Spring 4-21-2021

Analysis of Winter Weather Conditions and Their Relationship to Crashes in Nebraska

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ANALYSIS OF WINTER WEATHER CONDITIONS AND THEIR RELATIONSHIP TO CRASHES IN NEBRASKA

by

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A THESIS

Presented to the Faculty of

The Graduate College of University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Earth and Atmospheric Sciences

Under the Supervision of Professor Mark R. Anderson

Lincoln, Nebraska

April 2021

ANALYSIS OF WINTER WEATHER CONDITIONS AND THEIR RELATIONSHIP TO CRASHES IN NEBRASKA

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University of Nebraska, 2021

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Adverse weather conditions: such as changes in visibility, precipitation, wind speed, temperature, and road surface conditions, substantially impact highway and interstate safety. Therefore, an investigation into the winter weather conditions during highway and interstate crashes in Nebraska was conducted. Crash data were obtained from the Nebraska Department of Transportation (NDOT) for the years 2008 to 2018. In order to separate the non-winter weather related crashes and the winter weather related crashes, six filtrations were applied to make this possible. These filters were based on a few crash parameters: road classification, alcohol, and crash severity, and weather parameters within the crash data: road surface condition, weather condition I and II. Once the filtrations were applied for all crashes in the study period, winter weather data were found for each crash. Different aspects of both crash and weather data were then analyzed to obtain insights into the impacts of Nebraska weather on roadway crashes. National Weather Service winter weather alerts were also examined to see what type and severity of alert was issued at the time of fatal crashes. When synoptic-scale storm systems are present, Colorado lows are more deadly and cause more crashes than Alberta clippers. In addition, winter weather advisories were the most common weather alert issued during a fatality. From this information, whenever Colorado lows are being forecasted as the storm type, the public should be put on higher alert due to the number of

crashes this storm type causes. The characteristics of both of these storm types; including snowfall, wind speed, visibility, and temperature all change the impact of these storm types. Snowfall and high wind speeds result in blowing snow which reduces visibility, producing the most crashes. When looking at temperature only, most crashes occur when the temperature is around freezing, since the snow has a low snow to liquid ratio or due to re-freezing. Furthermore, the weather alerts need to continually improve on the impact-based method to help reduce the number of crashes and crash severity. The public will continue to travel, especially when winter weather advisories are issued, until there is a more severe warning issued. Ultimately, this research will quantify weather related factors associated with motor vehicle crashes in Nebraska.

ACKNOWLEDGEMENTS

I would like to thank my thesis advisor, Dr. Mark Anderson for his mentoring and guidance throughout the whole process. He was always able to answer any questions I had and would even reply to emails that I would send at all hours of the day. I would also like to thank Dr. Dawn Kopacz and Dr. Matthew Van Den Broeke for their contributions as my committee members.

I would like to thank the Nebraska Department of Transportation for funding this project. I would also like to thank the NDOT employees that answered any questions or concerns throughout my time working with them.

I would like to thank my collaborators on this project Muhammad Umer Farooq, an Engineering Ph.D. candidate, and Dr. Aemal Khattak for all their assistance and time with this research. I would also like to thank Logan Howard, Harrison Redepenning, Jonathan Camenzind and Logan Bundy for their time on this project.

I would like to thank my colleagues within the Department of Earth and Atmospheric Sciences at the University of Nebraska-Lincoln for their support and friendship throughout my time in graduate school. I would also like to thank my friends and family for their support and encouragement over the years. Lastly, I would also like to thank my fiancée for overwhelming support and patience throughout my time in graduate school.

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Chapter 1:

Introduction

Motor vehicle crashes continue to take a toll on human lives, by causing injuries, and property damage, and they continue to be a concern for transportation agencies. Among the factors affecting motor vehicle crashes, adverse weather is known to be a major element (Figure 1.1). Adverse road weather is comprised of weather and road conditions at the time of the crash.

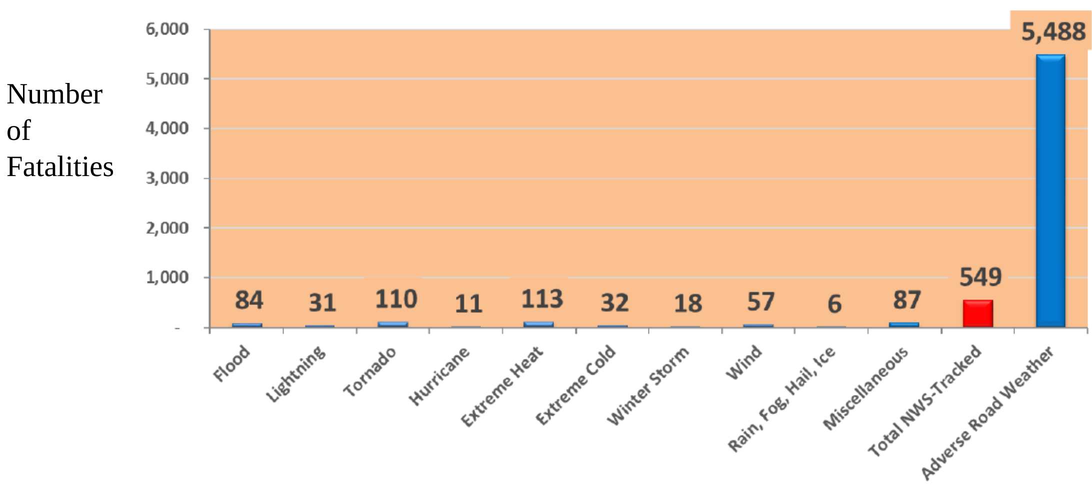

Figure 1.1 National impacts of adverse weather on roads compared to weather conditions (from Pisano 2017)

According to the Federal Highway Association (FHWA), 24% of weather-related vehicle crashes occur on snowy, slushy, or icy pavement and 15% happen during snowfall or sleet (FHWA 2021). Since adverse road weather considers all types of weather conditions, a study done by Andrey et al. 2003 found that snowfall contributes are more than rainfall to total number of collisions. In the state of Nebraska in 2019, 12% of all crashes and 6% of all crash fatalities occurred when there was snow or ice on the road (NDOT 2019). On the national scale, between 1994 and 2011, 9% of all weather-related crash fatalities took place on a snow or slushy pavement (Ashley et al. 2015). Fatalities are not the only concern when adverse road weather occurs. Average speeds on main roads are lower in winter due to decreased visibility and increased slipperiness (Perrels et al. 2015). The relative risk of an accident is six times higher for the conditions “icy road and heavy snowfall” (Malin et al. 2018).

In this study, winter weather data are gathered from 2008 through 2018 to investigate conditions leading up to and during crashes in Nebraska. The data will be transformed from a yearly format to a winter season format, 1 October to 31 May of the subsequent year, and filtered using six different parameters: snowfall, temperature, visibility, wind speed, whether the storm is Colorado low or Alberta clipper, and related moisture and wind flow patterns. Winter weather alerts, by the National Weather Service (NWS), such as a winter storm warning, will also be determined during fatal crashes to see if more fatalities occur when an alert is issued compared to no severe weather alert. The main research objective of this study is to obtain a better understanding of Nebraska crashes through statistical analyses of those weather conditions that cause the greatest safety concerns and identify potential implications for road maintenance activities.

All of the analyses developed for this project will provide insight into what role winter weather plays in car crashes in Nebraska. Using the findings from storm type characteristics and individual weather parameters will help contribute insight for forecasters to communicate the weather and hazards expected to transportation personnel and the public. Once this communication has reached the greatest level, the public, safety experts, and maintenance personnel will need to be advised of the present dangers presented by the current winter weather event.

Chapter 2:

Background

Winter weather causes adverse road conditions across the country. The risk of driving during winter weather increases the likelihood of a crash or injury. Many meteorological factors play a role in causing crashes during winter such as blowing snow, heavy snowfall rates, strong winds, and slick roads to name a few. These weather conditions are brought to the Nebraska area mainly by two types of synoptic-scale weather systems; Alberta clippers and Colorado lows. Colorado lows are longer lasting and have more snow. Alberta clippers have drier snow and are colder than Colorado lows. Both storm types have difficulties when it comes to forecasting. The National Weather Service (NWS) has recently introduced impact-based warnings and advisories instead of having the weather alerts be criteria based (NWS 2021). Criteria-based alerts are based on each NWS county warning area. As an example, in central Pennsylvania, a winter weather advisory is issued when the midpoint of the forecasted snow amount is at least three inches (DeVoir 2004). When the midpoint is less than three inches, no advisory is issued. Impact-based alerts were created to help communicate to the public, safety concerns when there is not a big snowstorm. NWS offices continue to communicate with their respective Department of Transportation (DOT) to help make roads safer.

2.1 Winter Weather Crashes

Transportation agencies are continually concerned with highway safety during winter seasons. Pisano et al. 2008 found that winter weather conditions initiate 24% of all crashes and 7,400 people are killed and more than 673,000 are injured during crashes that involve winter weather conditions each year. Furthermore, they found that winter weather related crashes along with all weather-related crashes account for 17% of all fatalities involving cars. Regionally, the Midwest has about 24% of all weather-related crashes occur when it is snowing or sleeting. One thing to note is that the Midwest has 22% of the USA's population; however, 40% of all weather-related crashes occur in this region.

The relative risk of crash and injury are higher during the first three winter precipitation events of the year as compared to subsequent events (Black and Mote 2015a). Eisenberg and Warner (2005) found a similar result when the number of crashes increased dramatically during the first month of winter that had snow. More specifically, they found that the first days of snow were more dangerous than the other snow days. Qiu and Nixon (2008) and Eisenberg and Warner (2005) found the fatality rate to increase during winter weather conditions. For Eisenberg and Warner (2005) this increase occurred on the first snow of the season and in Qiu and Nixon (2008) the fatality rate increased 9% compared to dry days. Most of the fatal car crashes involving winter precipitation occur during the daylight hours, whereas fatal crashes involving other weather conditions are more prevalent at night (Black and Mote 2015b).

As precipitation intensity increases, the overall risk of crashes and multiple vehicle crashes escalates. Call et al. (2018) found that crashes with at least 10 vehicles occurred when the intensity of the snow increased within the hour of the crash. The relative risk of a crash increases as the precipitation intensity goes from low to moderate; however, as the change goes from moderate to heavy, there is little change likely due to the reduction in travel during these times (Andrey 2010). Eisenberg (2004) found that as the precipitation intensity reaches heavy or very heavy, the overall fatality rate increases.

For lower precipitation rates, the fatality rate decreased since the lighter intensity causes drivers to be more careful when driving allowing for only minor and non-fatal crashes to occur. Similar to precipitation intensity, where people live and the posted speed limit also contributes to car crashes. A study by Andrey et al. (2013) in Canada found that the relative risk of crashes increased in rural areas compared to in cities, and when the posted speed limit increased.

Snowfall, precipitation, cloudiness, and wind speed decrease traffic intensity (Cools et al. 2009). They also found that within their study area, Belgium, when it does snow, the traffic intensity will be 3.8% lower than during non-snow weather. Snowfall, especially as the intensity increases, causes the most delays and reductions in travel (Tsapakis et al. 2013). Hanbali and Kuemmel (1993) did a study based on certain characteristics related to traffic volume and intensity. They found that the more severe a winter storm, the greater the reduction in traffic volume. In addition, reductions were greater for weekends and storms producing more precipitation. Lastly, their study found that drivers are less decisive about not going out when the storm is weaker and more decisive when the storm is stronger. Call (2011) found similar results and found that the traffic intensity decreased in both suburban and rural areas. These findings all show that many features of winter weather will decrease the traffic volume and no matter where people travel, the traffic intensity will be lower with adverse weather ongoing.

Temperatures also influence crashes during the winter. Temperatures are correlated with snowfall. The colder temperatures occur on days when there is snow rather than on non-snow days (Datla and Sharma 2008). This study found that the lowest temperatures cause significant reductions in traffic volumes. Combining this with the snow would only hamper the volume of traffic even more. The time of day that cold affects the traffic volume most is during the mid-morning hours, 8:00-10:00 LST. This slower traffic is on both recreational and commuter roads. When adding wind speed to the mix, blowing snow can occur. This occurs when the winds are strong enough to raise the snow particles to sufficient heights above ground so that horizontal visibility is reduced to six miles or less (Atmospheric Environment Service 1977).

2.2 Colorado Lows and Alberta Clippers

In this study, the weather system type, moisture flow and 850 hPa wind flow will be investigated during crashes. The two weather system types included Colorado lows and Alberta clippers. A Colorado low, as defined for this project, is a winter storm moving from the Colorado/Kansas/Oklahoma area eastward or northeastward across the region producing precipitation over Nebraska. During the event, blowing and drifting snow may take place. Colorado lows have a highly variable snowfall amount that could range from a dusting or inch to over a foot of snow with appropriate temperatures. Heavier snow results from a greater moisture supply, specifically from the Gulf of Mexico. Pairing greater moisture advection with a strong 850 hPa wind flow, results in heavier and longer lasting snows. During a Colorado low, the 850 hPa wind flows vary from a southwesterly flow, to a southerly, then an easterly and finally a northeast to northwesterly flow. The southwesterly flow occurs when the storm is in its beginning stages. The southerly flow is when the system is overhead of the area of interest. Lastly, the northerly and easterly flows are when the system moves out of the area; however, may still affect the specified area with wrap-around snow. A Colorado low can also get its moisture from the Great Lakes/East Coast after the storm has moved through the area and is producing a northeasterly or northerly wind flow over Nebraska. Forecasting the amount of snow and anticipating the location of the rain/snow line are reasons why forecasting these types of storms can prove difficult. Combining where the rain/snow line is with the wetter, heavier snow, longer duration, and how spatially large these events are, this results in greater impact to the road network than a typical Alberta clipper.

An Alberta clipper usually brings colder and drier Canadian air across the Plains reducing the water content of the atmosphere resulting in relatively lighter snowfalls. Alberta clippers have blowing and drifting snow during and after the event. The reason why there is drifting after the event is because the winds are strongest and usually located on the western side of the Alberta clipper in the region between the surface cyclone and the often-intense anticyclone trailing the clipper (Thomas and Martin 2007), and the snow to liquid ratio is higher, whereas the Colorado lows' winds are usually strongest during the storm. Drier Canadian air is dominant in these storms and the 850 hPa wind is almost always from the northwest or at least has a northerly component. These lighter snowfall amounts typically are less than half a foot due to the duration of the clipper. The duration of an Alberta clipper is usually only a few hours to a day since the system moves rapidly across the region. Due to the faster movement compared to a Colorado low, these types of storms can also be difficult to forecast.

2.3 Forecast

NWS personnel base their warnings on criteria that fit with the geographical and climatological history of the region. An example of this would be, in central Pennsylvania, if the forecasted snow amount is between two and four inches, the midpoint of this forecast is three inches which would call for a winter weather advisory to be issued. However, if the forecasted snow amount would be one to three inches, the two-inch midpoint would be less than the criteria to issue an advisory, so no advisory or statement is issued (DeVoir 2004). The paper discusses the issues with Lake Effect Snow Advisories and Warnings and how if the criteria are not met, then the NWS in Central Pennsylvania will not issue a warning or advisory. Since the paper was published in 2004, there have been subsequent improvements to the NWS procedures for issuing warnings and advisories (NWS 2021). In 2012, the NWS began experimenting with impact-based advisories and warnings to replace the current criteria for advisories and warnings. This was put into effect to help communicate the dangers of travel when there was not a big snowstorm, as well as help reduce the number of crashes. One of the goals of that project was to better meet societal needs in the most life-threatening weather events.

Over these last couple of winters, the issuance of advisories and warnings within the NWS Omaha/Valley region have seemed to increase. Advisories are now being issued when the NWS Omaha/Valley forecast region is going to receive less than the criteria meant for a winter weather advisory. The NWS in Omaha is issuing advisories if there is light snow that is going to occur during a rush hour or for an unusually early or late season event (NWS Omaha 2021). These advisories are preferentially issued during peak traffic times. Changing to impact-based alerts instead of criteria-based alerts is the NWS's way of helping the country become a Weather-Ready Nation (Uccellini and Hoeve 2019). The NWS is trying to publicly connect people to improved forecasts and warnings to help in the decisions that enable everyone to be as ready as possible when bad or extreme weather is on the way. Most importantly, the NWS is continuing to communicate with their respective Department of Transportation’s (DOT) to make the roads a safe place to travel during and after inclement weather.

Chapter 3:

Methodology

The goal of this project is to investigate winter weather at the time of and leading up to crashes and see if similarities within the weather conditions can be determined. This study will look at a 10-year period, 2008 to 2018. In addition, the type of synoptic weather system will be investigated to determine whether Colorado lows produce more crashes than Alberta clipper systems.

3.1 Crash Data

The crash data for this project were obtained from law enforcement and citizen reports of damage and injuries to the Nebraska Department of Transportation (NDOT) as part of their safety council archive (NDOT 2019). Since this research is focused on crashes during adverse winter weather conditions, a winter season time period is applied, defined as 1 October of the given year and ending 31 May of the subsequent year. For example, the 2008 winter season starts 1 October 2008 and ends 31 May 2009. Since crash reports are archived within NDOT by calendar year, NDOT data from two different years are combined to create a winter season.

After the winter season time period is established, the crash data are filtered to better represent the weather conditions during a crash (Figure 3.1). The first variable to focus the number of crashes is road classification (Var 1). Crashes taking place on state and federal highways, as well as interstate highways were collected. Crashes that occur on local roads, streets and recreational roads will be excluded. This is because NDOT covers only the highways and interstates for maintenance. This study wants to make sure the crashes are only associated with adverse winter weather, not alcohol (Var 2), therefore, all crashes with alcohol being reported will be excluded from the study. The third variable filtered is accident severity (Var 3). Crashes are organized by severity category; possible injury, visible injury, disabling injury, which was changed to suspected serious injury in 2015, and fatality. This study focuses on injury and fatality since those are more pressing than the other types of crash severity. Property damage only crashes are excluded from the dataset used by this project.

To obtain crashes during winter weather, crashes are further filtered using road surface condition (Var 4). Road surface conditions for this project only include icy, snow, slush, or wet conditions. Once the road surface condition is met, then weather condition I (Var 5), and weather condition II (Var 6) are collected. The reason behind two different weather conditions is that weather condition I is the primary weather condition occurring at the time of the crash. The second weather condition is used only if another weather condition is taking place or if the officer who reported the crash wanted to put another weather condition down. Only the wet road surface condition has further criteria, the wet road surface condition needs to have weather conditions I and II be either snow or ice to be contained in the dataset. For example, weather condition I could be snow and weather condition II could be blowing snow with a wet road surface condition. The reasoning for this filtration is because the crashes now have an adverse winter weather condition, compared to wet and rain for the weather condition.

After all six variables are filtered, the number of crashes dropped significantly from the original number of crashes per winter season. For example, 2008-2009 had 552 crashes compared to 15,806 from before the filtering of variables (3.5%). The highest number of crashes are reported during the 2009 winter season which also has the most snowfall during this 10-year timeframe.

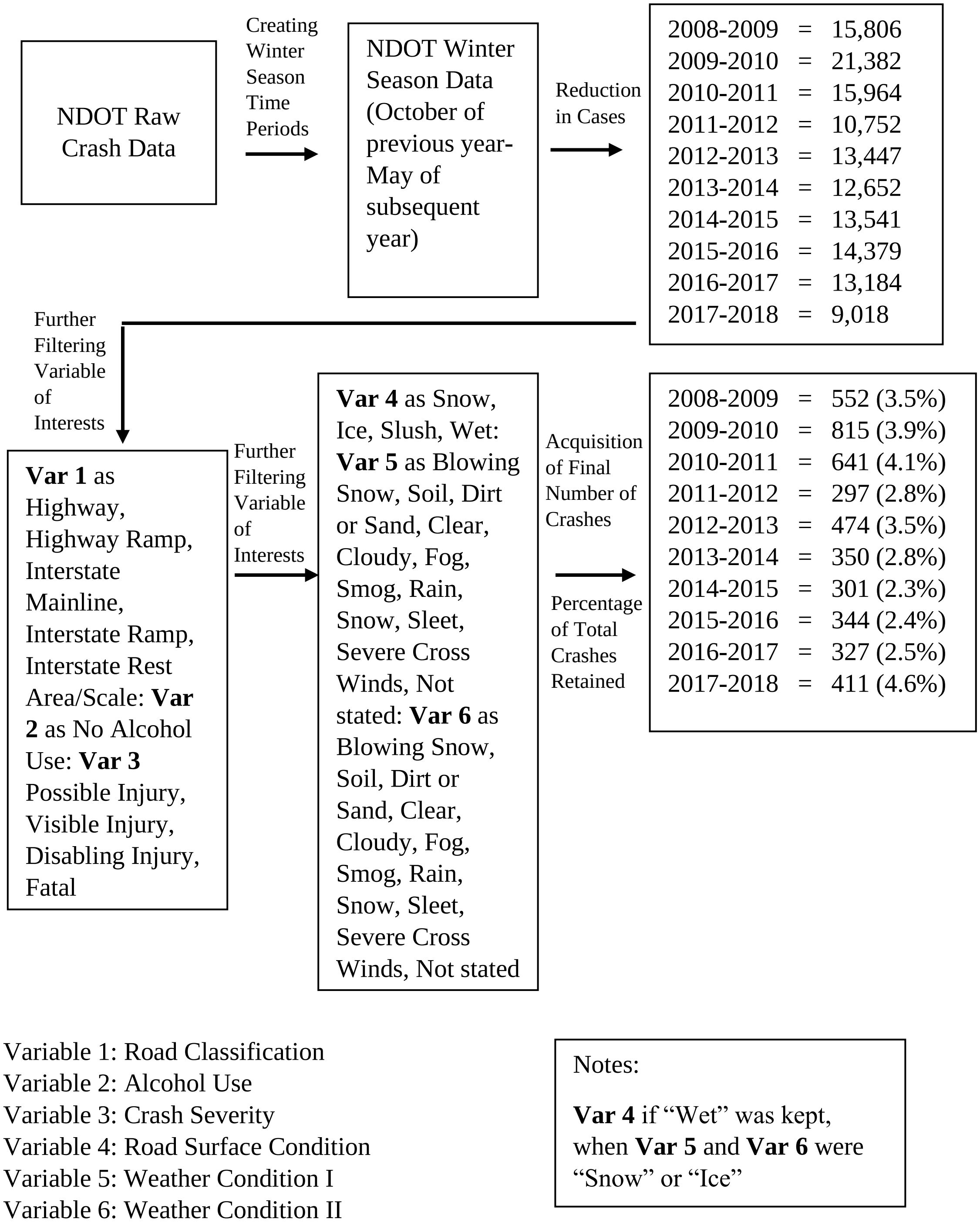

Figure 3.1 Data Filtration Process

3.2 Weather Data

Snowfall and icy conditions are major reasons for why crashes occur in the wintertime. Making sure driving conditions are safe and keeping the road surfaces snow and ice free is a major responsibility of transportation agencies. To understand the weather conditions during a crash, snowfall amounts, surface air temperatures, visibilities, wind speeds, and upper air conditions were obtained to augment the crash report with detailed weather conditions besides what is listed in the report. Surface weather parameters for the crash location and time were interpreted from archived automated surface observing system (ASOS) sites across Nebraska (Iowa Environmental Mesonet ASOS 2021). If a parameter had missing data at the ASOS station, data for the next closest time were obtained. If data at the next closest time also were missing, the next closest ASOS station was used for the original time of the crash. Since there are a limited number of ASOS stations across Nebraska, if a crash occurred between some stations, the closest three to five stations were looked at to provide an estimate of the observations nearest to the crash. In addition, these crash reports were not at the same time as the reported observations, so the closest time was chosen to represent the conditions closest to the crash occurring. Air temperature data were chosen as a parameter to see if the surface conditions would be frozen or not and with colder air temperatures the snowfall would be considered drier than air temperatures near the freezing point. It should be noted that these are air temperatures 1.5 m above the ground surface and may not represent the actual road surface temperatures at the crash site. Visibility and wind speed data were obtained to represent whether there could be blowing snow at crash time. NDOT considers blowing snow to occur roughly at 22 mph. This study used 25 mph as the lowest wind speed for blowing snow to occur.

Daily total snowfall data were obtained for a three-day window, starting two days prior to the crash, using the National Operational Hydrologic Remote Sensing Center (NOHRSC) Interactive Snow Information (NOHRSC radar 2021) and the NOHRSC National Snowfall Analysis (NOHRSC snow 2021). Once the data gathered from the Community Collaborative Rain, Hail, and Snow Network (CoCoRHaS) and the Cooperative Observer Program (COOP) observers have been entered, maps are then created to show snowfall for the crash locations. Snowfall is usually reported around the 12 Universal Time Coordinated (UTC) time frame each day. This is not a midnight-to-midnight observation period. For most of Nebraska, it is from 6 Local Standard Time (LST) (12 UTC) to 6 LST (12 UTC) the next day time frame for most of Nebraska. The western part of Nebraska would be 5 LST (12 UTC) since that area is in the Mountain time zone. The snowfall observation necessitates the creation of a weather day and not a calendar day for the analysis of crash data to better match with the weather parameters, especially the snowfall data. Therefore, all the weather data were collected on a 12 UTC to 12 UTC time frame for analysis periods (see Figure 3.2). Six-hour snowfall totals were obtained for one day before as well as the day of crash. Snowfall is usually reported around the 12 UTC time frame, so the six-hour totals covered the following times: 12-18 UTC, 18-00 UTC, 00-06 UTC, and 06-12 UTC. Crashes were then assigned to one of these six-hour periods. These timeframes matched when the snow was reported. Once this was done, the crashes were put into their respective timeframes. Depending on when the crash happened within the six-hour window, the crash might be affected by the amount of snow. There are other scenarios which could cause the crash to occur due to the snow. The first would be if it had snowed earlier in the weather day (i.e., another six-hourly period) and was not actually snowing at the time of the crash, still creating adverse winter weather conditions on the road surface. The snowfall could have occurred during the previous six-hour period or several days before the crash contributing to snow or ice cover from residual snowpack. Another scenario that happens is that snow is occurring at the time of the crash; however, there was no accumulation of snow, due to the warmer surface temperatures or due to the snow intensity not being as heavy, during the six-hourly period. Determining which of the above scenarios occurred with each crash is difficult to determine, so different possibilities were investigated. Daily snowfall and snow depth were investigated to see how much snow fell prior to the crash occurring.

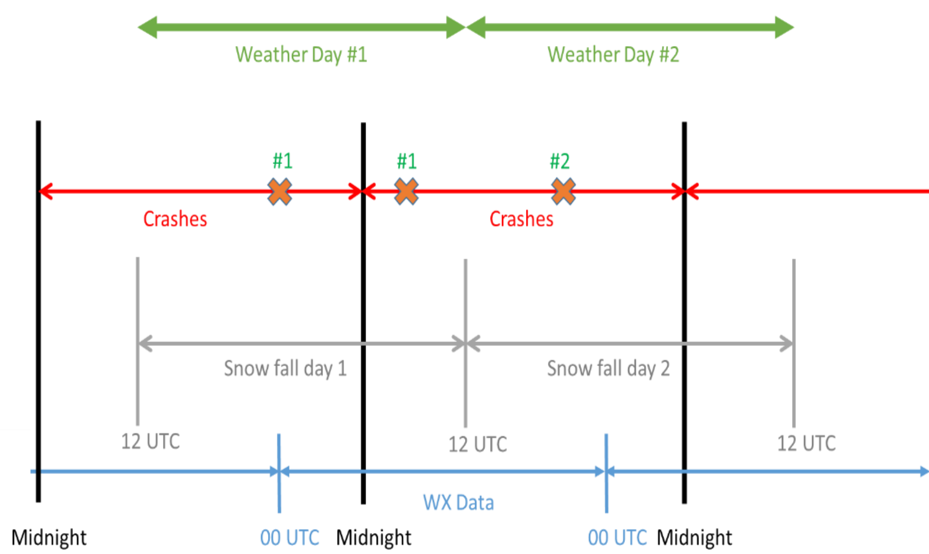

Figure 3.2 Weather day versus a midnight-to-midnight day.

NWS radar data were obtained to determine if precipitation was falling at the location and time of the crash (Iowa Environmental Mesonet RADAR 2021). Ground measurements were compared with radar returns to see if the radar confirmed that snow was occurring at the time of the crash. The radar data were also obtained to determine how long the snowfall was occurring prior to a crash. Since radar observations are taken every five minutes, radar data were only obtained from the time of the crash to six hours prior to the crash. Radar returns were obtained to help understand the weather at the time of the crash, since sometimes the road surface parameters would indicate snow or ice on the road; however, the radar would show that nothing fell in the six-hour timeframe prior to the crash. Radar data were also used to look at snow intensity. The intensity of the precipitation was based on radar reflectivity. When the reflectivity was green, that resulted in light snow. If the reflectivity was yellow, then the snow was moderate and if the reflectivity was orange, the snow was heavy. Even if the radar had no snow falling, the ground measurements were taken over the radar returns. One thing to note is that crash reports only indicate general weather conditions at the time of a crash, the reports do not list the daily snowfall amount or depth of fallen snow.

These individual parameters showed what was happening on the small scale, however, not what was occurring on the larger, synoptic-level scale. To interpret the larger scale mechanisms responsible for the individual parameters, storm-system type was looked at. Weather systems were separated into three categories: Colorado low, Alberta clipper, and Other to represent the types of storm systems affecting the Nebraska region. Other used features that were not associated with a Colorado low or an Alberta clipper: included stationary fronts, overrunning, upper-level disturbances, and/or snow squalls. The following definitions were from the NWS glossary (NOAA 2004). A stationary front is between warm and cold air masses that is moving very slowly or not at all. Overrunning occurs when a warm air mass is in motion above another air mass of greater density at the surface. An upper-level disturbance is an area that is characterized by cyclonic flow, a pocket of cold air, and sometimes a jet streak. These features make it possible for storm formation. A snow squall is an intense, limited duration, period of moderate to heavy snowfall, accompanied by strong, gusty surface winds. The system classification category was determined at the time of the traffic crash; however, sometimes the crash happened after a system had moved through the region, usually within one to two days, therefore the most recently occurring weather system was associated with that crash.

The type of system was identified by looking at surface and upper air conditions from the National Center for Atmospheric Research (NCAR) (NCAR 2021) and the Weather Prediction Center (WPC) (WPC 2021). The position and type of low-pressure system could be identified from the surface map, which shows temperature, pressure, dew point, wind speed and direction, sky conditions, and current precipitation. Upper air conditions, mainly the 850 hPa level, would further identify the moisture trajectory for precipitation and movement of the storm system allowing for classification of the weather system.

The 850 hPa flow, roughly 4,921 ft (1,500 m) above the surface, helps to show how the wind direction changes when the weather system classification moves over an area. For instance, as a weather system moves through, the wind direction ahead of the system would usually have a southerly component. After the system moves through, the wind direction changes, and a more northerly wind would be associated at this level. The

850 hPa flow also helps explain the advection of moisture into the region, aiding in the determination of precipitation amounts with differing wind directions.

Moisture flow at 850 hPa also indicates the moisture trajectory for the weather system. There are four moisture trajectory regions that were selected: Gulf of Mexico, Canadian Rockies, East Coast/Great Lakes, and Desert Southwest. Moisture trajectory from the Gulf of Mexico or East Coast/Great Lakes region is more likely related with heavy wet snowfalls and a Colorado low moving through the area. Moisture trajectory from the Desert Southwest could also be a part of a Colorado low; however, the amount of moisture is less than the Gulf of Mexico. Moisture trajectory from the Canadian Rockies is usually associated with Alberta clippers and lighter, drier snowfalls. Combining the individual features of the storm-system types allowed for this study to see which storm type was more deadly. Crash severity was looked at to answer this question.

In addition to the weather parameters, NWS Watches, Warnings, and Advisories (WWAs) (e.g., winter weather advisory, winter storm warning, blizzard warning, etc.) regarding winter weather were also obtained for the location and time of fatal crashes (Iowa Environmental Mesonet 2021) The WWAs were collected to determine if weather within the area was identified as a hazard during the crash.

Chapter 4:

Results

4.1 Snowfall

When snowfall measured three inches (7.62 cm) or less, 48% of reported crashes occurred (Figure 4.1). Less than 10% of crashes occurred when the snow was greater than three inches (7.62 cm). Thirty-nine percent of crashes occurred when there was no snowfall during the day of the crash. This does not mean there was no ice or snow on the road surface, just that there was no snow accumulation the day of the crash; however, there could have been snow accumulation before the crash. In order to see how much snow fell before and during the crash, three-day total accumulations were obtained (Figure 4.2). When there was snowfall over the three-day period, 61% of reported crashes occurred when snow accumulations were less than four inches (10.16 cm). Compared to the crash day snow totals, these results show that minimal snow totals were the cause of most crashes. Only 20% of the crashes occurred without snowfall falling during the three-day period. This result indicates that even though 39% of crashes occurred when no snow accumulated on the day of the crash, snow was on the ground at least the one to two days prior to the crash. If there was ice or snow on the roadway from the crash report and no snow was reported for the three days, these cases probably had snowfall occurring before the time cutoff used for this research. The results indicate that snowfall can accumulate over a several day period at the site of the crash.

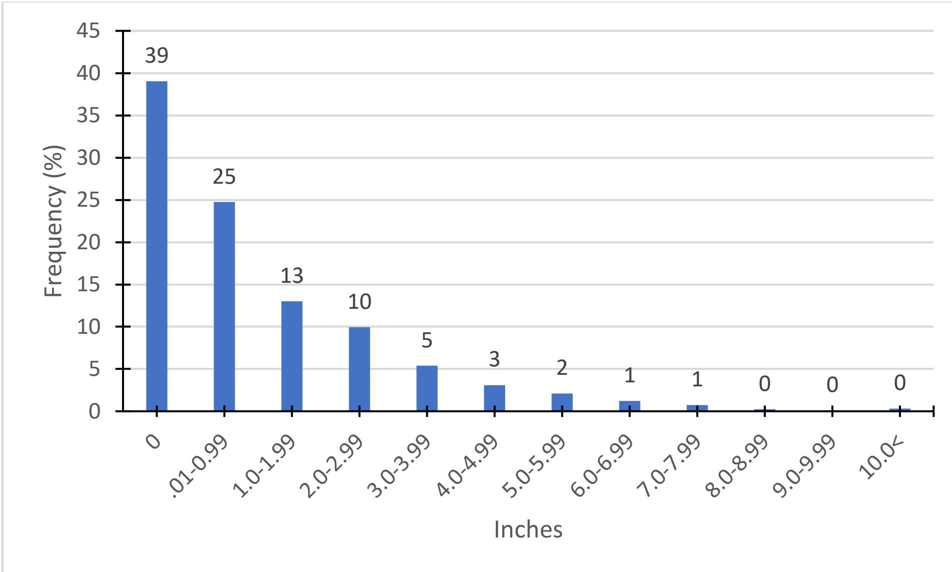

Figure 4.1 Total frequency of crashes with the daily snowfall amount on crash day

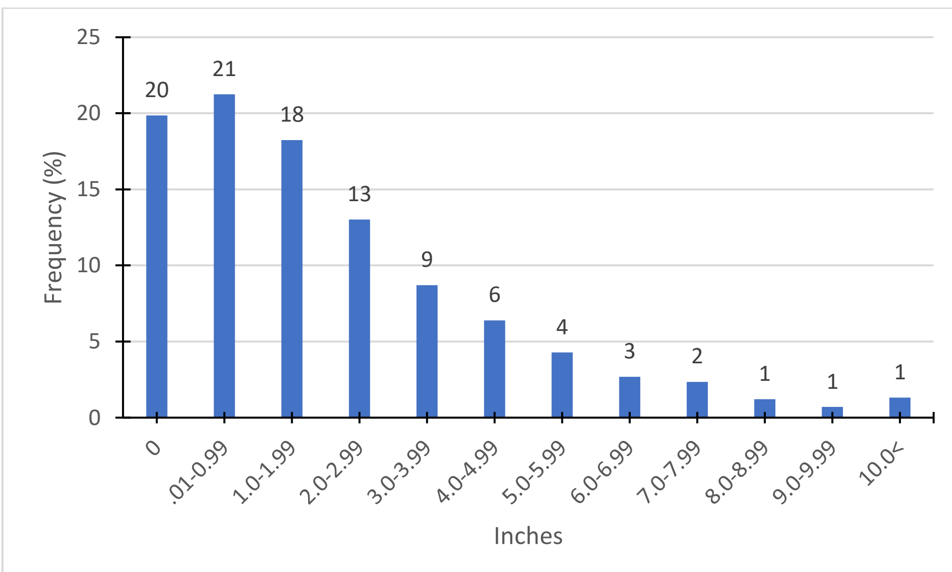

Figure 4.2 Total frequency of crashes with the three-day total snow depth

The highest frequency of crashes that took place in the six-hour time frame of when the crash happened was 54%, which occurred when there was zero inches of snowfall observed (Figure 4.3). More than 31% of the reported winter weather-related crashes occurred when there was less than one inch (2.54 cm) of snowfall during the six-hour period the crash occurred in. Snowfall between one and two inches accounted for another 10% of the crashes. Within the 10-year dataset, Nebraska had very few occurrences of when the snowfall was greater than two inches (5.08 cm) during the six-hourly period associated with a crash.

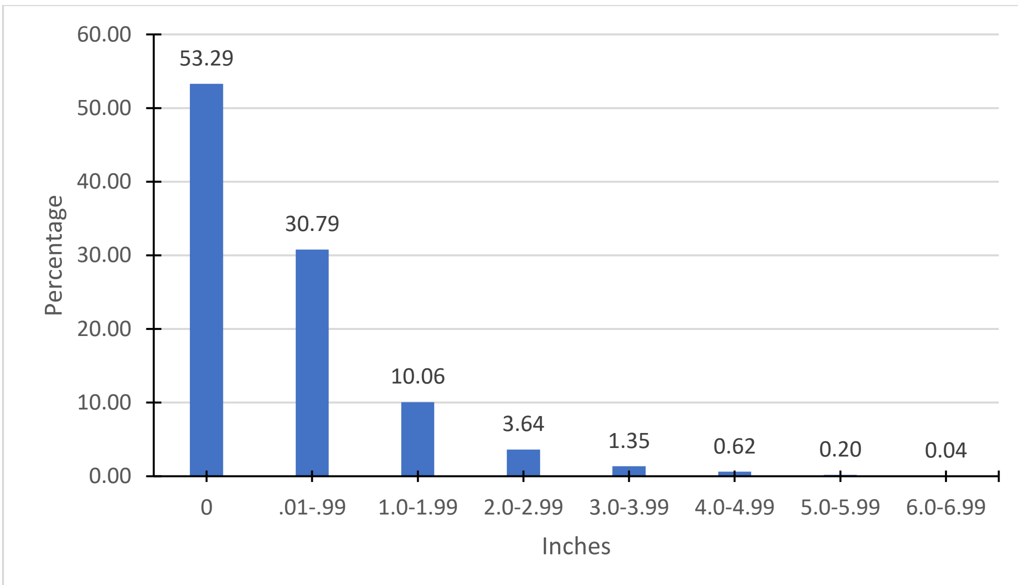

Figure 4.3 Total frequency of crashes associated with the snowfall amount that occurred in the six-hour timeframe when the crash happened

Snowfall during the six-hour period before the time of the crash provides another way to analyze the snow data and to see how many crashes occurred within this period before the crash (Figure 4.4). This was investigated because of the high number of crashes that occurred with zero inches of snow. The results are very similar to the six-hour period of the crash with over 80% having less than one inch (2.54 cm) of snow or no snowfall during the six-hourly period before the crash. Although the data are similar, the results from the six-hour period prior to the crash (Figure 4.4) to the six-hour period from the crash (Figure 4.3) does not compare the two periods together in any regard. When combined, only 20% of crashes had scenarios where there was snowfall in the six-hour period before the crash and no snowfall during the six-hour period of the crash.

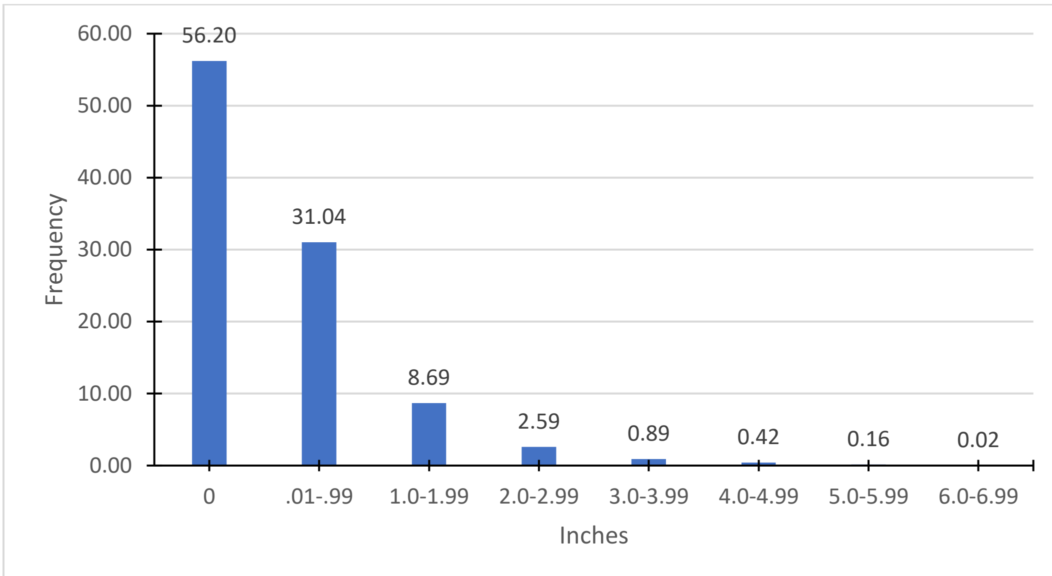

Figure 4.4 Total frequency of crashes with the snowfall amount that occurred six hours prior to the crash

Comparing the snowfall measurements with how long snowfall was observed prior to the crash, 70% of all crashes happened when snow had been observed greater than six hours before the crash (Figure 4.5). There are 14% of crashes that had no snow observed in the 72-hour timeframe of the study (represented by N/A). Thus, snowfall could have been observed before this period or there was no snow at all and it should not have been reported on the crash report. It was beyond the scope of this project to determine which was correct.

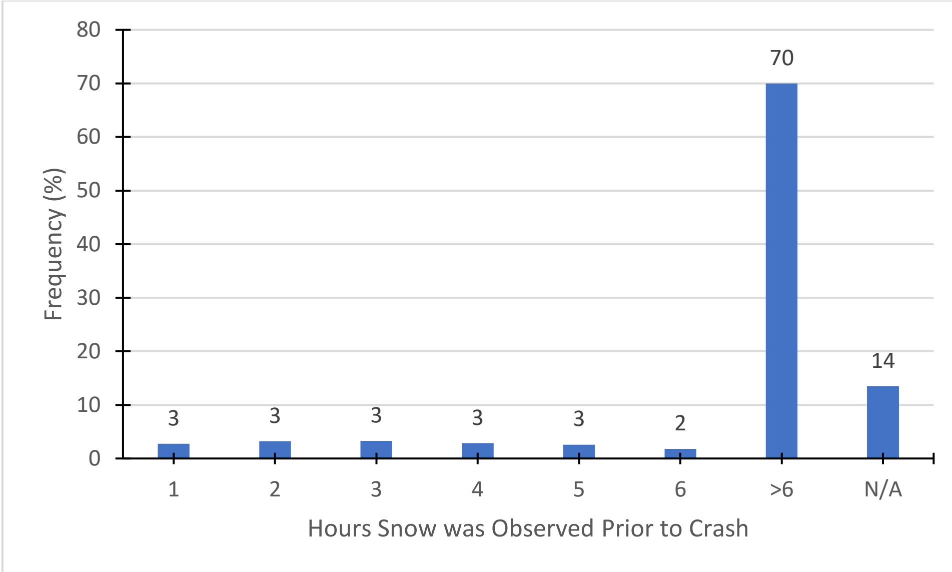

Figure 4.5 Total frequency of crashes with how long snow was occurring prior to the crash

Radar returns were used to confirm the ground measurement of snow. Radars returns also allow for precipitation intensity to be detected. Crashes that had some radar return occurring at the time and location of the crash, were responsible for 57% of all crashes (Figure 4.6). The lighter snow category was observed more than the moderate and heavy snow intensities. The other 43% of crashes that had no radar returns, which generally means that there was no snow occurring. However, the radar may not have detected snow for several reasons; the snowfall is so light that the radar does not pick it up, or the snowfall is developing below the radar beam.

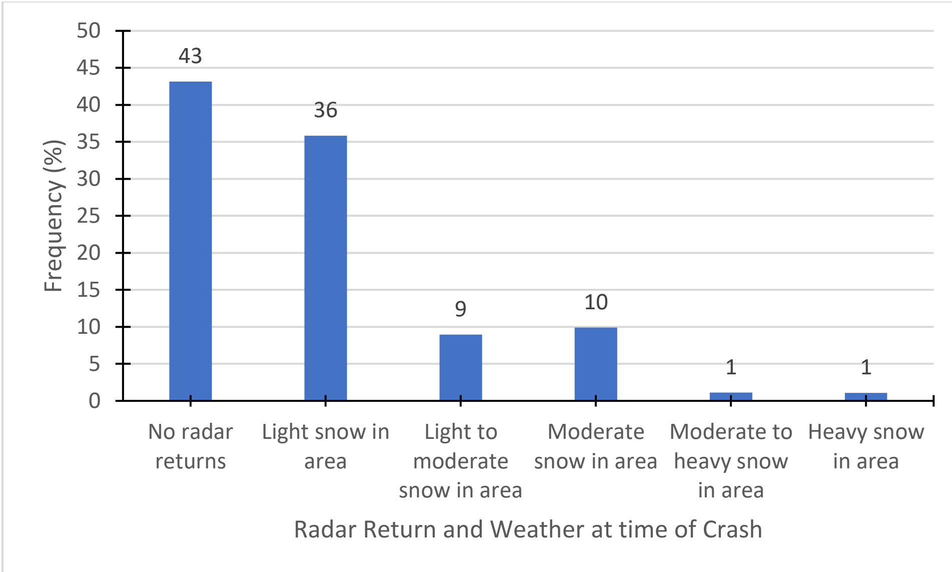

Figure 4.6 Total frequency of crashes with radar return and weather at time of crash

4.2 Temperature

When the air temperatures are around the freezing point, between 26°F (-3.33°C) and 37°F (2.78°C), 43% of all crashes occurred (Figure 4.7). This implies that many crashes may occur right at transition temperatures between ice and water. These temperatures may also imply snow that has a lower snow to liquid water ratio, due to these warmer surface temperatures. Blowing snow is less likely, since blowing snow is more likely to occur when the snow to liquid ratio is higher.

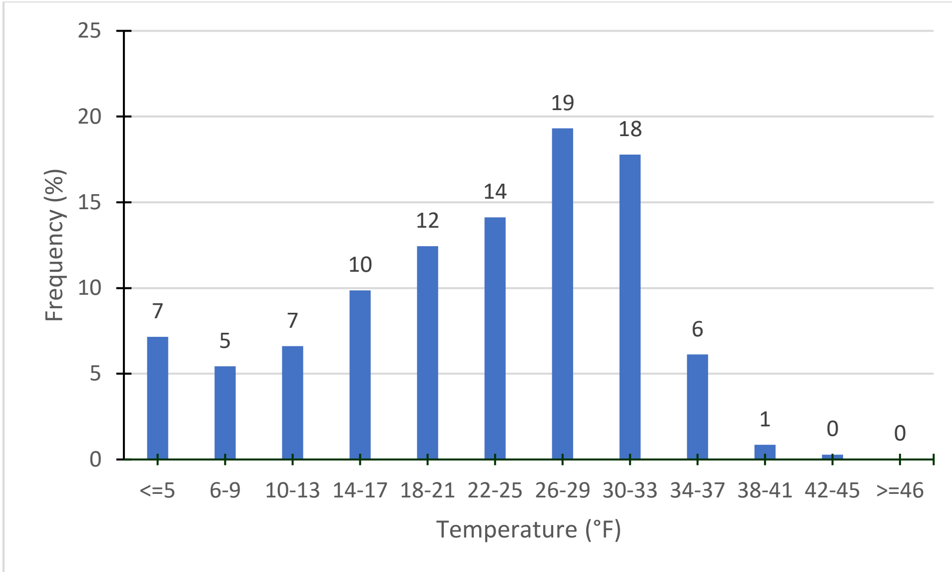

Figure 4.7 Total frequency of crashes with respect to temperature

4.3 Visibility

Snow events typically cause reductions in visibility. These reductions can be caused by the intensity of snowfall or blowing and drifting snow conditions. Visibilities of less than two miles were responsible for 31% of all crashes reported. When the visibility reported by the ASOS station was greater than or equal to 10 miles, 33% of crashes occurred during the study period (Figure 4.8). Low visibilities occur during the heaviest snow rates and blowing snow, which cause the worst conditions for drivers. Lower visibilities are probably caused by higher snowfall rates rather than blowing snow, since the wind speed analysis shows that wind speeds, less than 25 mph (11.18 m/s) were present during 85% of the reported crashes compared to high, greater than 25 mph (11.18 m/s) wind speeds (Table 4.1). Crashes that took place with higher wind speeds are more likely caused by blowing snow. Crashes occurring with higher visibilities are perceived to be associated with post-event, residual snow/ice on roadways. Therefore, as the visibility decreases, the number of crashes increases. Visibility greater than or equal to 10 miles means that either the snow had already stopped though it was still on the road surface, or it did not snow at all.

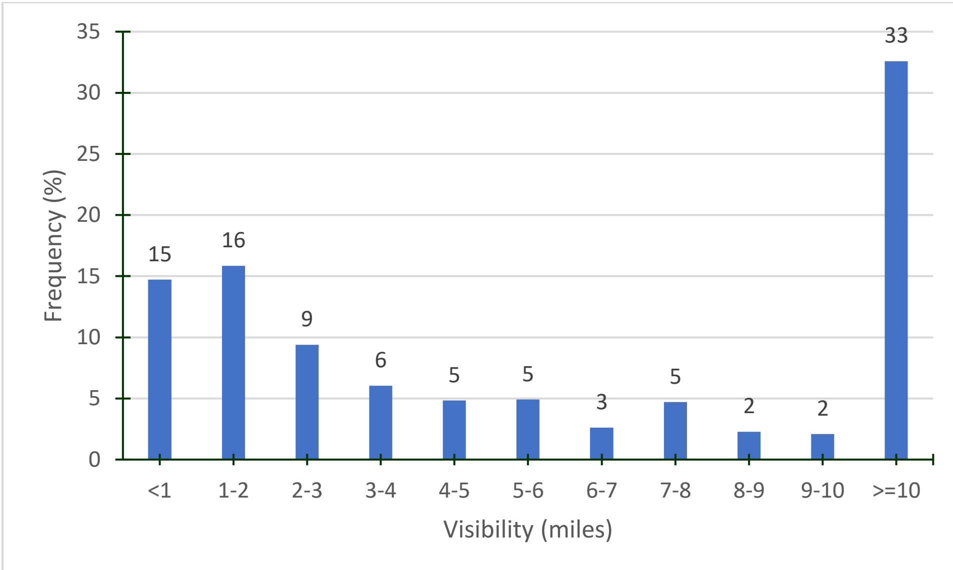

Figure 4.8 Ten-year winter season total frequency of crashes with visibility data

Table 4.1 Frequency and percentage (in parentheses) of crashes with respect to wind speed

Wind Speed (mph)	0	5	10	15	20	25	30	35	40	45	Total
Number of Crashes	245	1057	1079	899	605	356	182	57	24	7	4511
Percentage of Total	(5)	(23)	(24)	(20)	(13)	(8)	(4)	(1)	(1)	(0)	(100)

4.4 Storm System Type

Crash severity was investigated to see which storm type was more deadly. Looking at crash severity (i.e., injury versus fatality), possible injury type (the least severe injury type) had the highest number of crashes than any other injury type (Table 4.2). Crash severity was aggregated into three categories for the purpose of modeling its association with different variables including weather characteristics. The three categories were possible injury, visible injury, and disabling injury/fatal injury. The number of crashes then decreases as the crash severity increases. Colorado lows were associated with the greatest number of crashes with regards to the level of crash severity. Colorado lows were also the deadliest and most likely to cause some form of injury compared to Alberta clippers.

Table 4.2 Total frequency and percentage (in parentheses) of crashes with respect to crash severity with weather system data

Weather System Type	Possible	Visible	Disabling	Fatality	Storm Total
Colorado Low **Percentage of Crash Severity**	1158 (43)	497 (42)	209 (41)	38 (41)	1902
Alberta Clipper **Percentage of Crash Severity**	725 (27)	324 (27)	147 (29)	21 (23)	1217
Other **Percentage of Crash Severity**	832 (31)	373 (31)	153 (30)	34 (37)	1392
Crash Severity Total **Total Percentage**	2715 (100)	1194 (100)	509 (100)	93 (100)	4511

<u>4.4.1 Colorado Lows</u>

Colorado lows were responsible for 42% of crashes within the study period (Figure 4.9). For all winter seasons, except the 2014 winter season, Colorado lows were associated with at least 30% of all reported crashes (Figure 4.10). Therefore, Colorado lows are involved in more crashes than Alberta clippers or the Other category. The reasoning for this is that Colorado lows are larger and more prolonged than Alberta clippers. It is possible that crashes could occur on multiple days in a row across Nebraska due to the longer time it usually takes a Colorado low to traverse the entire state and crashes were collected across the state for each storm type.

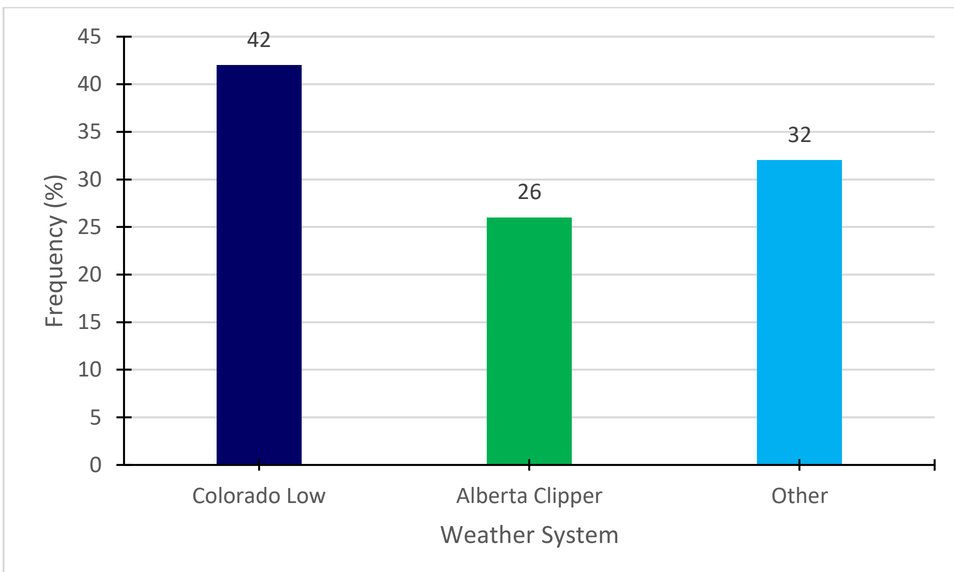

Figure 4.9 Frequency distribution of crashes by weather system type

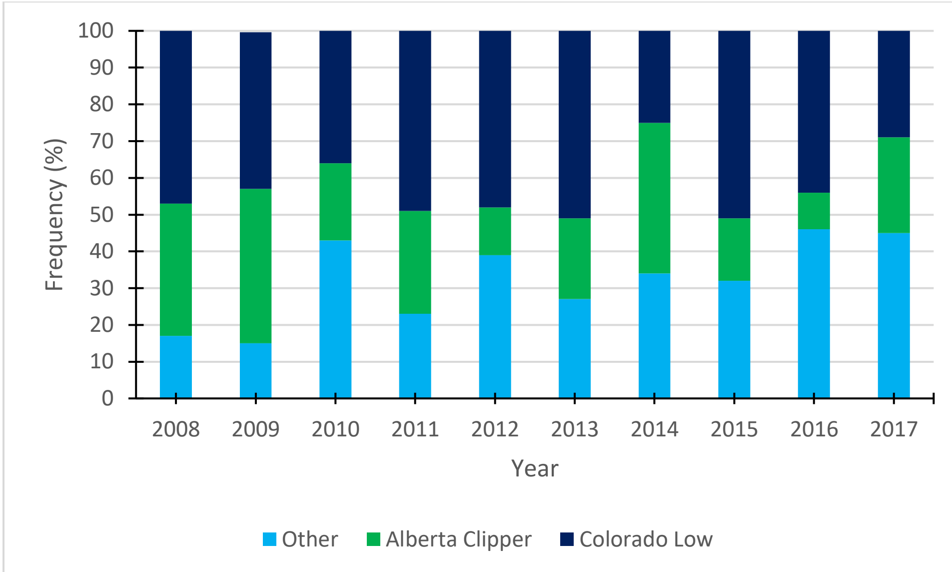

Figure 4.10 Yearly crashes by Colorado low (dark blue), Alberta clipper (green) and Other category (light blue)

The moisture trajectory data obtained would indicate that Colorado lows typically have a moisture trajectory from the Gulf of Mexico, Great Lakes/East Coast, and the Desert Southwest (Figure 4.11). Moisture trajectory from the Gulf of Mexico implies that the weather system has an ample supply of moisture to produce heavier snowfalls. Moisture trajectory that comes from the East Coast region occurs when the center of the low would be farther to the east of Nebraska and is able to bring in moisture from the Atlantic Ocean. Lastly, moisture advected from the Desert Southwest occurs when a Colorado low is beginning to develop or when it was farther to the south and/or southwest of Nebraska. Seventy percent of all crashes that occurred with a moisture trajectory from the Gulf of Mexico, were associated with Colorado lows (Figure 4.12). The other two moisture trajectories, Great Lakes/East Coast and Desert Southwest were much greater for Colorado lows than the Canadian Rockies moisture trajectory.

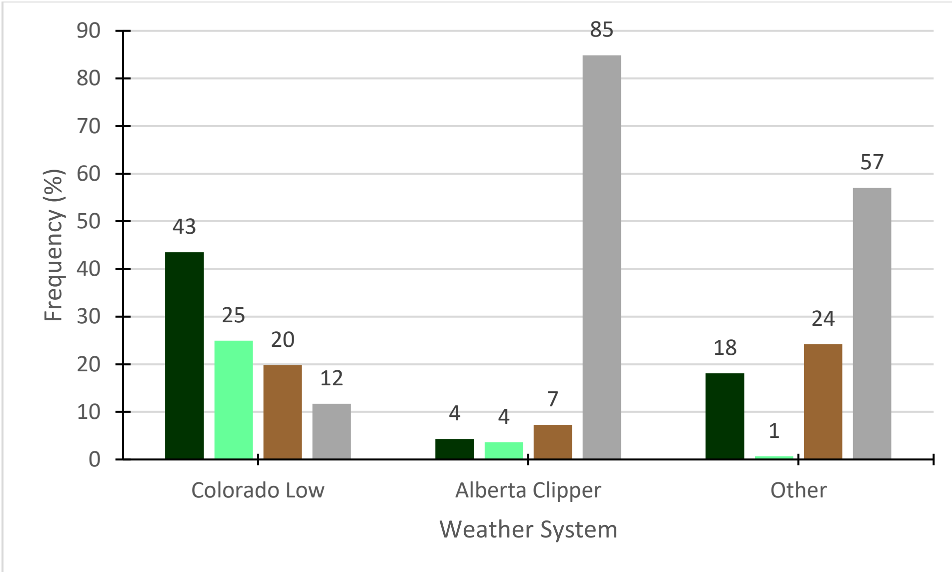

Figure 4.11 Crash frequency with respect to the weather system [with moisture flow from the following locations: Gulf of Mexico (dark green), Great Lakes/East Coast (light green), Desert Southwest (brown), Canadian Rockies (dark grey)]

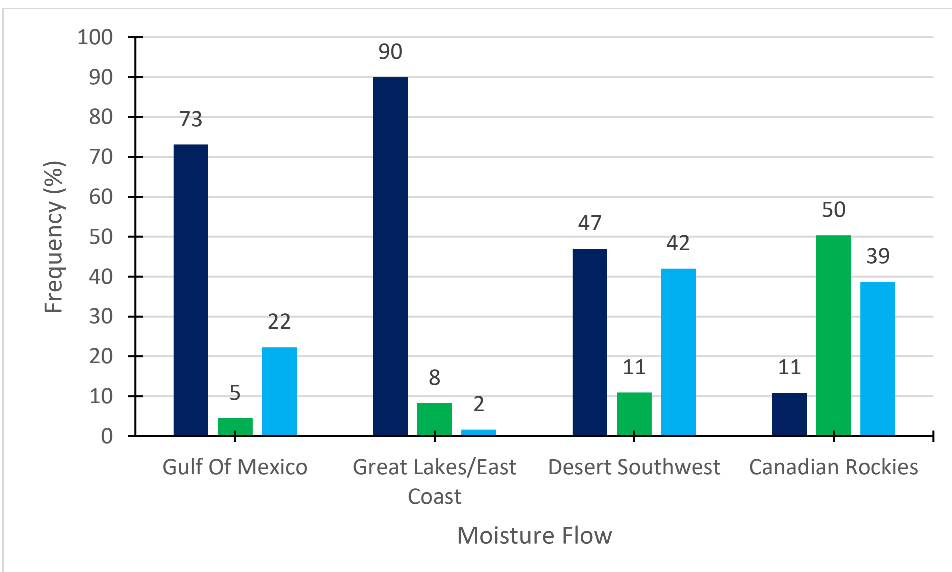

Figure 4.12 Crash frequency with moisture flow by Colorado low (dark blue), Alberta clipper (green), and Other category (light blue)

The 850 hPa wind is another parameter which helps to represent temperature and moisture advections occurring with the weather systems during a crash. As a Colorado low approaches Nebraska, the flow is southwesterly, allowing for the moisture trajectory to come from the Desert Southwest, which results in less precipitation. As a Colorado low continues to move across the state, more southerly wind components begin to occur, meaning that the moisture trajectory for a Colorado low would be from the Gulf of Mexico. This indicates that winds would now supply ample enough moisture, and possibly warmer temperatures, to the storm. Once the Colorado low moves far enough to the east, the wind fields shift from a southerly flow to a northeasterly flow so now the Great Lakes/East Coast area will be the source region for temperature and moisture.

As the Colorado low continues to move eastward (well east of the Nebraska region), the winds over Nebraska are from a more northerly direction. The northerly direction indicates colder temperatures and lower amounts of moisture resulting in snow with less water content. The drier snow, colder temperatures, and increased wind speed result in the possibility of blowing snow. There is much variation in the number of crashes; however, the majority of crashes for Colorado lows occurred when the winds were from a northerly direction (Figure 4.13). Crashes that occurred with the moisture trajectory from the Desert Southwest had either a southerly or northerly component (Figure 4.14). Most of the crashes that occurred with a moisture trajectory of the Gulf of Mexico had a southerly wind component. Lastly, the majority of crashes that occurred with a moisture trajectory of the Great Lakes/East Coast region had a northerly wind component. These results indicate the path that a Colorado low takes. Most of these crashes occurred when the dominant wind component of the moisture trajectory was associated with a crash.

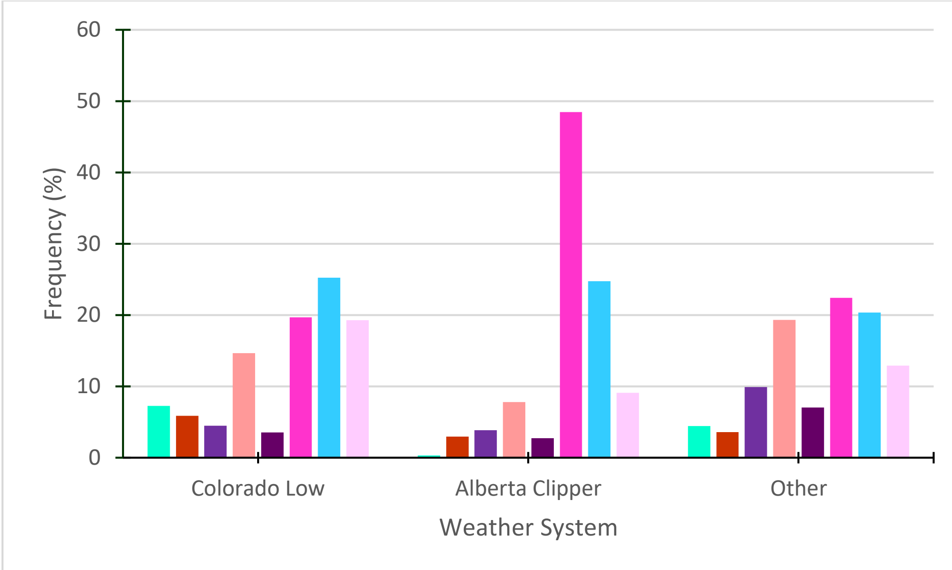

Figure 4.13 Crash frequency with respect to the weather system [850 hPa wind flow data from the following directions: east (teal), southeast (red), south (purple), southwest (rose), west (grey), northwest (pink), north (turquoise), northeast (lavender)]

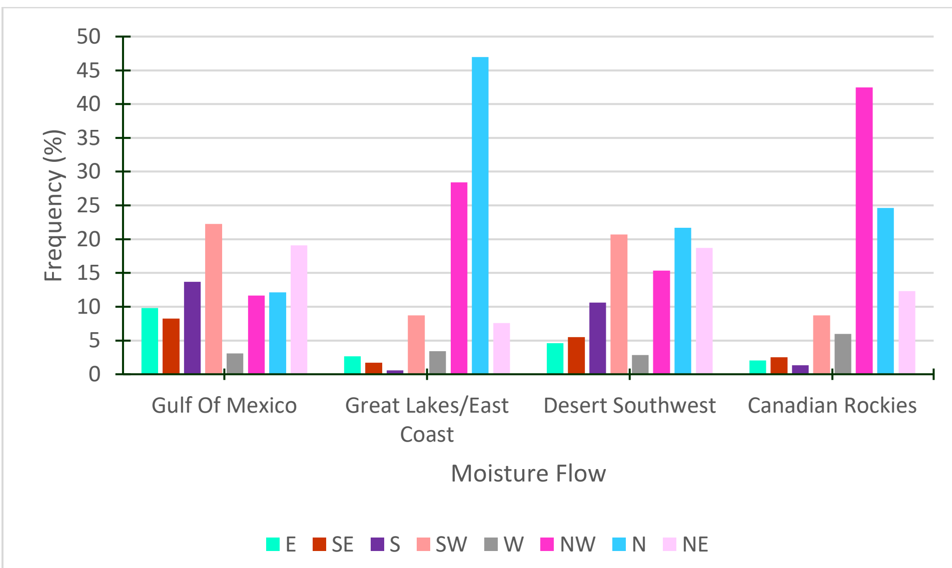

Figure 4.14 Crash frequency with respect to the moisture flow [850 hPa wind flow data from the following directions: east (teal), southeast (red), south (purple), southwest (rose), west (grey), northwest (pink), north (turquoise), northeast (lavender)]

4.4.2 Alberta Clippers

Alberta clippers were responsible for 26% of crashes in the study period (Figure 4.9), which is much lower than Colorado lows. The number of crashes related to Alberta clippers varies per season, with the 2014-15 winter season having the most and the 2012-13 season having the fewest number of crashes (Figure 4.10). The 2012-13 winter season occurred during a drought and there were fewer winter storm systems over Nebraska. Alberta clippers over Nebraska usually tend to occur from December through February.

In over 80% of crashes that occurred due to an Alberta clipper, the moisture trajectory was the Canadian Rockies (Figure 4.11). The movement of an Alberta clipper is southerly to southeasterly across the northern and central Great Plains before switching to a more easterly track. When the moisture trajectory was from the Canadian Rockies, about 50% of the crashes were associated with Alberta clippers (Figure 4.12). Due to the clipper's short lifespan and dry moisture trajectory, the amount of snow that could occur during these weather systems is generally lower when compared to a Colorado low. However, while the amounts might be lower, the dryness of the snow and stronger winds results in blowing and drifting snow. Almost 85% of all crashes that were caused by an Alberta clipper had a northerly wind component (Figure 4.13). Most of the crashes that occurred with a moisture source from the Canadian Rockies also had a northerly wind component (Figure 4.14).

4.4.3 Other Category

The Other category was associated with 32% of reported crashes that occurred in the 10-winter season study period (Figure 4.9). The number of crashes per winter season fluctuated as well (Figure 4.10). Moisture trajectory for the Other category was mainly from the Canadian Rockies (Figure 4.11). When the moisture trajectory originated from the Gulf of Mexico or Desert Southwest, this was typically associated with a stationary front that lines up somewhere across Nebraska or nearby. A snow squall would be an example of the Canadian Rockies moisture trajectory. When the Canadian Rockies are the moisture trajectory, almost 40% of all crashes were from the Other category (Figure 4.12), implying a drier snow. More than 40% of all crashes associated with the Desert Southwest moisture source are also from the Other category. Compared to Alberta clippers and Colorado lows, the Other category had more variety of where the winds were coming from (Figure 4.13). The winds from a northerly or southwesterly component are associated with drier snow that is easy to blow around, causing reduced visibility. When winds are from the south or southeast, this results in a moisture trajectory from the Gulf of Mexico which means that there is more moisture from this area, to potentially have a lower snow to liquid water ratio, then when the winds are from the north. Due to the variety of wind directions for the Other category, the distribution of crashes does not favor a specific direction (Figure 4.14). Whereas the Colorado low and Alberta clipper have preferred wind directions.

4.5 NWS Alerts

Using the fatal crashes in the analysis database, 56 out of the 93 occurred when an NWS winter weather alert was issued. Of those 56 fatal crashes, 35 had an active alert at the time of the crash (Figure 4.15). The most common NWS alert that was issued was a Winter Weather Advisory (Figure 4.16). Looking at the no alert category, there were 37 total fatal crashes during the ten-year winter season study period. These no alert fatal crashes usually had the road conditions being iced over, with the second highest amount being the snowy road condition (Figure 4.17). This information alone does not explain why there was no advisory issued. Looking at the snow totals for when there are no NWS alerts, the majority of fatalities occurred when the snow total was less than three inches for the three-day period (Figure 4.18). Due to the high number of fatalities occurring below three inches, threshold for winter weather advisory in Nebraska, this means that most people need an alert no matter how much is going to fall. Therefore, the NWS is switching to impact-based alerts, to help reduce these numbers.

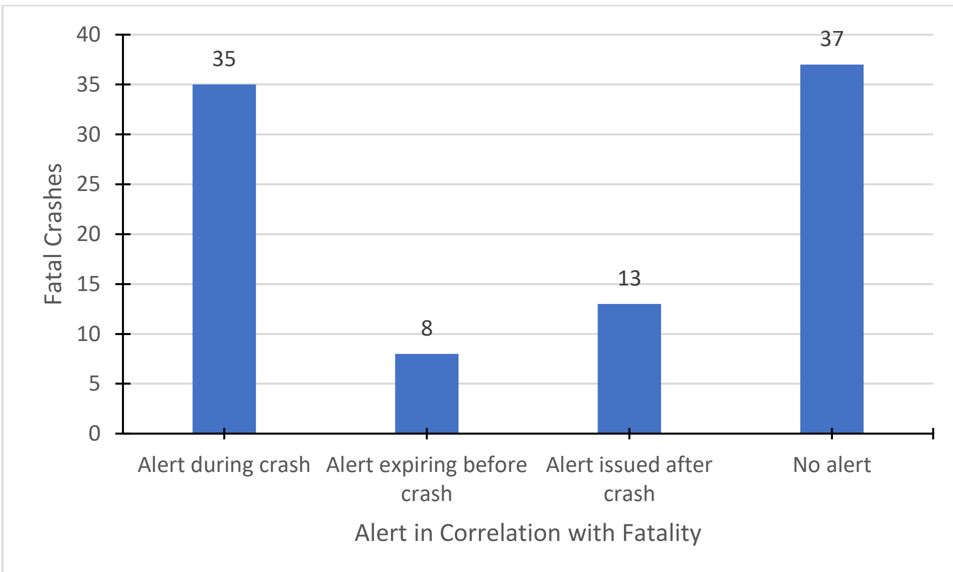

Figure 4.15 Fatal crashes and NWS alerts

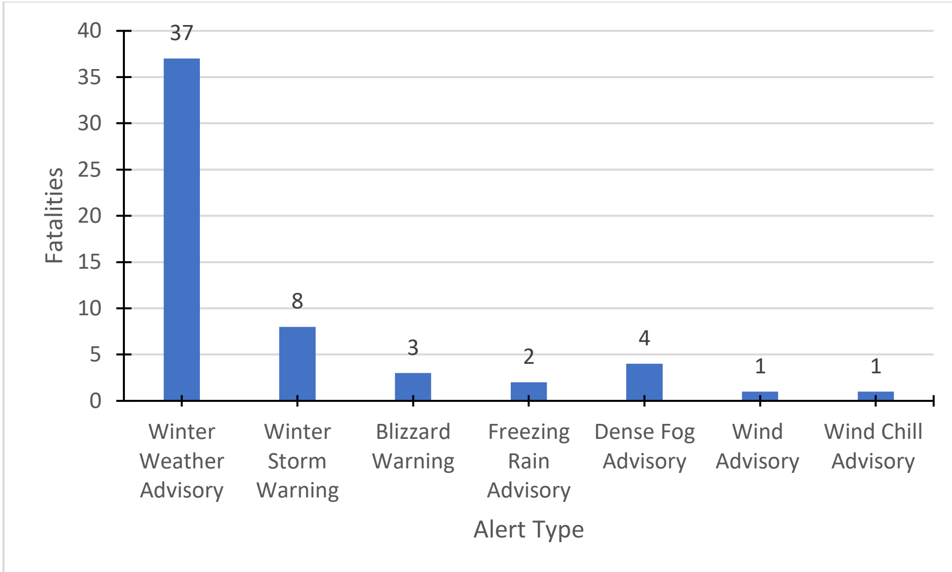

Figure 4.16 Fatal crash count when an NWS alert was issued

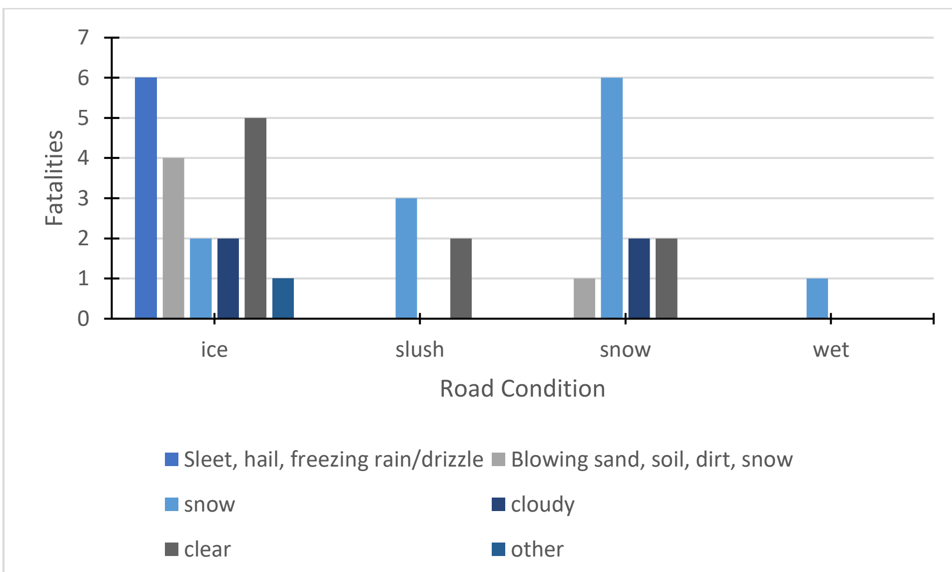

Figure 4.17 Fatal crash count when no alert was issued by NWS by road conditions [weather conditions: sleet (blue), blowing snow (grey), snow (light blue), cloudy (dark blue), clear (dark grey), other (light navy blue)]

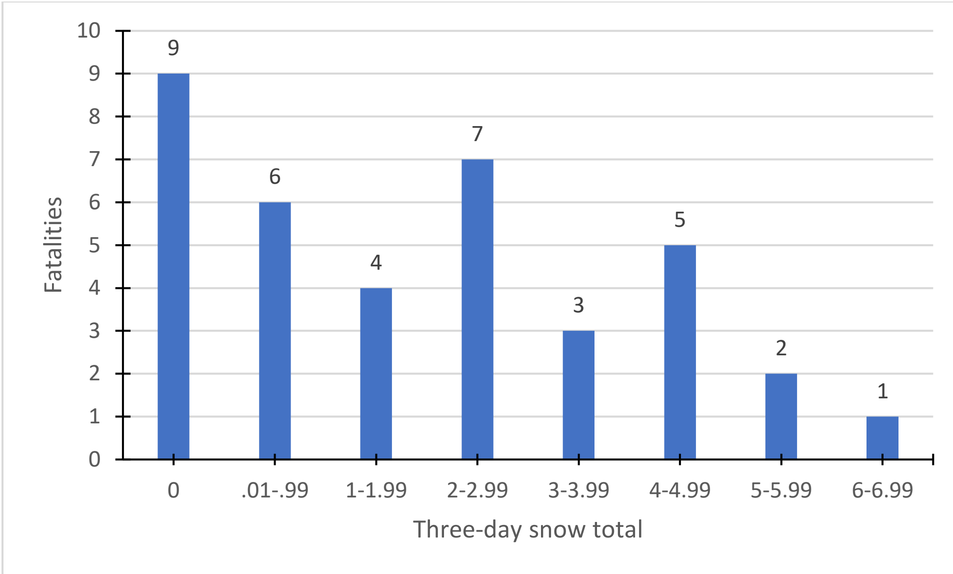

Figure 4.18 Three-day snow total for fatalities that had no NWS alert

Chapter 5:

Conclusions

This study focuses on a 10-year period from the 2008-2009 winter season through the 2017-2018 winter season to better understand how winter weather conditions might contribute to the occurrence of motor vehicle crashes in Nebraska. Crash data were filtered to better represent the weather conditions at the time of the crash to ensure that only crashes which were either directly, or likely directly associated with winter weather conditions were included. This research considered injury and fatality crashes only, due to the relative importance of these higher severity crashes with respect to road maintenance, road closures, emergency services personnel deployment, and human costs. Weather data were also obtained for 72 hours prior to a crash. Weather conditions before and at the time of the crash were investigated to figure out the nature of contributing weather conditions.

Most winter-weather related motor vehicle crashes were associated with minimal winter weather conditions. The reported crashes occurred when there were low snowfall amounts observed or due to snowfall that was already on the ground after precipitation ceased. These results provide information to help explain why winter maintenance operations activities need to continue after a storm has exited the region and the need for continued messaging of hazardous weather conditions. In addition, most crashes were of low severity (i.e., relatively minor injuries) and fatal crashes were relatively rare. These numbers are still high and is a point of interest for the NWS to help reduce these numbers by integrating impact-based alerts. Something important to note is that traffic volumes are usually lower during winter storms. This makes the actual risk of a crash larger than the findings of this analysis would suggest. Within the six-hour timeframe of when the crash happened and the six-hour timeframe prior to the crash, the greatest number of crashes had no accumulating snow. This means that most crashes had snow fall after the crash, prior to the crash, or prior to the three-day timeframe. Radar returns were gathered to be compared with the surface findings. According to radar returns, a majority of crashes had snow falling more than six hours leading up to or prior to a crash. The risk of a crash happening with temperatures near freezing was the highest compared to other temperatures. This implies that more crashes occurred in association with either wet snow, lower snow to liquid water ratios, or re-freezing. Lower visibilities also indicated a high risk for crashes. Higher snowfall rates can cause lower visibilities and may be associated with the greater risk. Since the greatest number of crashes occurred with wind speed less than 25 mph, blowing snow does not appear to be a large risk factor. Higher visibilities also represented a high number of crashes. Higher visibilities suggest that crashes took place when there was no snow or after the snow had fallen with ice- or snow-covered roads. With respect to crash severity, the number of crashes decreased as the severity increased.

Investigation into storm system type showed Colorado lows were responsible for more crashes than Alberta clippers. Colorado lows also have more crashes in each severity category than Alberta clippers, making Colorado lows more deadly than clippers. From a year-to-year standpoint, there were some variations in the number of crashes; however, for most of the years, there were more Colorado lows than clippers. After exploring the storm system type, moisture flow and 850 hPa wind were considered. When comparing the individual moisture trajectory results, the highest percentage of crashes for three of the four moisture trajectories, Desert Southwest, Gulf of Mexico, and Great Lakes, took place when the system type was a Colorado low. Colorado lows had the highest number of crashes occurring with a moisture trajectory from the Gulf of Mexico and Alberta clippers had their greatest number of crashes associated with a Canadian Rockies moisture trajectory. Wind flow results at 850 hPa for Colorado lows revealed how crashes mainly occurred when the winds are from the north. This implies that more crashes occurred after the system had moved out of the region. On the other hand, Alberta clippers had a very high percentage of crashes with a northerly component. This is consistent with the typical trajectory of clippers moving into the region from the northwest.

Forecasting alerts, such as a winter weather advisory or winter storm warning, are important for communicating winter weather conditions to the general public and transportation agencies. Therefore, crashes that had an associated fatality were examined to see if NWS alerts were issued and what types of alert were active during the crash. Most of the crashes had an alert issued during the time of the crash. For the crashes that included an alert, the majority of these were winter weather advisories. This means that more fatal crashes occur during less severe alerts, such as winter weather advisories.

There are a few limitations and exclusions of the crash data worth noting. Property damage and non-reportable crashes were not considered in the crash data. Injury and fatality crashes are associated with higher priority; however, many property damage crashes can have significant road impacts as well. Using all accident severities in the future would be important since that offers a more complete picture. Alcohol is not involved for this research. The goal of this study was to look at crashes specifically caused by winter weather conditions. A similar project could be done to compare alcohol related instances with all-weather conditions. Lastly, the road type was limited to interstates, interstate ramps, and state and federal highways. There are many crashes that occur on local roads and driveways, which were not considered. Including all types of roads in future work would be important to know where crashes occur and what weather conditions were associated with the crash event.

Another exclusion of the crash data was the criteria used to define a winter weather-related crash. If the weather condition I was rain, all crashes were removed. Future research using rain could help with determining how the number of crashes differs with a rain/snow line in the region. This would provide greater insight into how frozen precipitation, including freezing rain, affects crashes compared to liquid precipitation. Within these criteria, there were still some outliers. For example, if wildlife was involved in motor vehicle crashes that took place when adverse road and/or weather conditions were occurring, these may not be attributable to the weather conditions alone. Without a detailed crash narrative or self-report from the involved parties, it would be impossible to determine how conditions contributed to the collision.

The weather data have additional limitations such as the temporal resolution and availability of the data. Snowfall data, in particular, are only available at six-hourly increments. The snowfall data does not allow for detailed consideration of the weather conditions when a crash occurs. When gathering the weather information, unless a crash occurs close to one of the weather stations, estimation of weather parameters is needed based on the weather conditions occurring at the closest ASOS stations. One solution for this problem would be to add more weather stations, especially in areas that either do not have any weather stations or where there is more population.

Looking forward, there are some potential future directions of the research beyond this analysis. First, as noted above, inclusion of all crashes would be worthwhile for a more robust assessment of crashes and weather conditions. Another direction worth undertaking would be a "hotspot" identification where particularly problematic road segments with several crashes during winter weather conditions are identified. These road segments could possibly be in locations that additional safety measures (e.g., lighting, guardrails, roadway redesign) could be implemented to help reduce the number of crashes and/or severity. Lastly, investigating where winter maintenance took place, were the roads plowed or treated with chemicals, would also be interesting.

In conclusion, the ability to characterize, quantify, and associate winter weather conditions with the frequency and severity of vehicular crashes provides crucial insight for transportation personnel as well as weather forecasters. This information is vital to winter maintenance activities, operational decisions, and public messaging campaigns. The fundamental purpose of forecasters and transportation agencies is to provide the public with the greatest level of communication as to what types of weather and hazards are to be expected. This analysis will better inform both the transportation and meteorological communities of the ever-present dangers presented by winter weather on the roads.

References

Andrey, J. (2010). Long-term trends in weather-related crash risks. *Journal of Transport Geography*, *18*(2), 247–258. doi:10.1016/j.jtrangeo.2009.05.002

Andrey, J., Hambly, D., Mills, B., & Afrin, S. (2013). Insights into driver adaptation to inclement weather in Canada. *Journal of Transport Geography*, *28*, 192-203.

Andrey, J., Mills, B., Leahy, M., & Suggett, J. (2003). Weather as a chronic hazard for road transportation in Canadian cities. *Natural Hazards*, *28*(2-3), 319-343.

Ashley, W. S., Strader, S., Dziubla, D. C., & Haberlie, A. (2015). Driving blind: Weather-related vision hazards and fatal motor vehicle crashes. *Bulletin of the American Meteorological Society*, *96*(5), 755-778.

Atmospheric Environment Service, 1977: *Manual of Surface Weather Observations (MANOBS)*. 7th ed. Environment Canada, 332 pp.

Black, A. W., & Mote, T. L. (2015a). Effects of winter precipitation on automobile collisions, injuries, and fatalities in the United States. *Journal of Transport Geography*, *48*, 165-175.

Black, A. W., & Mote, T. L. (2015b). Characteristics of winter-precipitation-related transportation fatalities in the United States. *Weather, Climate, and Society*, *7*(2), 133-145.

Call, D. A. (2011). The Effect of Snow on Traffic Counts in Western New York State. *Weather, Climate, and Society*, *3*(2), 71–75. doi:10.1175/wcas-d-10-05008.1

Call, D. A., Wilson, C. S., & Shourd, K. N. (2018). Hazardous weather conditions and multiple‐vehicle chain‐reaction crashes in the United States. *Meteorological Applications*, *25*(3), 466-471.

Cools, M., Moons, E., & Wets, G. (2010). Assessing the impact of weather on traffic intensity. *Weather, Climate, and Society*, *2*(1), 60-68.

Datla, S., & Sharma, S. (2008). Impact of cold and snow on temporal and spatial variations of highway traffic volumes. *Journal of Transport Geography*, *16*(5), 358–372. doi:10.1016/j.jtrangeo.2007.12.003

DeVoir, G. A. (2004). High impact sub-advisory snow events: The need to effectively communicate the threat of short duration high intensity snowfall. Preprints, *20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction, Seattle, WA.* American Meteorological Society; P10.2. [Available at https://www.weather.gov/media/ctp/HISA/68261.pdf.]

Eisenberg, D. (2004). The mixed effects of precipitation on traffic crashes. *Accident Analysis & Prevention*, *36*(4), 637–647. doi:10.1016/s0001-4575(03)00085-x

Eisenberg, D., & Warner, K. E. (2005). Effects of snowfalls on motor vehicle collisions, injuries, and fatalities. *American Journal of Public Health*, *95*(1), 120-124.

Federal Highway Administration (FHWA) (2021). Snow and Ice. Accessed 9 March 2021. [Available at https://ops.fhwa.dot.gov/weather/weather_events/snow_ice.htm]

Hanbali, R. M., & Kuemmel, D. A. (1993). Traffic volume reductions due to winter storm conditions. *Transportation Research Record,* (1387).

Iowa Environmental Mesonet ASOS (2021). Download ASOS/AWOS/METAR Data. Iowa Environmental Mesonet.https://mesonet.agron.iastate.edu/request/download.phtml?network=NE_ASOS. Accessed 9 March 2021

Iowa Environmental Mesonet RADAR (2021). RADAR & NWS Warnings. Iowa Environmental Mesonet. https://mesonet.agron.iastate.edu/GIS/apps/rview/warnings.phtml. Accessed 9 March 2021

Malin, F., Norros, I., & Innamaa, S. (2018). Accident risk of road and weather conditions on different road types. *Accident Analysis & Prevention*, *122*, 181–188. doi:10.1016/j.aap.2018.10.014

National Center for Atmospheric Research (NCAR). (2021). Image Archive. http://www2.mmm.ucar.edu/imagearchive/. Accessed 9 March 2021

National Operational Hydrologic Remote Sensing Center (NOHRSC). (NOHRSC radar 2021). Interactive Snow Information. https://www.nohrsc.noaa.gov/interactive/html/map.html. Accessed 9 March 2021

National Operational Hydrologic Remote Sensing Center (NOHRSC). (NOHRSC snow 2021). National Snowfall Analysis. https://www.nohrsc.noaa.gov/snowfall/index.html. Accessed 9 March 2021

National Weather Service (NWS 2021). Impact Based Warning Goals. Accessed 9 March 2021. [Available at https://www.weather.gov/impacts/goals]

National Weather Service (NWS Omaha 2021). Winter Products Issued by the National Weather Service in Omaha. Accessed 15 April 2021. [Available at https://www.weather.gov/oax/winter-products]

Nebraska Department of Transportation (NDOT) (2019). Crash data. Accessed 1 July 2019. [Available at https://dot.nebraska.gov/safety/crash/]

National Oceanic and Atmospheric Administration. National Weather Service. (NOAA) (2004, November 1). Glossary. *NOAA's National Weather Service*. https://w1.weather.gov/glossary/. Accessed 7 April 2021

Perrels, A., Votsis, A., Nurmi, V., & Pilli-Sihvola, K. (2015). Weather conditions, weather information and car crashes. *ISPRS International Journal of Geo-Information*, *4*(4), 2681-2703.

Pisano, P. (2017, September 12). Federal Highway Administration Road Weather Management Program. *STSMO Weather Workshop*. https://systemoperations.transportation.org/wp-content/uploads/sites/22/2017/05/FHWA-Road-Weather-Management-Program.pdf. Accessed 9 March 2021

Pisano, P. A., Goodwin, L. C., & Rossetti, M. A. (2008). US highway crashes in adverse road weather conditions. Extended Abstract. In *24th Conference on International Interactive Information and Processing Systems for Meteorology, Oceanography and Hydrology, New Orleans, LA.*

Qiu, L., & Nixon, W. A. (2008). Effects of Adverse Weather on Traffic Crashes. *Transportation Research Record: Journal of the Transportation Research Board*, *2055*(1), 139–146. doi:10.3141/2055-16

Thomas, B. C., & Martin, J. E. (2007). A Synoptic Climatology and Composite Analysis of the Alberta Clipper. Weather and Forecasting, 22(2), 315–333. doi:10.1175/waf982.1
Accessed 13 March 2021

Tsapakis, I., Cheng, T., & Bolbol, A. (2013). Impact of weather conditions on macroscopic urban travel times. *Journal of Transport Geography*, *28*, 204–211. doi:10.1016/j.jtrangeo.2012.11.003

Uccellini, L. W., & Ten Hoeve, J. E. (2019). Evolving the National Weather Service to build a Weather-Ready Nation: Connecting observations, forecasts, and warnings to decision makers through impact-based decision support services. *Bulletin of the American Meteorological Society*, in press.

Weather Prediction Center (WPC), 2021: *Image Archive.* https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php
Accessed September 2021