather conditions are more likely to play a role in winter-weather-related fatalities on highways than on nonhighways. We suggest a reason for this difference is that low visibility plays a greater role in fatal crashes on highways, likely because of comparatively higher vehicle speeds. On nonhighways, however, the same visibility reduction is less of a concern because drivers have more time to react because of their lower vehicle speed. These results suggest that the use of variable-message signs along highways may be beneficial to warn motorists of the potential for rapidly deteriorating weather conditions.

The odds of a fatality with deteriorating weather having a WSW are greater than those with nondeteriorating weather, regardless of the road type (OR 1.47; 95% CI 1.28–1.69 for highways and OR 1.40; 95% CI 1.14–1.72 for nonhighways). This implies that WSWs and deteriorating weather are strongly linked, such that events with deteriorating weather are more likely to have WSWs. WSWs are thus a suitable avenue for forecasters to include additional messaging to alert motorists of hazards associated with changing weather, if such conditions are anticipated.

4. Discussion

In this paper, weather conditions and WSW issuances for fatal motor-vehicle crashes from 2008 to 2019 in the United States that occurred during winter-weather conditions (i.e., during active winter precipitation or on icy, slushy, or snowy roadway surfaces) were analyzed. Approximately 1000 such fatalities occurred each year, primarily in the Northeast, Central, and East-North-Central climate regions.

Examination of precipitation-type reports within an hour of fatal crashes revealed that nearly half of the fatalities occurred in snow only, 30% in ice pellets or mixtures without freezing precipitation, and <10% in freezing precipitation. Even fewer fatalities had no precipitation reported, meaning precipitation ended at least an hour prior to the crash, but roadways were still icy, snowy, or slushy. These fatalities imply that ending precipitation does not necessarily mean that road conditions have improved, thus the threat of winter weather can linger on roadways; 75% of fatalities with snow and 60% of fatalities with other precipitation types had consistent precipitation types within the 3 h leading up to the crash. This suggests that fatalities are primarily associated with ongoing, consistent winter precipitation, and that motorists should always exercise caution for the entire duration of winter-weather conditions. Notably, however, 40% of

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fatalities during freezing precipitation had the freezing precipitation first occur within the hour. This suggests that the onset of freezing precipitation is an important factor in fatal crashes, so the timing of precipitation types is important to communicate to motorists.

We examined how precipitation intensity, obscurations, and visibility change in the hours leading up to fatal crashes. More than 40% of fatalities had deteriorating weather conditions, defined as the beginning of precipitation or any obscuration to visibility, increasing precipitation intensity, worsening obscurations, or visibility reductions of ≥25%. One-third had improving weather conditions with the cessation of precipitation or any obscuration, decreasing precipitation intensity, improving obscuration, or visibility increases of ≥25%. Of these fatalities with improving weather conditions, only 25% were associated with fair weather conditions (i.e., no precipitation, no obscurations, and visibility > 8.0 km), implying that weather conditions were still less-than ideal for most fatalities with improving weather conditions. Last, <20% had consistent weather conditions leading up to fatal crashes. These classifications are strongly tied to visibility changes, where nearly 80% of fatalities in the deteriorating and improving categories had corresponding visibility changes. Further, precipitation and obscuration changes were also often associated with visibility changes. Of all the prevalent-weather conditions examined, visibility is arguably the most important weather variable in motor-vehicle crashes because it provides an indication of how far ahead of the vehicle a driver can see, which corresponds to the time that the driver has to react to an upcoming hazard, depending on their speed. Because visibility is so strongly correlated with other weather conditions (i.e., precipitation and obscuration changes), its role in motor-vehicle crashes should be examined further in future studies.

Only one-third of the fatalities had WSWs valid for the crash; however, all WSWs examined include messaging related to road hazards. Specifically, WSWs identify road hazards (e.g., "roads will become slick") and include action items or precautionary statements (e.g., "slow down and use caution while driving," "avoid travel"). Some WSWs have more detailed action items, such as encouraging motorists to remain informed of the current and forecasted weather and roadway conditions, or to keep emergency kits in their vehicle. We found that although the specific language used for both the road-hazard identification and calls to action varied, many were repetitive owing to the use of text formatters that populate the WSW based on gridded forecast data and additional forecaster input or modification. Whereas these formatters may have built-in language modification to express higher-impact or hazards levels (e.g., "extremely hazardous" vs "hazardous"), the WSWs do not clearly convey these tiered levels. Thus, the identification of road hazards by the NWS is primarily communicated in their standard text products at a single binary (yes/no) level when WSWs are issued. In other words, road hazards are not communicated at subadvisory thresholds (unless an SPS is issued), and the language used in WSWs for high-impact events is similar to that during lower-impact events.

The NWS recently announced plans to replace advisories and SPSs with plain-language headlines that describe the hazard as part of its Hazard Simplification program (NWS 2021). Because >80% of fatalities with WSWs had advisories as opposed to warnings, it is crucially important to consider how road hazards will be messaged in the updated system. Further, because there is no explicit tiered rating system within WSWs as it relates to road hazards and impacts, and because the remaining two-thirds of fatalities did not have WSWs (and thus no messaging of road hazards), it is important also to consider how the NWS will communicate road hazards and specific impacts during *all* winter-weather conditions. We note, for instance, that winter-weather conditions with an advisory could be more impactful for motorists than conditions with a warning based on nonmeteorological factors, such as time of day, traffic patterns, and availability of resources to clear the roads. Similarly, weather conditions not meeting WSW-issuance criteria could be just as hazardous as those with a WSW. In light of this, a system complementary to existing WSW protocols that conveys tiered road-hazard impact levels uniformly across the CONUS may be beneficial to inform motorists of road hazards, regardless of WSW status. Currently, the NWS is in development of an experimental tool as part of the winter storm severity index (WSSI; Weather Prediction Center 2021) to identify hazardous winter-weather conditions on roadways and assign an impact ranking from no impacts to extreme impacts (J. Kastman 2021, personal communication; Weather Prediction Center 2021).

During winter-weather periods with an exceedingly high number of separate fatal crashes, ~70% of fatalities with no WSW still had road-hazard messaging in NWS text products issued by the WFO. This suggests that road hazards associated with winter weather are often still recognized and messaged by the NWS. The NWS plays an integral role in forecasting and communicating hazards associated with winter weather, and that role extends beyond just issuing WSWs. For example, the Pathfinder initiative facilitates collaboration between NWS WFOs, the Federal Highway Administration (FHWA), state DOTs, and private-sector agencies to assess the impact of weather on transportation, and to develop consistent, concise messaging for motorists (FHWA 2018). Such messaging tactics, particularly through the use of social media, can provide additional situation-specific details about road hazards beyond what are currently included in WSWs. Our research of WSW language as it relates to road hazards prompts our recommendation for human-factors studies to identify best practices for messaging road hazards moving forward. Potential outcomes from such future studies may include using consistent messaging among WFOs when similar road-hazard impacts are anticipated, using amplified phrasing to convey higher-end impacts level (e.g., "dangerous life-threatening travel"), and identifying what specific phrases and language would persuade motorists to appropriately modify their driving behavior (e.g., slowing down and changing or canceling their travel plans).

We examined several non-weather-related crash attributes to gain insight into crafting targeted and effective messaging in the future. Two-thirds of winter-weather-related fatalities occur on highways, and fatalities are more likely to occur on

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highways during winter weather than during nonadverse conditions, so the use of variable-message signs along major roadways is encouraged when winter-weather conditions are anticipated. Further, these signs can be an effective communication mechanism to target motorists where fatal crashes occur more frequently. Although half of winter-weather-related fatalities involve only one vehicle, there is a shift toward fatal crashes involving more than one vehicle, particularly when WSWs are issued. We suggest that messaging should urge motorists to leave more room between vehicles and educate motorists on best practices to regain control of their vehicles in order to reduce the involvement of additional vehicles. Large trucks are more likely to be involved in fatal winter-weather-related crashes, and they most often involve more than one vehicle. We encourage partnerships between the trucking industry and both public and private weather sectors to ensure the safety of all motorists while also minimizing the impact to commercial transportation. Over one-half of winter-weather-related fatalities involve motorists speeding or driving too fast for conditions. Further, speeding is 5–6 times as likely in fatal crashes during winter weather than during nonadverse conditions. Current WSWs often encourage motorists to slow down, yet motorists should slow down even more than they already do. This messaging should be employed for winter conditions in general via other messaging platforms (e.g., variable-message signs and social media). Last, messaging should alert motorists if deteriorating weather is anticipated, particularly along highways and within WSWs.

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Data availability statement. Fatality data used for this study are openly available through NHTSA's FARS (https://www.nhtsa.gov/research-data/fatality-analysis-reporting-system-fars). ASOS data are openly available through the Iowa State University's Iowa Environmental Mesonet archive (https://mesonet.agron.iastate.edu/request/download.phtml). WSW shapefiles used for this study are openly available through the Iowa State University's Iowa Environmental Mesonet archive (https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml). NWS text products (WSWs, AFDs, and SPSs) used in this study are openly available through the Iowa State University's Iowa Environmental Mesonet archive (https://mesonet.agron.iastate.edu/wx/afos/list.phtml).

APPENDIX

Details of Odds Ratios and Confidence Intervals

Weighted-mean odds ratios (referred to simply as odds ratios in the text) and 95% confidence intervals are computed in accordance with the theory detailed in Fleiss et al. (2003). Each year has an odds ratio of OR = $[(A/C)/(B/D)]$, where A is the number of fatalities with the attribute of interest during the weather condition of interest, B is the number of fatalities with the attribute of interest during the comparison weather condition, and C and D are the number of fatalities without the attribute of interest during the weather condition of interest and the comparison weather condition, respectively. For example, in the case of determining the odds ratio of highway fatalities during winter-weather versus nonadverse conditions, the attribute of interest is for the fatality to occur on a highway (as opposed to on a nonhighway), the weather condition of interest is winter-weather conditions, and the comparison weather condition is nonadverse conditions. This OR is then log transformed as $y_i = \log(\mathrm{OR})$ to ensure a normal distribution with variance $\upsilon_i = (1/A) + (1/B) + (1/C) + (1/D)$. Each year's y_i has a weighting of $w_i = 1/\upsilon_i$, and the weighted-means odds ratio is determined for the set of g years as

$$\overline{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right)$$

with a 95% confidence interval of

$$\exp\left[\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right) \pm \frac{1.96}{\sqrt{\sum_{i=1}^{g} w_i}}\right].$$

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