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An Observational Study of Winter Weather-Related Traffic Crashes in Nebraska

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AN OBSERVATIONAL STUDY OF WINTER WEATHER-RELATED TRAFFIC CRASHES IN NEBRASKA

by

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University of Nebraska, 2019

Advisor: Mark R. Anderson

The responsibilities of meteorologists have evolved over time from simply providing a forecast to needing to also understand how those predictions will impact society and then communicating those risks in a clear, concise, and consistent manner. Increased motor vehicle crash numbers due to adverse weather conditions represent one such impact worthy of further study. Snowfall, in particular, significantly increases the overall risk of a crash, which can result in extensive property damage, severe injuries, and even loss of life.

This project seeks to supplement traffic crash information in Nebraska by assessing how snowfall impacts crashes across the state. Crash data were obtained from the Nebraska Department of Transportation (NDOT) for the years 2007 through 2017. Total number of crashes, injuries, and fatalities are first evaluated temporally by year, month, day of week, and time of day. Crashes with snow reported by the investigating official as the primary or secondary weather condition were then identified. Variations between snow-related crashes and all crashes were calculated to identify how snowfall affects temporal crash distributions. It was found that snow-related crashes increase crash totals on weekends as well as during the morning hours relative to all crashes. The spatial distribution of snow-related crashes was also assessed at the individual crash, county, and NDOT district locations. The versatility of the newly developed Nebraska Winter

Severity Index (NEWINS) is also evaluated to determine its utility for determining how different winter storm severities impact snow-related crash totals. Furthermore, the individual meteorological variables that go into creating the NEWINS are also assessed. In general, it was found using the NEWINS that longer duration, larger winter storms caused the highest number of crashes. In addition, winter events with higher snowfall totals and lower visibilities also resulted in higher crash totals. Lastly, high impact crash days were identified from daily crash totals and the occurrence of multi-vehicle chain-reaction crashes, the largest of which resulted in a 31-car pileup. This project seeks to provide insight into when and where Nebraskans are typically at greater risk of a crash due to winter weather conditions.

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Chapter 1: INTRODUCTION

In 2017 alone, motor vehicle crashes resulted in over 1.8 million injuries and over 34,000 fatalities across the United States (National Highway and Traffic Safety Administration (NHTSA) 2019). In fact, motor vehicle crashes are the leading cause of death for persons under the age of 24 (NHTSA 2018). The state of Nebraska had an average of 16,868 injuries and 216 fatalities per year over the past decade from traffic crashes (Nebraska Department of Transportation (NDOT) 2019a). Moreover, inclement weather conditions make up about 24% of traffic incidents across the U.S. (Pisano et al. 2008). As the weather community continues its efforts to increase consistency in their messaging and work toward providing improved Decision Support Services (DSS) to build a Weather Ready Nation (Uccellini and Hoeye 2019), it is becoming increasingly necessary for forecasters to not only understand how to predict the weather and also the consequences of those forecasts. Forecasters need to be aware of a prediction's impact across multiple sectors, including the risk of traffic crashes, using every tool at their disposal to get the message out to increase public awareness of when conditions become hazardous for drivers. For instance, if people are not aware of large hail in a thunderstorm moving across the interstate, or a quick bust of snow moving through causing sudden reductions in visibility, they may not take the appropriate protective actions.

The Nebraska Department of Transportation (NDOT) has taken several steps in recent years to tackle some of the challenges of weather's impact on traffic collisions across the state, even hiring a full-time meteorologist in 2016 (Jesse Schulz 2018, personal communication). They have also mounted live cameras on snow plows for the general public to access to provide increased awareness of current snow conditions (NDOT 2019c). They have also implemented a Maintenance Decision Support System (MDSS), to cut down on maintenance costs as well as provide improved weather information to maintenance and snow-plow crews (Barnhardt 2019). In addition, NDOT has partnered with researchers at the University of Nebraska-Lincoln on several projects, including the recent development the Nebraska Winter Severity Index (NEWINS) to classify individual winter events as well as entire winter seasons by their overall severity level (Walker et al. 2019). In collaboration with the National Weather Service (NWS), NDOT also adopted the Pathfinder program in 2018 in an effort to take weather forecasts and expected road conditions into a consistent message about impacts for the general public (Federal Highway Administration (FHWA) 2016, National Weather Service (NWS) 2018a). The combination of these efforts should help increase awareness of hazardous driving conditions and potentially reduce the risk of weather-related crashes across the state.

To complement these efforts by NDOT, using detailed crash information obtained for the years 2007 through 2017, this study seeks to add to the current understanding of traffic crashes in the state of Nebraska. Crashes, injuries, and fatalities will be assessed both temporally and spatially, with an emphasis on snow-related incidents. Furthermore, one of the primary objectives of this research is to assess the utility of existing transportation department tools that can be expanded upon to evaluate snow-related crash risk. This will be done with the NEWINS by assessing crashes based on winter storm severity as well as each of the seven weather variables that combine to create the NEWINS.

In addition to major winter storms that drop several inches of snow, even snowfall events receiving less than 1 inch (2.54 cm) of snow have been found to cause significant impacts on travel (DeVoir 2004). Moving rapidly in quick bursts or squalls, these snow events can cause sudden reductions in visibilities, making driving hazardous without much snow accumulation taking place. DeVoir (2004) refers to these types of events as high impact, sub-advisory (HISA), in part, because they typically do not meet official NWS winter weather advisory criteria. Thus, high impact crash days are also identified, including days with the highest number of crashes as well as days with large multi-vehicle pileups. This is done to help determine which weather conditions typically cause the state’s most hazardous travel days.

Chapter 2: BACKGROUND

2.1 Motor Vehicle Crashes

The National Highway and Traffic Safety Administration (NHTSA) publishes several reports on country-wide traffic statistics each year. The NHTSA has two separate departments that conduct the detailed motor vehicle crash research, known as the Office of Vehicle Safety Research and the Office of Behavioral Safety Research (NHTSA 2019). In addition, state departments of transportation, including the Nebraska Department of Transportation (NDOT), create their own annual and monthly reports summarizing various traffic crash statistics across their state (NDOT 2019a). These reports form the basis for decision making on future roadway projects, safety messaging and more.

Traffic studies are not limited to government departments. University researchers have conducted a wide array of studies dissecting various aspects of traffic crash data. For instance, temporal studies similar to this project have been conducted to assess how crashes vary by year, month, day of week (DOW), and time of day (TOD) (Edwards 1999, Farmer and Williams 2005, Sivak 2009, Weast 2018). Others have focused on the economic and societal impacts of traffic crashes (e.g. Blincoe et al. 2015). Some have looked into driver behavior, such as video studies of traffic (e.g. Fu et al. 2015) and utilizing social media to detect traffic crashes in real time (e.g. Zhang et al. 2018).

There are a myriad of variables included in traffic crash reports that can be considered for study, including driver specific data (e.g. age, gender, vehicle type), roadway characteristics (e.g. road classification, surface type), as well as weather conditions. Much of the previous traffic crash literature has focused heavily on crashes resulting in severe injuries and fatalities. This has been aided by NHTSA'S accessible Fatality Analysis Reporting System (FARS), a database of all vehicle-related fatalities across the United States (NHTSA 2019). Motor vehicle crash research is not limited to the United States, with studies on traffic crashes conducted across Europe (e.g. Perrels et al. 2015), Southeast Asia (e.g. Hu et al. 2011), and the Middle East (e.g. Dastoorpoor et al. 2016).

2.2 Winter-Weather Crashes

Adverse weather-related traffic crashes account for as much as 24% of all traffic crashes in the United States (Pisano et al. 2008) and 13.1% of all Nebraska crashes between 2007-2017 (NDOT 2018). Winter weather is especially dangerous, often resulting in very slick roadways. An average of 688 fatalities from crashes occur each year across the U.S. due to winter weather conditions, which is more than all other official weather hazards combined (Figure 2.1; FHWA 2019, NWS 2019). For example, between 2007 and 2016, there were only on average 28 fatalities per year directly attributed to winter storms (NWS 2019). Black and Mote (2015a) argue that fatalities that occur from winter weather-related crashes do not receive adequate attention from the weather community since they are considered indirect and not reported in official *Storm Data*. Some studies have looked at how weather conditions impact road usage (e.g. Eisenberg and Warner 2005, Cools et al. 2010) and found significant reductions in traffic intensity during winter weather conditions. This reduction in speed, in turn, can

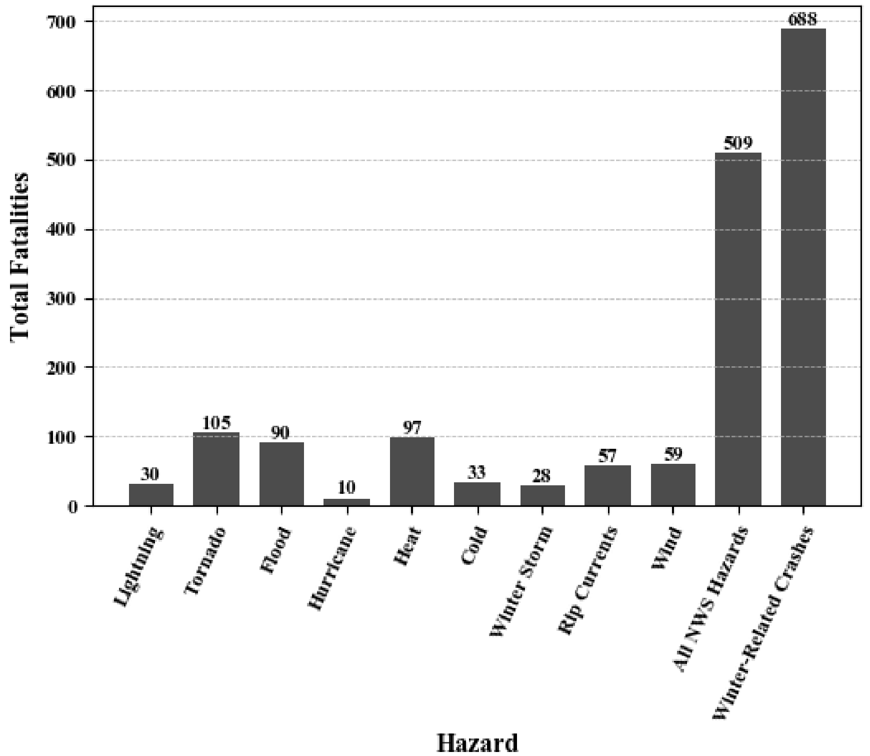


Figure 2.1: Average number of fatalities per year for several meteorological hazards between 2006 and 2017 (numbers taken from FHWA 2019 and NWS 2019).

help reduce the overall severity of a crash. When accounting for these reduced traffic volumes, Black and Mote (2015b) found that snowfall can increase crash rates by as much as 84 percent, while only increasing fatality rates by 9%. Others have looked into modelling as a means of predicting future crashes (Shaheed et al. 2016).

2.3 Multi-Vehicle Crashes

Some crashes result in dangerous chain-reaction crashes also referred to as multi-vehicle crashes. Call et al. (2018) define multi-vehicle crashes as a series of collisions related to one another. These crashes often occur with a single crash that stops the flow of traffic which then causes additional crashes when motorists are unable to stop in time, especially when visibility is low (Call et al. 2018). They use the minimum criterion of 10 vehicles in their analyses to define a significant multi-vehicle crash, although some multi-vehicle crashes across the U.S. have involved hundreds of vehicles. These types of crashes are often the result of reduced visibilities, with 25% of crashes studied by Call et al. (2018) occurring under snow or blowing snow conditions.

Work that initially inspired this project considers the underestimated impacts involving seemingly lower-end HISA winter weather events, including quick moving snow squalls (DeVoir 2004). The sudden reductions in visibility and rapidly deteriorating road conditions under these snow squalls have been known to cause significant traffic pileups, despite only a trace to a couple inches of snow accumulating (DeVoir 2004). Call et al. (2018) also found when looking at radar signatures that snowfall rates often increased rapidly within one hour before a large multi-vehicle crash. This is consistent with HISA events described by DeVoir (2004). It has also been found that risk for multi-vehicle crashes is increased during high traffic volume periods, especially evening rush hours (Black and Mote 2015a). HISA snow events present a unique communication challenge that the weather and transportation communities are working toward addressing. In 2018, partially in response to the work of DeVoir (2004), the NWS has implemented a new Snow Squall Warning product, similar to other short fused warnings (e.g. Thunderstorm, Tornado, and Flash Flood Warnings), that send alerts over the Emergency Alert System to the public (NWS 2018b). Until the number of weather-related injuries and fatalities can be reduced significantly, additional study is necessary to provide forecasters and decision makers additional information to help protect lives and property.

2.4 NEWINS

NDOT has been taking a rather proactive approach to reduce the number of winter weather-related crashes in the state. On average, Nebraska receives over 40 in. (101.6 cm) of snow in the western Panhandle per snow season (Figure 2.2). Snow season totals generally decrease in areas south and east of there, with the southeastern corner of the state only receiving around 20 in. (50.8 cm) of snowfall per winter season on average. With the goal of reducing the number of motor vehicle crashes and fatalities in mind, one potential avenue of winter weather-related crash research worth exploring is the versatility of existing state transportation department tools to provide additional information on crash risk and how they can apply differently to aid efforts to reduce the number of crashes that occur.

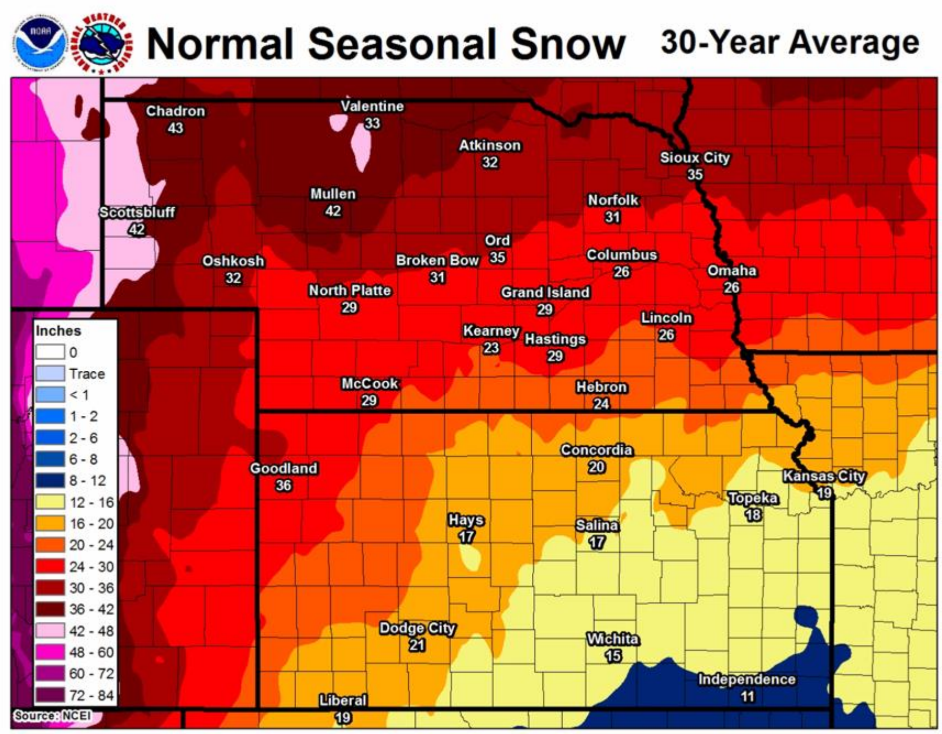
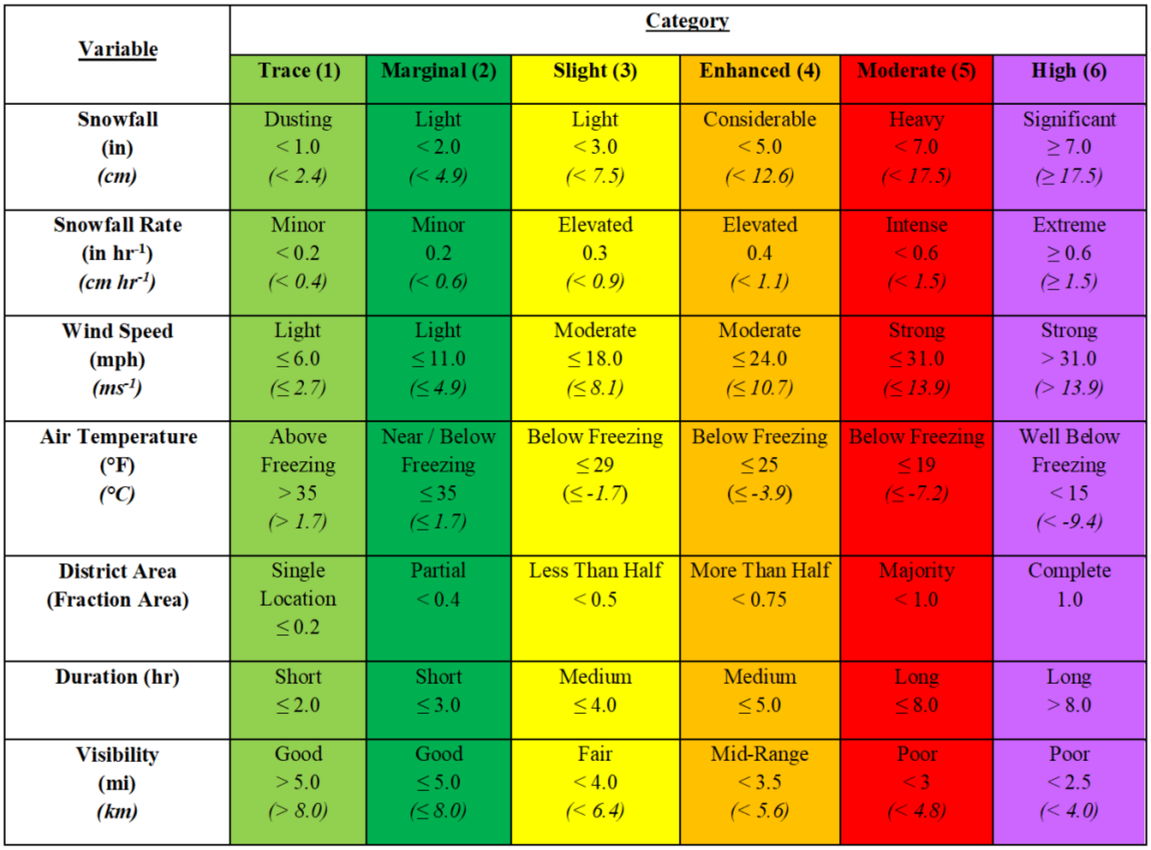


Figure 2.2: 30-year averaged seasonal snowfall totals for the state of Nebraska (taken from NWS 2017).

To accomplish this goal, a recently developed Winter Severity Index for NDOT, known as the Nebraska Winter Severity Index (NEWINS) (Walker et al. 2019), will be assessed for this study. The NEWINS is a categorical storm classification framework that considers both atmospheric conditions and road impacts in its development. It separates winter storms into specific categories ranging from 1 to 6, similar to the system the Storm Prediction Center implemented for their severe weather outlooks (SPC 2016). It was developed with NDOT road weather and maintenance needs in mind using seven meteorological parameters determined essential to measuring winter storm impacts, including wind speed, snow rate, snowfall duration, snowfall totals, air temperature, visibility, and district area (Walker et al. 2019). Each of these variables are also classified into the six categories depending on their expected impact to roadway maintenance operations which are used for the weighted equation to compute the NEWINS (Table 2.1). Since the NEWINS is a relatively new framework for assessing winter storm severity in Nebraska, this study will be the first to assess how it might help expand the current understanding of motor vehicle crashes, injuries, and fatalities statistics in the state of Nebraska.

Table 2.1: NEWINS weather variable categorical classifications obtained from district-wide averages of each weather variable during the periods of observed snowfall (taken from Walker et al. 2019).



Variable	**Category**					
	Trace (1)	**Marginal (2)**	**Slight (3)**	**Enhanced (4)**	**Moderate (5)**	**High (6)**
Snowfall **(in)** ***(cm)***	Dusting < 1.0 *(< 2.4)*	Light < 2.0 *(< 4.9)*	Light < 3.0 *(< 7.5)*	Considerable < 5.0 *(< 12.6)*	Heavy < 7.0 *(< 17.5)*	Significant ≥ 7.0 *(≥ 17.5)*
Snowfall Rate **(in hr^{-1})** ***(cm hr^{-1})***	Minor < 0.2 *(< 0.4)*	Minor 0.2 *(< 0.6)*	Elevated 0.3 *(< 0.9)*	Elevated 0.4 *(< 1.1)*	Intense < 0.6 *(< 1.5)*	Extreme ≥ 0.6 *(≥ 1.5)*
Wind Speed **(mph)** ***(ms^{-1})***	Light ≤ 6.0 *(≤ 2.7)*	Light ≤ 11.0 *(≤ 4.9)*	Moderate ≤ 18.0 *(≤ 8.1)*	Moderate ≤ 24.0 *(≤ 10.7)*	Strong ≤ 31.0 *(≤ 13.9)*	Strong > 31.0 *(> 13.9)*
Air Temperature **(°F)** ***(°C)***	Above Freezing > 35 *(> 1.7)*	Near / Below Freezing ≤ 35 *(≤ 1.7)*	Below Freezing ≤ 29 *(≤ -1.7)*	Below Freezing ≤ 25 *(≤ -3.9)*	Below Freezing ≤ 19 *(≤ -7.2)*	Well Below Freezing < 15 *(< -9.4)*
District Area **(Fraction Area)**	Single Location ≤ 0.2	Partial < 0.4	Less Than Half < 0.5	More Than Half < 0.75	Majority < 1.0	Complete 1.0
Duration (hr)	Short ≤ 2.0	Short ≤ 3.0	Medium ≤ 4.0	Medium ≤ 5.0	Long ≤ 8.0	Long > 8.0
Visibility **(mi)** ***(km)***	Good > 5.0 *(> 8.0)*	Good ≤ 5.0 *(≤ 8.0)*	Fair < 4.0 *(< 6.4)*	Mid-Range < 3.5 *(< 5.6)*	Poor < 3 *(< 4.8)*	Poor < 2.5 *(< 4.0)*

Chapter 3: DATA AND METHODOLOGY

3.1 Study Region and Data

The state of Nebraska serves as the study region for this project. It is situated within the Great Plains region of the United States and has an approximate surface area of 77,358 square miles (200356.3 km^2). It is divided by two time zones, mountain time in western portions of the state (primarily the Panhandle), and central time in central and eastern portions of the state. The state is also transected from east to west by Interstate-80, a major transcontinental freeway, and serves as one of the main thoroughfares for transporting goods and people across the state. The official population of Nebraska as of the 2010 census was 1,826,341, with most people residing in eastern portions of the state and areas along Interstate-80, includes the state's two most populous cities of Omaha and Lincoln. This population distribution is important when evaluating people driven data, such as traffic crashes. Nebraska is further divided into 93 individual counties ranging in size from 247 mi^2 (639.7 km^2) in Sarpy County to over 6000 mi^2 (15539.9 km^2) in Cherry County. These county boundaries serve as guidelines, with some minor exceptions, for NDOT, which divides the state into eight separate districts (Figure 3.1) to delineate areas that are responsible for their own road maintenance, construction operations, snow plows, and staffing (NDOT 2019c, Walker et al. 2019).

In an attempt to better understand how snow-related crashes occur across Nebraska, traffic crash data were obtained from NDOT for all reported crashes beginning 1 January 2007 through the end of 2017 (NDOT 2018). All data from NDOT were compiled from individual crash reports submitted by state and local law enforcement

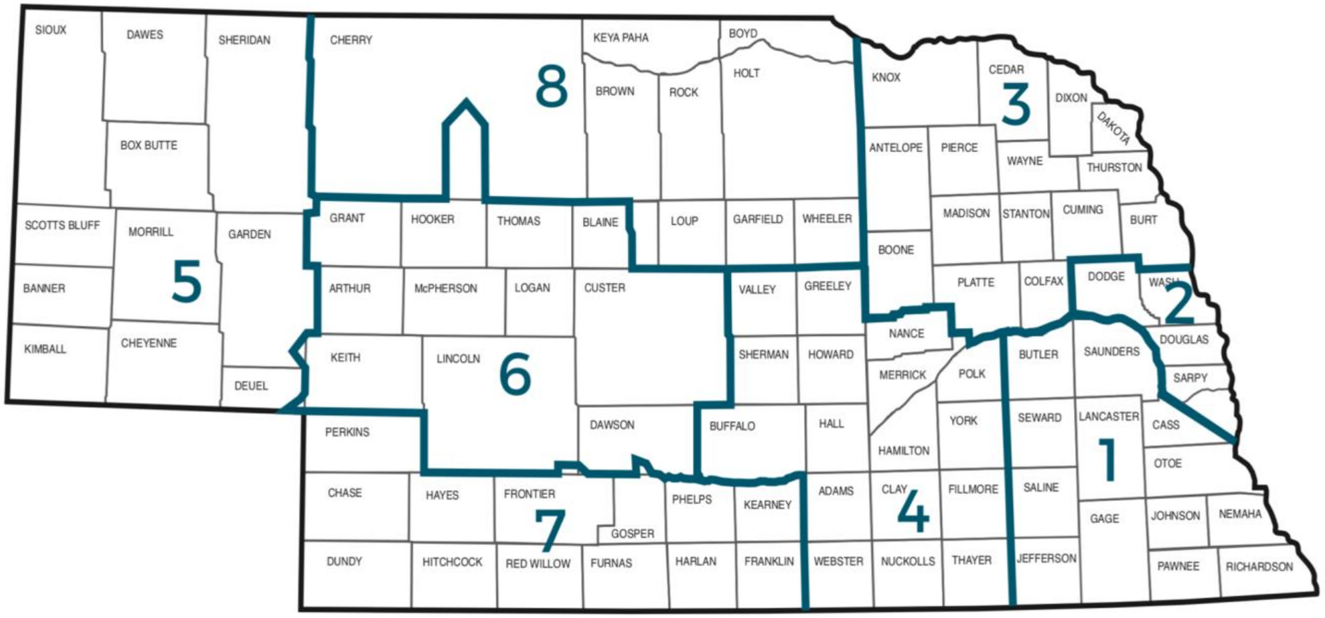


Figure 3.1: Nebraska county map divided into the official eight NDOT maintenance districts (taken from NDOT 2019b).

agencies. The threshold for a reportable crash in Nebraska is defined as one in which at least one individual has estimated property damages greater than $1000 or a crash that results in injury or death to any individual (NDOR 2009). Detailed information collected and evaluated for each crash event include the date and time of occurrence in local standard time (LST), location (county, latitude, longitude and roadway), alcohol involvement, number of vehicles involved in a crash, number of injuries and fatalities, and primary and secondary weather types. Driver specific data were not evaluated for this project. A detailed guide, as well as a blank crash report for local and state law enforcement officers (NDOR 2009, NHTSA 2009) provide examples for what is included in a standard investigating officer's report.

NEWINS data from Walker et al. (2019) were also evaluated, including the computed NEWINS and each of the seven weather variables incorporated into the NEWINS by their categorical distributions for the years 2007-2016 (Table 2.1). Values for 2017 were computed using the same method as Walker et al. (2019). Each NDOT district was assigned an NEWINS category on days with accumulating snow using a weighted equation of the seven weather variables with a major emphasis on snowfall totals. These weather variables were collected from several weather stations across the state and averaged across each district during the period of snowfall, representing a daily, district-averaged value (Walker et al. 2019). These weather conditions occurred within the 24-hour period prior to the typical time of snowfall reports in the state (approximately 7:00 LST). This timeframe was taken into account when assigning specific NEWINS event data to an individual crash report. Additional details on the methodology used for the development of the NEWINS are available in Walker et al. (2019).

3.2 Data Management and Quality Control

In order to assess the impact winter weather has on crashes across the state, attempts were made to reduce the number of factors that could potentially overshadow the role of weather conditions. The most easily identifiable risk factor for crashes obtained in this dataset was alcohol involvement. Without driver specific data, contributing circumstances such as driving too fast for conditions or driving while distracted were not considered. The decision was ultimately made to remove all crashes coded as having alcohol involvement from the analyses. This resulted in a reduction of 4.6% of crashes, 7.1% of injuries, and 33.6% of fatalities from the crash database.

Manually entered crash data are prone to errors, as was the case with the NDOT crash data. Efforts to analyze and quality control the data were done to account for discrepancies. The reported time of a crash contained the most easily identifiable errors. Quality control procedures included assigning values outlined in the NDOT crash data codebook (NDOT 2016). Entries of 2499 and 0 were considered unknown and were, thus, set as null. Additionally, a number of crashes were entered with reported times containing apparent errors, such as a crash occurring at 11:72 LST. This was likely due to the 7 and 2 being switched around during entry; however, crashes with a reported time containing this sort of error were set as null. In total, 5.0% of crashes did not have a valid reported time and are not included in any hourly specific analyses. Crashes were also assigned to hourly groups to more simply analyze the crash data by hour of day.

NEWINS values were then combined with the NDOT crash data. In order to do so, crashes were first assigned to a specific NDOT district. For the purpose of this study, each of Nebraska's 93 counties were assigned to the district wherein the majority of its surface area resides (Figure 3.2). The only exception to this is Cass County, which is almost evenly split between Districts 1 and 2. For simplicity, all crashes that occurred in Cass County were assigned to District 1. Since crashes were reported in local time, these needed to be converted to Coordinated Universal Time (UTC) in order to be properly paired with the NEWINS data. Each crash was assigned a time zone based on the county it resides in. Only Cherry County is situated in both central and mountain time zones, so time zones for crashes that occurred there were assigned using -100.85°W as an approximate line of longitude that generally runs along the time zone division through the county. Dates and times for the transitions between Daylight Savings Time and Standard Time were then identified and assigned to each crash to then allow all crashes to be assigned a UTC time. Only crashes that occurred during the transition from daylight to standard time were not assigned a UTC time as it is not possible to determine which UTC hour they occurred. These crashes and any without a valid reported time were not included in the NEWINS analyses (Section 4.4). Lastly, crashes were assigned an NEWINS date and category based on their designated district and UTC time.

3.3 Data Analyses

Similar to Black and Mote (2015a), the data are analyzed across multiple time scales in order to better understand the annual, monthly, daily, and hourly differences that exist unrelated to weather conditions. Violin plots used in this study are to help visualize the inter-year variability of data (Figure 3.3). Violin plots are commonly utilized to display probability densities of data smoothed by a kernel density estimator (i.e. the overall width of the shaded area is proportional to the number of values located there). A

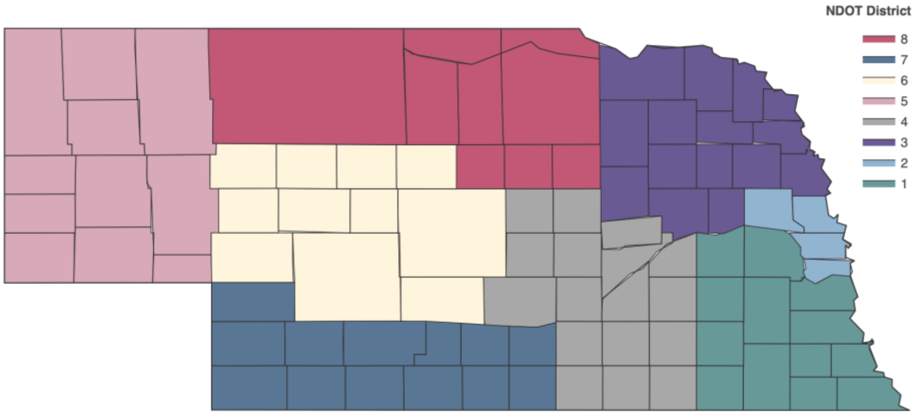


Figure 3.2: Modified NDOT district map (adapted from NDOT 2019b).

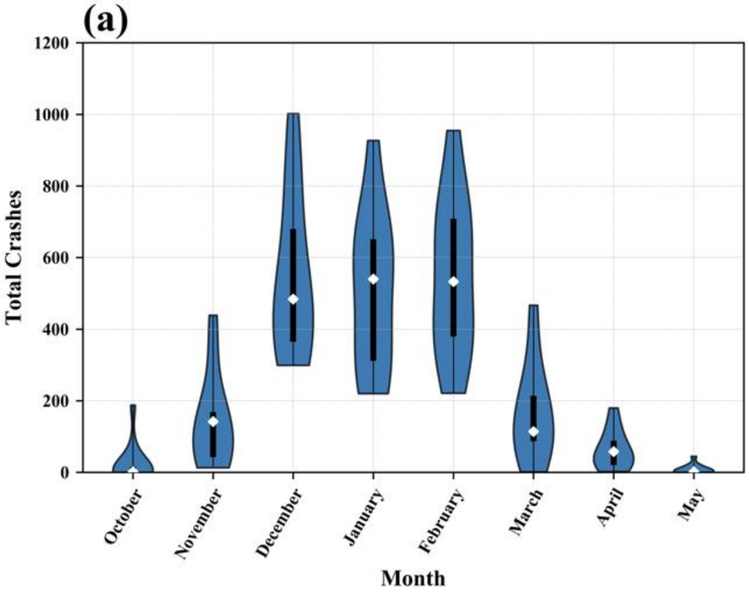


Figure 3.3: An example of a violin plot using real crash data.

narrowing of the violin plot indicates potential outliers when compared to other years, as represented by the month of October in Figure 3.3. Medians are indicated by white diamonds. The 25th and 75th percentiles are represented by the larger black bar, and the thin black lines denoting the range of the data. All additional violin plots will use this format. In all figures, blue is used to represent individual crashes, orange for injury data, and red for fatalities.

With winter weather serving as the primary inspiration for this research, analyses of the reported weather conditions by investigating officials were also done. First, crashes without any inclement weather reported were removed. This includes weather conditions reported as clear, cloudy, unknown, and none. For the purposes of this study, inclement weather-related crashes are defined as crashes with a reported primary or secondary weather type of fog, smog, or smoke, rain, sleet, hail, freezing rain or freezing drizzle, snow, severe crosswinds, blowing sand, soil, dirt, or snow, and when the weather condition is reported as other. Then, to determine which crashes were the result of winter weather conditions, crashes which had snow reported as falling during the crash by the investigating official were identified. Crashes that occurred during exclusively sleet, hail, freezing rain or freezing drizzle conditions were not included in this study. This was done in an effort to remain consistent with methodology used by Walker et al. (2019) when developing the NEWINS. Moreover, Black and Mote (2015b) found that the type of winter precipitation does not have a significant impact on the relative risk of a crash. A few of the reported snow-related crashes occurred outside Nebraska’s typical snow season during the months of June-September. Although snow has fallen as early as September in Nebraska, the first snowfall of the season doesn’t typically occur until at least October (Figure 3.4). Each of these crashes were examined to verify whether or not they were coded erroneously, including the crashes in September, using archived radar and surface observations. This resulted in the removal of 13 additional crashes, seven injuries, and no fatalities from the snow-related crash analyses. It is also worth noting that the initial removal of alcohol-related crashes removed 2.7% of snow-related crashes, 4.4% of snow-related injuries, and 11.9% of snow-related fatalities. Considering that winter weather data are often interpreted within the bounds of a winter season, December, January and February or snow-year, snow-related crashes were also assessed by snow season October through May, in addition to the other temporal scales. In addition, the number of days with snow-related crashes reported were obtained for each year, month, and day of week to provide additional insight into the temporal variability in number of winter events.

The chi-squared goodness-of-fit test was performed for all temporal analyses. It is commonly used to determine whether values are statistically significant when compared to a hypothesized distribution or expected value. An example null hypothesis evaluated using the chi-squared goodness-of-fit test is one in which the distribution of data is considered uniform (Goswami and Sonowal 2009). This provides a way to test whether or not variability within the results can be explained by something other than chance. For all temporal traffic crash results, the expected values utilized for the chi-squared goodness-of-fit tests were study period averages for each temporal scale. An additional comparison was made to test the differences between snow-related crashes and all crashes. This was done by setting the expected value (null hypothesis) for the chi-squared goodness-of-fit test to scaled values using totals from all crashes. To do this, the sums of

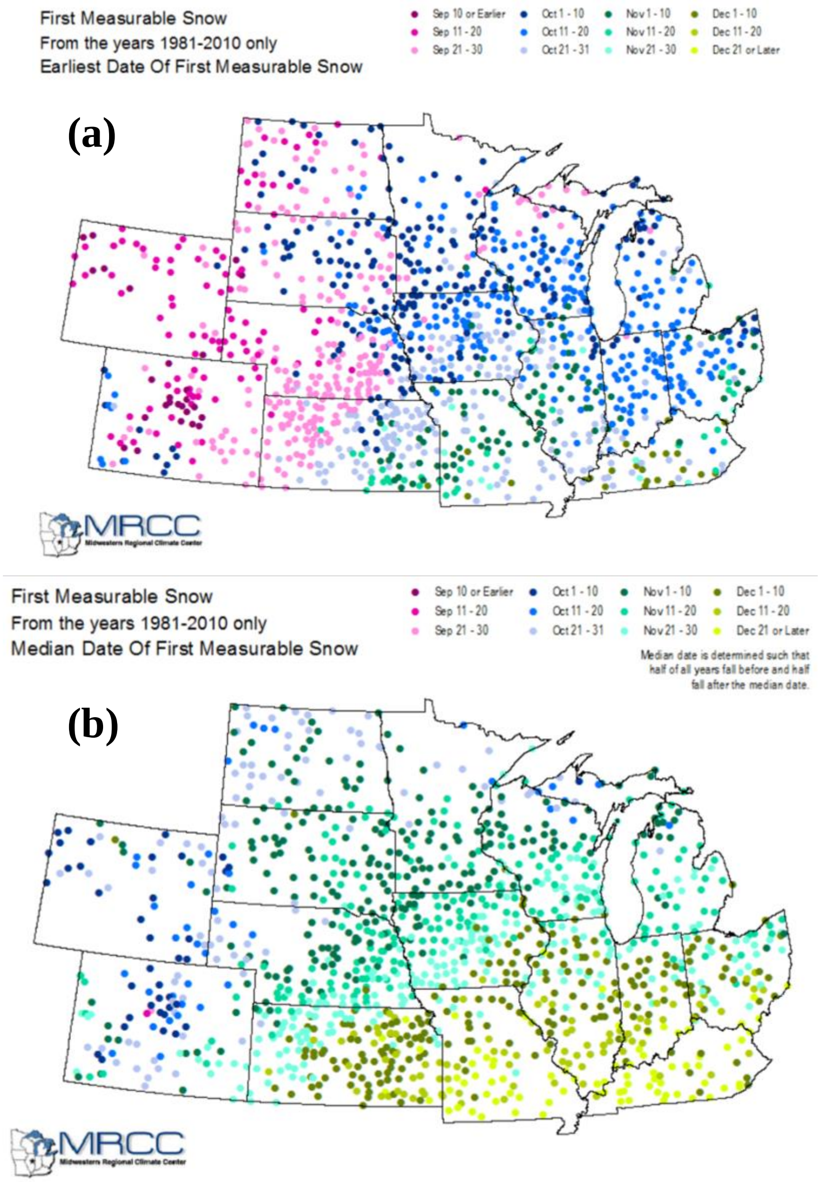


Figure 3.4: (a) Earliest date of first measurable snowfall, and (b) median date of first measurable snowfall across portions of the Midwest from 1981-2010 (taken from Midwest Regional Climate Center (MRCC) 2019).

all snow-related crashes, injuries, and fatalities are first obtained for each temporal scale. The distributions (or percentages) of all crashes for their respective time scales are then scaled to the total number of snow-related crashes to create the expected values. The statistical significance of this variation between snow-related crash results to that of all crashes is then tested.

Crashes, injuries, and fatalities are also analyzed spatially across the state using county, and latitude and longitude when reported. To account for the population density distribution across the state, county specific populations from 2010 census data were obtained (United States Census Bureau (USCB) 2019). Considering the important role of I-80 and other major highways for out-of-state traffic, estimated yearly vehicle miles travelled within each county were also acquired (NDOT 2019a). Both population data and vehicle miles travelled were used to normalize snow-related crash totals to help identify areas that have a greater relative risk of a crash in snowy conditions.

One of the primary research objectives for this study is to determine whether the NEWINS can serve as a beneficial tool for understanding crash, injury, and fatality risk during adverse winter weather conditions. This was done by assessing crashes based on their winter storm severity (NEWINS category) as well as each of the seven weather variables that combine to create the NEWINS. To control for how often an NEWINS level winter storm event occurred, the total number of days an NEWINS category is assigned to a district was also obtained. This was also done for each of the seven weather variables. It is worth noting that an individual date can be counted more than once if NDOT districts were assigned differing categories for the same winter storm.

In an attempt to evaluate what causes one winter storm to have more crashes than others despite having seemingly similar conditions, days considered high impact were identified, the first of which locates days having 300 or more individual crashes on a particular calendar day. It was determined that many of these days were heavily influenced by district population, especially from NDOT Districts 1 and 2. Thus, the highest two crash dates for each district were also obtained to provide better spatial coverage of winter weather impacts across the state. Multi-vehicle chain-reaction crashes were then identified using the same minimum criterion defined by Call et al. (2018) as crashes involving at least 10 vehicles. This was also done to find evidence that multi-vehicle crashes in Nebraska are strongly associated with HISA events.

Two of the state's largest chain-reaction crashes occurred on a single calendar day within one hour of each other as the result of a passing snow squall and high wind conditions leading to localized reductions in surface visibilities. In order to better understand what causes these hazardous crashes, it is worth evaluating the weather conditions leading up to and during them. Additionally, it is necessary to identify any other factors which may explain why these crashes occurred, including the forecasted weather conditions and how they were communicated to the public. Ultimately, the goal is to determine how to improve forecaster recognition of situations that tend to cause these types of crashes, and the best way to do this is by conducting a more in-depth analyses of one of these high impact days.

Chapter 4: RESULTS AND DISCUSSION

Due to the multi-faceted nature of traffic incidents, there is a seemingly endless number of ways in which to assess the crash data. In order to properly discuss what was found in this project, this chapter is separated into five primary sections. The first section provides an assessment of all non-alcohol-related crashes that occur during the study period. These results are then used to provide comparisons in the next section to assess the impact winter weather, and more specifically snowfall, has on crashes across the state. The spatial distribution of snow-related crashes across the state is also briefly discussed. The NEWINS and each of the seven weather variables that make up its weighted linear equation are then evaluated to determine their overall usefulness for identifying risk of snow-related crashes. Lastly, dates that are considered high impact for the state are discussed.

4.1 All Crashes

A number of studies (e.g. Weast 2018, Farmer and Williams 2005) have looked into how fatal traffic crashes vary temporally across the country to better understand when they typically occur. Following a similar approach for Nebraska, all reported motor vehicle traffic collisions that took place during the study period without reported alcohol involvement were investigated in this section temporally by year, month, day of week (DOW), and time of day (TOD). Results for total number of crashes, injuries, and fatalities are included. These findings help set the stage for looking at winter weather-related crashes.

4.1.1 Annual

An average of 43,324.8 crashes occurred each year in Nebraska from 2007 to 2017 (Table 4.1). The highest number of crashes occurred in 2007 with 47,148 total crashes. The number of crashes declined the next five years, reaching a low of 39,210 in 2012 (Figure 4.1). Some have found that this dip in crashes can be related to economics, including impacts of the “Great Recession” of 2008 (He 2016). Additionally, 2012 was a severe drought year for Nebraska and across the Midwest, which added financial stressors and other impacts to communities across Nebraska (Jedd et al. 2018) as well as a reduction in number of winter weather events (Walker et al. 2019). The number of crashes then increases after 2012 through the end of the study period (Table 4.1, Figure 4.1).

Injuries from motor vehicle crashes average 15,741.5 reports each year. A similar early period decline exists for total injuries with numbers generally increasing after 2012. Statistical tests were run using the chi-square goodness-of-fit test to determine if the variability between yearly totals were statistically significant when compared to the mean as an expected value. Using averages as the expected values, the variation between years for total crashes and injuries was found to be statistically significant ($\mathcal{X}^2(10) = 23.21$, $p < 0.01$); however, total fatalities were not found to be statistically significant. The years 2007 and 2015 were the deadliest for traffic incidents in Nebraska for the period with 161 and 165 fatalities occurring each year respectively. The average number of fatalities per year over the study period was 143.5. Although fatality numbers decreased steadily through 2012 to 124 fatalities, they have remained variable since then, which helps explain the lack of statistical significance. This suggests that additional work needs

Table 4.1: Number of crashes, injuries, and fatalities per year

Year	**Crashes**		**Injuries**		**Fatalities**	
	Total	Rank	Total	Rank	Total	Rank
2007	47148	1	17379	1	161	2
2008	44846	3	16366	5	144	5
2009	45174	2	16454	4	141	6
2010	43826	6	15448	7	135	9
2011	41929	8	14855	8	129	10
2012	39210	11	14539	11	124	11
2013	40186	10	14800	9	141	6
2014	41619	9	14639	10	145	4
2015	43554	7	15528	6	165	1
2016	44580	4	16655	2	137	8
2017	44501	5	16494	3	157	3
Average	**43324.8**		**15741.5**		**143.5**	

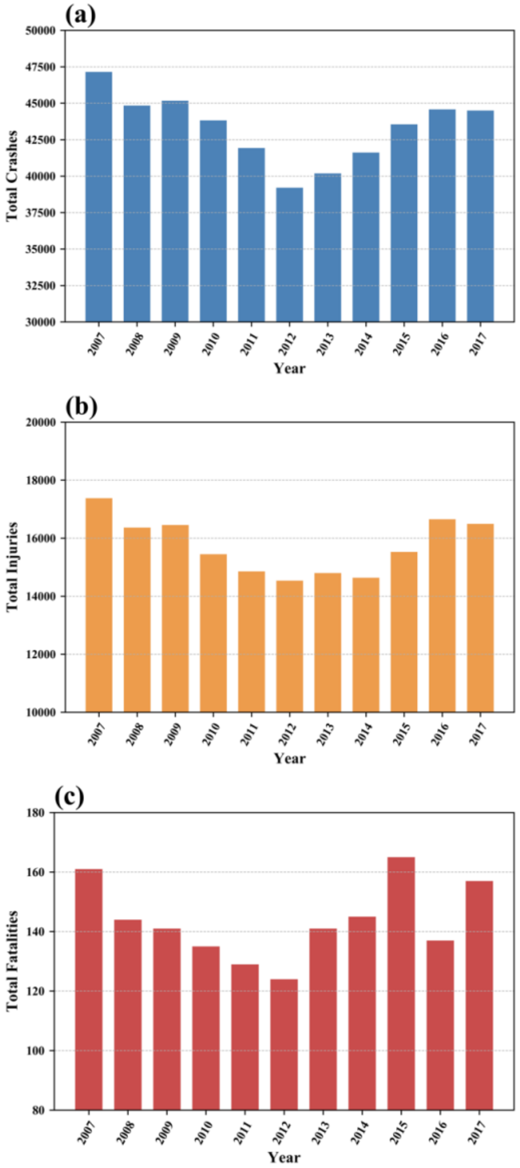


Figure 4.1: Total number of (a) crashes, (b) injuries, and (c) fatalities per year.

to be done to reduce the total number of fatalities across the state due to motor-vehicle crashes.

4.1.2 Month

During a given month, on average, 3610.4 crashes occur each year in Nebraska (Table 4.2). The months of October through January had above average crash totals, peaking in December with 4394.3 crashes (Figure 4.2). Considering the median start of Nebraska's snow season ranges between mid-October in the Panhandle and the end of November in southeastern portions of the state (Figure 2.2), this increase in crashes is consistent with previous studies that have found that a higher number of monthly crashes occur at the beginning of a winter season as people become refamiliarized with winter weather-related driving conditions (Eisenberg and Warner 2005). The fewest number of crashes occurred in the spring months of March and April. When looking at the variability between years for each specific month (Figure 4.2), the winter months of December through February had a notably higher variability in crash totals. This variability in the winter months could potentially be explained by the variability in number of impactful winter weather events that take place during a given snow season (Walker et al. 2019). In contrast, crash numbers during the summer months each year are quite consistent with each other.

An average of 1311.8 injuries occurred each month as the result of motor vehicle crashes (Table 4.2). Despite having a higher number of crashes near the beginning of the snow season, the highest amount of injuries occurred prior to this between August and October. Variability in number of injuries by month was not as apparent when compared

Table 4.2: Average annual crashes, injuries, and fatalities by month

Month	**Crashes**		**Injuries**		**Fatalities**	
	Avg Total	Rank	Avg Total	Rank	Avg Total	Rank
January	4001.4	2	1242.7	9	11.2	7
February	3508.7	7	1138.4	12	10.4	9
March	3106.8	12	1140.2	11	10.2	10
April	3201.4	11	1210.3	10	9.1	12
May	3524.5	6	1385.3	4	10.2	10
June	3466.6	8	1339.7	6	13.7	4
July	3282.0	10	1337.0	7	14.4	2
August	3441.7	9	1435.0	1	14.7	1
September	3538.9	5	1408.2	3	12.6	5
October	3939.4	3	1432.0	2	10.6	8
November	3919.2	4	1301.5	8	12.3	6
December	4394.3	1	1371.3	5	14.2	3
Average	**3610.4**		**1311.8**		**12.0**	

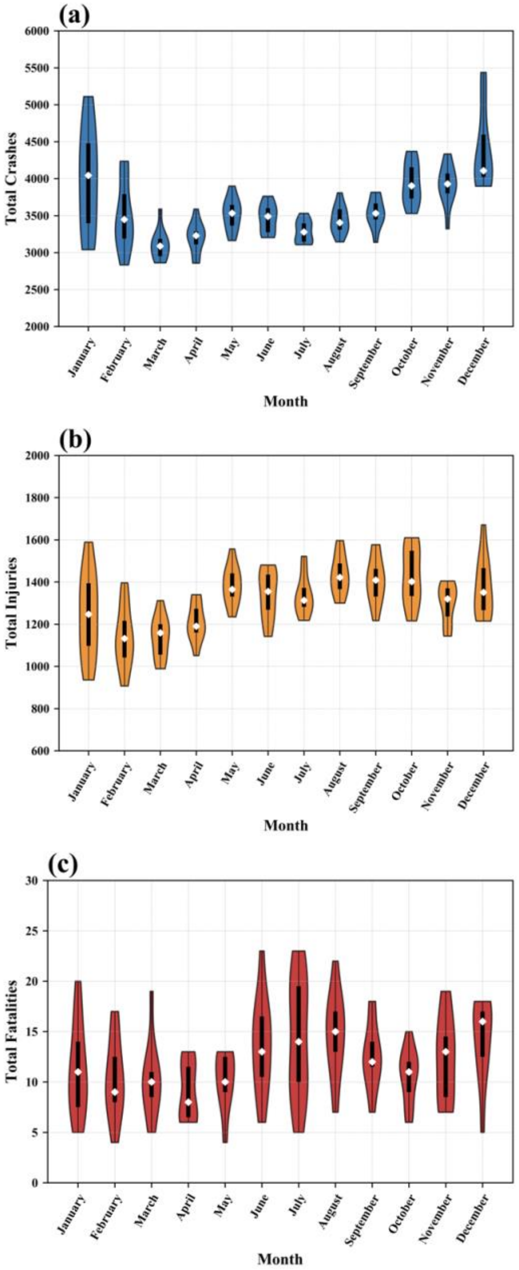


Figure 4.2: Violin plots of total (a) crashes, (b) injuries, and (c) fatalities by month.

to the difference in total monthly crashes between the winter and summer seasons. This difference could be related to previous research that found drivers often reduce their driving speeds during winter weather conditions, which in turn helps to decrease the overall severity of a crash despite higher crash totals (Eisenberg and Warner 2005). This could also help explain the below average injury totals for January and February. As was the case for total crashes, the number of injuries in January had a higher variability between years for the months of January and February than that of other months (Figure 4.2).

Although the differences in average monthly crashes and injuries were statistically significant compared to the mean ($\mathcal{X}^2(11) = 24.73,\ p < 0.01$), variability by month for average total fatalities was not; however, there are a couple things still worth noting. On average, twelve fatalities occurred each month in Nebraska (Table 4.2). The variability for a given month as shown in Figure 4.2, provides some credence that monthly totals are somewhat unaffected by the variables examined in this study. Despite this high variability between specific years for each month, there was still a general peak in median fatalities during the summer months of June through August (Figure 4.2). This is consistent with previous studies that have shown that summer months are often the deadliest for motor vehicular travel due to increased recreational travel, especially between Memorial Day and Labor Day (Weast 2018).

A secondary peak occurs in the month of December for the study period (Table 4.2). In contrast to what was discussed previously about reductions in driving speeds during winter weather conditions helping to reduce the overall severity of a crash, this may not always the case because of the secondary increase in fatalities in December.

In fact, Eisenberg and Warner (2005) did note other studies had conflicting findings from theirs.

4.1.3 Day of Week

When accounting for variation in average yearly crashes by DOW, a disparity exists between weekend days and the middle of the week (Table 4.3, Figure 4.3). Most crashes occurred during what is considered the standard 5-day work week, beginning on Mondays with 6342 average yearly crashes then peaking on Fridays with 7491 (Table 4.3). Furthermore, the number of average crashes on Saturdays and Sundays had from 1000 to 2000 fewer crashes respectively than the average weekday. During non-holiday periods, traffic volumes are higher when the majority of people are commuting to and from work or school. It is also important to note that this significant reduction in crashes on weekends could have been enhanced by the removal of alcohol-related crashes, which often occur late Friday and Saturday nights (NDOT 2017). This weekend-to-weekday division also exists for total injuries (Figure 4.3), with the highest number of injuries also occurring on Fridays with 2706, that compared to 1626 average injuries on Sundays. This variability by DOW for average yearly totals is statistically significant for both crashes and injuries when compared to an expected mean value of 6189.3 ($\mathcal{X}^2(6) = 16.81,\ p < 0.01$). In general, the number of fatalities does not vary much by DOW (Table 4.3) and was not found to be statistically significant; however, Sundays have a notably higher variability between years when compared to the other six days (Figure 4.3), having also had both the highest and lowest daily total fatalities for an individual DOW. In contrast, Weast (2018) found fatalities totals on

Table 4.3: Average annual crashes, injuries, and fatalities by DOW

DOW	Crashes		Injuries		Fatalities	
	Avg Total	Rank	Avg Total	Rank	Avg Total	Rank
Sunday	4309.8	7	1626.1	7	20.3	4
Monday	6342.3	5	2312.4	4	20.9	3
Tuesday	6553.7	3	2361.9	3	19.4	6
Wednesday	6466.6	4	2297.0	5	20.3	4
Thursday	6662.0	2	2401.1	2	21.5	2
Friday	7491.1	1	2706.0	1	22.4	1
Saturday	5499.3	6	2037.1	6	18.8	5

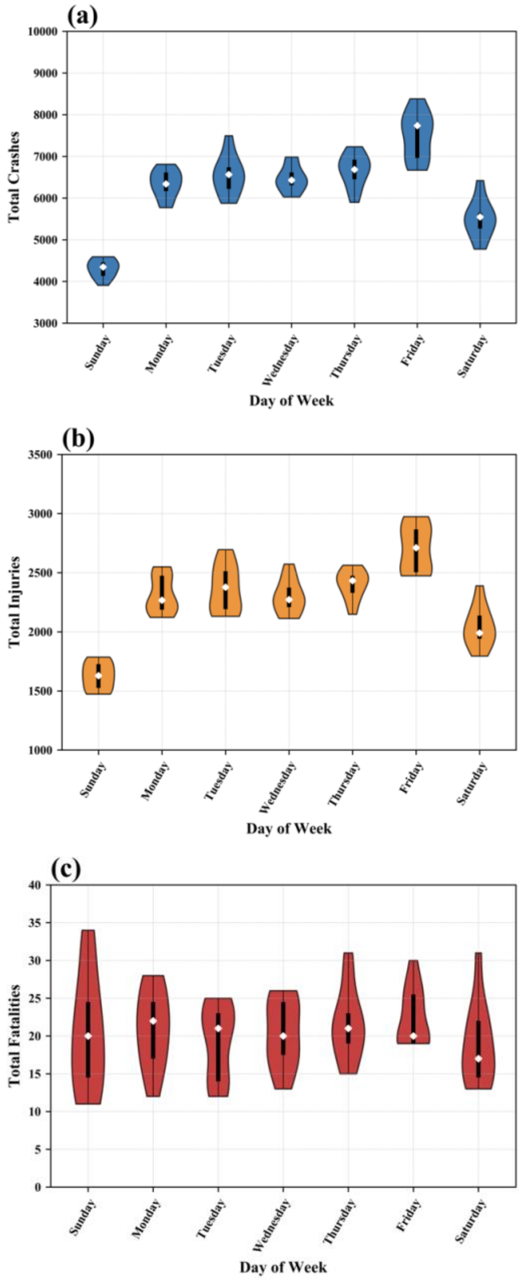


Figure 4.3: Violin plots of total (a) crashes, (b) injuries, and (c) fatalities by DOW.

weekend days to be significantly higher than during the workweek. This difference could likely be explained by the removal of alcohol-related crashes in this study.

4.1.4 Time of Day

After increasing the temporal resolution to individual hours of a day, two prominent peaks in average annual crashes materialized (Table 4.4, Figure 4.4). The first occurred during the 7:00 LST morning rush hour when people often begin their morning commutes to work. The second period lasted from approximately 15:00 through 18:00 LST. This time is often considered the afternoon and evening rush hour period as people are heading home from work. Twenty-six percent of all daily crashes occurred during this three-hour timeframe. Numbers during these two periods were also likely enhanced by the academic school year when parents typically take their children to and from school. The distribution of total injuries by TOD followed a similar pattern to total crashes (Figure 4.4), both of which were statistically significant ($\mathcal{X}^2(23) = 41.64$, $p < 0.01$). The variability of fatalities by TOD was also significant ($\mathcal{X}^2(23) = 35.17$, $p < 0.05$). The number of fatalities was more evenly distributed across the daytime hours compared to total crashes and injuries, and the morning and afternoon peaks are not as well defined. Instead, the number of hourly fatalities generally increases throughout the morning and early afternoon hours before peaking from 14:00 through 16:00 LST. This timing is fairly consistent with findings by Weast (2018), who found that the most fatalities tended to occur between 15:00 and 17:00 LST. There is enough variability between years for specific hours that this may not always be the case. Overall, fatality numbers then decreased into the evening and overnight hours as traffic volumes were

Table 4.4: Average annual crashes, injuries, and fatalities by TOD

TOD (LST)	Crashes		Injuries		Fatalities	
	Avg Total	Rank	Avg Total	Rank	Avg Total	Rank
0:00	578.6	19	157.3	19	2.0	20
1:00	546.5	22	132.5	21	1.7	22
2:00	403.8	22	99.6	22	1.3	23
3:00	285.7	24	66.3	24	0.8	24
4:00	289.5	23	74.6	23	1.8	21
5:00	564.4	20	147.1	20	3.6	16
6:00	1112.2	16	312.0	17	5.5	13
7:00	2718.5	4	1025.5	5	7.4	8
8:00	2104.7	10	703.2	10	6.5	10
9:00	1639.5	13	580.2	13	6.0	12
10:00	1745.7	11	650.0	11	6.3	11
11:00	2148.1	9	812.3	9	6.9	9
12:00	2573.4	5	986.9	6	8.5	7
13:00	2388.1	8	959.9	7	9.3	5
14:00	2499.9	6	1058.4	4	10.2	1
15:00	3569.1	2	1500.7	1	10.0	2
16:00	3459.6	3	1443.2	3	9.4	4
17:00	3633.9	1	1492.1	2	9.5	3
18:00	2432.7	7	959.7	8	8.9	6
19:00	1700.7	12	638.0	12	5.3	14
20:00	1445.8	14	503.3	14	5.2	15
21:00	1414.3	15	452.4	15	3.5	17
22:00	1078.4	17	344.9	16	2.9	18
23:00	787.5	18	236.2	17	2.2	19

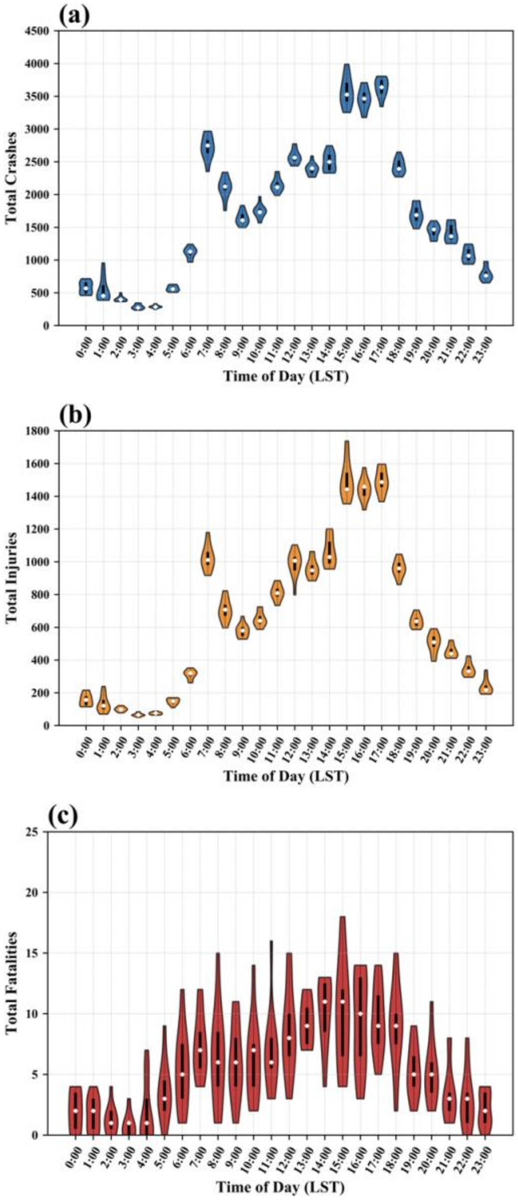


Figure 4.4: Violin plots of total (a) crashes, (b) injuries, and (c) fatalities by TOD.

reduced. According to an NDOT (2017) report, over 70% of alcohol-related crashes in Nebraska occur in dark conditions. This would help to explain why fatality numbers are so low during the overnight hours in this dataset when compared to other reports that include alcohol-related crashes.

4.2 Snow-Related Crashes

The FHWA defines weather-related crashes as any crash occurring in inclement weather conditions (i.e., rain, sleet, snow, fog, severe crosswinds, or blowing snow/sand/debris) or on slick pavement (i.e., wet, snowy/slushy, or icy) (FHWA 2016); however, this study focuses mainly on crashes where weather conditions are ongoing, rather than the specific road conditions reported. Thus, all further analyses are limited to motor vehicle incidents with a reported adverse primary or secondary weather condition, similar to methods by Black and Mote (2015a). In the state of Nebraska, 13.1% of all crashes during the study period occurred when the primary or secondary weather conditions were considered adverse (Table 4.5).

Although the majority of the weather-related crashes and injuries occurred in rain with 39.3% and 43.0% respectively, 32.3% and 27.3% of weather-related injuries occurred when it was snowing (Table 4.6). The majority of weather-related fatalities also occurred in snow (28.0%). Snowfall can lead to dangerous driving conditions by reducing tire adherence to the roadway and impairing visibility among other things (Eisenberg and Warner 2005). Given the considerable impact snow has on traffic crashes in the state, this section will assess all crashes with snow reported as either the primary or secondary weather condition. Similar to Section 4.1, the results for this section are also investigated

Table 4.5: Study period totals and percentages of crashes, injuries, and fatalities by reported primary and secondary weather conditions

Weather Condition	**Crashes**		**Injuries**		**Fatalities**	
	Total	**%**	**Total**	**%**	**Total**	**%**
Inclement Weather	62346	13.1	22495	13.0	225	14.2
Non-Weather	414213	86.9	150661	87.0	1355	85.8

Table 4.6: Study period totals and percentages for crashes, injuries, and fatalities of reported primary and secondary weather conditions considered ‘inclement weather’

Weather Condition	**Crashes**		**Injuries**		**Fatalities**	
	Total	**%**	**Total**	**%**	**Total**	**%**
Fog, smog, smoke	3189	4.7	1219	4.9	29	11.0
Rain	26892	39.3	10682	43.0	50	18.9
Sleet, hail, freezing rain/drizzle	8294	12.1	3019	12.2	47	17.8
Snow	22109	32.3	6779	27.3	74	28.0
Severe crosswinds	2674	3.9	1132	4.6	25	9.5
Blowing sand, soil, dirt, snow	4529	6.6	1775	7.2	30	11.4
Other	675	1.0	211	0.9	9	3.4

temporally, including differences by year and snow-year, month, DOW, and TOD. Data for the number of crashes, injuries, and fatalities are also included.

4.2.1 Annual

An average of 2009.2 snow-related crashes occurred each year during the study period resulting in an average of 615.6 injuries and 6.7 fatalities (Table 4.7). The highest number of crashes occurred in 2011 with 2813 total, and the lowest number was the following year in 2012 with 1170 total crashes. When comparing snow-related crashes to an expected number of crashes, based on results found in Section 4.1, there were more snow-related crashes than expected during the beginning of the period through 2011 (Figure 4.5). As discussed previously, 2012 was a drought year for the state, and the sudden reduction in snow-related crashes could potentially be explained by how there were fewer snow events that year (Walker et al. 2019). Years in the latter half of the study period mostly have lower than expected crashes totals. Overall, there is a general decrease in the number of snow-related crashes through the study period. This decrease cannot be fully explained by the number of snow events that occur each year (Figure 4.6). There is a general reduction in events in 2012, 2015, and 2017; however, there is no noticeable relationship. Numbers for total snow-related motor vehicle injuries per year is comparable to that of total crashes. The statistical significance of the difference between snow-related crashes and all crashes was also determined using scaled totals for all crashes as the expected values to then compare with the number of snow-related crashes using the chi-squared goodness-of-fit test. The variation between years for both

Table 4.7: Totals incidents, expected total incidents, and differences between the two, for snow-related crashes, injuries, and fatalities by year

Year	**Crashes**			**Injuries**			**Fatalities**		
	Total	Exp	Dif	Total	Exp	Dif	Total	Exp	Dif
2007	2444	2186	258	807	680	127	9	8	1
2008	2164	2080	84	699	640	59	8	7	1
2009	2770	2095	675	818	643	175	5	7	-2
2010	2294	2032	262	711	604	107	9	6	3
2011	2813	1944	869	878	581	297	7	6	1
2012	1170	1818	-648	397	569	-172	8	6	2
2013	1854	1864	-10	624	579	45	6	7	-1
2014	2197	1930	267	587	573	14	10	7	3
2015	1676	2020	-344	449	607	-158	7	8	-1
2016	1319	2067	-748	385	651	-266	2	6	-4
2017	1400	2064	-664	417	645	-228	3	7	-4
Average	**2009.2**			**615.6**			**6.7**		

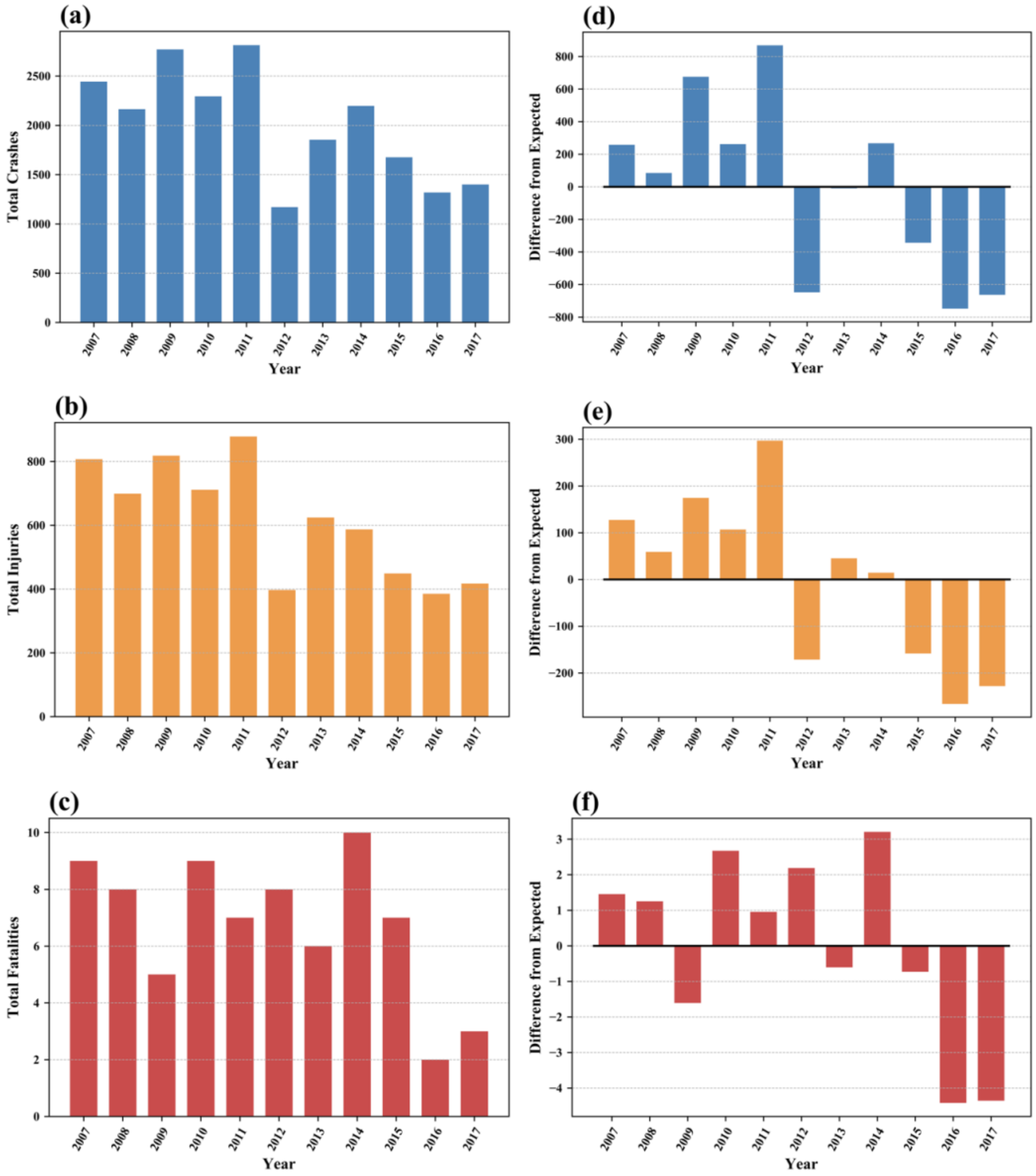


Figure 4.5: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by year; and differences between snow-related and expected values by year for (d) crashes, (e) injuries, and (f) fatalities.

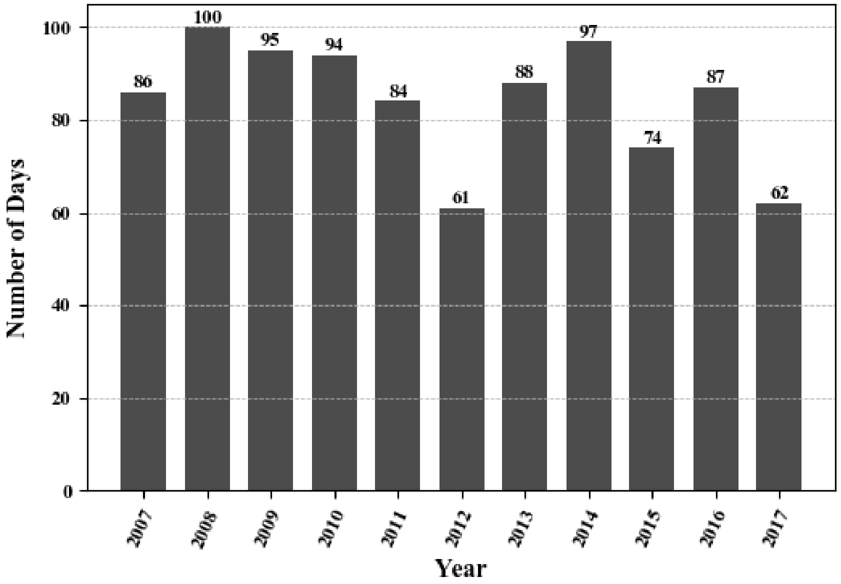


Figure 4.6: Number of days with a reported snow-related crash by year.

snow-related crashes and injuries is statistically significant ($\mathcal{X}^2(10) = 23.21, p < 0.01$). This means that the variability between can be explained by something other than chance.

Black and Mote (2015a) found that winter weather-related motor vehicle fatalities showed a declining trend over time; however, variability in snow-related fatalities between years for Nebraska was not found to be statistically significant. This lack of significance may be due to fatality numbers remaining somewhat consistent the first nine years of the period before a larger drop in snow-related fatalities in 2016 and 2017. It is possible something has changed in recent years to explain this sudden drop, including how NDOT has implemented a number of changes in an attempt to reduce the overall impact of weather-related crashes in the state, including hiring a meteorologist staff member in 2016, the development and use of the MDSS in 2017, and starting the Pathfinder initiative to improve collaboration with the weather community and NWS in 2018 (Jesse Schulz, personal communication; Barnhardt 2019; FHWA 2016).

4.2.2 Snow-Year

Winter weather data are often interpreted within the bounds of a winter season or snow-year. As a result, snow-related crashes were also analyzed by snow season, as defined by Walker et al. (2019) as July 1 through June 30 of the following year. This was done for the 2007-2008 through 2016-2017 winter seasons (Figure 4.7). Note that crashes that occurred during the first half of 2007 and the second half of 2017 were not included in these analyses. Overall, there was a general decrease in total crashes and injuries through the period by snow-year. The impact of the drought on snow-related crash totals is still apparent during the 2011-2012 snow season.

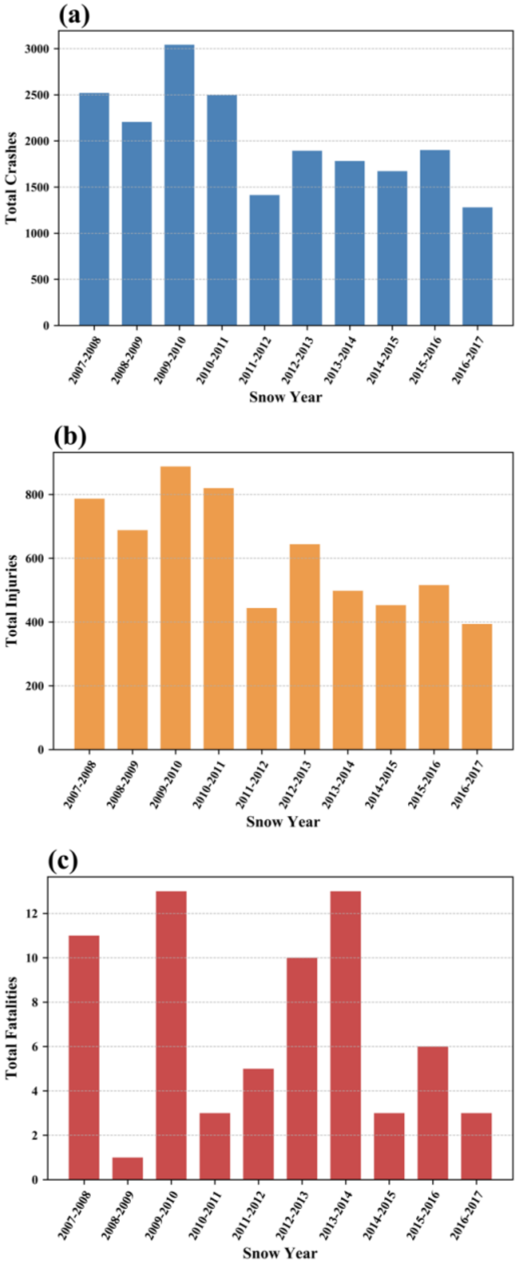


Figure 4.7: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by snow-year.

Due to the considerable amount of variability in total fatalities by snow-year, it is difficult to find any patterns for number of fatalities (Figure 4.7); however, the reduction in total fatalities at the end of the period is consistent with the end of period reduction in fatalities found in Section 4.2.1, and may suggest that if recent efforts by NDOT were, in fact, helping to reduce the number of snow-related fatal crashes, as stated previously, then their influence may have begun as early as the 2014-2015 winter season rather than in 2016. Remarkably, only one fatality occurred during the 2008-2009 snow season. At first glance the absence of multiple fatalities for an entire winter season appears somewhat suspicious; however, it does not appear that this can be explained by the under reporting of snow conditions by investigating officials considering there was not a comparable drop in total crashes or injuries during the same season. In fact, when considering the total number of NEWINS category days per snow season from Walker et al. (2019), there were only 257 snowfall days during the 2008-2009 winter season compared to 305 days in both the 2007-2008 and 2009-2010 winter seasons with an average of 246.7 days for their entire study period of 2006-2016. This difference in number of winter event days per snow season could serve as a possible explanation as to why there were such varied fatality totals between these three snow seasons in particular.

4.2.3 Month

Considering that the first snowfall in Nebraska doesn’t typically occur until at least October (Figure 3.4), crashes are assessed in order by month from October through May to more appropriately highlight Nebraska’s snow season. The variations of total snow-related crashes, injuries, and fatalities by month were found to be statistically significant ($\mathcal{X}^2(7) = 18.48,\ p < 0.01$). As expected, the highest number of snow-related crashes and injuries occurred during the months of December, January, and February (Table 4.8). There is also a considerable amount of year-to-year variability for those three months, as shown in the violin plots in Figure 4.8. This variability can likely be explained, in part, by the differences in number of Category Days (Walker et al. 2019) and number of crashes by snow-year (Figure 4.6).

Total snow-related fatalities in January are less than half that of both December and February. The higher number of fatalities in December are again consistent with findings by Eisenberg and Warner (2005) that early-season snow storms are often more dangerous before drivers become better accustomed to winter driving conditions, and they also suggest that the relative risk tapers off for each subsequent snow event. In fact, Andrey (2003) argued that the first three snowfalls of the season are the most problematic and carry the greatest relative risk. The decrease in snow-related fatalities during January would indicate such reduced risk; however, February had a much higher number of fatalities than January which would be contradictive to the expectation that increased driver experience will reduce the number of crashes over time. When accounting for number of days with snow-related crashes reported, there are more days in January than February (Figure 4.9). Thus, the number of winter events does not explain this decrease in January. It is also worth noting that there are years where no fatalities occur in each of the eight snow season months, including December through February (Figure 4.8), exemplifying how variable snowfall is during the winter in Nebraska.

Table 4.8: Totals incidents, expected total incidents, and differences between the two, for snow-related crashes, injuries, and fatalities by month (during the snow season)

Month	Crashes			Injuries			Fatalities		
	Total	Exp	Dif	Total	Exp	Dif	Total	Exp	Dif
October	306	2941	-2635	90	949	-859	8	9	-1
November	1577	2926	-1349	515	862	-347	8	10	-2
December	6001	3281	+2720	1687	908	+779	20	12	+8
January	5567	2987	+2580	1725	823	+902	7	9	-2
February	6018	2620	+3398	1811	754	+1057	20	9	+11
March	1823	2320	-497	656	755	-99	9	9	0
April	698	2390	-1692	247	802	-555	2	8	-6
May	106	2631	-2525	41	918	-877	0	9	-9

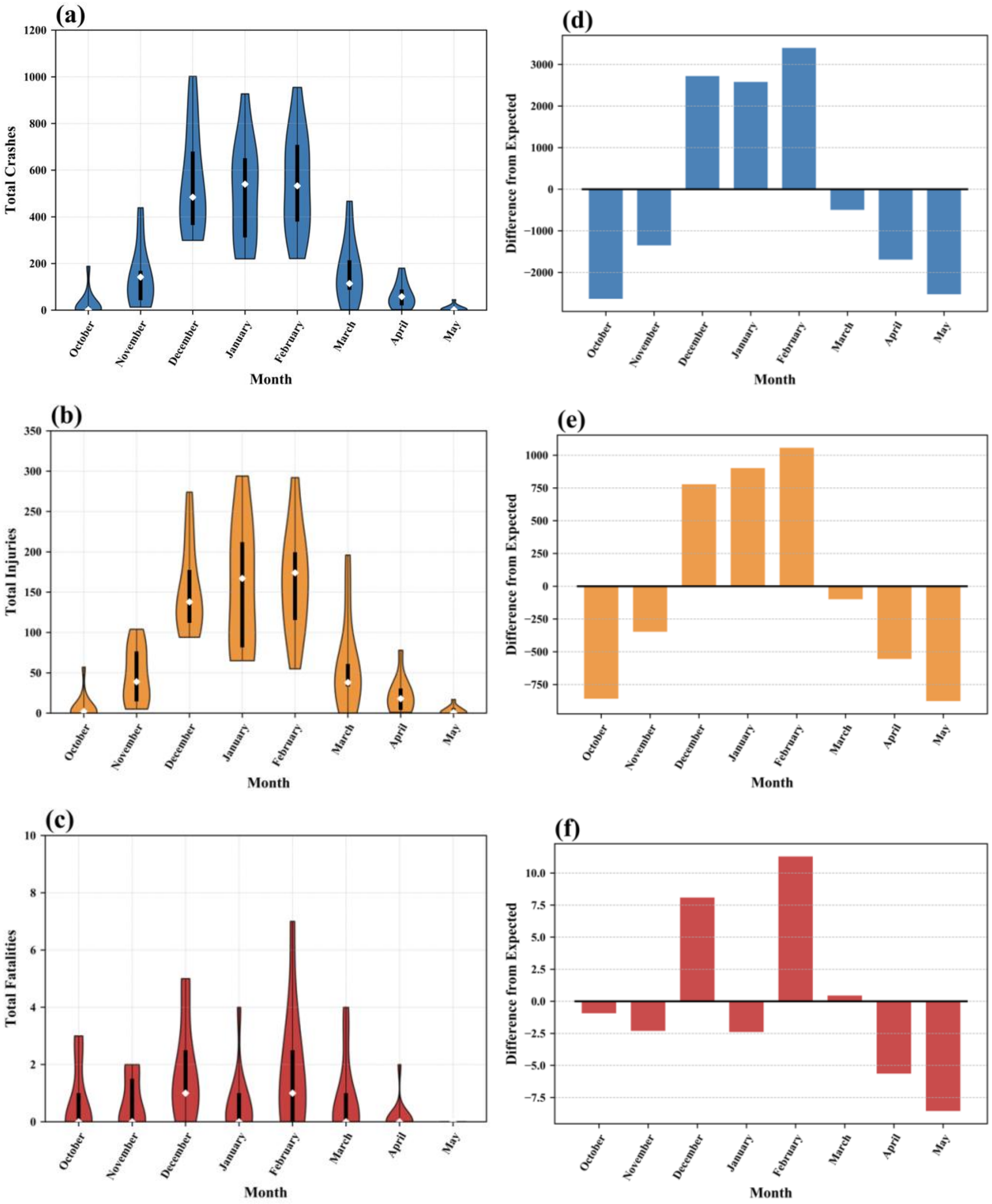


Figure 4.8: Violin plots of total snow-related (a) crashes, (b) injuries, and (c) fatalities by snow season months; and differences between snow-related and expected values by month for (d) crashes, (e) injuries, and (f) fatalities.

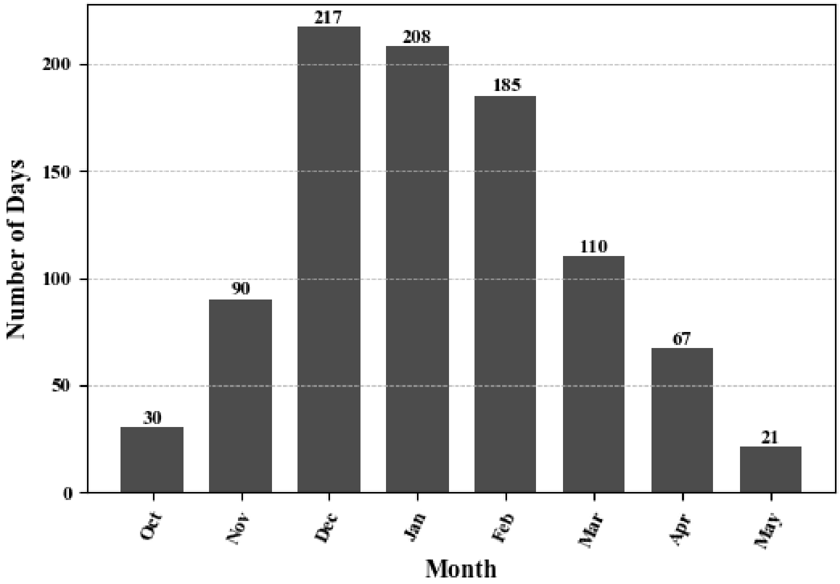


Figure 4.9: Number of days with a reported snow-related crash by month.

4.2.4 Day of Week

In contrast to all crashes, snow-related crashes do not exhibit a well-defined difference between weekdays and weekends (Table 4.9). The highest number of snow-related crashes occur on Fridays, with both Thursdays and Saturdays also having above average crash totals. When compared to expected DOW crashes, there is a significantly higher number of snow-related crashes on weekend days (Figure 4.10). Moreover, total snow-related injuries results by DOW are very similar to snow-related crashes. The variability of both snow-related crashes and injuries by DOW, including their differences from the expected values are statistically significant ($\mathcal{X}^2(6) = 16.81$, $p < 0.01$). This result is contradictory to findings by Hanibali and Knemmel (1993) who found that discretionary travel (i.e. weekend trips) are more likely to be cancelled due to inclement winter weather conditions than non-discretionary travel (i.e. weekday commutes to and from work/school). Additional studies are necessary regarding driver behavior and decision making to determine whether people are, in fact, deciding not to limit their discretionary travel during adverse winter weather conditions. There are also two outlier spikes displayed in both total crashes and injuries in the violin plots (Figure 4.10), indicating that abnormally high totals occurred in a specific year on Tuesdays and Fridays. This may be influenced by one or more specific high impact days that resulted in a large number of crashes which will be discussed more in depth in Section 4.5.

The variation by DOW and the differences from the expected are also statistically significant for snow-related fatalities ($\mathcal{X}^2(6) = 16.81, p < 0.01$). The highest number of snow-related fatalities also occurs on Thursdays while the lowest took place on

Table 4.9: Totals incidents, expected total incidents, and differences between the two, for snow-related crashes, injuries, and fatalities by DOW

DOW	**Crashes**			**Injuries**			**Fatalities**		
	Total	Exp	Dif	Total	Exp	Dif	Total	Exp	Dif
Sunday	2837	2199	+638	916	700	+216	11	10	+1
Monday	2862	3235	-373	942	995	-53	9	11	-2
Tuesday	2965	3343	-378	910	1016	-106	10	10	0
Wednesday	2878	3299	-421	893	988	-95	6	10	-4
Thursday	3434	3398	+36	952	1033	-81	17	11	+6
Friday	3669	3821	-152	1046	1164	-118	11	12	-1
Saturday	3456	2805	+651	1113	876	+237	10	10	0

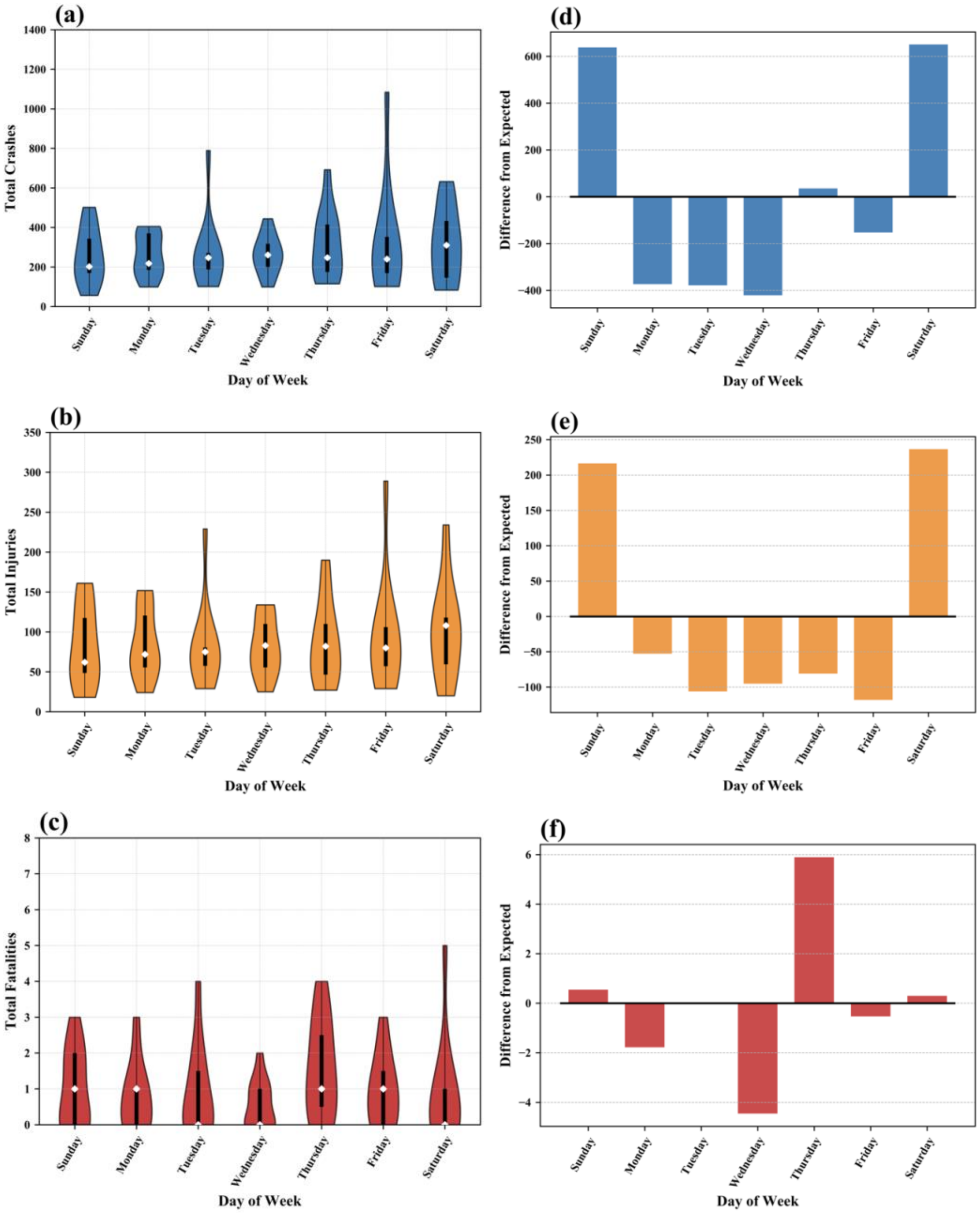


Figure 4.10: Violin plots of total snow-related (a) crashes, (b) injuries, and (c) fatalities by DOW; and differences between snow-related and expected values by DOW for (d) crashes, (e) injuries, and (f) fatalities.

Wednesdays (Table 4.9). This is also better represented in the differences between snow-related crashes and expected totals (Figure 4.10). When looking at number of days with reported snow conditions by DOW, Wednesdays, and Thursdays both had the same number of days, with 127 days (Figure 4.11). This is surprising considering the significant difference between Wednesday and Thursday fatality totals. The highest number of days with snow-related crashes reported occurs on Saturdays with 142 days.

4.2.5 Time of Day

Several studies (DeVoir 2004, Black and Mote 2015a, Andrey et al. 2013) discuss the importance of TOD when assessing winter weather-related crashes. As was the case with all crashes in Nebraska, snow-related crashes exhibit two peaks that highlight the typical morning (7:00 LST) and afternoon rush hours (15:00 LST) (Table 4.10). The total number of crashes during these two hours are quite similar, with 1514 and 1537 total crashes occurring respectively. In addition, afternoon snow-related crashes, particularly from 14:00-16:00 LST, exhibited a higher range in yearly totals when compared to all other hours (Figure 4.12). This suggests that some years likely had snowfall events causing a much higher impact on crash totals during the afternoon commute, similar to discussions by DeVoir (2004) on how HISA winter events, in particular, can result in crash numbers significantly amplified during weekday rush hour traffic.

Black and Mote (2015a) found that a higher percentage of winter weather-related crashes occurred during the daytime hours compared to non-winter crashes across the U.S. They also found that the opposite was the case overnight, with a lower percentage of winter-related crashes occurring than non-winter crashes. When comparing snow-related

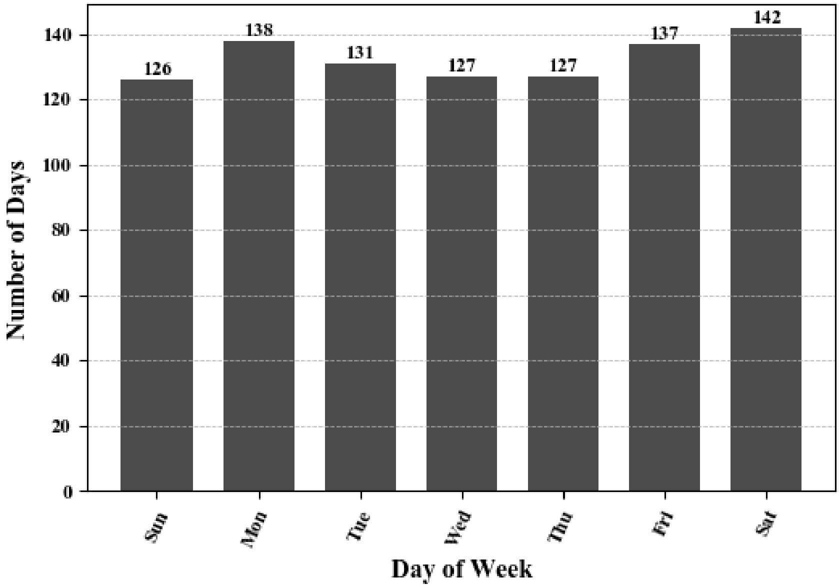


Figure 4.11: Number of days with a reported snow-related crash by DOW.

Table 4.10: Totals incidents, expected total incidents, and differences between the two, for snow-related crashes, injuries, and fatalities by TOD

TOD (LST)	**Crashes**			**Injuries**			**Fatalities**		
	Total	Exp	Dif	Total	Exp	Dif	Total	Exp	Dif
0:00	307	298	+9	81	68	+13	0	1	-1
1:00	317	282	+35	60	57	+3	0	1	-1
2:00	239	208	+31	66	43	+23	1	1	0
3:00	171	147	+24	36	29	+7	0	0	0
4:00	201	149	+52	53	32	+21	0	1	-1
5:00	424	291	+133	109	64	+45	6	2	+4
6:00	739	573	+166	246	135	+111	1	3	-2
7:00	1514	1401	+113	514	444	+70	11	4	+7
8:00	1478	1085	+393	422	305	+117	9	4	+5
9:00	1258	845	+413	351	251	+100	1	3	-2
10:00	1249	900	+349	377	282	+95	4	3	+1
11:00	1228	1107	+121	360	352	+8	3	4	-1
12:00	1280	1327	-47	455	427	+28	7	5	+2
13:00	1160	1231	-71	348	416	-68	2	5	-3
14:00	1185	1289	-104	461	458	+3	9	5	+4
15:00	1537	1840	-303	484	650	-166	4	5	-1
16:00	1387	1783	-396	454	625	-171	2	5	-3
17:00	1339	1873	-534	460	646	-186	2	5	-3
18:00	1146	1254	-108	388	416	-28	5	5	0
19:00	838	877	-39	295	276	+19	2	3	-1
20:00	667	745	-78	209	218	-9	1	3	-2
21:00	609	729	-120	167	196	-29	0	2	-2
22:00	499	556	-57	155	149	+6	1	2	-1
23:00	425	406	+19	91	102	-11	1	1	0

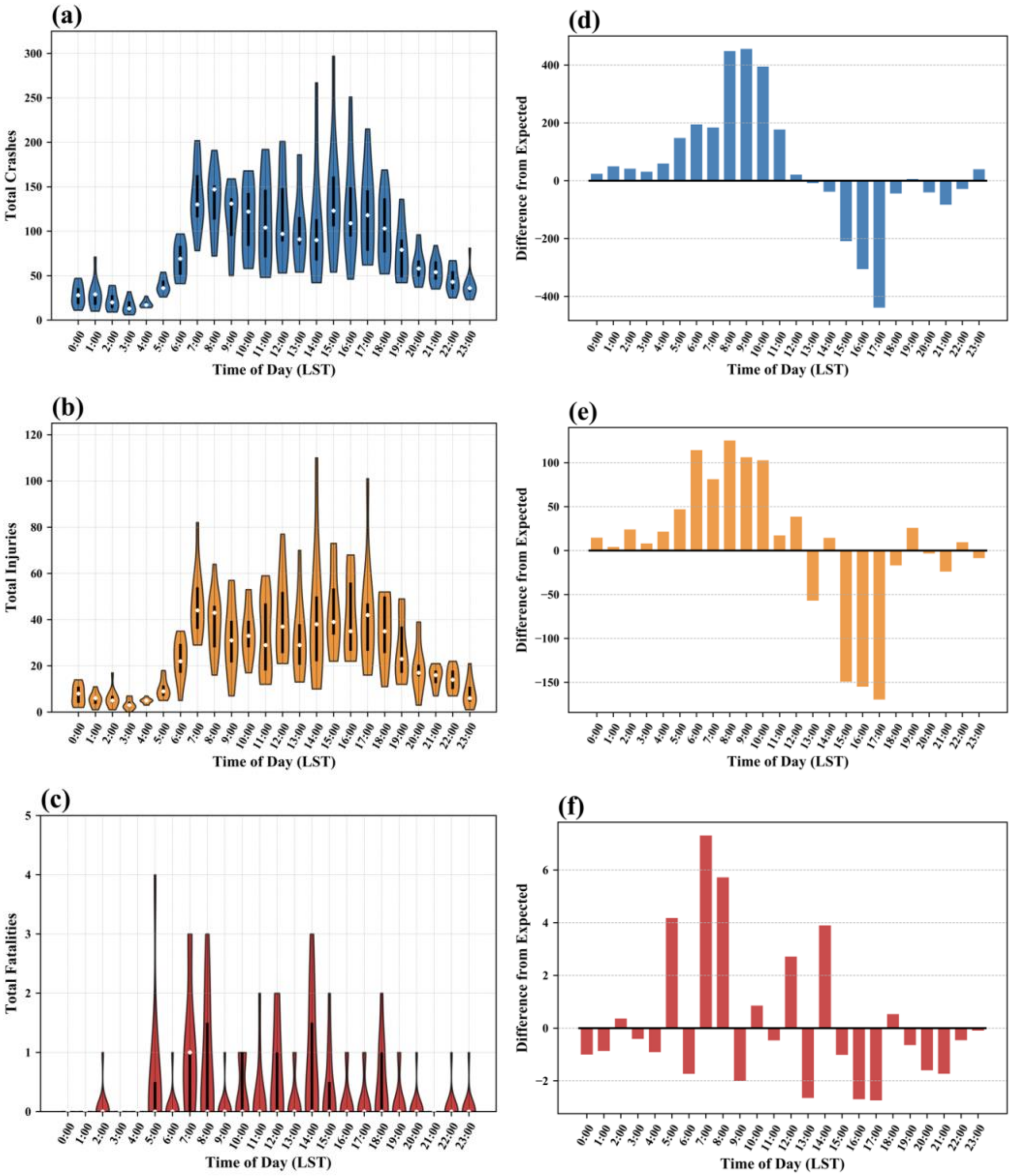


Figure 4.12: Violin plots of total snow-related (a) crashes, (b) injuries, and (c) fatalities by TOD (LST); and differences between snow-related and expected values by TOD for (d) crashes, (e) injuries, and (f) fatalities.

crashes in Nebraska to expected total crashes, the differences show that morning hours had a higher number of snow-related crashes, while afternoons had lower values than expected (Figure 4.12). Snow-related crash totals during the overnight hours did not vary much from the expected total crashes. Therefore, the risk for a snow-related crash increases during the morning hours, while the overall risk of a snow-related crash is reduced in the afternoon. This is in contrast to the day-night distinction described by Black and Mote (2015a). This increased risk for crashes in the morning could possibly be explained by a number of factors, including people not being fully aware of the dangerous driving conditions before leaving for work, re-freezing on roadways due to colder morning temperatures forming black ice under the snow, and reduced maintenance operations and staffing during the overnight hours preventing roadways from being fully cleared or salted prior to when people commute in the morning.

Total snow-related injuries also peak during the same hours as snow-related crashes, also having similar differences between mornings and afternoons totals from what was expected (Table 4.10, Figure 4.12); however, rush hour peaks are not as well defined for snow-related injury totals. The values for both snow-related crashes, injuries, and fatalities, as well as their differences from the expected values are statistically significant ($\mathcal{X}^2(23) = 41.64, p < 0.01$). The highest total number of snow-related fatalities occurred in the morning at 7:00 LST. A secondary peak occurs in the afternoon at 14:00 LST. As is the case in Black and Mote (2015a), most snow-related fatalities occurred during the daylight hours. In general, fatality values are more sporadic by TOD (Figure 4.12). When looking at differences from expected, certain hours of the day appear to have a higher risk of a crash compared to a typical day, including 5:00, 7:00, 8:00, 12:00, and 14:00 LST (Table 4.10).

4.3 Spatial Distribution

In order to obtain a better understanding of how snow-related crashes, injuries, and fatalities varied spatially across the state, scatter plot maps of reported latitude and longitude locations were created (Figure 4.13). Plotted snow-related crashes and injuries clearly identify the locations of Nebraska's road network and major population centers. The cities of Omaha and Lincoln in eastern Nebraska are especially prominent. Interstate-80 (I-80), Nebraska's longest major thoroughfare, transects the entire state from west to east. Additionally, I-80 has the highest posted speed limit of any roadway in the state at 75 mph (120.7 km/h), which was 10 mph (16.1 km/h) above the highest highway speed limit prior to 2018 when several divided highway speed limits were increased to 70 mph (112.7 km/h). As a result, the overall severity of snow-related crashes is likely increased for those traveling along it. In contrast to the crash and injury maps, snow-related fatalities appear to be spread out more evenly across the state, aside from the notable minimum in the Sandhills in north-central Nebraska.

When grouping crashes by county, the highest number of snow-related crashes, as expected, occurred in Douglas and Lancaster Counties, which include Nebraska's two largest cities of Omaha and Lincoln respectively (Figure 4.14). As was the case in the scatter plot maps in Figure 4.13, county level data also highlights areas of the state with higher population densities. The counties with the highest average total fatalities also appear to be situated mostly along the I-80 corridor. It is also worth noting that in addition to the increased traffic volumes, the majority of Nebraska's more populous cities

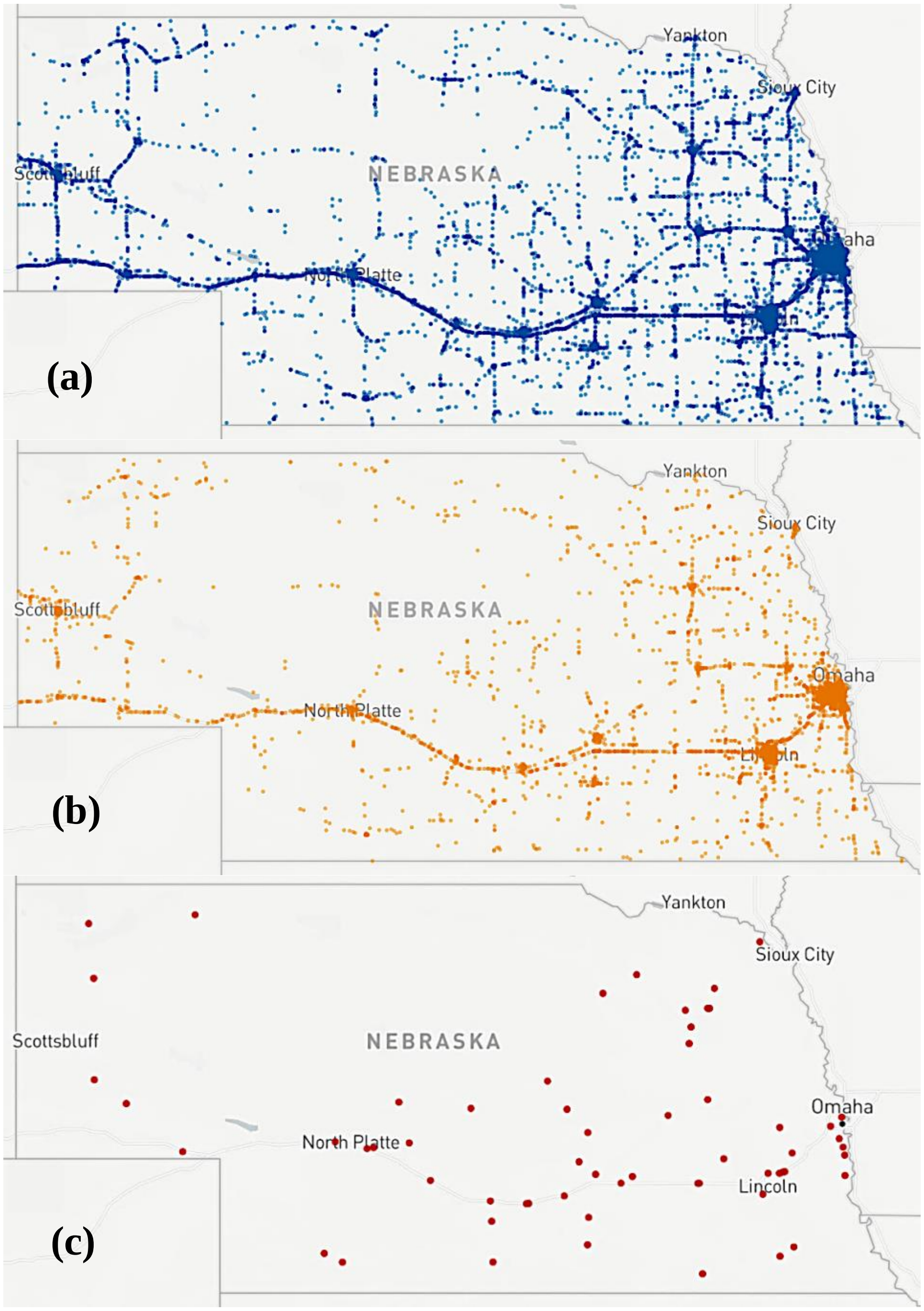


Figure 4.13: All snow-related (a) crashes, (b) injuries, and (c) fatalities during the study period plotted using reported latitude and longitude locations.

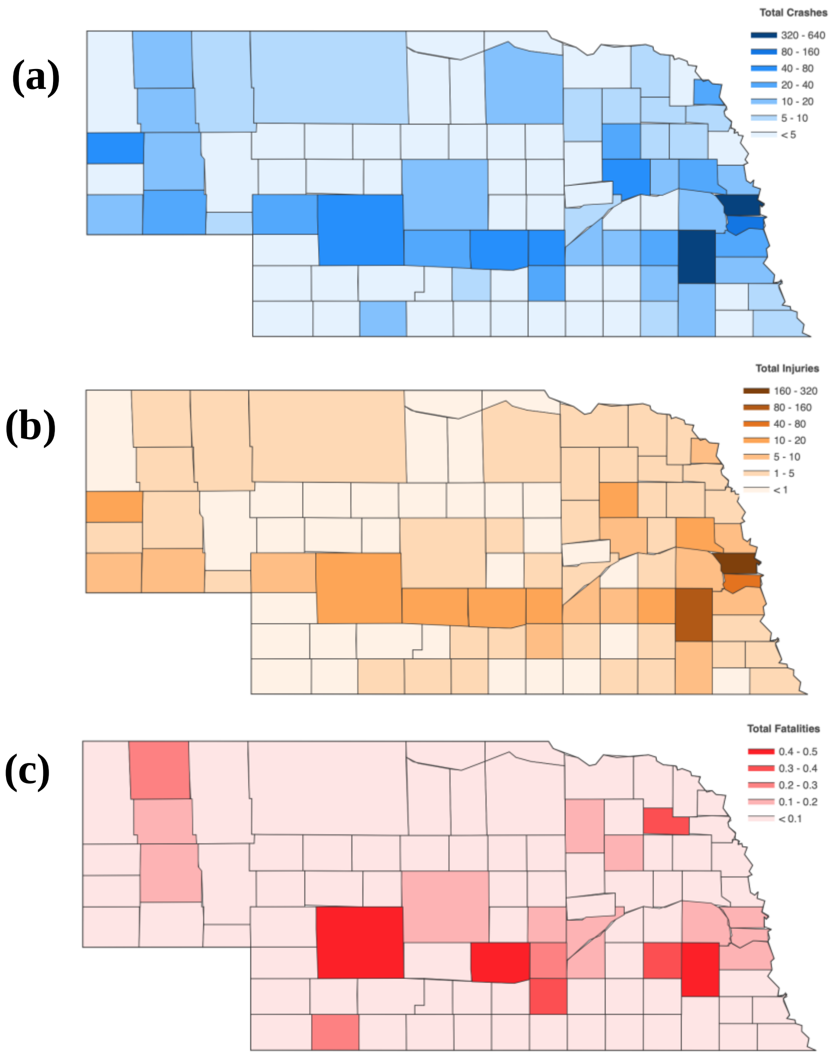


Figure 4.14: Average total snow-related (a) crashes, (b) injuries, and (c) fatalities per year by Nebraska county.

reside along I-80 and the Platte River. Considering population density is clearly a key factor in explaining where crashes occur spatially across the state, an attempt was made to account for this population bias by normalizing crash totals by county population. Using 2010 census data for each county (USCB 2019), number of crashes per 1000 individuals are obtained to help identify counties that have an increased risk of snow-related crashes relative to their total population. The counties with the highest number of snow-related crashes and injuries relative to population mainly reside in the northwestern portions of Nebraska, especially the Panhandle region (Figure 4.15). This region of the state experiences the highest seasonal snowfall totals on average (Figure 2.2) which could explain why there is an increased number of snow-related crashes and injuries relative to the population size in that region. No notable pattern exists for snow-related fatalities relative to population size.

Since not all traffic in Nebraska is entirely local, it is also important to account for out-of-state travelers and any commercial interests that pass through the state along its major interstates and highways. Efforts were made to account for this by normalizing crash totals using NDOT estimated vehicle miles traveled per county from 2010 (NDOT 2019a). Although the average number of crashes, injuries, and fatalities are not concentrated in a specific region of the state as was the case with the population-relative maps, more broadly, counties containing the state’s more populous cities have notably higher crash and injury totals relative to the estimated miles travelled within them (Figure 4.16). Several counties in the Nebraska Panhandle have higher numbers as well. Scotts Bluff County, in particular, has the highest total crashes and injuries per billion miles travelled than that of any other county in the state. Numbers for snow-related

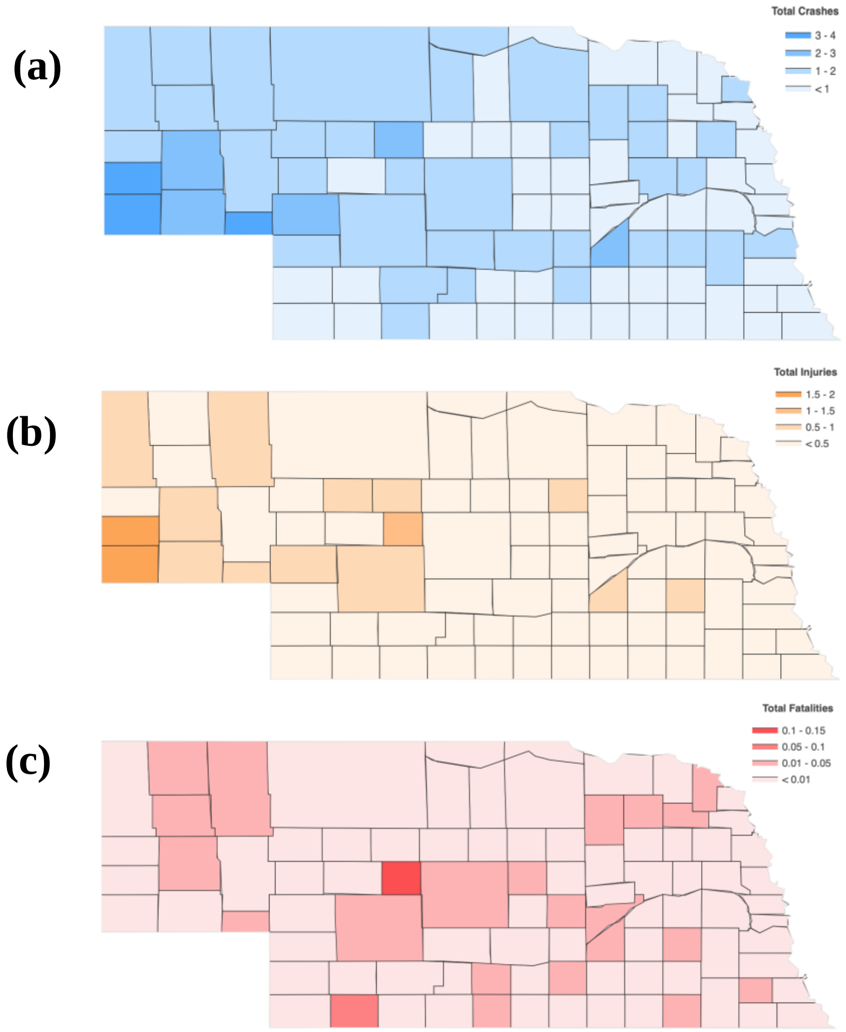


Figure 4.15: Average total snow-related (a) crashes, (b) injuries, and (c) fatalities per 1000 individuals per year by county.

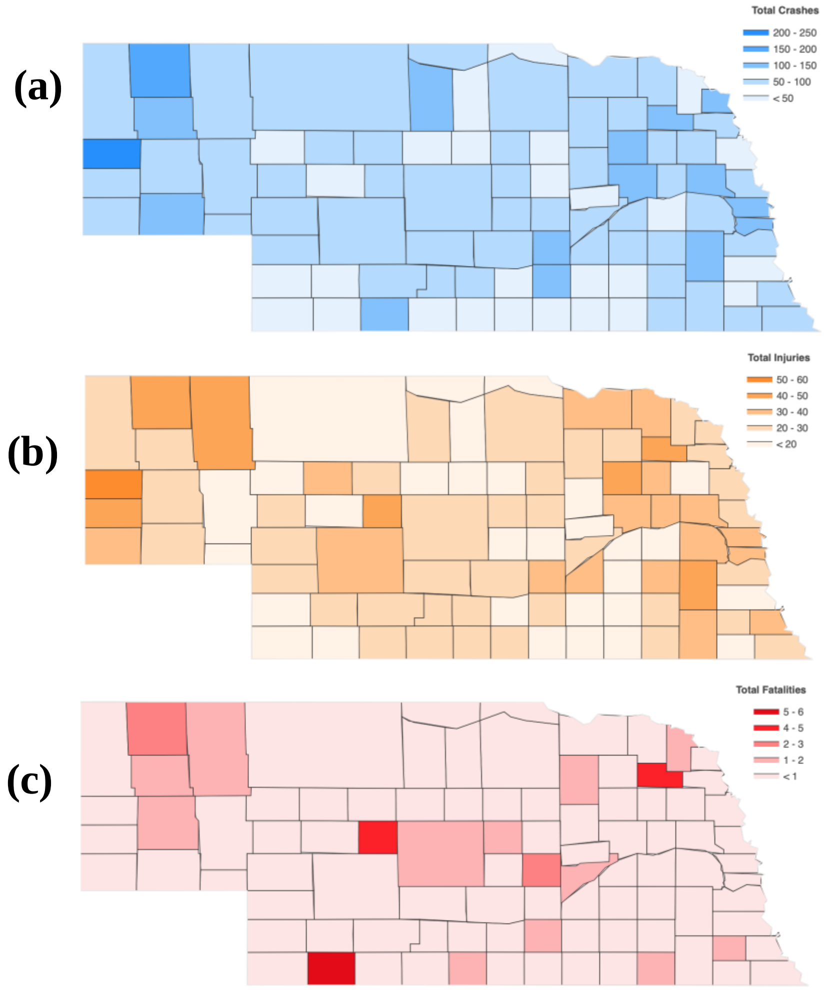


Figure 4.16: Average total snow-related (a) crashes, (b) injuries, and (c) fatalities per year per billion miles travelled.

fatalities by miles travelled are fairly consistent across the state; although three counties (Wayne, Logan, and Hitchcock) have four or more fatalities per billion miles travelled while the rest of the state's counties generally have fewer than two. This can be explained by the combination of having multiple snow-related fatalities occurring in each county despite their low average vehicle miles travelled.

4.3.1 NDOT Districts

Nebraska is divided into eight districts by NDOT (Figure 3.1), whose boundaries were modified slightly for this project as outlined in Section 3.2 by assigning each county to a specific district based on which district the majority of its surface area resides in (Figure 3.2). These districts are important for NDOT's maintenance operations and snow removal (Walker et al. 2019). The NEWINS considers winter conditions for each NDOT district, thus it is worthwhile to look at how crashes varied between districts prior to discussing the NEWINS in Section 4.4.

Although it has the smallest land area of the eight districts, District 2, which includes the city of Omaha, has the highest number of snow-related crashes and injuries with 8113 total crashes occurring during the study period (Table 4.11). District 1, including the city of Lincoln, has the second highest with 5309 (1656) total snow-related crashes (injuries). Despite having the highest number of total crashes, District 2 has one of the lowest numbers for total snow-related fatalities with only four, second only to District 8, which had no snow-related fatalities. The highest number of fatalities (19) occurred in District 4 in south-central Nebraska and District 1 (16) in southeastern Nebraska.

Table 4.11: Snow-related crash, injury, and fatality totals by study period, per year, per 10000 individuals, and per billion miles travelled for each NDOT District

District	Population	Annual Vehicle Miles *in billions	Crashes				Injuries				Fatalities			
			Total	Avg Yearly	Per 10000 People	Per billion miles traveled	Total	Avg Yearly	Per 10000 People	Per billion miles traveled	Total	Average Yearly	Per 10000 People	Per billion miles traveled
District 1	471696	4.42	5309	482.6	10.23	109.20	1656	150.5	3.19	34.06	16	1.5	21.6	0.33
District 2	808797	6.20	8113	737.5	9.12	118.97	2484	225.8	2.79	36.43	4	0.4	5.4	0.06
District 3	179114	1.93	2063	187.5	10.47	97.14	631	57.4	3.20	29.71	11	1.0	14.9	0.52
District 4	222888	2.90	2598	236.2	10.60	81.32	755	68.6	3.08	23.63	19	1.7	25.7	0.59
District 5	83920	1.28	1784	162.2	19.33	126.85	508	46.2	5.50	36.12	10	0.9	13.5	0.71
District 6	81999	1.59	1404	127.6	15.57	80.46	472	42.9	5.23	27.05	9	0.8	12.2	0.52
District 7	54407	0.75	497	45.2	8.30	59.87	164	14.9	2.74	19.75	5	0.5	6.8	0.60
District 8	26447	0.45	333	30.3	11.45	67.85	102	9.3	3.51	20.78	0	0.0	0.0	0.00

As was noted with the county level analyses of traffic crashes, population has a big influence on snow-related crash and injury totals. To account for this, the same method was applied to district totals by normalizing the number of crashes by population, except values are reported per every 10,000 individuals rather than every 1000 (Table 4.11). When accounting for population, District 5 (i.e. the Panhandle) has the highest number of crashes and injuries. This coincides well with previous discussions of county level data where District 5 typically has a higher average snowfall totals per winter season than other areas of the state (Figure 2.2) which could serve as a crucial factor in that region's increased risk of snow-related crashes and injuries. Districts 2 and 7 had the fewest number of snow-related crashes relative to population size. It is worth noting that this reduction in numbers in District 2 could be the explained by its smaller land area. Accounting for the areal extent of a district would be worth looking into in any future studies. Districts 1 and 4 continue to exhibit higher total fatalities compared to the other districts even when accounting for population. When accounting for vehicle miles travelled, Districts 1, 2, and 5 have the most snow-related crashes with over 100 occurring per billion miles travelled resulting in over 30 snow-related injuries and at least one fatality (Table 4.11).

4.4 NEWINS

A primary objective of this research is to evaluate existing real-world tools to assist in reducing the number of snow-related motor vehicle crashes, injuries, and fatalities across the state. As noted in Section 2.4, one potential avenue that could help fill a gap in the current body of knowledge on winter weather crashes is to examine existing state Department of Transportation winter severity indices, and other similar tools, such as NDOT's MDSS, to identify if additional utility exists with those tools to help improve the overall understanding of weather-related crashes.

The recent development of the NEWINS, a categorical storm classification framework that captures both atmospheric conditions and road impacts across the state of Nebraska for NDOT (Walker et al. 2019), provides the perfect model to begin this process. In fact, Walker et al. (2019) mention continued evaluation of the versatility of the NEWINS, such as comparing it independently with transportation data, would be worth exploring. An important benefit of the NEWINS is that it considers both the contributions of several meteorological parameters both spatially and temporally. As such, this section seeks to lay the groundwork for further investigation of the NEWINS as a tool for assessing crash totals and severity, including an assessment of the NEWINS categories (1-6) and each of the seven classified weather variables that make up its weighted equation (Table 2.1).

4.4.1 NEWINS Category

The NEWINS classifies individual winter weather events into one of six categories (Table 2.1) , from Category 1 (low impact storms) to Category 6 (high impact storms) (Walker et al. 2019). Using event date and district number obtained from the NEWINS winter storm classifications, each crash was assigned to one of the six NEWINS categories. Crashes without a valid reported time were not assigned an NEWINS category. In addition, any snow-related crashes with a valid time that were not assigned to an NEWINS category likely occurred during what Walker et al. (2019) referred to as a Category 0 day where snow was observed, but no accumulation was recorded. They also note that during their study period from 2006-2016, there were 39% more days with observed snowfall compared to days with snow accumulation.

The majority of snow-related crashes and injuries occur during Category 1 and Category 2 days (Figure 4.17), with the frequency of crashes and injuries generally decreasing with increasing NEWINS category. The majority of fatalities occur during Category 2 and 3 days, both with 21 fatalities. Category 1, 4 and 5 had six fatalities each, with Category 6 days having no fatalities. Although it appears that higher categories may be less dangerous considering they a lower number of snow-related crashes, injuries, and fatalities, it is difficult to make conclusions about risk and likelihood of occurrence for a particular category without considering the number of days during which an NEWINS level snow event occurs. Thus, the total number of days an NEWINS category is assigned to a district when a snow-related crash was also reported was obtained (Figure 4.18). It is important to note that an individual date can be counted more than once if the NDOT districts were assigned different categories for the same winter storm. As was found by Walker et al (2019), the frequency of category days decreased with increasing category. A total of 427 Category 1 days occur during the 11-year study period, with there being only eight Category 6 days (Figure 4.18). Although not shown, 624 days were not assigned to an NEWINS category, likely during one of the Category 0 days when snow fell although did not accumulate.

Using values from Figure 4.18, snow-related crash, injury, and fatality totals were normalized to account for the frequency of category days (Figure 4.17). Both snow-related crashes and snow-related injuries exhibit higher numbers for Category 4 and 5 when accounting for number of category days. In general, the number of total

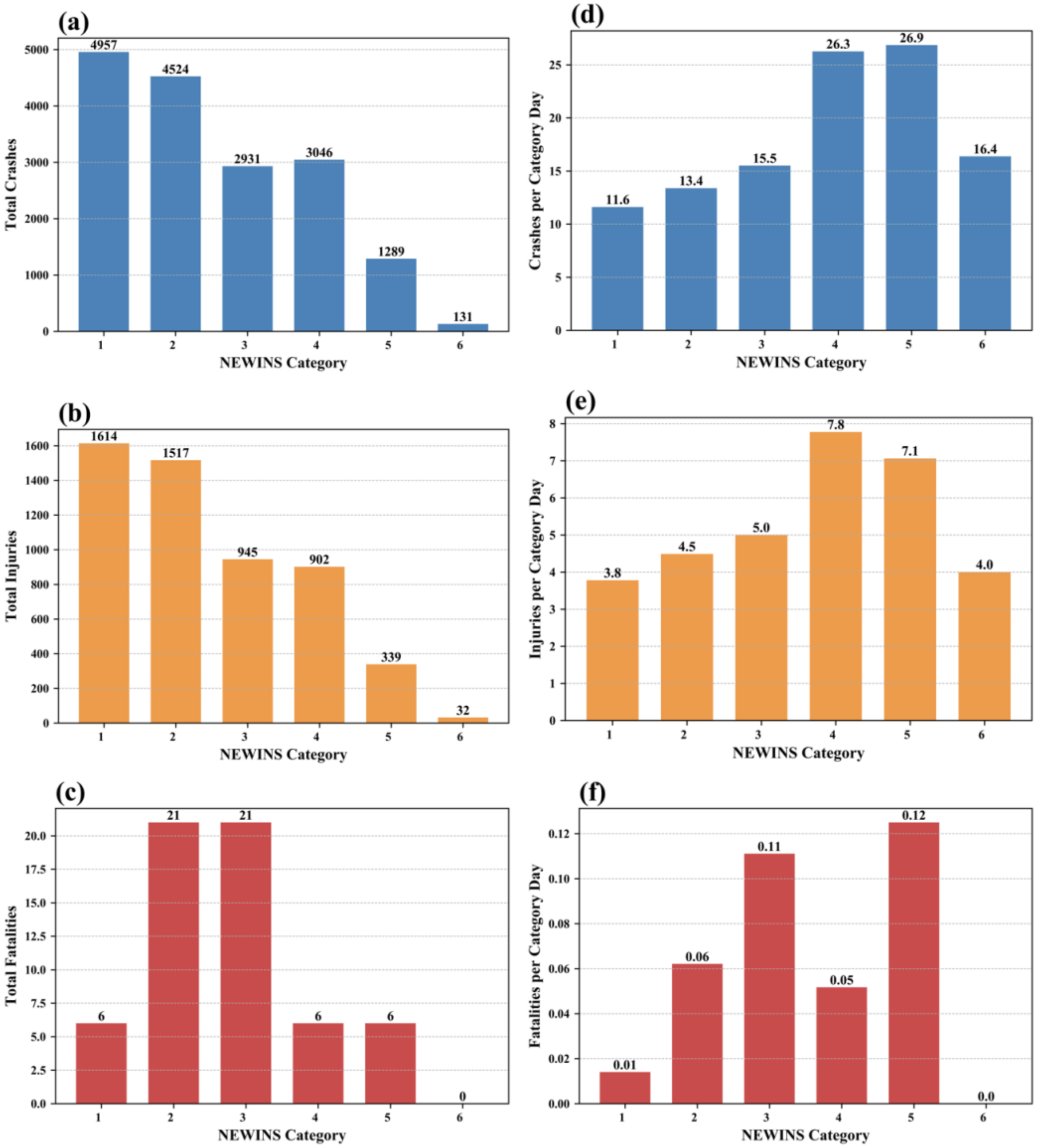


Figure 4.17: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by NEWINS category and number of snow-related (d) crashes, (e) injuries, (f) fatalities per category day by NEWINS category.

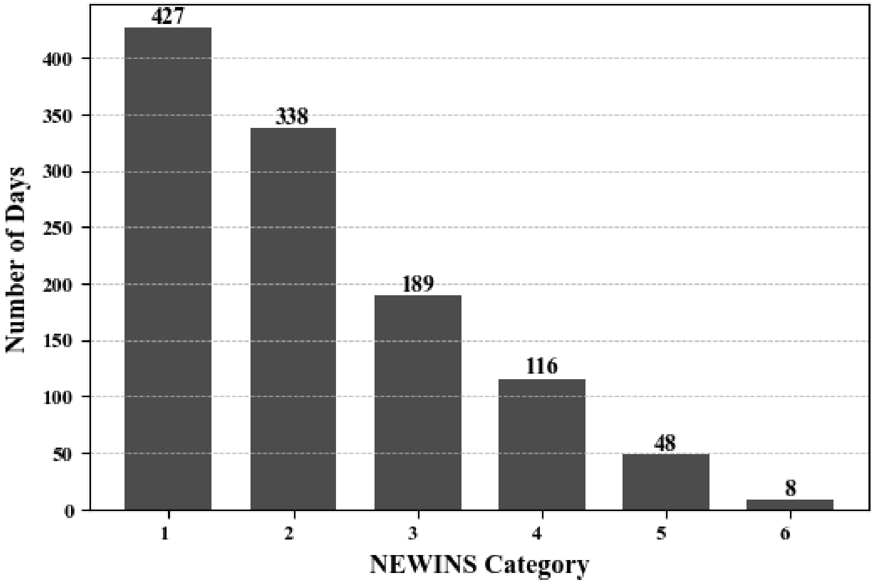


Figure 4.18: Total number of days assigned to an NEWINS category from 2007-2017.

crashes per category day increase with increasing category. These results are somewhat surprising as it has been shown in previous studies that when conditions become more severe, drivers tend to reduce their speeds, thus reducing the risk of severe injuries and fatalities compared to number of crashes (Eisenberg and Warner 2005, Cools et al. 2010). Although there were only eight Category 6 days during the entire study period, it is noteworthy that no fatalities occurred when conditions were this extreme (Figure 4.17). It is possible that the reduction in totals across all of variables for this category is due to the overall severity of winter weather conditions that likely led to extensive road closures and hindering law enforcement and emergency services' efforts to respond to stranded vehicles and crashes when they occurred.

4.4.2 Categorical Weather Variables

The NEWINS categories are assigned using a weighted equation that incorporates seven individual weather variables, including snowfall duration, air temperature, wind speed, visibility, snowfall totals, snow rate, and district area. Each variable will be assessed for snow-related traffic crashes, injuries, and fatalities using the same classifications used by Walker et al. (2019) as shown in Table 2.1 in an attempt to remain consistent with their methodology and allow for easier comparisons. In addition, using the classifications from Table 2.1, the number of category days are computed for each individual variable. This was done to account for when certain weather conditions occur more frequently, thus inflating totals and causing it to be more difficult to determine which conditions pose a greater risk for drivers. It is necessary to stress again that the values collected for each of these variables are district-averaged. Without having high-resolution in-situ data, it is not currently possible to determine what the specific conditions were for every crash.

Snowfall duration encompasses the length between the first and last observation of winter precipitation within a given district per NEWINS date. Days with longer winter weather events were found to have a higher frequency of reported snow-related crashes, injuries, and fatalities (Figure 4.19). It is reasonable to conclude that the longer a storm lasts, the more people are exposed to the risk of the winter weather conditions. It would be worth pairing this variable with previous findings by TOD (Section 4.2.5), to determine whether longer duration events during the day, as opposed to at night, are more impactful. Walker et al. (2019) note in their methodology used to create the classifications for snowfall duration were distributed at equal lengths, thus there is little change in the frequency of crashes by snowfall duration when accounting for number of category days.

When accounting for air temperature, total snow-related crashes and injuries appear quite variable (Figure 4.20); however, a higher number of snow-related fatalities occur when air temperatures are between 29 and 35ºF (-1.7 and 1.7ºC). When accounting for number of NEWINS category days, it does appear that as air temperatures decrease, the frequency of crashes and injuries increases slightly. The opposite is still the case for total snow-related fatalities, with a higher number of fatalities with increasing temperature, up until it becomes too warm for frozen precipitation (i.e. > 35ºF)(1.7ºC). It may also be the case that as temperatures begin to transition from above freezing to below freezing people may still be driving too fast for conditions leading to more severe crashes resulting in greater risk of a fatality. There may also be some influence of

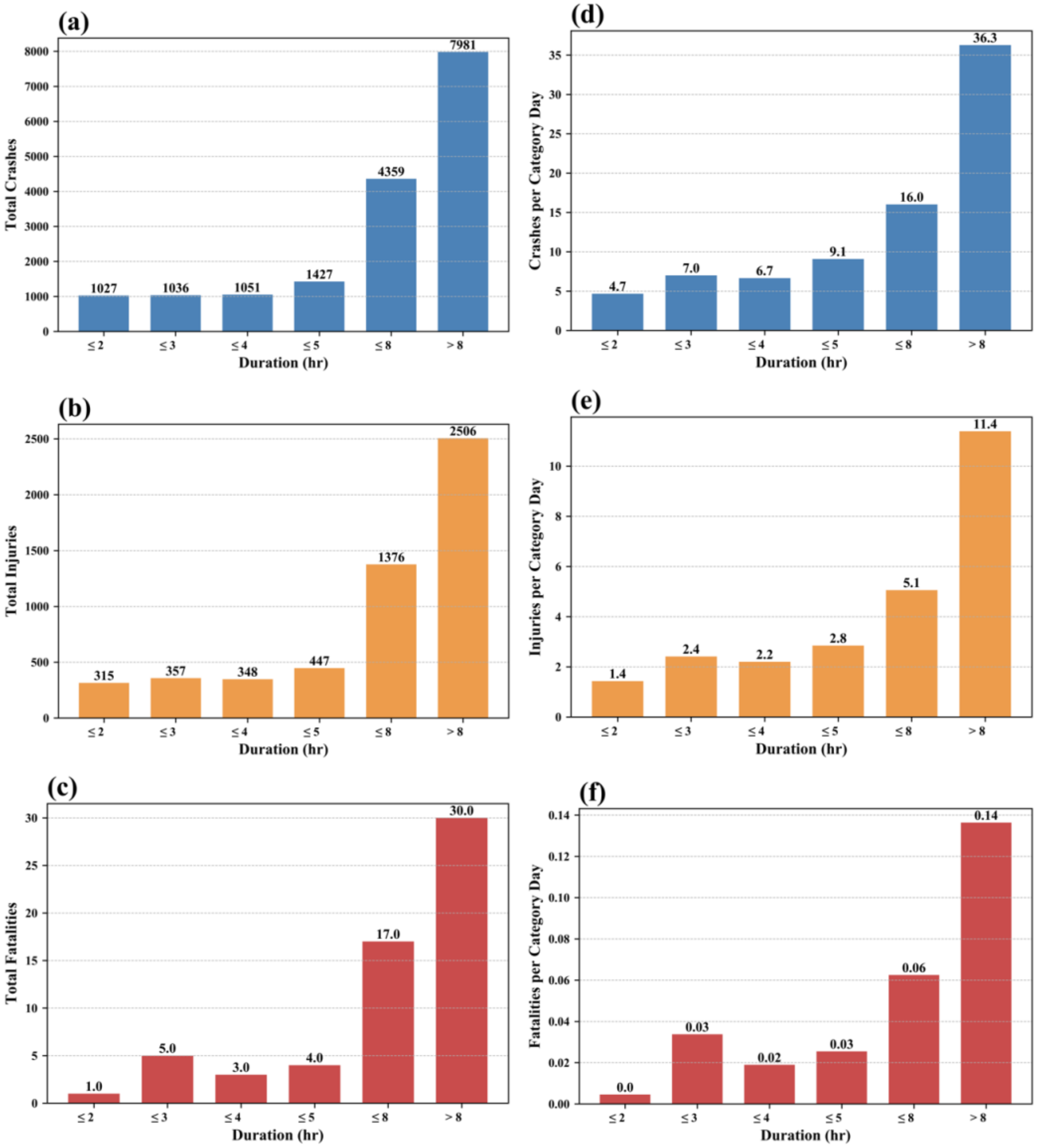


Figure 4.19: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by snowfall duration and number of snow-related (d) crashes, (e) injuries, (f) fatalities per NEWINS category day by snowfall duration of snow event.

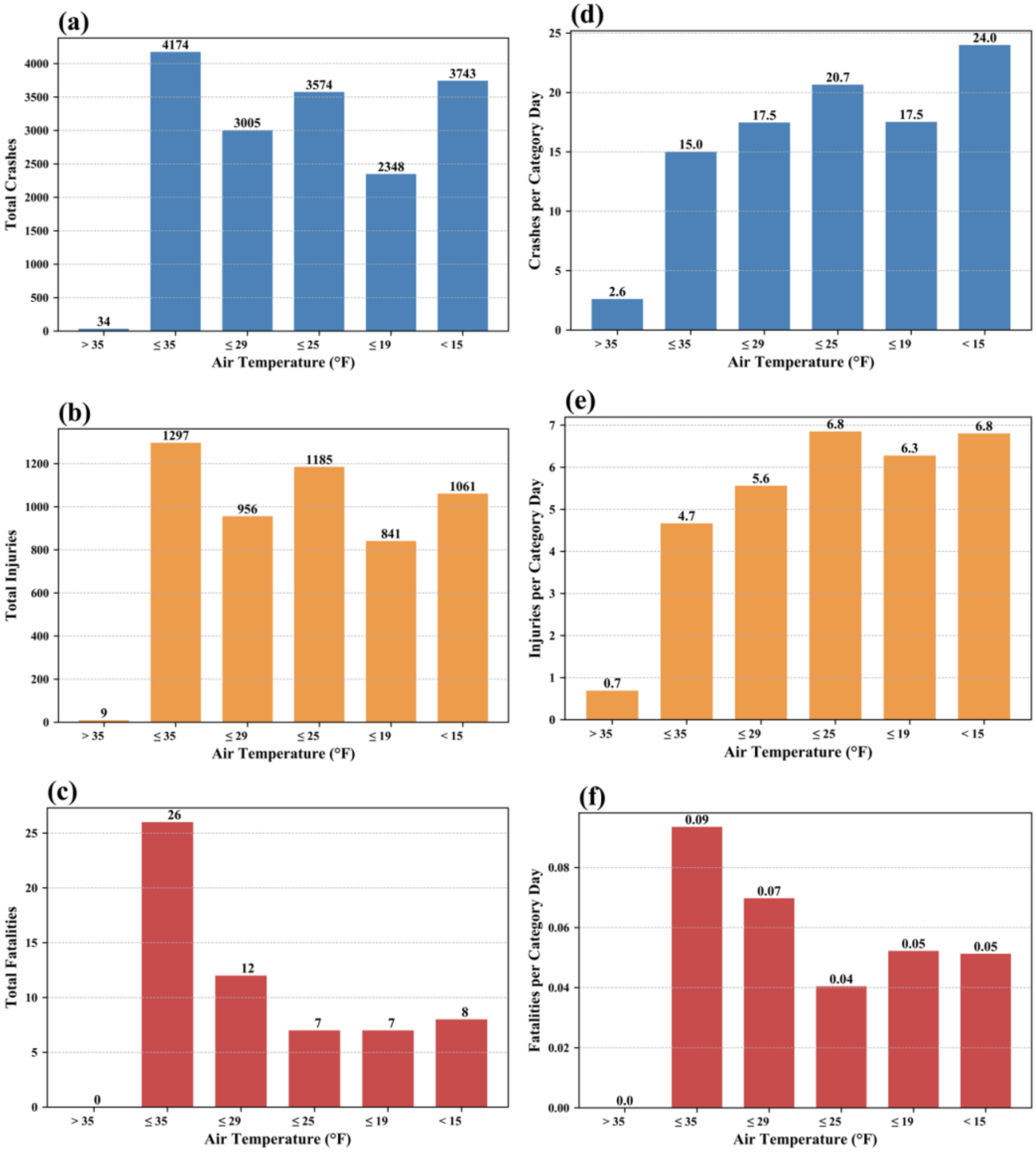


Figure 4.20: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by air temperature and number of snow-related (d) crashes, (e) injuries, (f) fatalities per NEWINS category day by air temperature.

roadway icing that are not fully captured in the reported weather conditions.

The highest number of snow-related crashes and injuries occurred when wind speeds were greater than 6 mph (5.7 kts) and less than 18 mph (15.6 kts) (Figure 4.21). As noted by Cools et al. (2010), increased wind speed significantly decreases traffic volumes, so in addition to there being fewer high wind days, there are also fewer people driving when wind speeds are strong. The highest number of snow-related fatalities occurred with winds between 6 and 11 mph (5.2 and 9.6 kts). When accounting for number of days these wind conditions occurred, the peak in crashes and injuries is not as apparent. Based on these findings, wind speeds, as computed for the NEWINS, do not appear to play a crucial role in the risk of a crash or injury. The number of snow-related fatalities when accounting for category days does weakly indicate that there is an increasing frequency of fatalities with increasing wind speed.

Call et al. (2018) state that in conjunction with increases in snow intensity, sudden decreases in visibility often occurred just prior to a crash. Likewise, obstructed visibility-related crash fatalities were found to be much more common than other weather hazards (Ashley et al. 2015). This also appears to be the case when accounting for the NEWINS computed visibilities (Figure 4.22). A higher number of crashes, injuries, and fatalities occur as visibility decreases, primarily when visibility is less than 2.5 miles (4.0 km). Again, it is worth reiterating here that the district averaging may artificially increase the observed visibilities. The classifications for visibility were also distributed equally by number of events, so few changes occur to the overall distribution of incidents when accounting for number of category days.

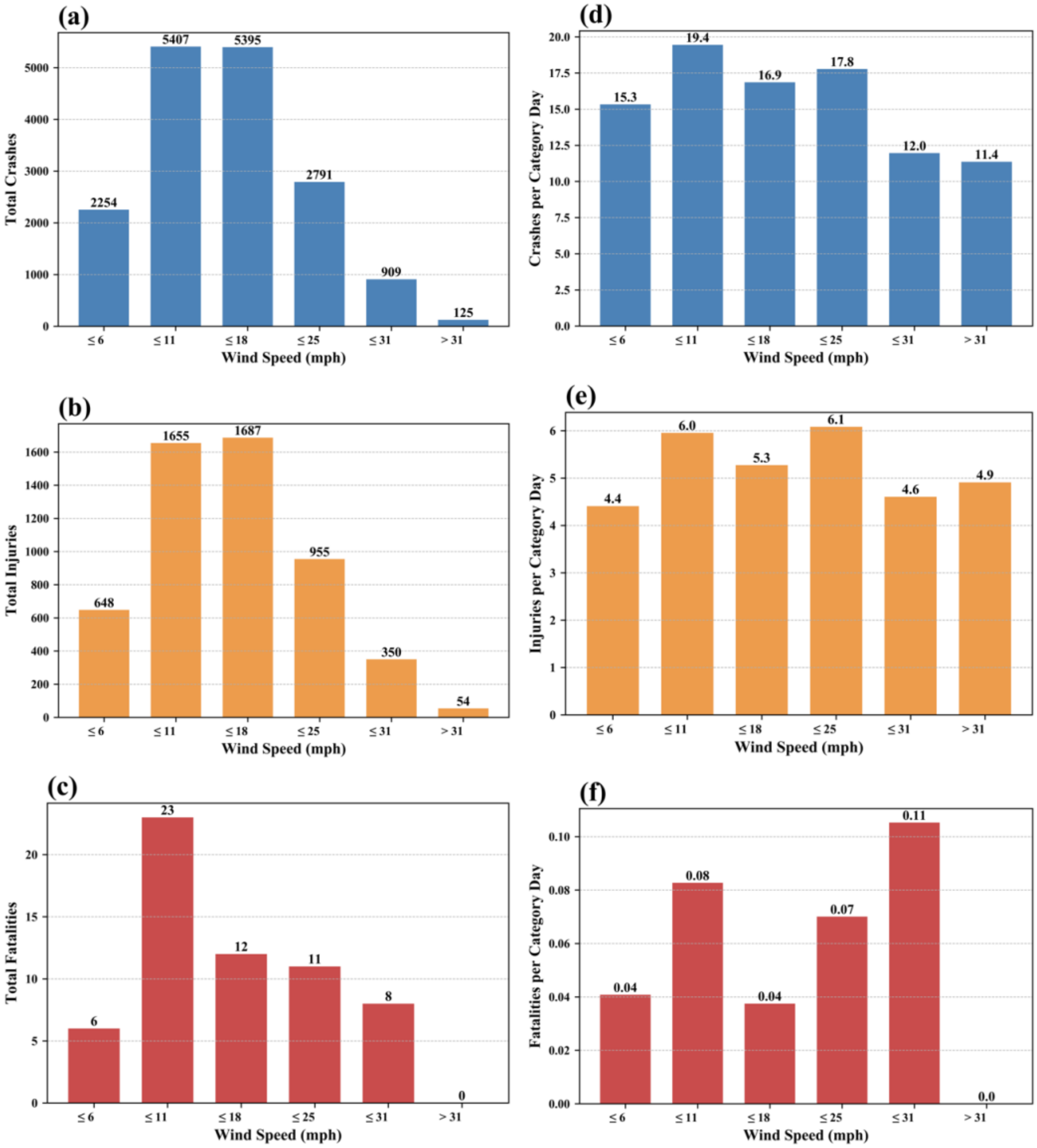


Figure 4.21: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by wind speed and number of snow-related (d) crashes, (e) injuries, (f) fatalities per NEWINS category day by wind speed.

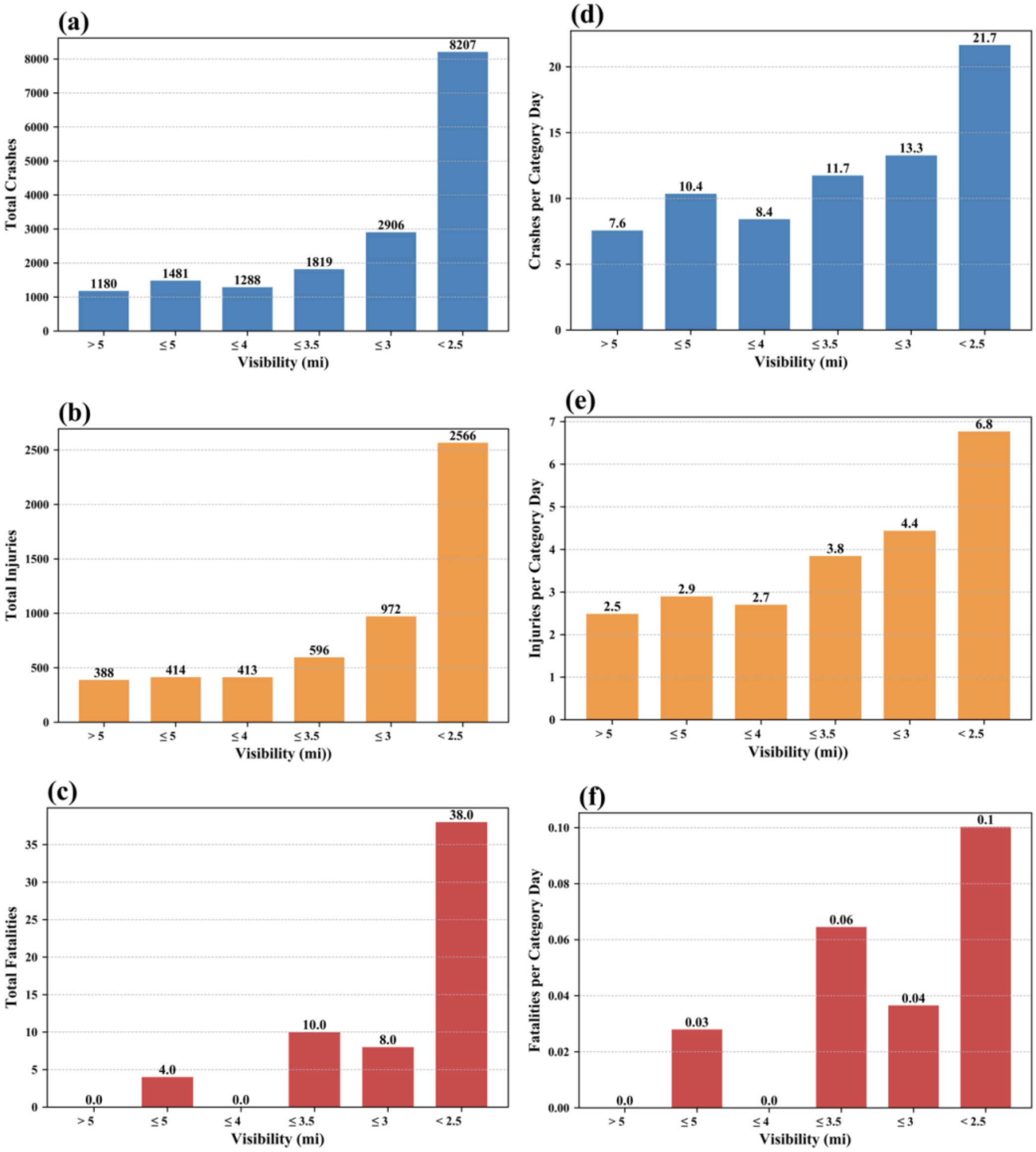


Figure 4.22: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by visibility and number of snow-related (d) crashes, (e) injuries, (f) fatalities per NEWINS category day by visibility.

The highest number of crashes and injuries occur during weather events with snowfall totals of less than 1 inch, with the frequency of crashes decreasing with increasing snowfall totals (Figure 4.23). This is mainly due to there being a greater number of lower end snowfall events during a typical snow season. The highest number of fatalities occurs when snowfall totals between 1 and 3 inches (2.54 and 7.62 cm). This suggests that the severity of snow-related crashes is more severe for winter events that have at least 1 inch of snow. One thing worth mentioning is that snowfall is weighted as 80% of the total computed NEWINS (Walker et al. 2019). Thus, the results are expectedly similar to the NEWINS categories (Figure 4.18). When accounting for number of days for snowfall totals, the number of a crashes and injuries are greatest for snowfall events totaling 3 to 7 inches (7.62 to 17.78 cm) (Figure 4.23). This helps to explain the higher numbers for Category 4 and 5 events for the NEWINS. These higher snowfall totals result in a greater risk of severe crashes. Fatalities also generally increase with increasing snowfall totals. No fatalities occurred on days with snowfall over 7 inches (17.78 cm). As was discussed previously, there were only a small number of days with this much snowfall during the entire period. In addition, this could also be partially explained by conditions severe enough to significantly reduce travel speeds and reduce the severity of crashes.

Snow rate is a derived parameter calculated by dividing the reported snowfall totals by the snowfall duration. Due to the impact of district and temporal averaging of the snow rate variable, it is unable to capture the inherent variability that makes snow rate a critical aspect of winter weather event (e.g., Walker et al. 2019). It has been previously found that increases in snowfall intensity and the resultant drop in visibility increase the

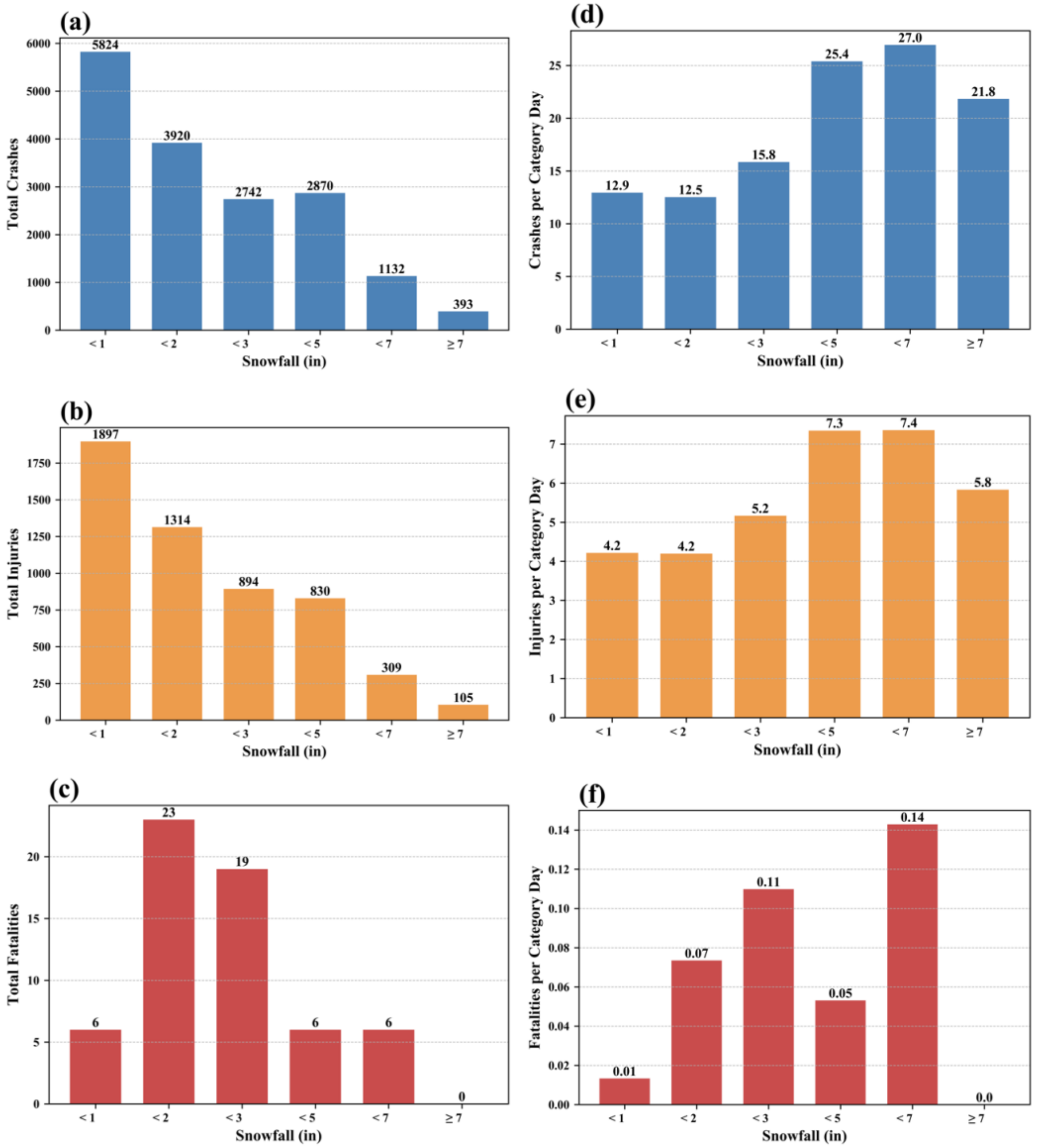


Figure 4.23: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by snowfall total and number of snow-related (d) crashes, (e) injuries, (f) fatalities per NEWINS category day by snowfall total.

relative risk of crash and injury compared to less intense snowfall (Black and Mote 2015b, Call et al. 2018). In contrast to these findings, there are much higher numbers of crashes, injuries, and fatalities for events that have lower snow rates (Figure 4.24). In spite of the district averaging, the number of crashes and injuries for higher snow rates do show a notable increase before being normalized by number of days. The frequencies of snow-related crashes and injuries still increase with decreasing snow rate; however, this is not as defined. Consistent with Andrey et al. (2003) no clear pattern exists for fatal crashes based on snow rate, which they propose is likely due to drivers making adjustments to their speeds which reduces the risk of fatal crashes when conditions get more severe.

The district area is computed by dividing the number of ASOS stations that reported frozen precipitation by the total number of possible stations within that district, denoted as the fractional area (Walker et al 2019). The frequency of total snow-related crashes, injuries, and fatalities generally increases with increasing district area (Figure 4.25). The majority of reported crashes occurred when at least 75% of the region was experiencing winter weather conditions. This seems valid that as the areal extent of a winter storm increases, a higher number of people are at risk of being in a crash. When accounting for number of category days, total crashes, injuries, and fatalities still show the same general distribution of more incidents occurring with increasing district area.

4.5 High Impact Days

The top 10 worst crash days on average in the U.S. occur according to Weast (2018) during the summer months around major holidays (e.g. Independence Day,

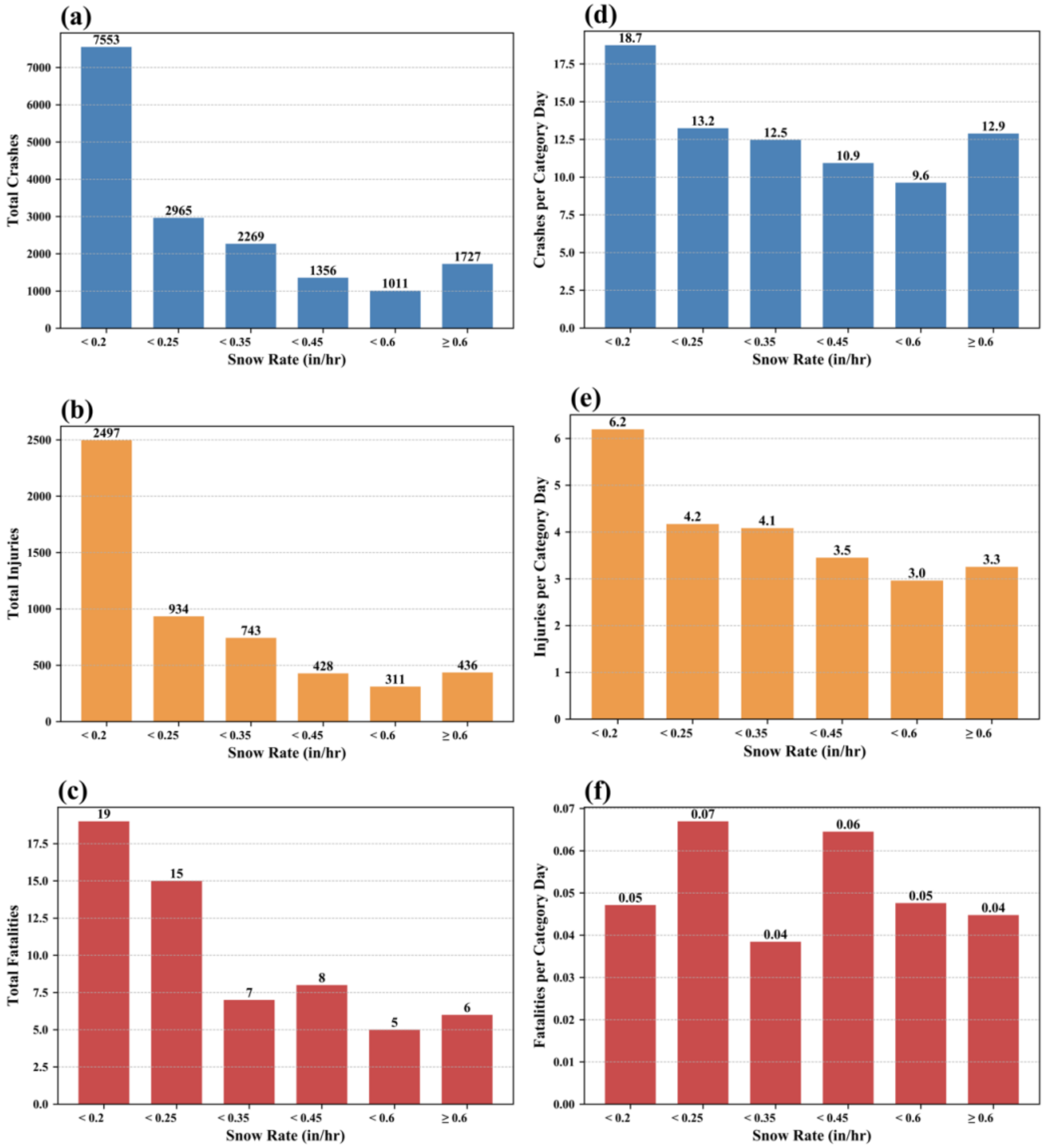


Figure 4.24: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by snow rate and number of snow-related (d) crashes, (e) injuries, (f) fatalities per NEWINS category day by snow rate.

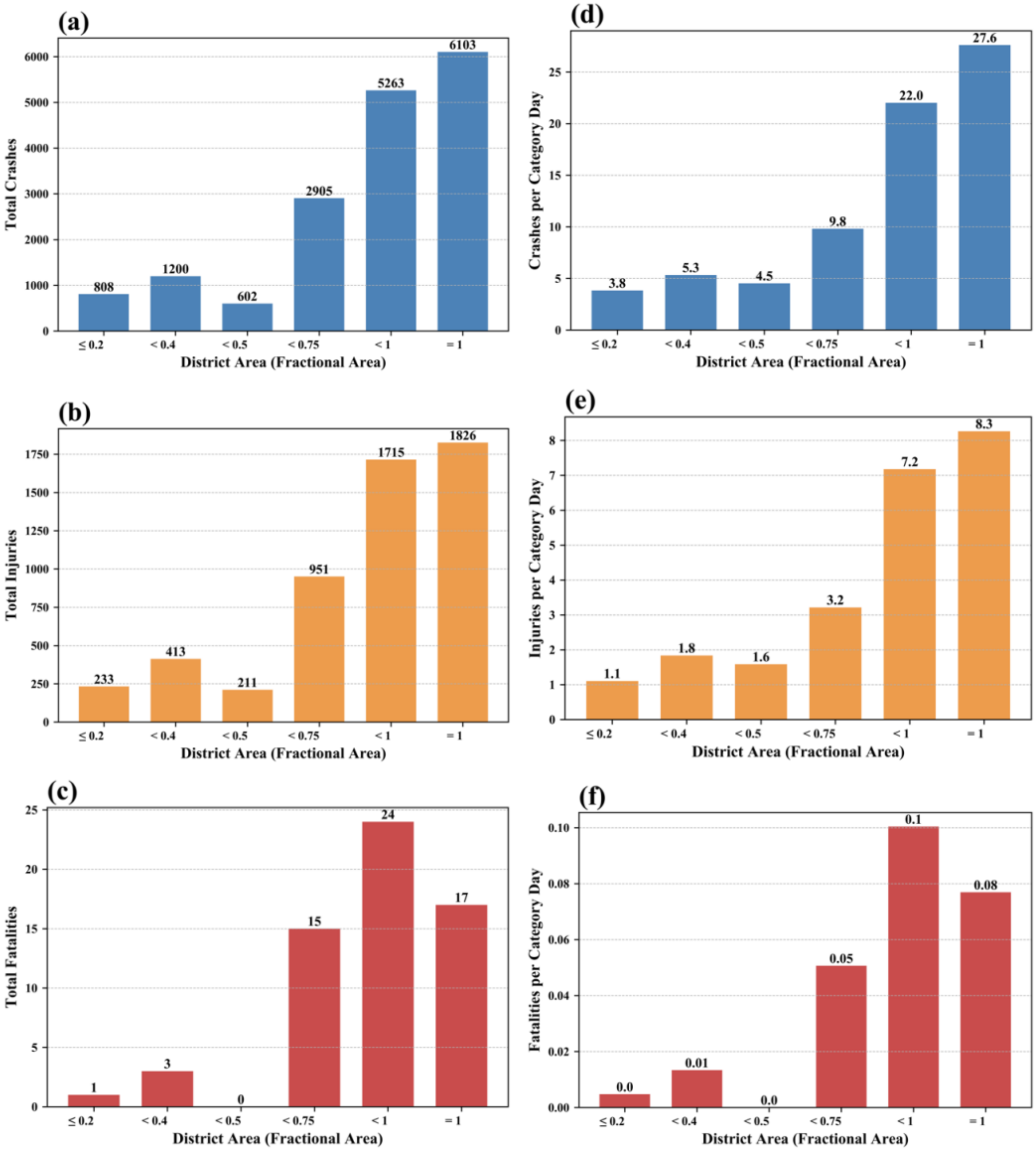


Figure 4.25: Total snow-related (a) crashes, (b) injuries, and (c) fatalities by district area and number of snow-related (d) crashes, (e) injuries, (f) fatalities per NEWINS category day by district area.

Labor Day weekend); however, when looking at the worst individual non-averaged crash days, they tend to occur during the winter season. To determine when these higher impact days occurred in Nebraska, a threshold of crashes having at least 300 individual crash reports was used to identify high impact crash days between 2007 and 2017 (Table 4.12). In total, 19 days met this criterion, with every year having at least one high impact crash day. The date with the highest number of crashes occurred on 13 February 2009 with 612 total crashes reported, resulting in 145 injuries and 1 fatality with the majority of crashes occurring with a primary weather condition reported as snow. The deadliest crash day occurred on 16 December 2016 during freezing rain/drizzle conditions resulting in a total of six fatalities. It is also worth noting that some of these higher impact days likely contributed to the outlier spikes represented in the violin plots for DOW and TOD (Figures 4.10, 4.12). The majority of these higher impact days occurred during the first half of the study period, where 2011 had the greatest number of days with a total of four. Beginning in 2012 only one high impact crash day occurred in the state each subsequent year. All of the crash days occurred during the winter season between the months of November and March and during either adverse winter weather conditions or clear days when residual snow- and ice-covered roadways. Of these, 13 occurred primarily when snow was falling and three occurred during freezing rain/drizzle. When considering the maximum NEWINS category in the state, 14 days occurred when Category 4 and 5 winter storms were impacting the state. This suggests that high crash days in Nebraska are frequently associated with major winter weather systems, even if the crashes do not necessarily happen in districts that received the highest amount of snow.

To reduce the influence of population and traffic volumes in Districts 1 and 2

Table 4.12: List of highest traffic crash days in the state (≥ 300 crash incidents)

Date	Crashes		Injuries		Fatalities		Primary Weather Condition	Max State NEWINS
	Total	Snow-Related	Total	Snow-Related	Total	Snow-Related		
13-Feb-2009	612	479	145	118	1	0	Snow	5
5-Feb-2008	525	431	139	119	2	2	Snow	4
24-Dec-2015	472	333	102	71	2	2	Snow	5
6-Dec-2007	471	241	121	51	1	1	Snow	4
16-Dec-2016	410	39	159	9	6	1	Freezing Rain	3
8-Dec-2011	409	314	87	75	3	3	Snow	4
3-Dec-2011	399	325	123	99	1	1	Snow	5
15-Nov-2014	393	291	84	61	1	1	Snow	4
16-Dec-2008	379	228	96	60	0	0	Snow	4
24-Feb-2011	375	293	118	102	2	0	Snow	4
14-Dec-2009	360	70	99	17	2	0	Cloudy (Snow on Road)	2
5-Feb-2010	358	199	80	37	1	1	Snow	4
21-Dec-2017	335	62	102	21	2	0	Freezing Rain	3
14-Feb-2010	334	153	200	85	2	1	Snow / Blowing Snow	2
31-Jan-2011	330	89	89	28	0	0	Freezing Rain	4
25-Feb-2008	312	228	122	60	3	0	Snow / Freezing Rain	3
5-Jan-2010	312	18	70	6	0	0	Clear (Snow on Road)	4
19-Dec-2012	309	198	77	55	2	2	Snow	5
10-Mar-2013	303	220	118	78	1	0	Snow	5

(Table 4.11) on determining which days are considered higher impact for the state, the top two crash days per district were also identified (Table 4.13). This resulted in the addition of six dates that were not previously considered. As expected, each of the top district specific days also occurred during inclement winter weather conditions or when snow and ice was still present on roadways. Only four out of the 13 unique days had any reported fatalities, with a maximum of two fatalities occurring in District 1 on 5 February 2008. This is consistent with previous research that suggests the reduction in traffic speeds due to winter weather conditions reduces the overall severity of a crash resulting in fewer total fatalities (Eisenberg and Warner 2005). For districts with lower overall populations, (i.e. Districts 5-8; Table 4.11), seven out of eight crash days occurred in November and December (Table 4.13). These early season crash numbers could indicate that people in these districts have not yet become accustomed to winter driving conditions this early in the season. In fact, rural area drivers may adapt to the winter driving conditions more quickly than those in urban areas. They also are more likely to have four-wheel drive vehicles and pickup trucks (Rakauskas et al. 2009). This could help explain why more urban regions of the state still experience high crash days much later into the winter season.

The limitations of analyzing high impact days solely by the number of crashes fails to consider when specific crash events are more severe than others. For instance, a crash that involves several vehicles will only be denoted as one crash event. Thus, it is necessary to also take into account days in which crashes involve multiple vehicles. Similar to the threshold used by Call et al. (2018), all crashes involving at least 10 vehicles are identified (Table 4.14). These types of crashes are often referred to as

Table 4.13: List of the top two highest crash days per NDOT District

Date	Date	Crashes		Injuries		Fatalities		Primary Weather Conditions	NEWINS Category
		All	Snow-Related	All	Snow-Related	All	Snow-Related		
District 1	5-Feb-2008	198	184	48	47	2	2	Snow	4
	24-Feb-2011	196	170	62	55	1	0	Snow	4
District 2	24-Dec-2015	304	232	50	42	0	0	Snow	5
	13-Feb-2009	241	215	59	58	0	0	Snow	5
District 3	12-Jan-2009	118	58	66	33	0	0	Snow & Blowing Snow	2
	14-Feb-2010	58	28	29	12	0	0	Snow & Blowing Snow	2
District 4	13-Feb-2009	91	64	23	21	1	0	Snow	5
	3-Dec-2011	84	77	20	20	0	0	Snow	4
District 5	20-Nov-2015	37	32	10	8	0	0	Snow	2
	3-Dec-2013	36	28	14	11	0	0	Snow	4
District 6	19-Dec-2012	53	43	15	15	1	1	Snow	3
	12-Feb-2007	42	27	20	19	1	1	Snow	3
District 7	21-Dec-2017	25	1	3	0	0	0	Freezing Rain	1
	3-Dec-2011	16	13	3	0	0	0	Snow	3
District 8	30-Nov-2008	14	4	4	3	0	0	Clear (Icy Roads)	0
	20-Nov-2015	10	9	1	1	0	0	Snow	4

Table 4.14: List of all multi-vehicle chain-reaction crashes (≥ 10 vehicles)

Date	**Vehicles**	**Time (LST)**	**County (District)**	**Road**	**Weather Conditions**	**Injuries**	**Fatalities**	**NEWINS Category**
12-Jan-2009	31	15:15	Dodge (D1)	Hwy 30	Snow & Blowing Snow	20	0	1
12-Jan-2009	14	14:39	Saunders (D2)	Hwy 77	Severe Crosswinds & Snow	9	0	1
9-Jan-2011	14	12:30	Dawson (D6)	I-80	Snow	0	0	5
14-Feb-2010	14	11:36	Cass (D2)	Hwy 34	Snow & Blowing Snow	1	0	2
10-Mar-2013	11	8:30	Seward (D2)	I-80	Blowing Snow & Severe Crosswinds	7	0	5
14-Feb-2010	10	14:35	Cass (D2)	Hwy 6	Snow	3	0	2
7-Aug-2015	10	7:55	Douglas (D1)	Hwy 6	Clear	0	0	0

multi-vehicle chain-reaction crashes. Seven such crashes occurred in the state between 2007 and 2017, the most serious of which involved 31 cars northwest of the Omaha metro area at 15:15 LST on 12 January 2009 due to severely reduced visibilities caused by strong winds and a quick-moving snow squall. This same snow squall caused another 14-car pileup in neighboring Saunders county less than an hour earlier. 14 February 2010 also had two major chain-reaction crashes. Call et al. (2018) found that 25% of chain-reaction crashes across the U.S. occur in snow or blowing snow conditions, likely due to locally reduced visibilities. In contrast, 86% of Nebraska's chain-reaction crashes occurred in snow and blowing snow conditions. Only one crash occurred outside of the winter season in the month of August and was not impacted by adverse weather conditions. All of these crashes occurred on major highways where higher speeds likely prevented drivers from being able to stop in time before colliding with the stopped vehicles ahead of them (Call et al. 2018). Based on the reported crash times, each one occurred during hours that typically have higher traffic volumes, including the morning, noon, and afternoon rush hours, consistent with DeVoir (2004). NEWINS categories on crash days that fell within Nebraska's snow season varied from Category 1 to 5; however, the two days with multiple multi-vehicle crashes only occurred in NEWINS Category 1 and 2. This implies that these significant crashes occurred under conditions which may not be well captured by the NEWINS and could serve as potential HISA cases. This deserves future study to determine what conditions cause these types of crashes and how forecast messaging may have impacted driver decision making.

Chapter 5: SUMMARY AND CONCLUSIONS

This study provides insight into the temporal and spatial distributions of crashes in the state of Nebraska from 2007 through 2017. Incidents were evaluated for total crashes, injuries, and fatalities at the yearly, monthly, DOW, and TOD time scales. Snowfall was found to have an effect on snow-related crash occurrences at all time scales when compared to all crashes. Furthermore, analysis of the NEWINS showed that it can provide valuable insight into how severity of winter storms impacts crash frequencies. Additionally, the evaluation of individual meteorological variables from the NEWINS, when mindful of their district-averaging limitations, showed that they can also improve general understanding of which weather conditions often lead to higher crash incidences relative to a storm's categorical severity. Days which had the greatest number of crashes and multi-vehicle chain-reaction crashes help to verify the substantial impact winter weather conditions have on crashes across the state.

The temporal distribution of all crashes was first evaluated to provide a baseline for determining the impact snowfall has on crash occurrence across the state. It was found that crashes, injuries, and fatalities decreased in frequency through 2012 with a subsequent rise through the end of the study period. Accounting for month, December and January have the highest average yearly crash totals, albeit they also show the most year-to-year variability. Injuries occur more frequently in the fall and fatalities are more common during the summer months. When taking into consideration DOW, most crashes and injuries occur during the workweek, with fewer on the weekends. Fridays had the highest number of crashes, injuries, and fatalities on average. TOD shows the most significant temporal variation, with two distinct peaks in crash and injury totals during the morning and afternoon hours when traffic volumes are typically highest. The rush hour influence also exists in the fatality data, although the hour-by-hour variability is not as extreme.

Close to 30% of all inclement weather-related crashes, injuries, and fatalities in Nebraska occurred with snowfall as the primary or secondary weather condition. For this reason, snow-related crashes were also analyzed temporally to evaluate how their statistics vary compared to those of all crashes. Snow-related crash totals have generally decreased since 2011, meanwhile all crashes have been increasing since 2012. Snow-related fatalities are fairly consistent year-to-year before a notable drop occurs in 2016 and 2017. With respect to month, snow-related crashes typically occur between October and May in Nebraska. The highest number of crashes occur from December through February which also exhibit high year-to-year variability compared to other months. Fatalities occur most frequently in December and February, with unexpectedly low totals in January. When separated by DOW, rather than a workweek versus weekend days as was the case for all crashes, there is less variability between each DOW for snow-related crashes, implying that there is a higher number of snow-related crashes on weekends than expected. TOD distributions show similar peaks in morning and afternoon rush hours to that of all crashes; however, the morning hours have higher than expected totals while afternoon hours have lower than expected. This indicates that mornings are typically more dangerous relative to expected crash numbers. There is also considerable year-to-year variability between the early afternoon hours likely influenced by outliers from high impact crash days. Fatalities are more irregular by individual hour, though in general, mornings are also more dangerous than expected.

Spatial distribution analyses show that the majority of crashes and injuries occur along major roadways with high traffic volumes or in higher population areas. In contrast, fatalities are more evenly distributed across the state. Grouping crashes by county provided a way to account for population and traffic volume influences on the data. Expectedly, counties with the highest populations had the majority of snow-related crashes and injuries. In general, the greatest number of fatalities occur in counties along the I-80 corridor. When accounting for population, counties in the Panhandle have a notably higher risk of crash or injury. When accounting for average miles travelled within a county, there is less of a clear signal as to which areas are at greater risk. District level information was also obtained to provide useful information for NEWINS comparisons and supported the county level findings from a district averaging perspective.

Assessment of snow-related crashes using the NEWINS show the highest number of crashes occur under Category 1 and 2 conditions. When accounting for the number of days, Category 4 and 5 result in the highest number of crashes and injures per category day, suggesting that moderate to severe storms increase the likelihood of crashes across the state. Evaluation of the seven NEWINS meteorological parameters also resulted in some interesting findings, despite the district and temporal averaging limitations. Crash, injury, and fatality totals were found to increase with increasing snowfall duration. The air temperature results show a slight increase in crashes and injuries per category day as temperatures decrease. The majority of fatalities occur when temperatures are near freezing, suggesting the transition between melted and frozen precipitation on surfaces proves more deadly than crashes under colder temperatures. In general, the majority of crashes occur in light to moderate wind speeds; however, no associated risk based on wind speed was found per category day. As surface visibilities decrease, it is shown that the number of crashes, injuries, and fatalities increases, with the majority occurring when visibilities are less than 2.5 mi. (4.02 km). Since snowfall is weighted heavily in the NEWINS categories, the results look quite similar to the categories. The highest number of crashes occur on days which receive less than 1 in. (2.54 cm) of snow. When accounting for number of category days, snowfall totals between 3 and 7 in. (7.62 and 17.78 cm) have the highest number of crashes and injuries per category day. Counterintuitively, the NEWINS has a higher number of crashes when snow rates are lower, which is likely due to the impact of temporal averaging of the variable. Lastly, as expected, when district areal coverage of a winter storm increases, the frequency of crashes also increases. Preliminary findings show that evaluating the NEWINS and each of its meteorological parameters individually may prove useful for understanding potential crash risk based the particular weather conditions forecasted.

High impact days were identified using statewide totals having at least 300 crashes on a single calendar day. Crashes on each of these days were predominantly winter weather-related with a majority of those having snow reported as the primary weather condition. Every year in the study period has at least one high impact crash day. Due to population densities influencing statewide totals, the top two crash days per NDOT district were also obtained, adding six more days to the dataset. Top crash days in smaller population districts (i.e. Districts 5-8) tended to occur earlier in the season when compared to higher population districts (i.e. Districts 1-4). A total of seven multi-vehicle chain-reaction crashes involving at least 10 vehicles were found, all of which took place on a major highway or interstate having relatively higher posted speed limits likely making it more difficult for cars to stop in time. The top multi-vehicle crash day occurred on 12 January 2019, resulting in a 31-vehicle pileup caused by severely reduced visibilities due to strong winds and a quick moving snow squall which also caused another 14-car pileup on the same day.

A few limitations need to be taken into consideration for this project which impacted the results. First, traffic crash data are generated from crash reports filled out by investigating officers which are then entered into the crash database. This process can result in data entry errors, and not everything is always fully completed. In addition, the decision to remove any crash coded as having alcohol involvement was made in an attempt to limit its influence as a significant crash risk factor; however, this fails to consider several other behavioral decision-making factors (e.g. distracted driving, driving too fast for conditions) which are known to increase someone's risk of a crash. The reasoning behind not including driver level data was due to the study's primary focus on individual crash events. If incorporating several driver level factors, there are instances where one crash has several drivers involved overcomplicating the results. Lastly, an assessment of the impact weather forecast communications has on winter weather-related crashes and whether the issuance of NWS advisory and or warning products are worth future study.

Other future avenues of research could include identifying alternative methods to better capture crash level weather conditions other than the district-averaged NEWINS weather parameters. It would also be worth exploring whether storm characteristics, such as snow water equivalent (SWE), also plays a role in crash risk. This could be done through a climatological assessment of crashes relative to winter weather events, with an emphasis on high impact days. Overall, the goal of this study was to increase understandings of winter weather-related traffic crashes across the state. The results from this study accompanied with increased collaboration between state DOT's and the weather enterprise will hopefully, in turn, further the current progress being made toward reducing the number of weather-related crashes.

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