Characteristics of Recent Vehicle-Related Fatalities during Active Precipitation in the United States

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ABSTRACT

Data from the National Highway Traffic Safety Administration’s (NHTSA) Fatality Analysis Reporting System (FARS) database were used to identify vehicle-related fatalities that occurred during active precipitation from 2013 to 2017. Changes to FARS for 2013–present allow the identification of freezing rain, in addition to rain, snow, sleet, and precipitation mixtures as prevailing precrash atmospheric conditions. The characteristics of vehicle-related fatalities for each precipitation type identified in FARS were assessed in terms of total numbers, roadway surface conditions, location, and annual and diurnal variability. Vehicle-related fatalities were also matched to nearby Automated Surface Observing System (ASOS) and Automated Weather Observing System (AWOS) precipitation-type reports to determine their agreement with precipitation types documented in FARS. Of the vehicle-related fatalities examined, 8.6% occurred during precipitation, with these fatalities further divided by precipitation type of approximately 81% rain, 14% snow, and 5% sleet, freezing rain, and mixtures of precipitation. Unexpected discrepancies between the numbers of sleet- versus freezing-rain-related fatalities reveal that caution should be taken when using FARS to identify these precipitation types. ASOS/AWOS precipitation-type reports have moderate agreement with FARS at 20 mi (32.2 km), and are capable of distinguishing precipitation and nonprecipitation indicated in FARS. Rain and snow have good agreement between the databases, whereas sleet, freezing rain, and precipitation mixtures have significantly reduced agreement due to a combination of ASOS/AWOS limitations and suspected FARS limitations. To provide a more accurate account of precipitation types for fatal crashes, the use of crashes where FARS-identified precipitation types are confirmed by nearby ASOS/AWOS reports is suggested.

1. Introduction

Weather and precipitation can have a profound effect on vehicular traffic and vehicle-related crashes. At best, precipitation, cloudiness, and wind speeds can reduce the relative intensity of vehicular traffic (Cools et al. 2010). At worst, conditions can be hazardous to daily driving, resulting in an increased number of collisions, injuries, and fatalities as compared to fair-weather driving conditions (e.g., Andrey et al. 2003; Qiu and Nixon 2008). Inclement weather may deter driving or make drivers more cautious and reduce their speed (Evans 1991), which can partially offset the increased risk of crashes (Strong et al. 2010); however, precipitation still poses a safety hazard that accounts for as much as 25% of all collisions (Andrey et al. 2003). Although many of these crashes result in little more than property damage (e.g., Eisenberg and Warner 2005), the number of fatalities that occur during precipitation is significant.

Andrey et al. (2003) found that driving in any precipitation is linked to up to a 75% increase in the relative risk of collisions and a 45% increase in related injuries versus dry conditions. However, there is evidence that the relative risk of collision, injury, and fatality is also a function of precipitation type and intensity (e.g., Andrey et al. 2003; Qiu and Nixon 2008; Andrey 2010; Black and Mote 2015b; Black et al. 2017). Qiu and Nixon (2008) generalized from previous studies that snow increases crash rates by 84% and injury rates by 75%, versus rain (71% and 49%, respectively). Further, Andrey (2010) found the injury and fatality risks in Canada during rain have decreased from 1984 to 2002, whereas these risks...
during snowfall have remained constant. This was attributed to an overall improvement in vehicle and roadway safety rather than specific improvements during winter precipitation. Similarly, Black and Mote (2015b) found no trend for reduction in the relative risk of crash and injury during winter precipitation in the United States from 1998 to 2008.

Despite the number of collisions, injuries, and fatalities that occur during precipitation, there exists no comprehensive or standardized database of weather-related losses from which to develop a reliable account of the impacts of precipitation. Notably, there are three main resources to obtain storm-related losses: National Weather Service (NWS) reports published in Monthly Weather Review (1925–49), Climatological Data, National Summary (1950–58), or Storm Data (1959–present); published cases studies of specific weather events; and property-related losses totaling over $1 million (U.S. dollars) are catalogued by the property insurance industry (Changnon and Creech 2003). Each was found to be incomplete, inconsistent, or lacking sufficient detail to be a robust resource for multiple applications (e.g., Branick 1997; Changnon 1997; Gall et al. 2009; Black and Mote 2015a). Storm Data, for example, only includes storm-related fatalities that are a direct result of a weather hazard. However, fatalities resulting from crashes on slippery roadways caused by adverse weather, for example, are considered indirect fatalities (NOAA 2018). Estimates suggest 30–40 (Changnon 2007), or upward of 70 people (Borden and Cutter 2008) die directly from winter weather each year. Though significant, these estimates do not include indirect vehicle fatalities, and thus underestimate the total number of fatalities associated with winter weather by an order of magnitude (Black and Mote 2015a).

There are different approaches to evaluate precipitation’s effect on vehicle-related crashes and fatalities. Several papers utilize both meteorological and vehicle-related crash databases to identify precipitation type at the time of the incident (e.g., Andrey et al. 2003, and references therein; Eisenberg and Warner 2005; Andrey 2010; Andrey et al. 2013; references in Theofilatos and Yannis 2014; Black and Mote 2015b; Tamerius et al. 2016; Black et al. 2017; Chung et al. 2018, hereafter C18). However, the use of wet pavement and rain identifiers within crash reports, in addition to precipitation accumulation data, results in lower crash relative risks than those produced from only using meteorological data to identify precipitation periods (Black and Villarini 2019). Another approach to evaluate precipitation’s effect on vehicle-related incidents is to analyze crash data using a single database that includes precipitation type (e.g., Ashley et al. 2015; Black and Mote 2015a; Saha et al. 2016; Wang et al. 2017; Call et al. 2019; C18).

A majority of the literature on crashes and fatalities during precipitation focus on rain and/or snow. Few studies examine additional precipitation types, and those that do combine multiple precipitation types into single categories with inconsistent definitions, making conclusions about crash risks during specific precipitation types impossible. For instance, Andrey et al. (2003) defined “snow” as inclusive of sleet and freezing rain. Additionally, “winter precipitation” has varying definitions: sleet, freezing rain, and snow (Andrey et al. 2013); snow and sleet combined (Black and Mote 2015a); and two subcategories of snow and ice precipitation, the latter including sleet and freezing rain (Black and Mote 2015b). Similarly, some studies examine “all precipitation types” as the combination of rain, sleet, hail, and snow (Ashley et al. 2015; Black and Mote 2015a; C18). Given the varying categorizations of precipitation types, there is no information on the risk of crash during either sleet or freezing rain as distinct precipitation types, and no information on how those risks differ from rain and snow.

In the United States, the National Highway Traffic Safety Administration’s (NHTSA) Fatality Analysis Reporting System (FARS) database contains information on fatalities resulting from motor vehicle crashes. Before 2013, only rain, snow, and sleet/hail had separate attribute codes (NHTSA 2017a), whereas freezing precipitation was not accounted for (Black and Mote 2015a). Fortunately, recent changes to the FARS coding system include freezing rain attribute codes; thus, FARS now documents fatalities that occur during rain, snow, sleet/hail, freezing rain, and precipitation mixtures. Hereafter, vehicle-related fatalities that occur during any of these precipitation types are referred to as precipitation related. As precipitation-related fatalities are considered indirect fatalities, it is important to recognize that these crashes are not necessarily caused by precipitation, but simply occurred while precipitation was falling. Thus, precipitation-related fatalities herein may also represent a subset of fatalities attributed to alcohol, speeding, distracted driving, improper use of safety restraints, etc.; however, these attributes are beyond the scope of this study.

Vehicle-related fatality data tend to be of a higher quality than nonfatal crash data, which are subject to errors related to underreporting (Fridstrøm et al. 1995). Despite the higher quality of fatality data versus other crash data, the accuracy of precipitation
types documented in FARS is undetermined, yet largely considered accurate. To account for potential coding errors in FARS of winter, Black and Mote (2015a) omitted 0.5% of all fatalities during winter precipitation from 1975 to 2011 if snow was not reported or if any precipitation with above-freezing temperatures were reported at nearby weather stations for all warm-season (May–September) sleet and snow entries. To date, it is the only study to filter FARS precipitation types for possible inaccuracies.

C18 were the first to correlate FARS atmospheric conditions to weather conditions reported at nearby weather stations, specifically rain, snow, and fog. Therein, FARS fatal crash counts from 2007 to 2014 were matched with Quality Controlled Local Climatological Data (QCLCD) within 5, 10, and 20 mi (8.0, 16.1, and 32.2 km) of crash locations to assess the spatial coverage and quality of available weather data versus FARS atmospheric conditions, which were considered “true.” C18 found >75% of all fatal crashes are located within 20 mi (32.2 km) of a weather station in the United States, and that those stations have moderate agreement with FARS.

However, close examination of the methods in C18 warrants the use of caution when interpreting some of their other results. C18 state that weather reports come from land-based stations including Automated Surface Observing System (ASOS), Automated Weather Observing System (AWOS), Microcomputer Aided Paperless Surface Observations (MAPSO), aviation routine weather report (METAR), and Climate Reference Network (CRN) data; however, not all of these sources contain hourly weather-type information for their period of study. Thus, it is likely that the reports in C18 come almost exclusively from ASOS and AWOS, which are capable of reporting rain, snow, and fog, among other weather conditions. Within the METAR format of ASOS and AWOS observations, a remarks section can contain additional precipitation-related information, which can indicate if the station is automating precipitation-type reports, the precipitation identification (PI) sensor status, and the beginning and/or end times of additional precipitation types from the previous hour; it is unclear if C18 accounted for this information. Without careful examination of the remarks, it is impossible to know if the station is equipped with a PI sensor and/or if it is functioning properly. For example, not all AWOS stations have the PI sensor required to automate precipitation type. Without filtering these stations, any FARS fatality within 20 mi (32.2 km) would return clear/cloud conditions and result in higher than expected false negatives (i.e., adverse weather conditions in FARS but not in QCLCD data). Thus, one should take caution with the interpretation of these null values as clear/cloud conditions in C18.

The precipitation types now included in FARS allow for an analysis of precipitation types identified during fatal crashes. Although the impacts of rain, snow, and winter precipitation on traffic and crashes have been studied extensively, no study addresses sleet, freezing rain, and precipitation mixtures separately. In this study, FARS precipitation types are used to categorize fatalities, as outlined in section 2.

The purpose of this study is twofold: to analyze precipitation-related fatalities documented in FARS, and investigate the accuracy of identified precipitation types. Section 3 characterizes FARS total fatality count, roadway surface condition, location, and both annual and diurnal distributions as a function of precipitation type. Section 4 matches both precipitation-related and non-precipitation-related fatalities to nearby precipitation reports to assess the utility of meteorological data to document precipitation types during crashes, and the accuracy of precipitation types included in FARS. Section 5 includes a discussion, and a summary and conclusions are presented in section 6.

2. Methods
a. Characterization of precipitation type from FARS

We obtained NHTSA FARS vehicle-related fatality data for the years 2013–17. The database archives information from crashes resulting in the death of any individual within 30 days of the crash (NHTSA 2017a). Data entries of interest for this study were the date, time, location (latitude, longitude), number of fatalities, road surface condition, and atmospheric conditions involved with each crash. Each incident may have up to two coded atmospheric conditions that identify the prevailing conditions at the crash time as indicated by the crash report (NHTSA 2017a). Precipitation types...
are coded as rain or drizzle, sleet or hail, snow or blowing snow, and (beginning in 2013) freezing rain or freezing drizzle. Additional atmospheric codes that do not identify a precipitation type (e.g., clear, cloudy, fog/smog/smoke, severe crosswinds, and blowing sand/soil/dirt) were ignored and treated as if no additional atmospheric condition was identified. We defined a mixed precipitation category for any combination of identified precipitation types. Precipitation-related fatalities with a second atmospheric condition code of other, not reported, or unknown were not categorized further. Fatalities with blowing snow were considered snow related herein, as blowing snow applies to falling snow and/or snow on the ground set aloft by wind (NHTSA 2017a).

For weather-risk and meteorological purposes, it is desirable to distinguish fatalities related to sleet and hail, which form in different meteorological conditions but are not separated in FARS. Thus, sleet/hail-related fatalities were investigated further using the Storm Prediction Center’s Storm Reports (www.spc.noaa.gov/climo/online). Precipitation-related fatalities with sleet/hail coding and valid spatiotemporal attributes (i.e., latitude, longitude, date, and time) were analyzed to determine if hail was reported within 50 km and 1 h of the crash. If hail was not found, fatalities were assumed sleet related. Although hail and sleet can occur simultaneously in situations with both a subfreezing surface layer and elevated convection (e.g., Van Den Broeke et al. 2016), the purpose here is to remove large hail cases, which likely produce a distinct hazard that is beyond the scope of this study. The filtering found seven fatalities associated with hail; these were omitted from the analysis.

After separating fatalities into the respective precipitation-type categories (i.e., rain, snow, sleet, freezing rain, and precipitation mixtures), analyses were done on the total number of fatalities in each category, along with the location, time of day, and time of year of fatalities for each precipitation type. Roadway surface conditions related to precipitation identified in FARS (dry, wet, snow, ice/frost, standing/moving water, slush) were used to identify road conditions associated with each precipitation type.

b. Characterization of precipitation type from ASOS/AWOS

Only FARS entries with valid latitude, longitude, date, and time for the crash were spatiotemporally matched to meteorological data, which came from U.S. ASOS and AWOS sites, obtained from the Iowa Environmental Mesonet website (www.mesonet.agron.iastate.edu). ASOS data are often used to identify precipitation types (e.g., Reeves 2016), and have been used to identify crash-specific precipitation types (Black and Mote 2015b; C18). C18 found that ~75% of all FARS fatalities occur within 20 mi (32.2 km) of a surface-based weather station with moderate agreement, and we adopted this spatial criterion for our analysis.

A 1-h window (±30 min of the crash time) was used to account for potential precipitation start and end time differences between crash locations and the respective ASOS/AWOS site, changes in precipitation, and for consistency. Additional filtering of spatiotemporally matched reports was performed through examination of the METAR coding. Although a FARS fatality may match spatially with an ASOS/AWOS station, it was necessary to ensure that the site was operating correctly and able to report precipitation types within the ±30-min window.

Fatalities were considered to have no data available within the ±30-min window if the matched station 1) had no data available, 2) was unable to report precipitation types, or 3) had nonfunctioning precipitation-type sensors. Condition 1 occurred if the station was added to the ASOS/AWOS network after the crash date, or if the site was offline for maintenance at the time. Active ASOS/AWOS sites capable of automating precipitation types have an “AO2” designation within the METAR remarks (NOAA 1998). Condition 2 occurred if the site did not have the AO2 designation and no precipitation was reported by a human observer. Although a site may be equipped with a PI sensor, a freezing rain sensor is also required to report freezing precipitation. Both the PI and freezing rain sensors must be operating during the time of interest to distinguish multiple precipitation types, including freezing rain. Condition 3 occurred if one or both sensors were not functioning.2 If the spatiotemporally matched station was capable of reporting precipitation type and did not report precipitation, the fatality was considered to have no precipitation.

For consistency with FARS, ASOS/AWOS-identified drizzle and freezing drizzle were considered rain and freezing rain, respectively. Otherwise, ASOS/AWOS systems are able to report the same precipitation types used in FARS, among other weather phenomena (NOAA 1998). Stations equipped with the appropriate

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2 In the remarks, “PWINO” and “FZNO” or “FZRANO” indicate that the PI and freezing rain sensors are not operating, respectively (NOAA 1998). “FZNO” or “FZRANO” is only reported if “PWINO” is also reported, or if the ambient temperature is ≤36°F (≤2.2°C). Stations not equipped with a freezing rain sensor were still included so long as the PI sensor was operating and temperatures were >36°F (>2.2°C).
sensors are capable of automatically reporting rain, snow, and freezing rain. Unfortunately, only sites augmented by human observers can report sleet, hail, and precipitation mixtures (NOAA 1998; Reeves 2016); only 15% of ASOS locations have human observers (Elmore et al. 2015). Often, multiple precipitation types occur simultaneously at temperatures close to 0°C (e.g., Cortinas et al. 2004; Thériault et al. 2010; Stewart et al. 2015).

The present weather code in the METAR only indicates the precipitation types occurring at the time of the report, whereas automated reports with the AO2 designation and human-augmented reports document the beginning and end times of all precipitation types within the remarks. Thus, although ASOS/AWOS reports are often hourly, precipitation-type changes within the previous hour can be extracted from the METAR. The ±30 min window used for analysis applied to all precipitation types reported within that window, even if the actual report time stamp was outside the window. To account for transitions in precipitation type, all distinct precipitation types reported within the window were retained. For example, if snow transitioned to rain within the hour, the matched ASOS/AWOS-identified precipitation type was both rain and snow. Additionally, as there can be multiple ASOS/AWOS sites matched to a FARS fatality, distinct precipitation types from all stations were also retained. This allowed precipitation-type inhomogeneity to be accounted for, where possible. Due to the limited spatial extent of precipitation types such as freezing rain and sleet (e.g., Reeves 2016), this may be important for precipitation transition events, where multiple precipitation types occur within a small spatial extent.

c. Matching FARS to ASOS/AWOS precipitation-type reports

We first analyzed both precipitation- and non-precipitation-related fatalities to assess the number of fatalities that occurred within 20 mi (32.2 km) of an ASOS/AWOS site. A contingency table similar to the ones in C18 was made (Table 1) to assess the utility of ASOS/AWOS precipitation reports for traffic crashes. Statistical measures such as sensitivity, specificity, accuracy, and Cohen’s kappa were computed as defined in Table 1. This first analysis assumed that FARS is of adequate quality to distinguish precipitation from nonprecipitation; however, the accuracy of specific precipitation types was then assessed as described below.

For precipitation-related fatalities, we defined a match percentage for each FARS-identified precipitation type. Matches for a given precipitation type occurred when both FARS and ASOS/AWOS identify the same precipitation types. A partial match was defined if any of the given FARS precipitation types match at least one of the reported ASOS/AWOS precipitation types. Precipitation-related fatalities were considered unverified if no precipitation types match between FARS and ASOS/AWOS. Match percentages were defined as the sum of full and partial matches, divided by the total number of fatalities that had accompanying ASOS/AWOS precipitation data (i.e., the sum of no precipitation, matches, partial matches, and unverified fatalities). This match percentage quantifies how well the two datasets agree for specific precipitation types, while allowing for spatial and temporal uncertainty and limitations of both databases through the inclusion of partial matches.

### 3. Analysis of FARS precipitation-related fatalities

The yearly and total fatalities analyzed from FARS are included in Table 2, with precipitation-related fatalities categorized further by precipitation type. In the 5-yr period used for this analysis, 178,384 vehicle-related fatalities occurred in the United States, with 15,378 (8.62%) occurring during active precipitation. Precipitation-related fatalities are further characterized
as liquid precipitation (rain), frozen precipitation (snow, sleet), freezing precipitation (freezing rain), and precipitation mixtures.

a. Precipitation-related fatality totals

Of the 15,378 precipitation-related fatalities, 12,475 (81.12%) were rain related, 2,211 (14.38%) were snow related, and the remaining 684 (4.45%) were attributed to sleet, freezing rain, and precipitation mixtures (Table 2). Although these remaining precipitation types constituted the smallest percentage of all precipitation-related fatalities, we sought to identify the differences among sleet, freezing rain, and precipitation mixtures. Nearly half of the remaining fatalities were sleet related, 34.06% were precipitation-mixture related, and freezing-rain-related fatalities accounted for 15.79% of the remaining fatalities. Interestingly, there were over 3 times as many sleet-related fatalities, and over 2 times as many precipitation-mixture-related fatalities as freezing-rain-related fatalities. Although there exists no climatology of precipitation mixtures, Cortinas et al. (2004) did a climatology of sleet and freezing precipitation, and found that freezing precipitation is more frequent than sleet, and that the duration of sleet at a given location is most often 2 h, whereas freezing precipitation is more likely to last longer. Reeves (2016) also found that, on average, freezing precipitation lasts 35–40 min at a location, whereas sleet lasts 10 min. Thus, in the context of typical sleet and freezing rain frequencies and durations, the significant difference in their related fatalities is even more striking given the seemingly inverse relationship between exposure and number of related fatalities.

The disproportionate number of sleet- versus freezing-rain-related fatalities was also evident in precipitation mixtures; the total number of sleet-mixture-related fatalities was 178, versus 124 freezing-rain-mixture-related fatalities, with 104 fatalities as the combination of sleet and freezing rain (Table 2). Sleet/freezing-rain-related fatalities represented 44.64% of all mixtures, and were as numerous as freezing-rain-only-related fatalities (Table 2). Although both precipitation types can be concurrent (e.g., Cortinas et al. 2004; Jones et al. 2004; Van Den Broeke et al. 2016; Tobin and Kumjian 2017), the large number of sleet/freezing-rain-related fatalities relative to snow/sleet-related fatalities is seemingly inconsistent with results from Cortinas et al. (2004). Those authors found that sleet occurs by itself only 30% of the time, whereas freezing precipitation occurs by itself 69%–73% of the time. Table 2 shows that sleet is reported by itself in FARS 65.83% of the time, and freezing rain is reported by itself 46.55% of the time when each precipitation type is reported as one of the atmospheric
condition attributes. This, again, indicates a discrepancy between FARS precipitation-type data and meteorological expectations. Cortinas et al. (2004) also found that sleet and snow are the two most frequent precipitation types to occur concurrently with freezing precipitation, and that sleet most often occurs with snow, followed by either freezing precipitation or rain. Again, the number of sleet- and freezing-rain-mixture-related fatalities does not agree with the climatology performed by Cortinas et al. (2004), as the number of sleet/freezing-rain-related fatalities far outnumbered any other mixture. Note that there is no physical basis for fatalities categorized with both rain and freezing rain; liquid precipitation impinging upon the road is either supercooled, freezing on impact (i.e., freezing rain), or it is not (i.e., rain).

Although rain dominates the number of precipitation-related fatalities over snow, only 33.05% of mixtures involve rain, versus 37.34% of mixtures involving snow, with 15.02% of all mixtures as the combination of rain and snow. Because mixed precipitation often occurs with winter precipitation transitions between rain and snow, it is unsurprising that both precipitation types occur at similar frequencies in the mixed precipitation category.

b. Roadway surface conditions

For each precipitation type in Table 2, the numbers of fatalities associated with each road surface conditions are shown in Table 3. For all precipitation types, wet roads dominate (81.64%), followed by snow (8.05%) and ice/frost (6.84%). To focus on winter precipitation types, we removed rain-related fatalities from these totals, indicating that the highest number of winter-precipitation-related fatalities occurred on snowy roads (41.95%), followed by ice/frost (32.17%) and wet (17.15%).

Next, we examined the impact of transitional precipitation types (defined here as sleet, freezing rain, and precipitation mixtures) by removing contributions of snow-related fatalities from the winter precipitation types. Precipitation-type transition regions are typically bounded by snow on one side and rain on another, and may include precipitation in the form of wet snow, rain and snow mixed, freezing precipitation, and sleet (e.g., Ackley and Itagaki 1970; Stewart 1992). Of the transitional-precipitation-related fatalities, 55.95% occurred on roads characterized as ice/frost, followed by 24.08% characterized as wet and 9.40% as snow.

Some unexpected discrepancies in FARS between precipitation types and roadway conditions are apparent in Table 3. For instance, there should not be dry road surface conditions during active precipitation (NHTSA 2017a), but are likely documented if precipitation has just begun, or is very light. Two additional discrepancies are road conditions of ice/frost for rain-related fatalities, and wet road conditions for freezing-rain-related fatalities. FARS only documents one attribute for roadway surface conditions, so it is not possible to identify situations of, for example, liquid water on top of ice. Such situations may occur if rain falls onto preexisting ice surfaces that have not fully melted; both phases may exist in equilibrium for $T_{\text{sfc}} \sim 0^\circ\text{C}$ and create roadway conditions different from either icy or wet surfaces. We speculate that first responders would likely identify the road here as ice/frost due to the slicker conditions of ice versus liquid. However, it is possible that atmospheric conditions of rain with ice/frost surface conditions are used instead of a freezing rain attribute. This may occur if a state’s police crash report does not have an option for freezing rain, and thus cannot be mapped to FARS as freezing.

<table>
<thead>
<tr>
<th>Precipitation type</th>
<th>Roadway surface condition</th>
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<tbody>
<tr>
<td></td>
<td>Dry</td>
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<td>Rain</td>
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<tr>
<td>Snow</td>
<td>31</td>
</tr>
<tr>
<td>Sleet</td>
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</tr>
<tr>
<td>Freezing rain</td>
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<tr>
<td>Rain/snow</td>
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<tr>
<td>Rain/sleet</td>
<td>0</td>
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<tr>
<td>Rain/freezing rain</td>
<td>0</td>
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<tr>
<td>Snow/sleet</td>
<td>0</td>
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<tr>
<td>Snow/freezing rain</td>
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<tr>
<td>Sleet/freezing rain</td>
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<tr>
<td>Transitional precipitation</td>
<td>2</td>
</tr>
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rain (NHTSA 2017b). Freezing-rain-related fatalities with wet roadway surface conditions likely have either the atmospheric or the roadway surface condition incorrectly attributed. The majority of rain/freezing-rain-related fatalities had ice/frost roadway conditions, suggesting freezing rain was the most likely atmospheric condition.

c. Climatology of precipitation-related fatalities

The location of vehicle-related fatalities during rain, snow, sleet, freezing rain, and precipitation mixture within the contiguous United States are plotted in the top panels of Figs. 1–5, with graduated circle sizes indicative of fatality numbers. Major roadways are also plotted, revealing that a large portion of the fatal crashes occurred along major roadways. This is expected, given that major roads tend to have higher vehicle speeds than minor roads, which can increase the risk of a fatal crash (e.g., Farmer 2017). Additionally, more fatalities occurred near locations with larger population densities, such as the eastern half of the United States, along the Pacific coastal regions, and clustered around large urban areas.

Rain-related fatalities occurred all over the United States, whereas snow-related fatalities occurred more prominently in northern regions (Fig. 1a). The general location of sleet- and freezing-rain-related fatalities corresponds well with locations from Cortinas et al. (2004) with >1 annual median day of sleet and freezing rain precipitation, respectively (Figs. 2a and 3a). Interestingly, there were several sleet-related fatalities reported outside of the outlined region in the western
portions of the United States, whereas very few freezing-rain-related fatalities lie outside the outlined region. Wintry precipitation mixtures were also mainly reported in similar regions (remember that the majority of precipitation mixtures were sleet and freezing rain), but several reports and even multiple fatality crashes lie west of the region, similar to sleet-related fatalities.

The percentage of all vehicle-related fatalities per month and the percentage of precipitation-related fatalities per month are included in Fig. 6. The annual distribution of vehicle-related fatalities is consistent with Ashley et al. (2015) where the percentages are higher during the warm season, coinciding with increased vehicle miles traveled versus cool season driving. The annual distribution of precipitation-related fatalities is inversely related, where precipitation-related fatalities occurred more frequently during the winter season, reaching a peak in December and a minimum in July. The average, minimum, and maximum number of fatalities that occurred in each month from 2013 to 2017 for rain, snow, sleet, freezing rain, and precipitation mixtures are shown in the lower panels of Figs. 1–5. The largest number of rain-related fatalities occurred between October and January; however, this period also shows the greatest variability in the number of fatalities, which may be attributed to interannual and regional variability of precipitation over the 5-yr period of study. For example, January 2014 had the lowest number of rain-related fatalities (136) versus January 2017 with the maximum (392). Precipitation in the western and southern portions of the United States in January 2014 was several inches below normal, whereas California and the South received above-normal amounts of precipitation in January 2017, leading to a noticeable clustering of rain-related fatalities in those regions during that month (not shown; water.weather.gov/precip). Possible reasons for the higher number of rain-related fatalities during winter months include increased travel for holidays and fewer hours of daylight. The change

Fig. 2. As in Fig. 1, but for snow-related fatalities (black circles/bars) from 2013 to 2017.
from daylight savings time to standard time can also have a temporary, but significant impact on motorists as they adjust to the abrupt shift in daylight hours (e.g., Sullivan and Flannagan 2002; Johansson et al. 2009). A secondary maximum in rain-related fatalities occurred between March and June, which is more typical of the annual precipitation profile for the United States with the most precipitation occurring during the warm season.

Unsurprisingly, winter-precipitation-related fatalities (e.g., snow, sleet, freezing rain, and mixtures) occurred most prominently during the winter months. At least one fatality occurred each year between November–May for snow and sleet, December–January for freezing rain, and November–March for precipitation mixtures (Figs. 2b, 3b, 4b, 5b). Most fatalities for each winter precipitation type occurred in December and January.

A kernel-density estimation of the probability distribution function of the local time of day all vehicle-related fatalities and individual precipitation-type related fatalities are presented in Fig. 7. The diurnal cycle of all vehicular fatalities is again consistent with Ashley et al. (2015), featuring two morning peaks around 0200 and 0700 LT, and a broader maximum in the midafternoon to evening hours. Rain-related fatalities were similarly aligned, most frequently occurring in the evening (~1900 LT), but with similar morning peaks. Other precipitation types had a bimodal distribution with a single morning and evening peak, making the dual morning peak for rain unique. Snow-related fatalities had a slight enhancement in the early morning hours similar to the first peak for rain-related fatalities, but the more prominent feature is the higher probability throughout the day, with slight enhancement between 0800 and 1000 LT, and again between 1600 and 1800 LT. These hours correspond to what are typically considered “rush hour” traffic periods. Similar trends existed for sleet- and precipitation-mixture-related
fatalities, with higher probability throughout the day, and only a slight enhancement in the morning (0800 LT) and early afternoon (1400 LT). Freezing-rain-related fatalities also exhibited a bimodal distribution, but with a significant enhancement between 0600 and 0800 LT, and less extreme probabilities later in the day (1800 LT). Though unique to freezing-rain-related fatalities, this result was expected given that freezing rain is more likely to occur in the morning than any other time of day (Cortinas et al. 2004), owing to the surface temperature minimum often occurring around sunrise. In contrast, Cortinas et al. (2004) found sleet to have less diurnal variability, which was consistent with the near-constant probability for sleet-related fatalities during daytime hours.

The timing of precipitation-related fatalities is a convolution of human behavior and meteorological factors. Interestingly, there is a spread in the peak hours of the different precipitation-related fatalities, for example, between 0600 and 1000 LT and 1400 and 2000 LT for the morning and evening peaks, respectively. It is possible that a limited number of fatalities for each precipitation type is slightly skewing the results, and that more data may result in the morning and evening peak distributions moving closer to those for all vehicle-related fatalities. However, it is also plausible that the distinct precipitation types may alter human driving behavior, resulting in the disparity in peak hours observed. For example, motorists may elect to drive earlier or later than usual to account for different precipitation types (e.g., Barjenbruch et al. 2016), thus altering the peak driving hours typically observed.

4. Assessment of nearby precipitation-type reports

a. Precipitation- versus non-precipitation-related fatalities

The first analysis was to determine the accuracy of ASOS/AWOS to distinguish precipitation and
nonprecipitation in the context of FARS and assess the overall agreement of the databases (Table 4). This analysis also provided a test of the methods to determine how many fatalities occurred within 20 mi (32.2 km) of an ASOS/AWOS site and how many entries were discarded owing to the inability of a station to report precipitation type. Of the 15,209 precipitation-related fatalities, 12,984 (85.37%) occurred within 20 mi (32.2 km) of an ASOS/AWOS station, compared to 139,388 (86.72%) of the 160,725 non-precipitation-related fatalities. No data were available for 8.29% of matched precipitation-related fatalities, and for 8.30% of matched non-precipitation-related fatalities. Notably, whereas 18.20% of precipitation-related fatalities matched to ASOS/AWOS sites reporting no precipitation, precipitation was only reported for 6.23% of non-precipitation-related fatalities.

To test the sensitivity of our spatial analysis, we restricted the spatial threshold to 5 mi (8.0 km), and only 20.98% of precipitation-related fatalities matched to a nearby ASOS/AWOS site. No data were available for 15.07% of matched fatalities, higher than the 20 mi (32.2 km) range due to a fewer number of matching sites per fatality increasing the likelihood that matched sites were unable to report precipitation type. Given the closer proximity, 17.89% of the matched fatalities had no precipitation reported nearby, showing no significant improvement over the 20 mi (32.2 km) distance threshold. This result highlights the fact that the sensors typically cannot detect rain falling at a rate of <0.01 in. h$^{-1}$, snow that increases very gradually, and any precipitation that occurs during a power failure will not be detected (NOAA 1998).

The sensitivity (80.15%) and specificity (93.21%) indicate that ASOS/AWOS are capable of distinguishing precipitation and nonprecipitation for any FARS condition. The accuracy is also high (92.10%), confirming that the systems have the ability to provide a reliable account of precipitation conditions near fatal
vehicle-related crashes. The Cohen’s kappa value (0.59) shows that FARS and ASOS/AWOS data have a moderate agreement up to 20 mi (32.2 km), consistent with C18 for all adverse weather conditions.

b. Precipitation-related fatalities

Of the 15,370 categorized precipitation-related fatalities in Table 2, 15,178 (98.75%) had valid latitude, longitude, date, or time entries in FARS and were retained for further analysis. These fatalities are included in Table 5, categorized by precipitation type and by how they matched to nearby ASOS/AWOS stations and precipitation-type reports. The match percentage of each FARS-identified precipitation is also included. The 76.80% match percentage for all precipitation-related fatalities indicates a high degree of confidence for ASOS/AWOS to identify precipitation types documented in FARS correctly. Rain-related fatalities had a 79.07% match percentage, which dominated the high match percentage for all precipitation types. Winter-precipitation-related fatalities (i.e., excluding rain-only-related fatalities) had a reduced match percentage of 65.42%, primarily dominated by snow-related fatalities (77.87% match percentage). Fatalities related to transitional precipitation types (i.e., sleet-, freezing-rain-, and precipitation-mixture-related fatalities) had only a 25.37% match percentage. The lowest match percentages of the single precipitation types were for sleet

Fig. 6. Percentage of all vehicle-related fatalities (gray) by month, and the percentage of all vehicle-related fatalities that are precipitation-related (black) by month for 2013–17.

Fig. 7. Kernel-density estimation of the diurnal probability distribution function of all vehicle-related fatalities (gray dashed) and precipitation-related fatalities related to rain (green), snow (black), sleet (purple), freezing rain (blue), and precipitation mixtures (pink) for 2013–17.
(8.47%) and freezing rain (26.58%), whereas sleet/freezing-rain-mixture-related fatalities had a 24.24% match percentage. Remaining precipitation mixtures had match percentages >44% largely owing to partial matches with ASOS/AWOS reports of rain or snow.

The low match percentages for sleet-related fatalities were expected given that ASOS/AWOS systems are unable to report sleet unless augmented by a human observer. It was surprising that freezing-rain-related fatalities also had a low match percentage. Undetected freezing drizzle may be partially responsible for the reduced match percentage: it has lower precipitation intensity than freezing rain, and ASOS/AWOS cannot detect precipitation rates <0.01 in. h⁻¹ (NOAA 1998). Another explanation for the reduced match percentages is the fact that ASOS/AWOS systems are located 2 m above the surface; temperature differences between the sensors and the roadways are possible.

### 5. Discussion

There is approximately a 3:1:2 ratio of the number of sleet- to freezing-rain- to precipitation-mixture-related fatalities. The significant difference between the numbers of sleet- and freezing-rain-related fatalities counters the perception that freezing precipitation is more dangerous than frozen precipitation; one expects the number of freezing-rain-related fatalities to outnumber those associated with sleet. This counterintuitive finding may be attributable to a number of explanations. First, it is possible that sleet is over-reported in FARS, or that freezing rain is under-reported. We speculate that both human error and limitations of state-specific accident reports may be responsible for these potential biases. For example, graupel (i.e., heavily rimed snowflakes, or “snow pellets”) may be mistaken as sleet by first responders. Indeed, a number of sleet-related fatalities had snowy road surface conditions. Sleet also has alternative definitions in Europe and colloquially in the United States (where it means a rain/snow mixture), which could lead to mistaken reporting. Evidence for this can be found in the roadway surface conditions of wet or slush for sleet-related fatalities. Similarly, the number of rain-related fatalities with ice/frost road surfaces suggests that some of these may actually be freezing-rain-related fatalities. Freezing rain can only be reported in FARS if the police accident report specifies freezing rain as an atmospheric condition or within the accident description. If a state does not have

### Table 4. Contingency table and statistical measurements of FARS and ASOS/AWOS precipitation data for 2013–17.

<table>
<thead>
<tr>
<th>ASOS/AWOS</th>
<th>Total</th>
<th>No ASOS/AWOS</th>
<th>No Data</th>
<th>Precipitation</th>
<th>No precipitation</th>
<th>Statistical measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>FARS Precipitation</td>
<td>15209</td>
<td>2225</td>
<td>1077</td>
<td>9544</td>
<td>2363</td>
<td>Sensitivity: 80.15%</td>
</tr>
<tr>
<td>No precipitation</td>
<td>160725</td>
<td>21337</td>
<td>11575</td>
<td>8680</td>
<td>119133</td>
<td>Specificity: 93.21%</td>
</tr>
<tr>
<td>PPV: 52.37%</td>
<td>NPV: 98.06%</td>
<td>Accuracy: 92.10%</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Cohen’s kappa: 0.5914

### Table 5. Total number of precipitation-related fatalities with valid latitude, longitude, date, and time attributes to match with ASOS/AWOS station reports, separated by precipitation type. Fatalities that did not occur within 20 mi (32.2 km) of an ASOS/AWOS station are in the “no ASOS/AWOS” column. Remaining fatalities are categorized by matching to ASOS/AWOS sites with: 1) no data available; 2) no precipitation reported; 3) fully matching precipitation types; 4) partially matching precipitation types; or 5) nonmatching (e.g., unverified) precipitation types. The match percentage (defined in section 2c) is computed for each FARS-identified precipitation type.

<table>
<thead>
<tr>
<th>Precipitation type</th>
<th>Total</th>
<th>No ASOS/AWOS</th>
<th>No data</th>
<th>No precipitation</th>
<th>Match</th>
<th>Partial</th>
<th>Unverified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>12330</td>
<td>1576</td>
<td>849</td>
<td>1963</td>
<td>7570</td>
<td>262</td>
<td>110</td>
</tr>
<tr>
<td>Snow</td>
<td>2172</td>
<td>491</td>
<td>172</td>
<td>280</td>
<td>1010</td>
<td>165</td>
<td>54</td>
</tr>
<tr>
<td>Sleet</td>
<td>339</td>
<td>73</td>
<td>30</td>
<td>56</td>
<td>1</td>
<td>19</td>
<td>160</td>
</tr>
<tr>
<td>Freezing rain</td>
<td>108</td>
<td>25</td>
<td>4</td>
<td>27</td>
<td>6</td>
<td>15</td>
<td>31</td>
</tr>
<tr>
<td>Rain/snow</td>
<td>34</td>
<td>8</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>Rain/sleet</td>
<td>39</td>
<td>9</td>
<td>4</td>
<td>5</td>
<td>0</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Rain/freezing rain</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Snow/sleet</td>
<td>39</td>
<td>13</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>17</td>
<td>4</td>
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<tr>
<td>Snow/freezing rain</td>
<td>11</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Sleet/freezing rain</td>
<td>97</td>
<td>20</td>
<td>11</td>
<td>15</td>
<td>1</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>All precipitation</td>
<td>15178</td>
<td>2219</td>
<td>1076</td>
<td>2357</td>
<td>8592</td>
<td>534</td>
<td>400</td>
</tr>
<tr>
<td>Winter precipitation</td>
<td>2848</td>
<td>643</td>
<td>227</td>
<td>394</td>
<td>1022</td>
<td>272</td>
<td>290</td>
</tr>
<tr>
<td>Transitional precipitation</td>
<td>676</td>
<td>152</td>
<td>55</td>
<td>114</td>
<td>12</td>
<td>107</td>
<td>236</td>
</tr>
</tbody>
</table>
freezing rain as an option, however, it cannot be mapped to the proper FARS attribute (NHTSA 2017b).

A second possibility is that, although freezing rain may occur more frequently than sleet and for a longer duration, spreading treatments (e.g., salt) on roadways or warmer road surfaces compared to surrounding surfaces may prevent an ice glaze from forming on the road. Thus, freezing rain may not occur as readily on roads as it does on other surfaces, such as overhead wires or tree limbs. Accounting for such differences would require specific information about the roadway surface type, temperature, and recent spreading treatments. Third, it is possible that the known dangers of freezing rain have altered driver behavior significantly (e.g., reducing speeds owing to limited traction or deterred traveling) and consequently reduced the number of fatal crashes during freezing precipitation. This may not be true for sleet, as drivers may not be as cautious as they are in freezing rain. If the precipitation types included in FARS were accurate, the discrepancy in the total number of sleet- and freezing-rain-related fatalities would then indicate that freezing rain has a significantly lower relative risk of fatality than sleet. This result would be striking, but not unprecedented as reduced vehicle speeds have a partially offsetting impact on the relative risk of fatality during adverse weather conditions (e.g., Qiu and Nixon 2008; Strong et al. 2010).

6. Summary and conclusions

FARS contains information on prevailing atmospheric conditions at the time of a fatal vehicle-related crash, including precipitation type. Approximately 8.6% of crash fatalities on U.S. roadways in 2013–17 occurred during active precipitation. Of these precipitation-related fatalities, 81% involved rain, 14% involved snow, and the remaining 5% involved sleet, freezing rain, or precipitation mixtures. Roadway surface conditions were primarily wet for precipitation-related fatalities, snow for winter precipitation, and ice/frost for transitional winter precipitation (e.g., sleet, freezing rain, and wintry precipitation mixtures), which is consistent with expectations. The locations of precipitation-related fatalities are also consistent with expectations: rain-related fatalities were heavily concentrated along coastal regions and the eastern half of the United States, whereas snow-related fatalities occurred primarily in northern regions. Sleet-, freezing-rain-, and wintry-precipitation-mixture-related fatalities primarily occurred in regions with >1 median day yr\(^{-1}\) of sleet or freezing rain as identified by Cortinas et al. (2004), though others occurred in western portions of the United States where sleet and freezing rain occur less frequently according to those authors.

Vehicle-related fatalities occurred most frequently during the warm season, whereas precipitation-related fatalities occurred most often during the cool season. Although the most snow-, sleet-, freezing-rain-, and precipitation-mixture-related fatalities occurred during the cool season (as expected), rain-related fatalities also were most numerous in the cool season and exhibited the most variability within the 5-yr study period. It is unclear if the large number of cool-season rain-related fatalities is a persistent feature, or if it resulted from unseasonably wet conditions for particular geographic locations, for example. This highlights a limitation of the relatively short study period; additional years of data would be required to establish a more comprehensive climatology. Additionally, this study analyzed the data on a national scale, whereas regional analyses may be beneficial to assess annual distributions of fatalities further.

Vehicle-related fatalities are most likely to occur during the second half of the day, although there are peaks during both morning and evening periods roughly associated with rush-hour traffic times and another early morning (~0200 LT) period. Rain-related fatality distributions closely resemble the distribution for all vehicle-related fatalities, whereas other precipitation types have a broad daytime distribution, with only slightly elevated single morning and evening peaks. The enhanced morning peak in freezing-rain-related fatalities is consistent with freezing precipitation occurring most frequently in the morning hours when the surface temperature is often at a minimum prior to sunrise.

To determine the relative risk of specific precipitation types on fatal vehicle crashes, it is important to identify the precipitation type at the time of a fatal crash correctly. Recent changes to FARS now allow precipitation types at the time to assess precipitation type. We found that >85% of all vehicle-related fatalities within FARS from 2013 to 2017 occurred within 20 mi (32.2 km) of an ASOS/AWOS station. Of these fatalities, 8.3% corresponded to stations that were not capable of reporting precipitation types and defined a ±30-min window from the crash time to assess precipitation type. We found that >85% of all vehicle-related fatalities within FARS from 2013 to 2017 occurred within 20 mi (32.2 km) of an ASOS/AWOS station. Of these fatalities, 8.3% corresponded to stations that were not capable of reporting precipitation types. No precipitation was reported for 18.8% of these precipitation-related fatalities, and precipitation was reported for 6.2% of
non-precipitation-related fatalities. With a sensitivity of 80.2% and specificity of 93.2%, ASOS/AWOS systems are highly capable of distinguishing precipitation and nonprecipitation for FARS data. A Cohen’s kappa value of 0.59 indicates that ASOS/AWOS data have a moderate agreement up to 20 mi (32.2 km) for precipitation conditions, similar to the results of C18.

Precipitation identified in FARS corresponded well to ASOS/AWOS-reported precipitation types, with a 76.8% match percentage for all precipitation types. Keeping in mind that ~19% of the matched fatalities had reports of no precipitation, precipitation types identified by both FARS and ASOS/AWOS are overall likely to match each other. This holds true for rain and snow, with match percentages of 79.1% and 77.9%, respectively. Remaining transitional precipitation types (i.e., sleet, freezing rain, and precipitation mixtures) had only a 25.4% match percentage. Although it was expected that sleet-related fatalities would have a low match percentage (8.5%) owing to the limited ability of ASOS/AWOS systems to report sleet, the low match percentage for freezing rain (26.6%) was not anticipated. This latter result potentially highlights the prevalence of freezing drizzle in fatal crashes that is not as easily detected with ASOS/AWOS systems, and differences between freezing rain detection at sensor height (2 m above the ground) and conditions observed on road surfaces, which may be treated and/or warmer than the air. Thus, we conclude that ASOS/AWOS system information can be used to support future research of rain- and snow-related fatalities, but further work is needed for other precipitation types.

We showed possible biases within FARS, so one should use caution when using FARS to identify precipitation type. Conversely, limitations exist in the ASOS/AWOS networks to identify sleet, freezing rain, and precipitation mixtures. To provide an accurate account of precipitation type for fatal vehicle crashes, we suggest combining both precipitation-type sources and only analyzing those that have FARS-identified precipitation types confirmed by nearby ASOS/AWOS sensors. Although these methods invariably will reduce the total number of fatalities analyzed, it may still yield an appropriate number of crashes to analyze the risk of crash and injury until enough fatality data are available in FARS. There is evidence that precipitation type is a factor in determining the risk of crash, as highlighted by the disparate time of day that precipitation-related fatalities occur when separated by precipitation type, where freezing rain is most prominent during the morning hours both meteorologically and in the fatality data. The ultimate goal of our future research is to quantify the relative risks of vehicle crash, injury, and fatality associated with different precipitation types, following Black and Mote (2015b), with specific emphasis on sleet versus freezing rain. This research would be valuable because, although sleet and freezing rain may form in similar atmospheric conditions, the impacts for motorists may be substantially different. Given the low match percentage for freezing-rain-related fatalities, it would be worthwhile to investigate the conditions conducive to freezing rain on road surfaces. For example, the onset of freezing rain on roads likely has a complicated relationship with ambient and surface temperature, precipitation rate, or type of spreading treatment used.

Road Weather Information System (RWIS) data are desired to obtain precipitation and temperature information at the road surface to investigate freezing rain, and other precipitation types. Unfortunately, national RWIS data are limited in availability because only certain states archive data for public access. Road-surface-temperature models should also be used to distinguish freezing rain from rain on the roadway. Case studies of widespread winter precipitation may also be used to assess inaccuracies in FARS by utilizing polarimetric radar, temperature profiles, and model output to infer precipitation type.

With an understanding of the risks associated with specific precipitation types, and improved forecast accuracies for the timing and extent of specific precipitation types, motorists and officials can make informed decisions. Motorists may elect to alter their driving patterns or habits in adverse weather conditions, or choose to delay or cancel travel. Similarly, officials can devise appropriate strategies for preventative measures such as when and where to deploy plows, apply spreading treatments, alert motorists with signage, and post restricted speed limits.

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