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Katrina M. Hecimovic
University of Massachusetts Amherst, katrinahecimovic@gmail.com

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A QUANTITATIVE ANALYSIS OF THE IMPACTS FROM SELECTED CLIMATE VARIABLES UPON TRAFFIC SAFETY IN MASSACHUSETTS

A Thesis Presented

by

KATRINA MARIE HECIMOVIC

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

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Civil and Environmental Engineering

Transportation Engineering

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Approved as to style and content by:

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Michael A. Knodler Jr., Chair

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John Collura, Member

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Richard Palmer, Department Head
Department of Civil and Environmental Engineering

DEDICATION

To my family and friends for without their support I would not be where I am, especially my loving husband.

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I would like to thank my advisor, Michael A. Knodler, for his continued support, knowledge and flexibility through my graduate career. His love of the subject matter, natural teaching ability and dedication has touched many students' lives and I am lucky to be one. I would also like to extend my gratitude to John Collura for his helpful comments and suggestions at all stages of this project.

Thank you to UMassSafe for access and help acquiring the safety data and teaching me about the intricacies of the data warehouse. Team Traffic Operations and Safety at University of Massachusetts Amherst it was a pleasure learning, traveling and collaborating with you.

A special thank you to my husband, Dr. Austin S. Polebitski, for assisting in sorting and analyzing data, acting as a sounding board throughout the process, and inspiring me to persevere.

ABSTRACT

A QUANTITATIVE ANALYSIS OF THE IMPACTS FROM SELECTED CLIMATE VARIABLES UPON TRAFFIC SAFETY IN MASSACHUSETTS

FEBRUARY 2012

KATRINA M. HECIMOVIC, B.S.C.E., SEATTLE UNIVERSITY

M.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Michael A. Knodler Jr., Ph.D.

Current literature predicts that climate change may increase both the occurrence and severity of heavy rainfall events and winter precipitation in the Northeast United States. A potential increase in intense precipitation events related to climate change would theoretically also cause an increase in weather-related delays, increase in overall traffic disruptions, a substantive shift in travel behavior, and presumably a negative effect on safety and maintenance operations of highways. This current research study examines the existing impacts from both an operational and behavioral perspective of how weather events currently impact overall safety along routes in Massachusetts. A secondary objective of the research effort is to evaluate the extent to which this information is captured on the crash report form for subsequent use in safety analyses. Utilizing data from Massachusetts Department of Transportation, National Climatic Data Center (NCDC) and the University of Massachusetts Data Warehouse, crash statistics were examined during varied levels of weather events and compared with non-weather conditions. In addition, crash report forms were analyzed in comparison to NCDC weather data to determine the correlation between of the weather specific fields of the reports and to help determine if

crashes were weather-related. The results from the investigation show how the character of precipitation events impact traffic safety including both occurrence and intensity levels and in conjunction with existing weather predictions the relationships developed in this study are useful in evaluating how changes in extreme precipitation events projected for the Northeast may impact drivers' safety in the future.

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CHAPTER 1

INTRODUCTION AND OBJECTIVES

1.1 Introduction

Recent literature predicts that climate change may increase the occurrence, duration and intensity of heavy rainfall events and winter precipitation in the Northeast United States (1). The potential threats that climate change poses with regards to transportation systems are evident, "[b]ut MPOs and DOTs have little if any information on precisely what impacts they can expect, where, and in what time frames" (2). The 2000 Highway Capacity Manual (HCM) notes that adverse weather can adversely affect not only roadway capacity, but also reduces operating speeds (3). More generally, the HCM provides additional information to suggest that there is a variety of impacts on traditional traffic parameters and safety as a result of variations of weather (3). A potential increase in intense precipitation events related to climate change would also theoretically cause an increase in weather-related congestion and delays, increase in overall traffic disruptions, a substantive shift in travel behavior, and a negative effect on safety and maintenance operations of highways.

Literature proves the operational affects that weather has on traffic (4, 5, 6). The purpose of this study was to determine the safety related affect of weather on traffic, while simultaneously providing an assessment of our ability to capture this data. Additional insights into the magnitude of the various effects are needed to make more accurate assessments on the safety issues related to weather (7). Although several efforts have attempted to quantify or model this relationship there is a great deal of variability within both the results and the overall research procedures employed. This research study examined the existing impacts of how weather events currently affect overall traffic safety throughout the Commonwealth of Massachusetts. The results from the investigation attempt to quantify how the character of precipitation events directly impact traffic safety, and in conjunction with existing weather predictions, relationships developed in this study prove useful in evaluating how changes in precipitation events projected for the Northeast may impact traffic safety in the future. The correlations created can be applied to help assist the field of weather-responsive traffic management leading to more efficient operation of highways during adverse weather (8).

1.2 Problem Statement

In 2004, the Committee on Weather Research for Surface Transportations published a study stating that "weather significantly affects the safety and capacity of the nation's roadways" and that adverse weather is associated with over 1.5 million vehicular crashes per year resulting in approximately 800,000 injuries and 7,000 fatalities (9). Literature has proven that weather has an operational affect on traffic (4, 5, 6). In a case study about inclement weather in New England, Agbolosu-Amison et al. reported that weather affects traffic operations in the northeast region of the U.S. (10). Although weather's affect on traffic operations has been proven, the actual affect on traffic safety is not as documented and developing a true sense of the impact has become has become a question among transportation professionals.

A need existed to build on the previous research regarding weather and traffic safety with the objective of developing an improved understanding of the relationship between weather variables and traffic safety statistics. The primary purpose of this study was to use available crash, citation and weather data for a period of years within the Commonwealth of Massachusetts to identify the effect weather has on traffic safety. A secondary objective of this proposed study was to perform a data quality assessment on the aforementioned data to determine the extent to which weather related fields in the Massachusetts police-reported crash forms adequately record and portray the relationship between weather and traffic safety. Specifically, the research addressed whether the readily available crash data fields allow for the ability to assess and model the nature of the relationship between weather events and traffic safety. Overall, the study helps to provide a clearer sense of the overall relationship between weather and traffic safety and the data quality of weather-related fields on the police-reported crash forms.

1.3 Research Objectives & Hypotheses

The primary objective of this research was to model the relationship between weather variables and traffic safety statistics within the Commonwealth of Massachusetts. A secondary objective of this research was to assess the quality of the weather fields within the Commonwealth of Massachusetts police-reported crash report with respect to the ability to adequately record and portray the relationship between weather and traffic safety. Within the framework of this overarching objective a series of more specific project hypotheses were developed as follows:

1.3.1 Hypothesis 1

Crash and weather data from multiple sources can be analyzed and a relationship between safety and weather can be modeled.

1.3.2 Hypothesis 2

Specific crash factors resulting in differences in traffic safety impacts by weather condition can be identified.

1.3.3 Hypothesis 3

Utilizing crash-report form weather data and real-world weather data a strong correlation can be identified. The extent to which this matching relationship exists would only strengthen weather based safety analyses.

1.3.4 Hypothesis 4

A quantifiable amount of additional insight into the impact of weather on traffic safety can be provided by investigating the narratives on police-recoded crash report forms.

1.4 Scope

As noted above the primary objective of this research is to evaluate and model the safety-related impacts associated with weather. Although, there are additional weather-related impacts associated with the operational aspects of a roadway, these operational elements were beyond the scope of this research and are not included. With regards to the safety analysis, the scope of this research was limited to crash and weather data available for the Commonwealth of Massachusetts. The most significant limitation of the availability of quality crash data was due in part to changes with the police-reported crash form that occurred as part of a new crash data system in 2001 with years 2002 and 2003 displaying a learning curve of the new system (11). As a result, the scope of the crash data for this analysis began in 2004 spanning a six year crash period through the most recently completed year at the time of the study in 2009. Admittedly, there would be an inherent desire to incorporate exposure data that would allow for normalization of the crash data and correlation of crash rates; however this data was not archived for the period of analysis at the time of the study and as such is not included herein. The weather data for this research to compare with the weather fields on the police-reported crash form was taken from the National Climatic Data Center (NCDC).

CHAPTER 2

LITERATURE REVIEW

Generally speaking, most individuals would acknowledge that weather has an effect on roadway safety whether it is reducing visibility, reducing roadway friction or increasing driver stress. Andrey et al. summarized a history of finds as collision risk increasing with precipitation; snowfall has a greater effect then rainfall on crash occurrence, but usually with less severity; collision risk usually increases for the first snowfalls and freezing rain or sleet; and there appears to be a positive relationship between precipitation intensity and crash risk (12). Weather and traffic safety have been analyzed in a variety of way using a myriad of data with a significant degree of variability affecting the results. Edwards suggests a look into the relationship of the weather with other factors affecting crash occurrence (13). A significant amount of research has investigated an understanding of the relationship between weather on traffic safety, but a closer look into specific factors, relationships between factors and crash characteristics is still required (12).

The study herein used historic data available from the Massachusetts Department of Transportation Registry of Motor Vehicles crash data system which contains police-reported crash forms for safety and crash-related data and the NCDC weather data. To adequately understand the aspects related to the study several applicable areas of background material warrant further consideration and were the primary focus of the literature review task. These topics include the following:

- Identification of factors associated with weather-related crashes;
- Weather-related crash characteristics;

- Methods to collect weather-related traffic safety data

2.1 Identification of factors associated with weather-related crashes

To determine if a crash is weather-related, the factors included in the determination must be understood. Maze et al. found that weather events affect three main traffic variables: traffic demands, traffic flow relationships, and traffic safety (5). Evans displays that atmospheric conditions, or weather conditions, and roadway surface conditions are highly related, but not identical (14). For example, Evans states that the roadway surface is still wet after rain has stopped and it is temporarily possible to drive in the rain while the roadway surface is dry (14). So from a single weather event two separate weather-related factors may affect safety: roadway surface condition and precipitation. Cools et al. found that for a variety of trip purposes, a relationship existed between travel behavior and type of weather event (15) this may affect how many users are on the road during weather events, ultimately affecting crash numbers during weather events.

2.2 Weather crash characteristics

The majority of road crashes occur when weather is fine or clear. According to FARS 2001, approximately 84 percent of fatal crashes occur on dry roads and approximately 88 percent of fatal crashes occur under no adverse atmospheric conditions (14). Edwards states that the greater the frequency of occurrence of a specific weather condition the greater the proportion of crashes that occur during that weather condition (13). In 2001, Khattak and Knapp collecting weather, traffic, roadway geometry and traffic exposure data on seven highway sections in the state of Iowa found that more snowfall intensity resulted in less injury-resulting crashes, while higher gusts of wind resulted in crashes with more injury-resulting crashes (16).

Throughout previous research there have been various relationships between climate parameters and crashes determined. Edwards shows that 82 percent of England and Wales national crash averages occur in fine weather without heavy winds, with rain being the second most recorded weather condition at the time of a crash at 16.2 percent, snow and fog together make up less than 2 percent (13). In Golob and Recker's California study, research found that only 13 percent of all freeway accidents in California in 1998 occurred during wet road conditions (17). Nokhandan et al. analyzed average number of crashes per month under varying weather conditions: rain, snow, fog and heavy wind and found that the greatest number of crashes occurred when it was raining even in the months with little rain (18). Qin et al. found that for the 2000 through 2002 winter seasons in Wisconsin, a total of 7,037 snowstorm events were recorded and during more than half of the snowstorms (3,667 snowstorms), 17,294 crashes occurred resulting in 95 fatalities and 7,432 injuries(19). Pisano and Goodwin reported that in 2001, more than 22 percent of passenger vehicle crashes happened under adverse weather conditions, more than 450,000 in jury crashes and 6,900 fatalities (8). Whereas, Pisano and Goodwin reported that in 2001 almost 49 percent of weather-related crashes in passenger vehicles happened during a rain event and nearly 79 percent occurred on wet pavement (8). Pisano and Goodwin also reported that nearly 12 percent of the large-truck crashes in 2001 occurred during a weather event, rain, snow, sleet or fog, and almost 19 percent of the large truck crashes occurred while the pavement was wet, snow-covered, icy or slushy (8). In a four-year urban Canadian study, Andrey et al. found that on average, compared with 'normal' seasonal conditions precipitation was linked with a 75 percent increase in traffic crashes resulting in a 45 percent increase in injuries(12).

There have been many studies that have tried to find a correlation specifically between crash severity and other factors including weather. The findings of the studies have varied greatly from positive to negative relationships and significant to insignificant correlations. The tools used to model the relationships have varied as much as the results have from simple statistical analysis to logit and probit models. The effects that weather has on crash severity changes with differing weather variables. Andrey et al. summarized a history of finds as collision risk increasing with precipitation; snowfall has a greater effect then rainfall on crash occurrence, but usually with less severity; collision risk usually increases for the first snowfalls and freezing rain or sleet; and there appears to be a positive relationship between precipitation intensity and crash risk (12).

The majority of studies found little significant correlation between weather and severity and studies even found an inverse relationship between adverse weather conditions and an increase in crash severity. Nassar, Saccomanno and Shortreed in a 1994 study of Ontario, Canada crashes estimated a disaggregated model of crash severity based on sequential logit models based on differing factors, including road surface conditions. Road surface condition was used as a proxy for weather conditions since weather conditions when recorded sometimes vary from the weather conditions at the time of the crash, but road surface conditions can at times be more easily recordable after the fact. The Nassar, Saccomanno and Shortreed study found the correlation between crash severity and road surface conditions insignificant (20). Krull, Khattak and Council in a 2000 study analyzed severity in single vehicle crashes and found seven contributing factors with dry pavement as opposed to slippery pavement being one factor (21). Slippery pavement has a direct correlation to precipitation-baring weather conditions and dry pavement correlates to clear conditions. Toshiyuki and Shankar in a 2004 study of the severity in collisions with fixed objects in Washington State found that two separate factors, both an icy roadway surface and rain decrease the probability of more severe driver injury (22). Icy roadway conditions may correlate to a variety of weather conditions especially over the winter months. Donnell and Mason in a 2004 study found in interstate highway cross-median and median-barrier collisions, wet and icy pavement conditions are a significant factor in decreasing crash severity (23). There are differing theories for the inverse relationship between weather and crash severity that is found in some studies. Abdel-Aty in a 2003 study suggested that bad weather conditions may prompt drivers to slow down and keep a safe following distance (24).

Some studies though have found a significant and positive correlation between crash severity and weather conditions. Lee and Mannering found in a 2002 study that wet roadway surfaces increased the likelihood of evident and disabling injury or fatality in run-off-the-road crashes (25). Many studies that found significant and positive correlations between weather and crash severity coupled with other factors to increase the significance and make the parameters more specific. Some studies used additional factors of roadway geometry, crash configuration or roadway lighting conditions. In Abdel-Aty's 2003 study, it was found that crashes happening in signalized-intersections with bad weather and dark street lighting had significantly higher probability of severe injury. In that same study, Abdel-Aty also found that angle and turning collisions at signalized intersections in adverse weather and dark street lighting conditions are possible contributing reasons to higher probability of severe injury in those specific crash types (24). Jung, Qin and Noyce found in a study focusing on Wisconsin road data from between 2004 to 2006, that using a backward format of a sequential logistic regression model a clearly significant weather effect especially on fatal and incapacitating injury prediction (26). In a 2004 study of all 50 states crash severity data, Eisenberg found a negative and significant relationship at monthly analysis level, but at a daily analysis level a strong positive relationship was found. Daily levels may be explained as if it rained a lot yesterday today there will be fewer crashes on average; this explains a substantial negative lagged effect of precipitation across days within a state-month (27).

Eisenberg in his 2004 study, the mixed effects of precipitation on traffic crashes, did an extensive summary of past studies on the effects of precipitation of traffic crashes including severity and crash occurrence. Eisenberg's literature summary can be seen in Figure 1 and echoes the literature review performed in this study, mixed results (27).

Table 1
Summary of studies on effects of precipitation on traffic crashes

findings	Author (year)	Sample	Method	Key
For rainy weather, the :injury-only:non-injury crash ratio is 27:755 For dry weather, the ratio is 21:235:744	Edwards (1998)	England and Wales, 1980–1990	Compare severity mix of crashes during rain to severity mix during dry weather (weather conditions per police reports for crashes)	(A) I fatal: 18:2: (B) I
Significant rainfall-crashes correlation 0.27) Significant snowfall-crashes correlation 0.48)	Andreescu and Frost (1998)	Montreal, 1990–1992	Estimate correlation between daily precipitation amount and daily number of crashes	(A) : (r = (B) : (r =
Injury crash rate: in all four countries rainfall :ases it, snowfall decreases it Fatal crash rate: rainfall increases it in nark, is insignificant in Norway and Sweden, not recorded for Finland; snowfall decreases it enmark, Norway, and Sweden	Fridstrom et al. (1995)	Denmark, Finland, Norway, Sweden, 1973–1987	Generalized Poisson regression to estimate contributions of various factors, including weather, to monthly crash rates by county or province	(A) I incre (B) I Denr and i in D
Relative risk of crash during rain is 1.7 Relative risk returns to normal (1.0) within 1 h rain event	Andrey and Yagar (1993)	Calgary and Edmonton, 1979–1983	Matched-pair approach: compare "rain events" to comparable time periods without rain on different week	(A) I (B) I after
tive risk of crash during rain is 1.6 (CI 1.3–1.9)	Andrey and Olley (1990)	Edmonton, 1983	Matched-pair approach (as in Andrey and Yagar, 1993)	Rela
Injury accidents (Israel): relative risk during of 2.2 (method 1) or about 6 (method 2) Fatal crashes (US): relative risk during rain of (method 1) or 3.75 (method 2) In Israel, relative risk during rain highest ig months with sporadic rain	Brodsky and Hakkert (1988)	Israel 1979–1981, and eastern US (DE, DC, MD, VA) 1983–1984	(1) Difference in means: rainy vs. dry days (2) "Wet pavement index": compare percent of crashes reported to occur on wet pavement to percent of overall time pavement is wet (estimated using hourly rainfall data)	(A) I rain (B) I 2.18 (C) I durir
tive risk for fatal crashes on wet pavement is t 4	NTSB (1980)	US 1975–1978	"Wet pavement index" (see earlier)	Rela abou
Rainy days had about twice as many crashes on-rainy Crash severity (average number of injuries per lent) increased with rain in rural areas, but n urban areas	Bertness (1980)	Chicago and NW Indiana, 1976–1978	Matched-pair approach: compare rainy days vs. non-rainy days 1 week later or earlier	(A) I as n (B) (accic not i
About twice as many crashes during rain events Number of crashes increases linearly with rain unt Rain has no effect on crash severity ratio ries per crash)	Sherretz and Farhar (1978)	St. Louis area, summertime, 1971–1975	Matched-pair approach (as in Andrey and Yagar, 1993)	(A) / (B) I amo (C) I (inju

y).

Note: Unless stated otherwise, the term "crash" includes all types of crashes (fatal, injury-only, non-injur

Figure 1 Literature Summary from Eisenberg Study

2.3 Methods to collect weather-related traffic safety data

There are a variety of methods that have been used for collecting weather data and weather-related traffic data. Traffic crash and weather data can be collected straight from the police crash reports (13). Police recorded weather conditions may introduce error Shinar et al notes (28). For example, it the crash may have occurred during a precipitation event, but by the time the enforcement is on the scene the roadway may be wet, but the precipitation has ceased so the recorded weather is clear and the recorded roadway surface is wet. During a 1998 study of relationships among urban freeway accidents, traffic flow, weather and lighting conditions in California, Golob and Recker utilized accident data obtained from the California Department of Transportation Traffic Accident Surveillance and Analysis System (TASAS) (17). The TASAS crash database system is comprised of information from police reports along the California State Highway System, included in the crash documentation is specific information on the lighting, weather and pavement conditions (17). Qin et al. collected winter snowstorm event data from a variety of sources including winter snowstorm event data from the Bureau of Highway Operations at the Wisconsin Department of Transportation and crash data from the recorded motor vehicle traffic accident form (19). Similar to Massachusetts, the Wisconsin crash data is recorded by a law enforcement officer at the sight of the crash and has specific fields to record pre-coded weather and roadway condition descriptions as well as an area for a narrative which may include information about crash causation and contributing circumstances, like snow, rain, fog or other weather factors (19). For their Canadian study, Andrey et al. gathered weather data from the Meteorological Service of Canada (MSC), but found it difficult to compare MSC data with the weather fields on the crash reports, similar to those in Wisconsin and Massachusetts, due spatial proximity between the crash locations and the weather stations where the MSC weather data was collected (12).

CHAPTER 3

RESEARCH PROCEDURES

A series of tasks were developed in an effort to successfully complete the stated research objectives and evaluate the established hypotheses. More specifically, the weather based safety analysis and data quality assessment was completed through coordinated series of project tasks. The sections below describe the tasks that were performed to carry out the proposed research.

3.1 Task 1: Literature Review

The initial research task was to review current literature including literature focusing on climate change and weather affects of traffic operations and safety. A majority of the existing literature reviewed focused upon the relationship between weather-related elements, including precipitation, wind and roadway surface condition, with traffic operations and safety. This task was initiated in concert with the development of this study and remained ongoing throughout the completion of the research effort.

3.2 Task 2: Weather-related Crash Data Analysis

The initial step in completion of the need to begin more general research objectives study was to model the nature of the relationship between weather and traffic safety. The first step of this task was to collect weather-related crash data and weather data. Data collection efforts were coordinated with the University of Massachusetts Traffic Safety Research Program (UMassSafe) for safety data, including crashes, severity and police-reported crash report form field information. The weather data used in the analysis was downloaded from the NCDC archive of weather data.

UMassSafe is a research program residing on the University of Massachusetts Amherst campus that houses the UMass Safety Data Warehouse. Data stored in the warehouse include traditional datasets such as crash and citation data as well as less traditional highway safety data such as health care/ hospital data and commercial vehicle safety data. Figure 2 presents the structure of the UMassSafe Data Warehouse. Prior to being available for query queried from the data warehouse the crash data travels through a number of organizations. Enforcement professionals that arrive at the crashes where the damages are over $1000 record the information in the Commonwealth of Massachusetts standardized crash report form. The forms have over 40 fields to fill in ranging from time, date and weather conditions to conditions of the accident, state of the driver and damages. Historically, enforcement officers have claimed that the reports can be difficult to fill out and when arriving at the scene of a crash, some fields are difficult to adapt to a certain scenario or some of the fields are difficult to understand in general, so at times reports are not complete. Of the over 42 fields on the form approximately two-thirds are regularly filled out by the enforcement officers (11).

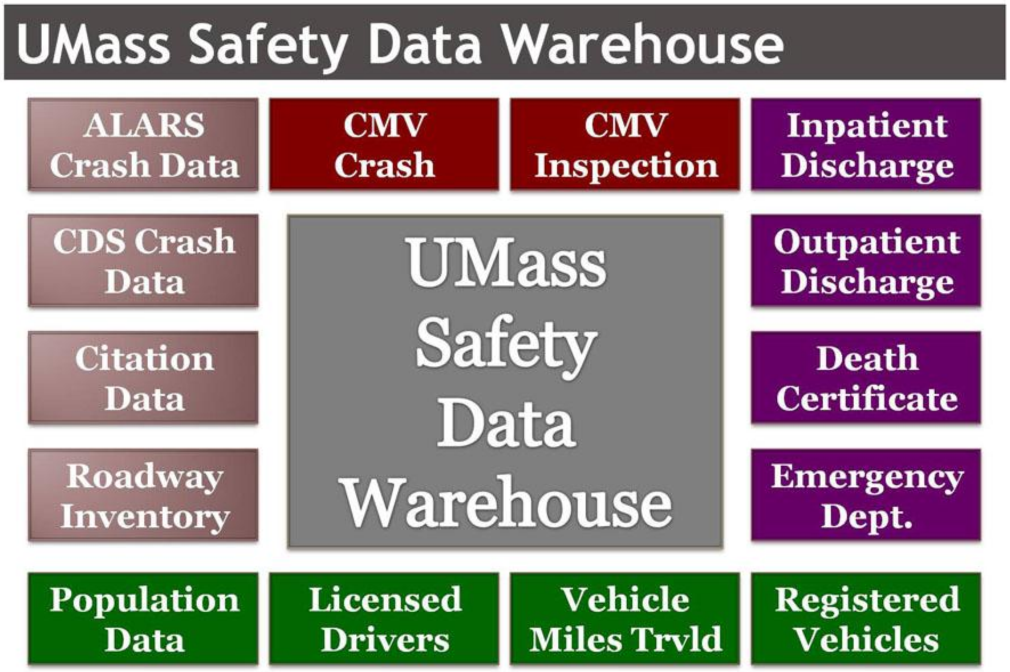


Figure 2 UMass Safety Data Warehouse

Subsequent to the field reporting, each enforcement agency sends either a hard copy of the crash form or in certain instances electronic data to the Massachusetts Registry of Motor Vehicles, or RMV, for collection. The RMV assigns each crash a number and enters the crash and the associated data into the Crash Data System, or CDS. From the CDS, the Safety Section of the Highway Infrastructure Division of the Massachusetts Department of Transportation (Mass DOT), geocodes the crash data. Mass DOT uses a geocoder developed by Geonetics to automatically locate the crash data and assign X- and Y-coordinates for each crash location. The Geonetics software typically geocodes approximately 90% of the crashes. Mass DOT periodically dumps the geocoded data back into CDS. Quarterly the CDS data is uploaded into the UMass Safety Data Warehouse. While the CDS program purges data every three years, UMassSafe stores the data enabling queries for analyzing historical patterns. Figure 3 depicts a flow chart of the data process prior to being queried.

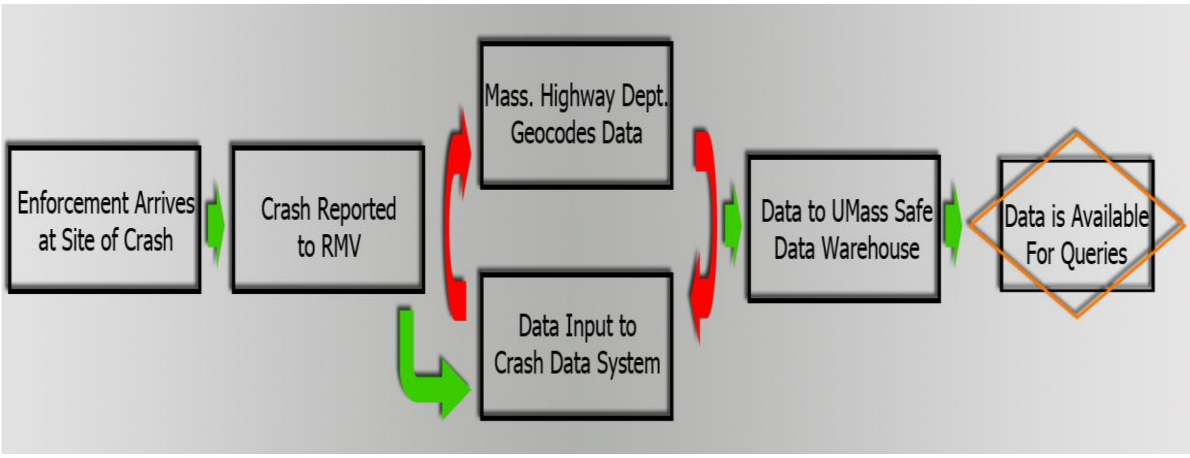


Figure 3 Massachusetts Crash Data Flow Chart

Once the data was prepared for querying, the second step of this task linked weather parameters to traffic safety. From the warehouse database query, assigned each crash a unique crash number and provided information about the each specific crash. Certain fields, or factors about the crash specifics, were chosen to be included in the crash analysis because of this data quality and common association with crashes.

For example, the *first harmful event* explains what the vehicle made the first contact with, whether it is another vehicle, a pedestrian or an inanimate object. This data is very important to understanding the crash dynamics which may or may not be directly related to the road surface condition or the weather.

Figure 4 presents a portion of crash factors that were analyzed in the research. Factors were analyzed for each available weather condition and to identify if any apparent trends were present. Following this preliminary step, the *severity* and several other factors were combined during analysis to make more specific comparisons and to see if crash severity differed in conjunction with other factors under differing weather conditions. Appropriate measures were taken to properly and statistically analyze the data.

FACTORS ANALYZED ACROSS WEATHER CONDITIONS

CRASH CHARACTERISTICS: severity manner of collision first harmful event first harmful event location
ENVIRONMENTAL CHARACTERISTICS: time of day day of week month weather ambient lighting road surface condition
ENGINEERING CHARACTERISTICS: roadway type TCD type intersection junction type traffic-way description

Figure 4 Crash Factors

The weather data used in the data analysis was taken directly from the police-recorded crash report forms from the weather fields. Four criteria were used for weather segregation, clear, rain, snow and sleet or hail. All other weather criteria had too small a percentage or were frequently coupled with one of the used criteria; for some portions of the research snow and sleet were combined to be snow/sleet. For example, cloudy is frequently coupled with clear as in there is no precipitation or rain as in the sky is cloudy and it is raining out. If either weather field was one of the main four criteria the crash was counted as a crash of that type. This produced a small percentage of double counted crashes, less than 2 percent.

The weather combination table shown in Table 1 was created to check the difference between the roadway condition and weather condition given on the crash report forms. This table was used to originally verify that the weather condition should be the factor used in the research rather than the roadway condition as in some previous studies (8, 20, 21, 22) and that both weather condition columns from the crash report should be used in calculating the rainy crashes. A sufficient correlation existed between road condition and weather to justify e the weather condition as the determining factor, but there was some margin of error as is shown in the following data analysis. Table 1 also shows that for the rain, weather code 3, it was important to use both columns of data because there were 32,360 crashes that occurred during a rain event that were marked only in the second weather code column not in the first weather code column. This could be for a variety of reasons, one being that weather code 2 is cloudy and since that comes before weather code 3, rain, it may be marked in the first column and rain, the precipitation weather variable, could only be marked in the second column.

Table 1 Weather Combination Table

Weather Code		Roadway Conditions							
		Dry		Wet		Snow		Ice	
Col 1 Clear	527277	478105	90.7%	21401	4.1%	7168	1.4%	9220	1.7%
Col 2 Clear	83476	75385	90.3%	3643	4.4%	988	1.2%	1230	1.5%
Col 2 Clear w/o Col 1 Clear	13528	10532	77.9%	1225	9.1%	421	3.1%	306	2.3%
Col 1 Rain	80090	1319	1.6%	74829	93.4%	886	1.1%	1027	1.3%
Col 2 Rain	39794	1421	3.6%	36418	91.5%	583	1.5%	497	1.2%
Col 2 Rain w/o Col 1 Rain	32360	1316	4.1%	29298	90.5%	555	1.7%	470	1.5%

3.3 Task 3: Data Quality Assessment

This task was initiated in an effort to quantifiably assess the data quality of the weather fields on the police-recorded crash form in two ways. The first was to check the accuracy of the weather-related fields on the crash form by the comparison and correlation of the weather-related field with captured NCDC weather data. The second was to gather information from the crash narrative from a sample of crash forms to determine the true impact of weather on the crash. In other words, this task attempted to determine if the crash simply occurred during adverse weather or the crash was related (i.e. caused, impacted, etc.) to the adverse weather.

3.3.1 Weather data, crash report form weather field comparison

The first step of Task 3 was the collection of the weather data. From the NCDC website, weather data was downloaded for the years of analysis for all of the appropriate weather stations throughout Massachusetts. The first level of analysis was to compare daily meteorological data against the weather fields on certain amount of selected crash reports by checking data points, crashes, within certain radii of weather stations. The NCDC works as a climatic data clearinghouse where data sources are submitted including many weather stations around the

U.S., including a weather station at the Worcester Regional Airport. The first location selected was this weather station at the Worcester Regional Airport because there was both daily and hourly weather data for this location.

There is a weather station that uploads its daily and hourly climatic data including precipitation and temperature to the NCDC database at the Worcester Airport. Data submitted to NCDC in general tends to be +/- 10% accurate even though the gages are managed by a variety of people and organizations. Lots of things can affect precipitation accuracy, like wind speed and precipitation type. At the Worcester Airport there is a heated bucket to gather precipitation so snow falling will still be captured as precipitation and temperature must be added to the analysis to break out rain versus snow. For this study, the temperature variable was not included in the analysis, but should be looked at in future studies.

Figure 5 shows all of the crashes that occurred in 2004 within given radii of the Worcester Regional Airport plotted using the crash x-y coordinates from the crash report form in ArcGIS software. The radii used were a half mile, one mile, 5 mile and 12.5 mile around the Worcester Regional Airport met station. The data assessment analysis was conducted in statistical language R. ArcGIS was used to plot the crashes onto a map to check how many crashes were within each radius around the Worcester Regional Airport with the number of crashes in each radii gathered using R. The numbers were the same until the five mile radius where the number of crashes differed slightly between ArcGIS and R due to the projection differences between the two programs.

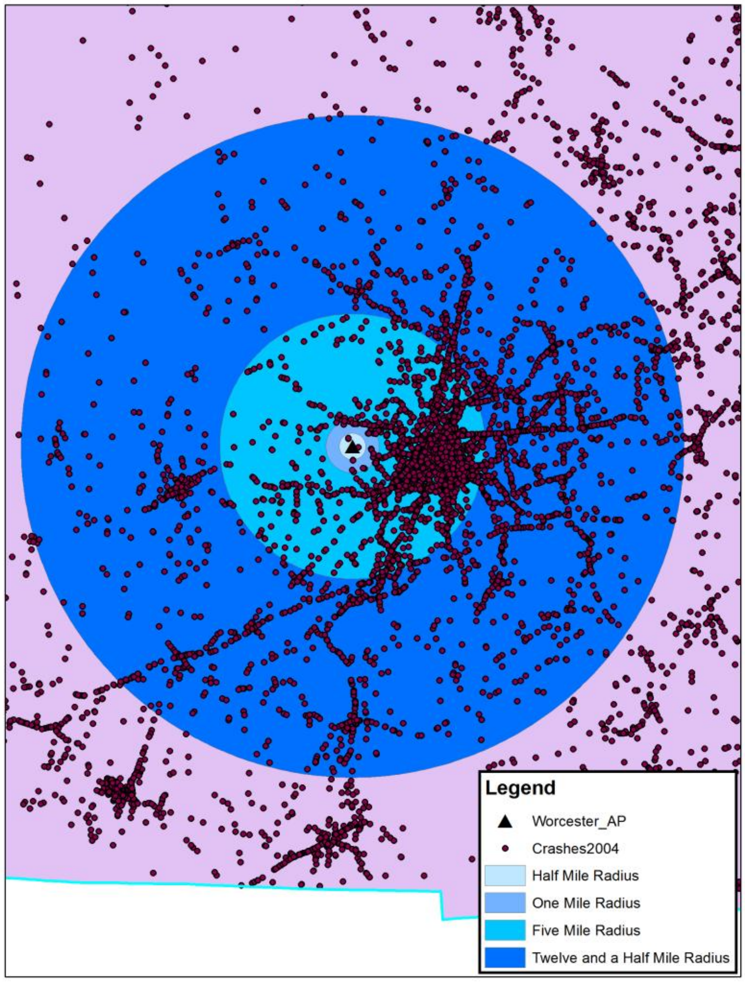


Figure 5 2004 Crashes within the Vicinity of the Worcester Airport

Two main items regarding the comparison of weather data and the crash report form data weather fields were examined. The first was if both columns of the crash weather field data needed to be used similar to the examination in Table 1, but for weather data versus crash weather data. This was done using both hourly and daily data. A cursory examination of the hourly weather data looked at days that were all clear meaning no precipitation fell on those days at all and days that were very rainy, total precipitation for the day more than a half inch. What the R program did was pick a day, take all of the crashes within the given radius of the airport and compare whether it was raining at all during that one hour period (starting from midnight to 1 AM). There were 1147 days out of 6 years (2004-2009) that had hourly data. For this hourly data a visual representation of all of the hourly crashes in a day and weather there was precipitation that occurred on that day or not and if the hour posted had precipitation was created that helped to confirm the information determined in Table 1.

When it was determined that both columns of weather fields from the crash report form should be used and that should be used and that the hourly data and daily data should be examined for the Worcester area, a simple comparison area, a simple comparison of NCDC weather data and crash report form recorded weather was made. First all of the made. First all of the crashes within each radius ring around the Worcester Regional Airport weather station were pulled weather station were pulled by X, Y coordinate in ArcGIS. The first radius was a half mile circle around the Worcester around the Worcester Regional Airport, the second was a ring between a half mile and mile radius, the third was a ring radius, the third was a ring between a mile and five mile radius and the fourth was a ring between a five mile and 12.5 a five mile and 12.5 mile radius.

Table 2 shows the crashes per radius ring for the six years (2004 through 2009), how many of those crashes had hourly NCDC weather data as well as daily weather data and that percentage breakdown. The radius rings were used so that proximity analysis could be performed. Those crashes were then segregated out along with the all of the crash report form data including date, time of day and the weather fields (both columns). The time of the crash was categorized into which hour of the day it occurred with hour one starting at midnight to easily compare to weather data which is categorized the same way. Then daily and hourly (if available) NCDC precipitation data were compared with the weather field data for each crash.

Table 2 Crashes per Radius Ring around Worcester Regional Airport

Radius (mile)	No. of crashes	No. of crashes w/ hourly data	% of crashes w/ hourly data
0.5	24	14	58.3%
1	327	187	57.2%
5	28749	16019	55.7%
12.5	23581	13365	56.7%

3.3.2 Crash report form narrative analysis

The second step of Task 3 involves the narrative of the crash report. A portion of the crash report narratives were downloadable from online, but the majority were only available in hard copy from the Massachusetts Registry of Motor vehicles. An excerpt from a Massachusetts Crash Report Form is shown in Figure 6. This study used one year (2009) of electronically downloadable crash report forms that were said to have narratives provided. Of the 114,696 2009 crash reports 40,086, or approximately 35%, included narratives and were electronically downloadable. Many of the crash reports had no information in the narrative and this could be due to no additional narrative information submitted or the information not tagged in the narrative. Due to the overwhelming large number of crash reports, 100 crash reports for each weather type (clear, rain, snow/sleet) were reviewed. To analyze a hundred crash report narratives for each of the three weather types, 150 crash reports for each weather type were selected with the intent of using one hundred in case there were some unusable reports or narratives of reports drawn. A random number generator was utilized to select the 150 crash report form crash numbers of each type of weather related crash. Some of each of the weather type crashes drawn did not have usable narrative sections, meaning there was something that had been entered in the narrative portion of the crash report form, but it was not text, usually it was a single character. For randomly selected clear weather crash reports, 103 reports were needed to get 100 crash reports with narratives; for rain 102 crash reports were needed and for snow/sleet 101 crash reports were needed.

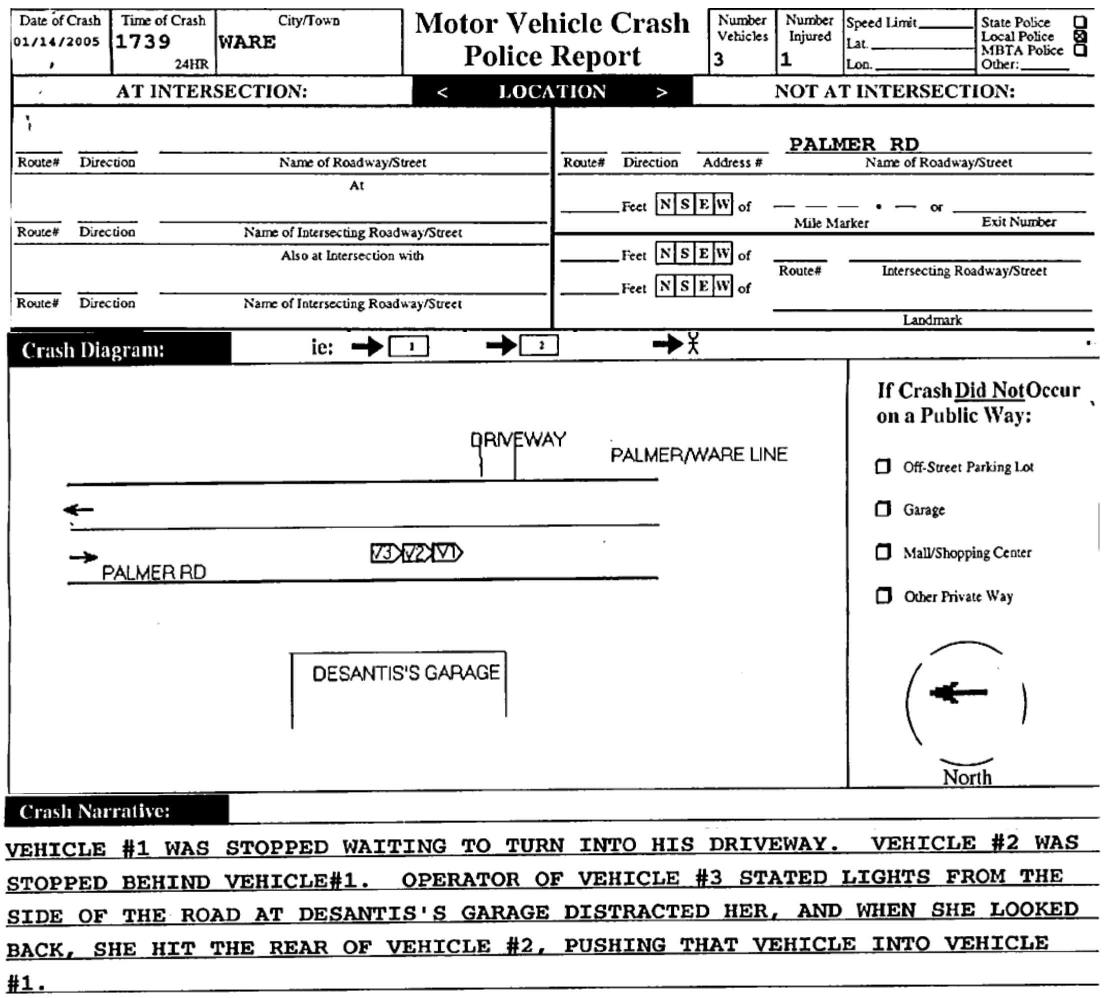

Date of Crash 01/14/2005
Time of Crash 1739 24HR
City/Town WARE
Motor Vehicle Crash Police Report
Number Vehicles 3
Number Injured 1
Speed Limit
Lat.
Lon.
State Police
Local Police
MBTA Police
Other:
AT INTERSECTION: < LOCATION > NOT AT INTERSECTION:
Route# Direction Name of Roadway/Street
At
Route# Direction Name of Intersecting Roadway/Street
Also at Intersection with
Route# Direction Name of Intersecting Roadway/Street
PALMER RD
Route# Direction Address # Name of Roadway/Street
Feet N S E W of Mile Marker or Exit Number
Feet N S E W of Route# Intersecting Roadway/Street
Feet N S E W of Landmark
Crash Diagram: ie: 1 2
DRIVEWAY
PALMER/WARE LINE
PALMER RD
V3 V2 V1
DESANTIS'S GARAGE
If Crash Did Not Occur on a Public Way:
Off-Street Parking Lot
Garage
Mall/Shopping Center
Other Private Way
North
Crash Narrative:
VEHICLE #1 WAS STOPPED WAITING TO TURN INTO HIS DRIVEWAY. VEHICLE #2 WAS STOPPED BEHIND VEHICLE#1. OPERATOR OF VEHICLE #3 STATED LIGHTS FROM THE SIDE OF THE ROAD AT DESANTIS'S GARAGE DISTRACTED HER, AND WHEN SHE LOOKED BACK, SHE HIT THE REAR OF VEHICLE #2, PUSHING THAT VEHICLE INTO VEHICLE #1.

Figure 6 Excerpts from Massachusetts Crash Report Form

The crash reports are filled out by either local or state police officers depending on the location of the crash. The split for the police crash report form for 2009 was approximately 62% local police and 38% state police. The police type split was checked for the hundred crash reports used for each of the specific weather type. The police type breakdowns are shown in

Table 3 and closely parallel the average police type split for all 2009 crashes not just those with electronically submitted narratives. The crash report narrative analysis provided insight into whether the crashes that occurred during weather events were actually weather-related crashes, if the weather or roadway surface has an actual affect on the crash.

Table 3 Crash Recorded by Police Type

Weather Type	Police Types	
	Local (percent)	State (percent)
Clear	64	36
Rain	59	41
Snow/Sleet	63	37
Average	62	38

CHAPTER 4

RESULTS OF WEATHER-RELATEDCRASH DATA ANALYSIS

4.1 Preliminary Crash Data Analysis

Following completion of the initial data preparation and appropriate levels of aggregation the data were analyzed in an effort to model the weather-safety relationship. The majority of crashes occurred during clear weather, which makes sense in Massachusetts climate with historic precipitation rates. There are 842,168 crashes for the six years of recorded data with 842,141 crashes with the weather field filled with some information. 74.9 % of all 2004-2009 crashes in MA occurred during clear weather. 15.9 % of all 2004-2009 crashes in MA occurred during rainy weather. 7.3 % of all 2004-2009 crashes in MA occurred during snowy weather and 1.9 % of all 2004-2009 crashes in MA occurred during sleeting weather (combined snow/sleet 9.2%).

For the Worcester area alone, the climate breakdown is similar to the breakdown of the crashes for the entire state, with 65% of days being defined as clear (precipitation totals less than 5/100ths of an inch), using daily totals of precipitation from the Worcester Airport meteorological station. Approximately 21% of the days fall into the rain category and 13% as snow days. The percents do not match exactly as Worcester only represents a portion of Massachusetts weather variability and the totals are aggregated to daily values whereas crashes occur in a rather continuous manner and follow traffic volume patterns.

Each of the factors mentioned in Figure 4 were examined for all three of the weather types: clear, rain, and snow and sleet. Figure 7 thru Figure 10 and Table 4 thru Table 12 show the percentage of the crashes that occurred for each weather type for some of the given variables in Figure 4. The distribution of crashes across months and weather types follows an expecxted pattern. Clear day crashes are evenly distributed throughout the year, with slightly elevated numbers of crashes occuring in July and August, months that have more clear days and likley higher traffic volumes do to tourism. The rain day crashes are highest in the shoulder months of winter, with the highest percent of rain day crashes in fall months. Snow and sleet day crashes distributed across four primary months, December through March, with the highest percent occuring in January. Figure 8 shows the percent of daily weather (no rain or clear, rain and snow) per month for the Worcester Regional Airport weather station. For the state Figure 7 shows that there is a much higher percentage of snow crashes in January and December and at least for the Worcester area of Massachusetts, Figure 8 shows that the percentage of clear and snow days are approximately even for those two months.

Figure 9 presents the distribution of crashes by weather type by time of day. The pattern of crashes reflects typical traffic volume patterns, with the only exception being snow crashes occuring on snowy days. On snowy days, there tends to be higher volumes of crashes occuring in the morning hours, with reduced numbers occuring in the afternoon hours. This could be related to either snow plowing schedules or the fact that roads are most slick in the morning as nights are cold, creating freezing road surface conditions or could be due to drivers not altering AM travel behavior due to snowy conditions, but adapting later in the day . Conversly, roads are warmest and tend to be cleared completely by afternoon hours.

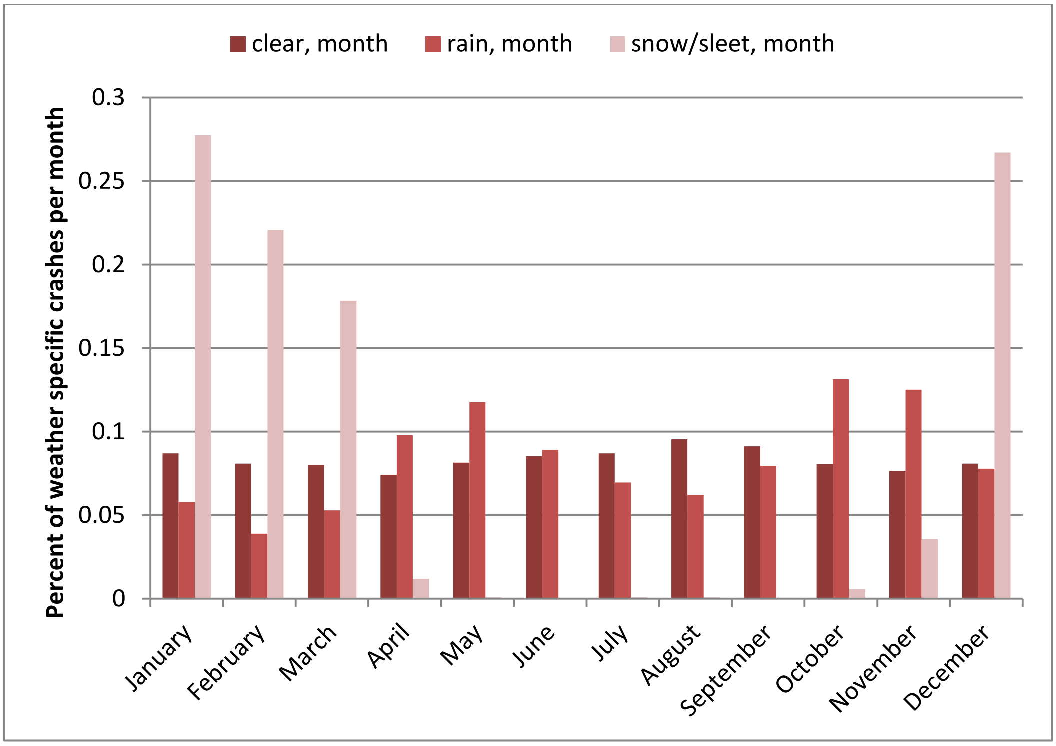


Figure 7 Percent of Weather Specific Crashes per Month

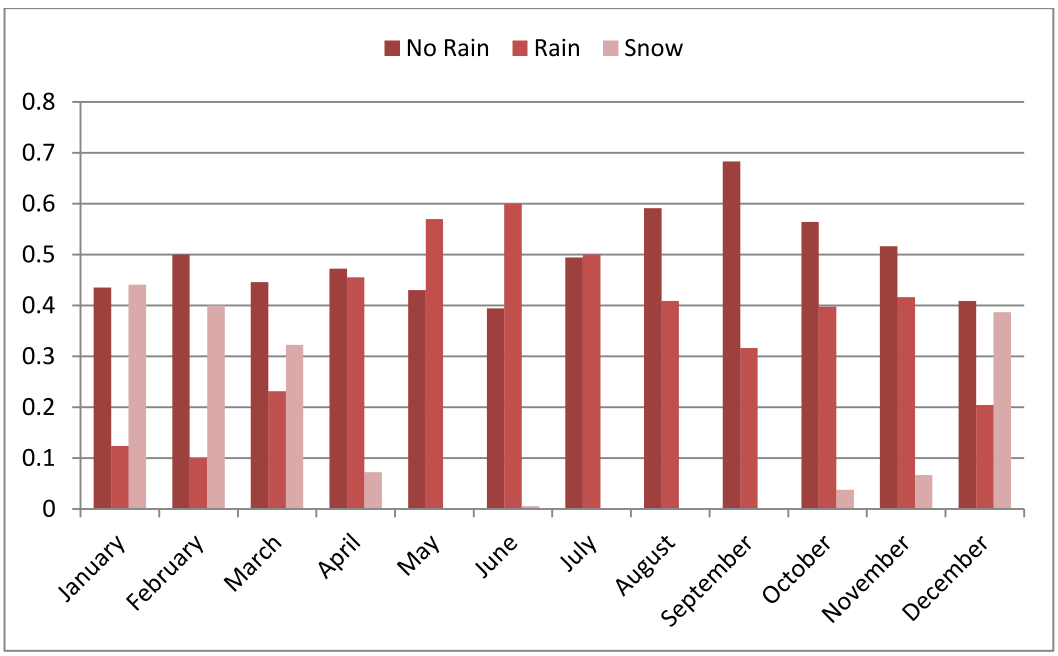


Figure 8 Worcester Percent of Days of Weather Type per Month

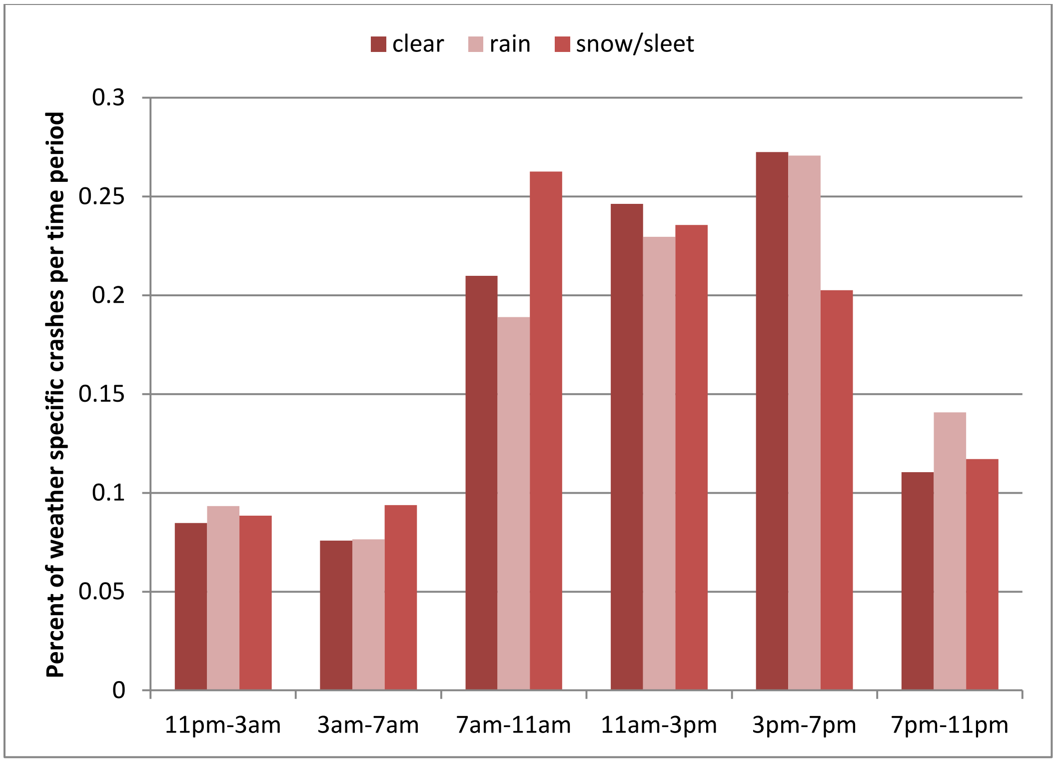


Figure 9 Percent of Weather Specific Crashes per Time Period

Figure 10 presents the breakdown of crashes and weather by day of week. The highest percent of crashes for all weather type categories occurs on Friday. The percent of clear weather crashes is evenly distributed across the rest of the work week, varying between 14-16% percent of clear day crashes for each weekday. Saturday and Sunday have the lowest percent of clear weather crashes. Rainy weather crashes are not as evenly distributed, with Sunday and Monday having the lowest percent of rainy day crashes, and the remaining days varying between 12-18%. Snowy days have the highest percent crashes on Sunday, Monday, Wednesday, and Friday (15-18%), and the fewest crashes on Tuesday, Thursday and Saturday (11-13%). An interesting feature in Figure 10 is the high percent of crashes on Sunday and Monday followed by a visually significant smaller percent of crashes on Tuesday, despite that Tuesday and Monday would have similar traffic volume patterns across the State. As previously stated, without normalization of the weather conditions some of the analysis is mute. Figure 11 shows the percent of daily weather (no rain or clear, rain and snow) per day of the week for the Worcester Regional Airport weather station. Figure 11 shows that for each day of the week the clear days in Worcester, where there was no precipitation, are about half with Mondays tending to be clearer than not and Saturdays having the highest percentage of rainy days.

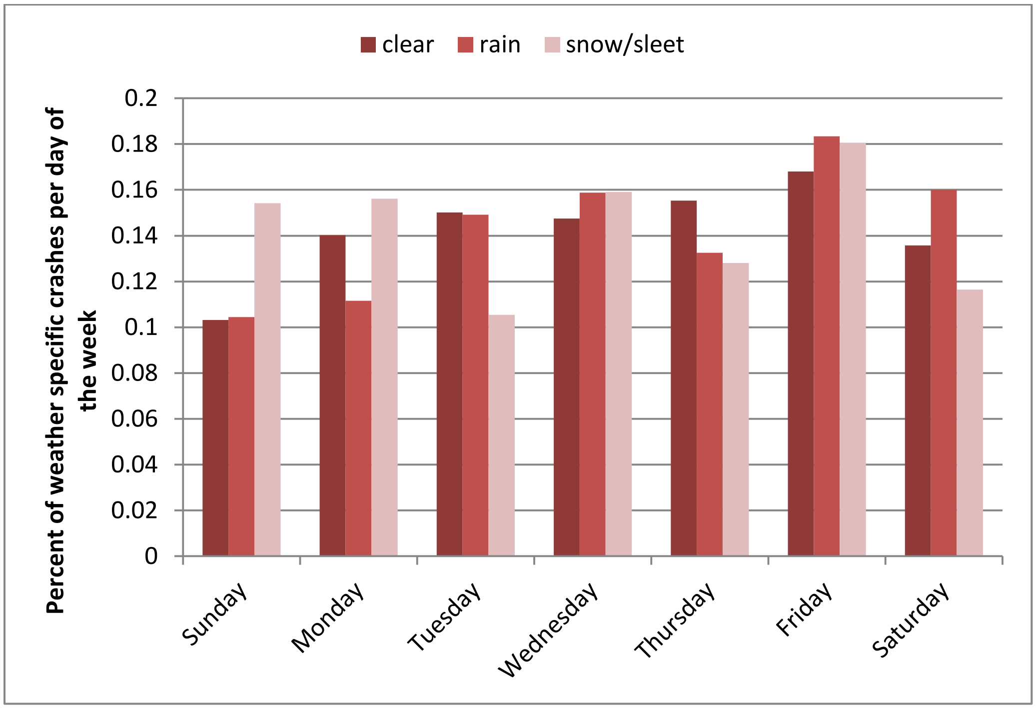


Figure 10 Percent of Weather Specific Crashes per Day of the Week

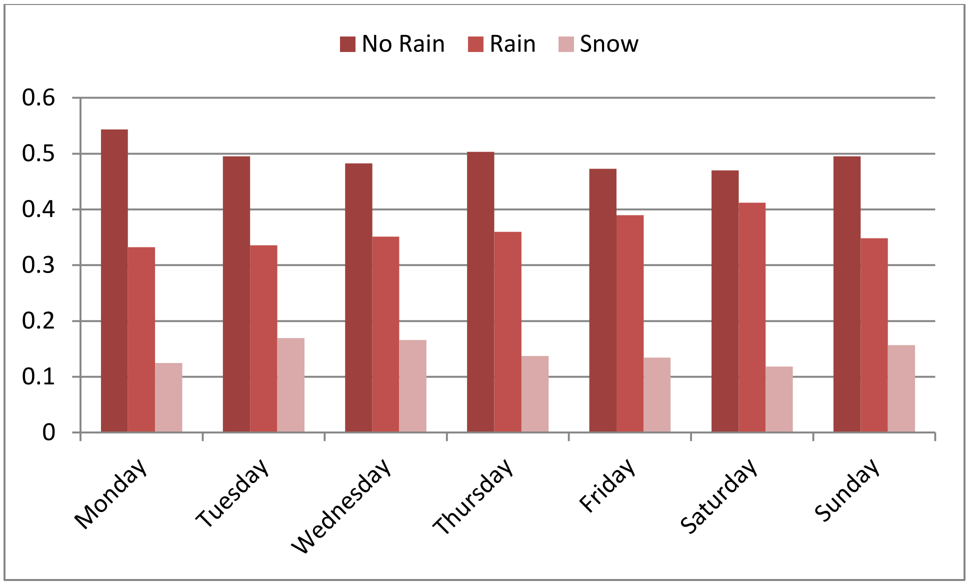


Figure 11 Worcester Percent of Days of Weather Type per Day of the Week

Some of the data analysis was better displayed in tabular form. Even though five to ten times more crashes happened in clear weather conditions than rainy or snowy/ sleety weather conditions, the breakdown of crashes happening in differing *ambient light conditions* were very similar with approximately two-thirds occurring during the daylight and a third occurring in the dark see Table 4. Dark consists of three *ambient light* categories from the crash report form: dark with a lighted roadway, dark with a not lighted roadway and dark with an unknown lighted roadway. Higher percentages of rain and snow/sleet crashes occurred in dark ambient lighting situations, approximately a third, whereas only about 24 percent of the clear weather crashes occurred in dark ambient lighting. There are also a higher percentage of clear crashes that occur during daylight (72.56%) than percentages of rain or snow/ sleet crashes that occur during daylight (approximately 60 percent for each).

Table 4 Percent and Frequency of Weather Specific Crashes per Ambient Light

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
Daylight	389984	72.56%	67248	60.45%	31131	59.77%
Dawn	5995	1.12%	2247	2.02%	1427	2.74%
Dusk	14246	2.65%	4827	4.34%	1752	3.36%
Dark	127205	23.67%	36923	33.19%	17772	34.12%
Total	537430	100.00%	111245	100.00%	52082	100.00%

In Table 5, the largest difference was between snow related crashes and clear crashes with single vehicle crashes occurring over twice as frequently during snow/ sleet then during clear weather conditions. The difference between the clear and rain related crashes were negligible in terms of manner of collision. In Table 6, the percent and frequency of weather specific crashes per *junction type* is shown. Crashes occurred most not at a junction for each weather type with the difference between the three weather types being high due to the high number of crashes. The highest percentage of crashes not at a junction per weather type is snow/ sleet, this could have a correlation with the higher number of single vehicle crashes in the snow/ sleet weather type. Table 7 discusses the weather specific crashes per *roadway surface conditions* with the dry roadway conditions during rain and snow/sleet crashes being the most interesting occurrences.

Table 5 Percent and Frequency of Weather Specific Crashes per Manner of Collision

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
Single Vehicle	94086	18.41%	24923	23.15%	21483	42.55%
Rear-end	174124	34.07%	34595	32.14%	9539	18.89%
Angle	155683	30.46%	33918	31.51%	11999	23.77%
Sideswipe	69854	13.67%	10568	9.82%	4937	9.78%
Other	17342	3.39%	3634	3.38%	2530	5.01%
Total	511089	100.00%	107638	100.00%	50488	100.00%

Table 6 Percent and Frequency of Weather Specific Crashes per Junction Type

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
Not at junction	264898	51.16%	53541	49.32%	33317	65.51%
4-way intersection	95918	18.52%	21291	19.61%	5315	10.45%
3-way intersection	110496	21.34%	24775	22.82%	9862	19.39%
Ramp	21257	4.10%	4401	4.05%	1000	1.97%
Other	25264	4.88%	4550	4.19%	1365	2.68%
Total	517833	100.00%	108558	100.00%	50859	100.00%

Table 7 Percent and Frequency of Weather Specific Crashes per Roadway Surface Condition

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
Dry	488637	91.52%	2635	2.36%	657	1.26%
Wet	22626	4.24%	104127	93.40%	6956	13.29%
Snow	7589	1.42%	1441	1.29%	36868	70.45%
Ice	9526	1.78%	1497	1.34%	5941	11.35%
Sand, mud, gravel	3738	0.70%	194	0.17%	52	0.10%
Water (standing, moving)	276	0.05%	893	0.80%	26	0.05%
Slush	1539	0.29%	701	0.63%	1831	3.50%
Total	533931	100.00%	111488	100.00%	52331	100.00%

Table 8 shows that for each control device there is similarity across the weather specific crash types. Table 9 shows that the approximately two-thirds of the crashes occurred on 2-way, not divided roadways for all three weather types. Table 10 and Table 11 show the percent and frequency of weather specific crashes per first harmful event and first harmful event location. The first harmful events have been condensed down from the crash report form list to collision with a fixed object including tree, telephone pole, and bridge among others; collision with another vehicle (vehicle in traffic, pedacycle, moped, etc.); collision with ditch or embankment and other, which includes collision with a pedestrian, rollover and jackknife along with other collisions. During clear weather collision with another vehicle was the highest at 81.25% much higher than the other weather codes especially snow/ sleet (57.71%). During snow/ sleet weather conditions collisions with fixed objects were the highest (34.53%) and collision with ditch or embankment was higher than percentages under rainy or clear conditions. Table 11 echoes these higher values with off-roadway collisions in snow/ sleet conditions with a larger percentage of roadside first harmful event locations and a smaller percentage of roadway first harmful event locations then clear or rain weather types. The severity of crashes under differing weather variables rings true to the previous studies (22, 23, 25) and is discussed in greater detail in the following text, see Table 12.

Table 8 Percent and Frequency of Weather Specific Crashes per Traffic Control Device

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
No control	339841	65.00%	69820	64.06%	40316	79.21%
Stop signs	67720	12.95%	14405	13.22%	4722	9.28%
Traffic signal	91755	17.55%	20280	18.61%	4659	9.15%
Flashing traffic signal	5331	1.02%	1318	1.21%	438	0.86%
Yield signs	13488	2.58%	2138	1.96%	414	0.81%
School zone signs	834	0.16%	158	0.14%	57	0.11%
Warning signs	3507	0.67%	806	0.74%	255	0.50%
Railway crossing device	358	0.07%	74	0.07%	37	0.07%
Total	522834	100.00%	108999	100.00%	50898	100.00%

Table 9 Percent and Frequency of Weather Specific Crashes per Traffic-way Description

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
2-way, not divided	315390	62.62%	66004	62.07%	34694	69.21%
2-way, divided	78130	15.51%	17065	16.05%	6712	13.39%
2-way , divided, median barrier	69207	13.74%	15834	14.89%	6400	12.77%
One-way, not divided	40921	8.12%	7443	7.00%	2325	4.64%
Total	503649	100.00%	106347	100.00%	50132	100.00%

Table 10 Percent and Frequency of Weather Specific Crashes per First Harmful Event

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
Collision with Fixed Object	51595	12.45%	15504	17.03%	14245	34.53%
Collision with Other Vehicle	336658	81.25%	70224	77.11%	23806	57.71%
Collision with ditch or embankment	4447	1.07%	1336	1.47%	1525	3.70%
Other	21639	5.22%	4001	4.39%	1677	4.07%
Total	414339	100.00%	91065	100.00%	41253	100.00%

Table 11 Percent and Frequency of Weather Specific Crashes per First Harmful Event Location

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
Roadway	352574	85.16%	75415	82.75%	28320	66.89%
Median	5010	1.21%	1683	1.85%	978	2.31%
Roadside	24097	5.82%	6202	6.80%	5919	13.98%
Shoulder - paved	3375	0.82%	775	0.85%	725	1.71%
Shoulder - unpaved	5649	1.36%	1565	1.72%	1409	3.33%
Shoulder - travel lane	558	0.13%	134	0.15%	105	0.25%
Outside roadway	22764	5.50%	5367	5.89%	4885	11.54%
Total	414027	100.00%	91141	100.00%	42341	100.00%

Table 12 Percent and Frequency of Weather Specific Crashes per Crash Severity

	clear		rain		snow/ sleet	
	(frequency)	(percent)	(frequency)	(percent)	(frequency)	(percent)
PDO	328729	69.07%	70541	69.95%	36445	78.10%
Injury	145730	30.62%	30051	29.80%	10167	21.79%
Fatal	1501	0.32%	252	0.25%	50	0.11%
Total	475960	100.00%	100844	100.00%	46662	100.00%

4.2 Additional crash severity data analysis

Many state highway safety plans are focused on severe/fatal crashes so there is impetus for this type of decision. *Crash severity* was one of the factors singularly examined. 70.0% of all 2004-2009 crashes in MA resulted in property damage only. 29.7% of all 2004-2009 crashes in MA resulted in injuries. Only 0.3% of all 2004-2009 crashes in MA resulted in fatalities. When looking at the additional analysis the initial analysis needs to be taken into consideration. Although fatal crashes are usually taken into more consideration in severity models because of the resulting economic loss associated with these crashes (26), there are a very small percentage of total crashes that result in a fatality. These percentages are calculated from crashes that could be identified in both the weather fields and the crash severity field. Crashes that did not have recorded weather data also did not have recorded crash severity as well as a majority of the crash report fields. There were a number of entries that had unknown, not reported, reported but invalid or other filled in for the weather entries on the crash form. There were also some crashes that had unknown crash severity information. The final number of crashes with adequate weather field information was 719,696 or approximately 85% of the total crashes reported with the crash report form between 2004 and 2009. Due to discrepancies with information in the crash severity portion of the crash report form there were only 635,728 of 842,168 total crashes from 2004 to 2009, 75%, used for this portion of the study. Some of the discrepancies were that the field did not have adequate information or the crash severity was not reported at the time of the crash due to the reporting officer not knowing at the point of record. To avoid this problem in the future, linked information from the personal level of information from the crash data warehouse could be used in place of overall crash severity. The crash severity information is at a crash level so if one fatality occurs in a crash the crash is counted as fatal, but sometimes this is not known at the time of the crash so some incapacitating injuries and fatalities are not accounted for. Crash severity is broken down into fatal crashes, injury resulting crashes, and property damage only (PDO) crashes.

Figure 12 and Table 13, show the breakdown of the Massachusetts crash data from 2004 to 2009 according to weather parameters and crash severity. As can be seen in the figure there are considerably more PDO crashes for each weather parameter and considerably lower fatal crashes in each weather parameter. The figure also displays that there is considerably more crashes that occur during clear weather, which correlates to the basic percentages without the weather and crash severity association.

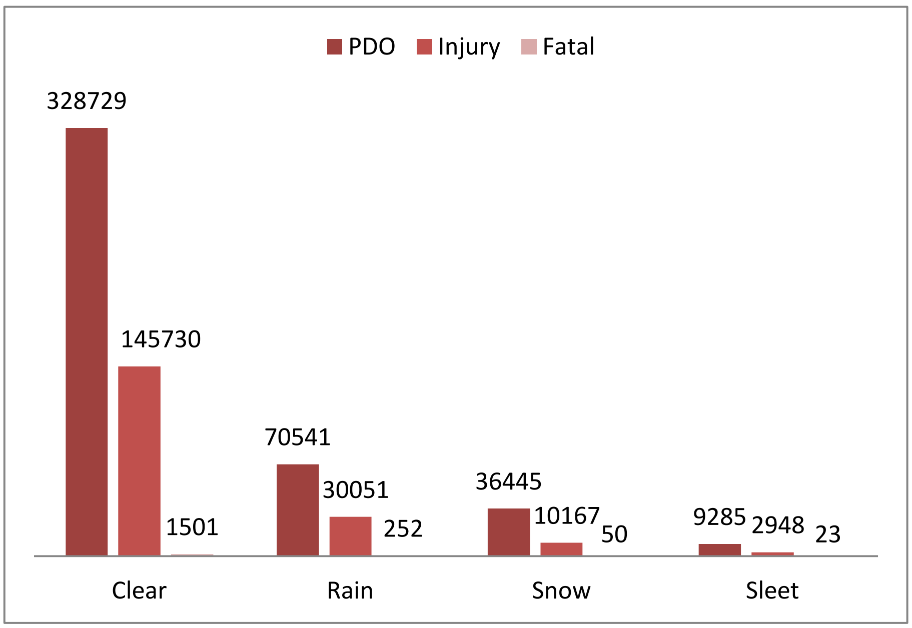


Figure 12 2004-2009 MA Crashes broken down by Weather and Crash Severity

Table 13 shows the same information as Figure 12, but expands on the information a little bit to show the percentages of each weather parameter for each crash severity and the percentages for each crash severity for each weather parameter. For example, the first column under clear is the number of crashes that occurred during clear weather for each crash severity, the next column is the percentage of the crash severity that occurred during clear weather (82.2 % of fatal crashes occurring in MA between 2004 and 2009 occurred during clear weather) and the third column is the percentage of clear weather crashes that resulted in each of the crash severities (69.1% of crashes occurring during clear weather in MA between 2004 and 2009 resulted in property damage only crashes).

Table 13 Breakdown of 2004-2009 MA Crashes

	Clear			Rain			Snow			Sleet			**Total**	
		%	%		%	%		%	%		%	%		%
PDO	328729	73.9	69.1	70541	15.9	70.0	36445	8.2	78.1	9285	2.1	75.8	**445000**	70.0
Injury	145730	77.1	30.6	30051	15.9	29.8	10167	5.4	21.8	2948	1.6	24.1	**188896**	29.7
Fatal	1501	82.2	0.3	252	13.8	0.2	50	2.7	0.1	23	1.3	0.2	**1826**	0.3
Total	**475960**			**100844**			**46662**			**12256**			**635728**	
	74.9%			15.9%			7.3%			1.9%				

The majority of all level of severity crashes occurred during clear weather which makes sense since there are a larger percentage of clear weather days. There is a larger percentage of fatal crashes that occur during clear weather (82.2%) then the portion of clear crashes to total crashes (74.9%). This is because there is a considerably lower rate of snow (2.7% to total snow rate of 7.3%) and lower rates of rain (13.8% to total rain rate of 15.9%) and sleet (1.3% to total sleet rate of 1.9%).

The next level of analysis was using the previous found relationships between weather parameters and crash severity and adding additional factors. Additional factors were looked at to hopefully bring to light the relationship between certain factor sets and crash severity, similar to what was found in Abdel-Aty's study (24) and many of the other studies. This is due to the inverse relationship that is found with preliminary analysis between weather parameters and crash severity, clear weather is more dangerous because more crashes occur during clear weather.

The four main categories that were analyzed with the weather parameter, crash severity data were *traffic description*, *traffic control device type*, *roadway junction type* and *manner of collision*. *Traffic description* categorizes the travelled way and roadway lane configuration including, 2-way traffic that is not divided, meaning it has not division between the differing directions of traffic, including a median or barrier, two-way traffic that is divided by a median or large area between travelled ways such as on some interstates, two-way with traffic divided by a median barrier, and one-way traffic where there lanes are not divided. *Traffic control device type* refers to mostly intersections where there would be a traffic control device, but also where there are no intersections. One category of traffic control device is no control that can be at intersections or at open stretches of roadway. The other categories of traffic control device are stop signs, traffic signals, flashing traffic signals, yield signs, school zone signs, warning signs and railroad crossing device. *Roadway junction type* is categorized as not a junction, for open roadway not located at a specific junction, 4-way intersections, T-intersections, Y-intersections, on and off ramps, traffic circles, five-point or more intersections, driveways and railway grade crossings. *Manner of collision* categorizes the data into single vehicle crashes, rear-end crashes, angle crashes, sideswipe crashes in the same direction, sideswipe crashes in the opposite direction, head-on crashes, and rear-to-rear crashes.

Figure 13 and Figure 14 refer to the next level of analysis where crashes per a specific weather parameter and specific crash severity were analyzed by the *traffic description*. Figure 13 shows the total magnitudes of crashes so the crash numbers are comparable across crash severity and weather condition type. Meaning that there are a lot more PDO crashes that occur on 2-way not divided roads for three weather scenarios, rain, clear and snow. There are also slightly more injury crashes that occur on 2-way undivided roads for rain and clear weather conditions then on the other traffic ways. Figure 14 shows the percent within a category of type of crash. This means that the percentages cannot be compared across the board, but can be used only to see which traffic description factor was most significant within that particular crash severity, weather parameter sector. This shows that in general 2-way not divided has the highest percentage of crashes for each crash severity, weather parameter combination except for injury, rain crashes where 2-way traffic divided with a median has the highest percentage with the combination. This also shows that in many combinations except the injury, rain combination, 2-way divided and 2-way divided with a median barrier have very similar percentages.

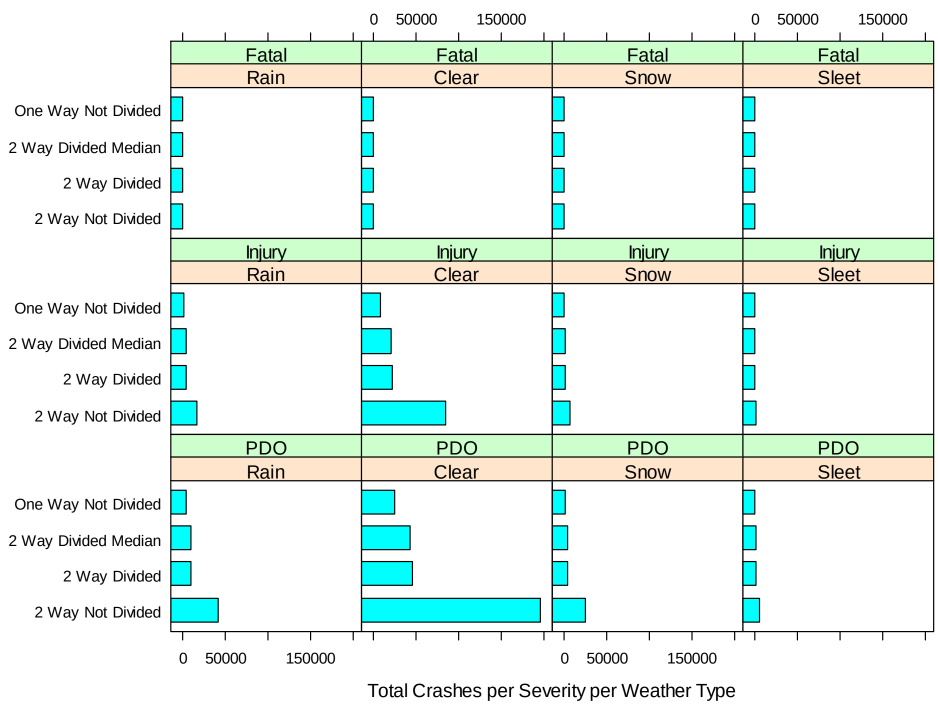


Figure 13 2004-2009 MA crashes by traffic description, weather parameter and crash severity

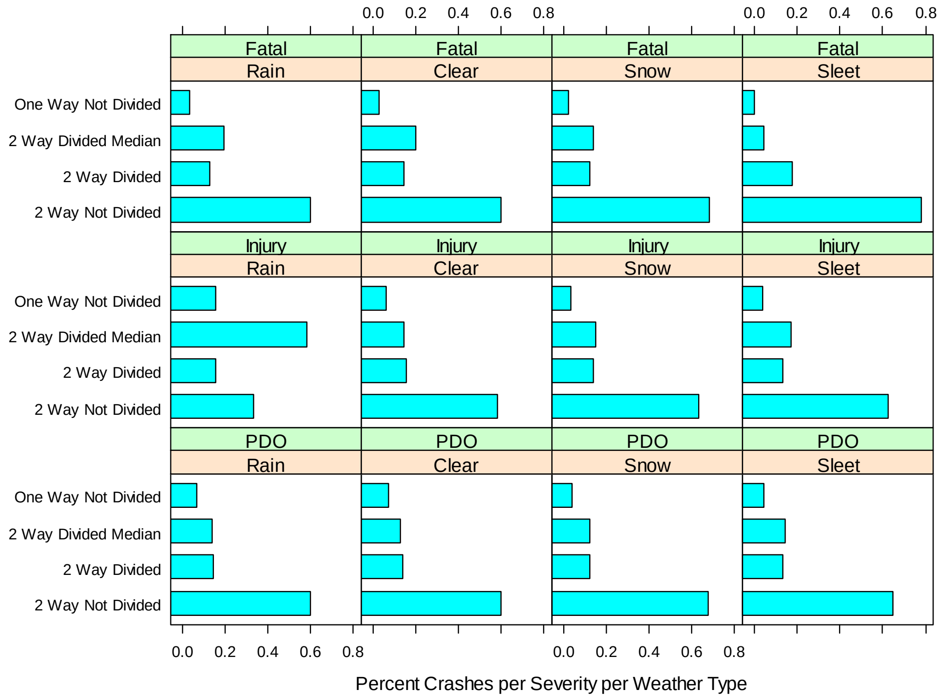


Figure 14 2004-2009 MA traffic description percent crashes per severity per weather parameter

Figure 15 and Figure 16 also refer to the next level of analysis where crashes per a specific weather parameter and specific crash severity were analyzed by the traffic control device. Figure 15 shows the total magnitudes of crashes per traffic control device so the crash numbers are comparable across crash severity and weather condition type. Meaning that there are a lot more crashes across the board (crash severity and weather parameter combinations) that occur at no-control areas. In general the next traffic control device for injury and PDO for rain and clear weather parameters seems to be traffic signal and then stop signs. Figure 16 shows the percent within a category of type of crash. This means that the percentages cannot be compared across the board, but can be used only to see which traffic control device factor was most significant within that particular crash severity, weather parameter sector. This shows in general the same information as the crash magnitudes does, but better exemplifies the snow and sleet percentages since their total crash numbers are significantly smaller.

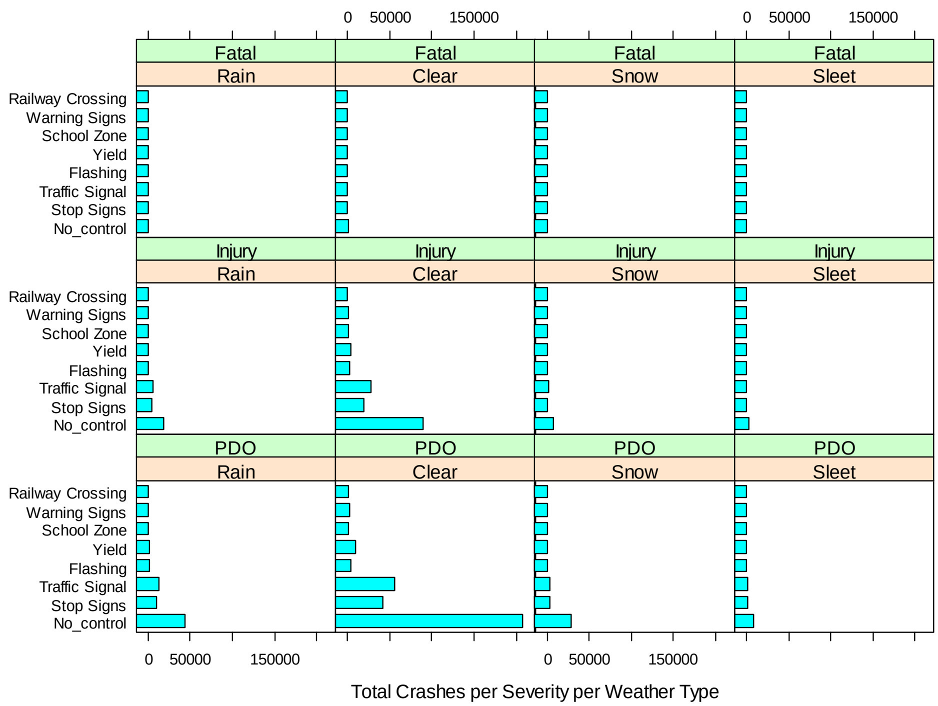


Figure 15 2004-2009 MA crashes by traffic control device, weather parameter and crash severity

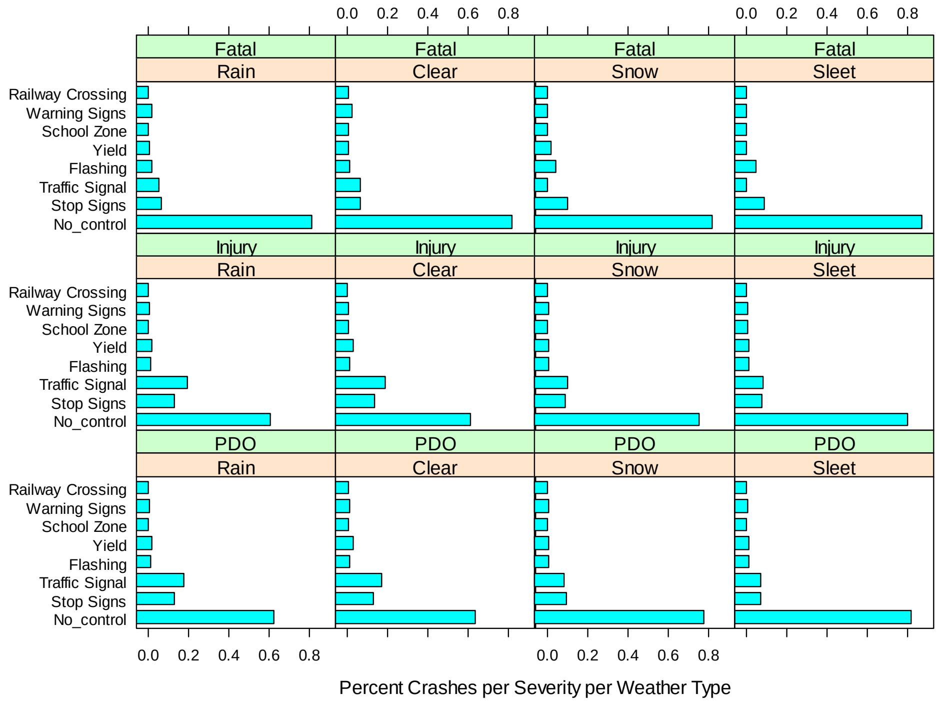


Figure 16 2004-2009 MA traffic control device percent crashes per severity per weather parameter

Figure 17 and Figure 18 also refer to the next level of analysis where crashes per a specific weather parameter and specific crash severity were analyzed by the roadway junction type. Figure 17 shows the total magnitudes of crashes per roadway junction type so the crash numbers are comparable across crash severity and weather condition type. Meaning that there are a lot more crashes across the board (crash severity and weather parameter combinations) that occur not at a junction. In general the next traffic control device for injury and PDO for rain and clear weather parameters and the snow, injury combination seems to be 4-way intersections and then T-intersections. Figure 18 shows the percent within a category of type of crash. This means that the percentages cannot be compared across the board, but can be used only to see which roadway junction type was most significant within that particular crash severity, weather parameter sector. This shows in general the same information as the crash magnitudes does, but better exemplifies the snow and sleet percentages since their total crash numbers are significantly smaller. This also shows some interesting peculiarities such as a slightly elevated percentage of crashes at driveways across the boards and for snow fatalities a slightly elevated percentage at traffic circles.

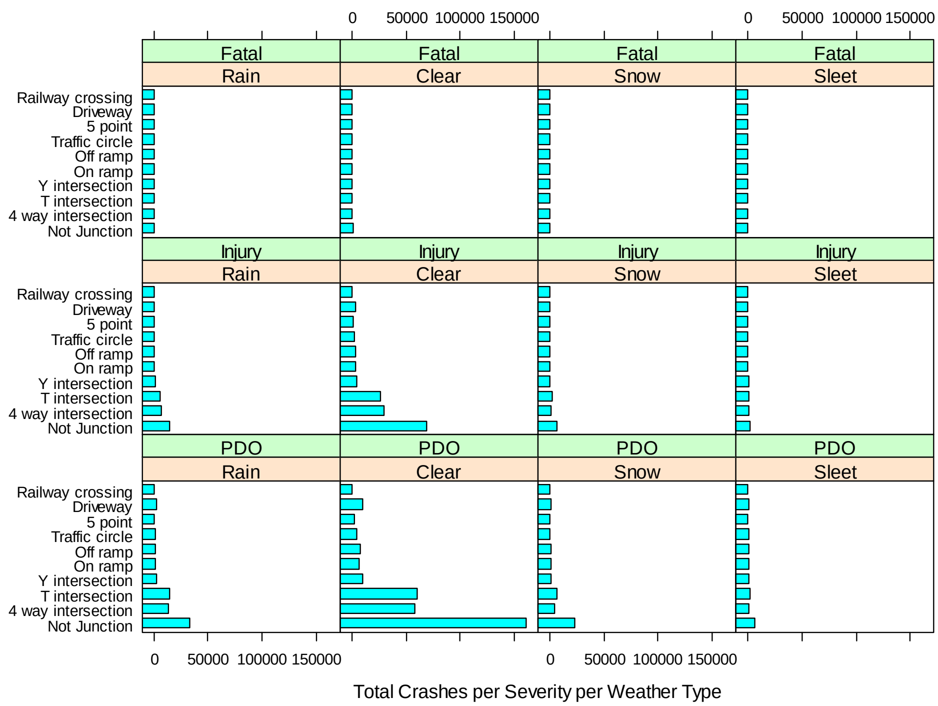


Figure 17 2004-2009 MA crashes by roadway junction type, weather parameter and crash severity

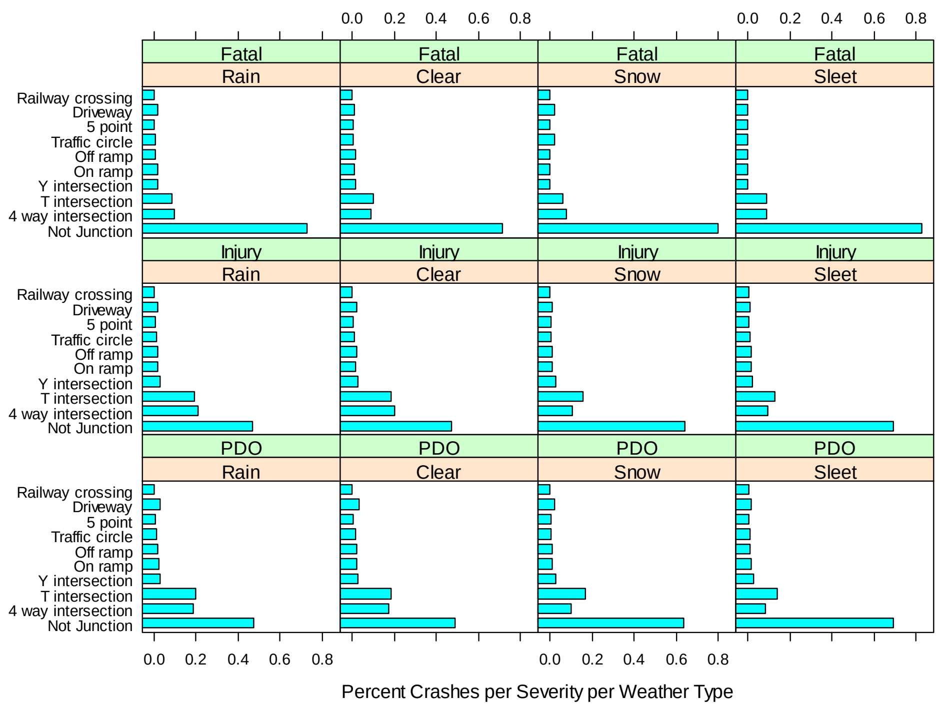


Figure 18 2004-2009 MA roadway junction type percent crashes per severity per weather parameter

Figure 19 and Figure 20 also refer to the next level of analysis where crashes per a specific weather parameter and specific crash severity were analyzed by manner of collision or crash vehicle configuration. Manner of collision tends to be associated in the literature as one parameter that is in general association with weather and crash severity. Figure 19 shows the total magnitudes of crashes per manner of collision so the crash numbers are comparable across crash severity and weather condition type. In general for rain and clear conditions and PDO and injury severity crashes, angle and rear-end crashes are the most common. Figure 20 shows the percent within a category of type of crash. This means that the percentages cannot be compared across the board, but can be used only to see which manner of collision was most significant within that particular crash severity, weather parameter sector. Of the previously analyzed additional parameters, manner of collision sheds the most light on specific relationships. Across the weather parameters for fatal crashes, the highest percentage of crashes were single vehicle with head-on and angle close behind. This is consistent with previous research about run-off the road and fatal single vehicle crashes. For sleet and snow, single vehicle crashes and then angle crashes produce the highest percentage of injury crashes and PDO crashes. Whereas for rain and clear, the percentages echo the overall crash numbers for injury and PDO crashes with the highest percentages in angle and rear-end with single vehicle and sideswipes in the same direction close behind.

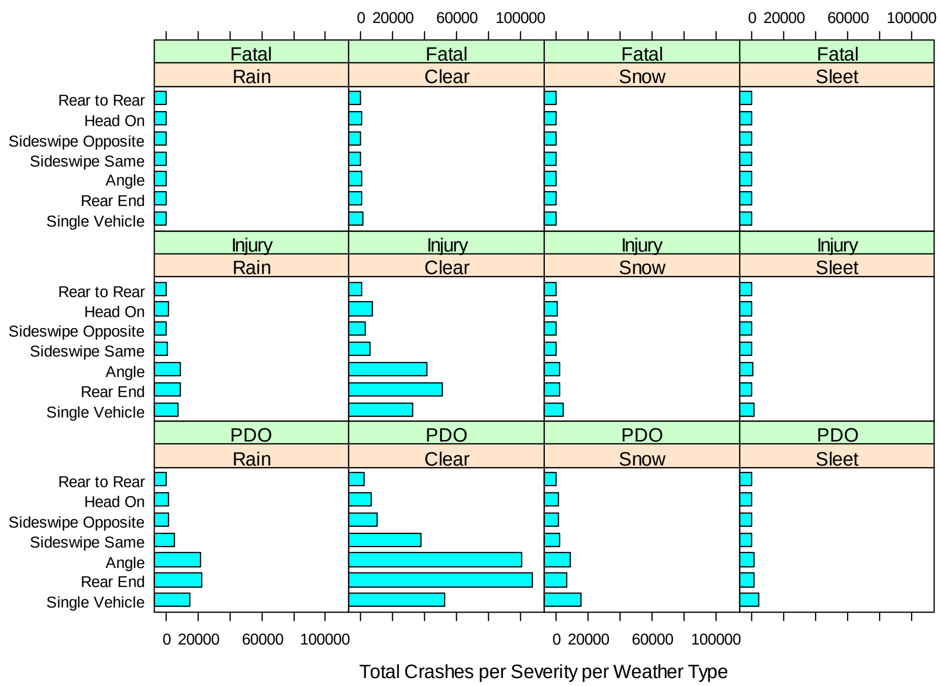


Figure 19 2004-2009 MA crashes by manner of collision, weather parameter and crash severity

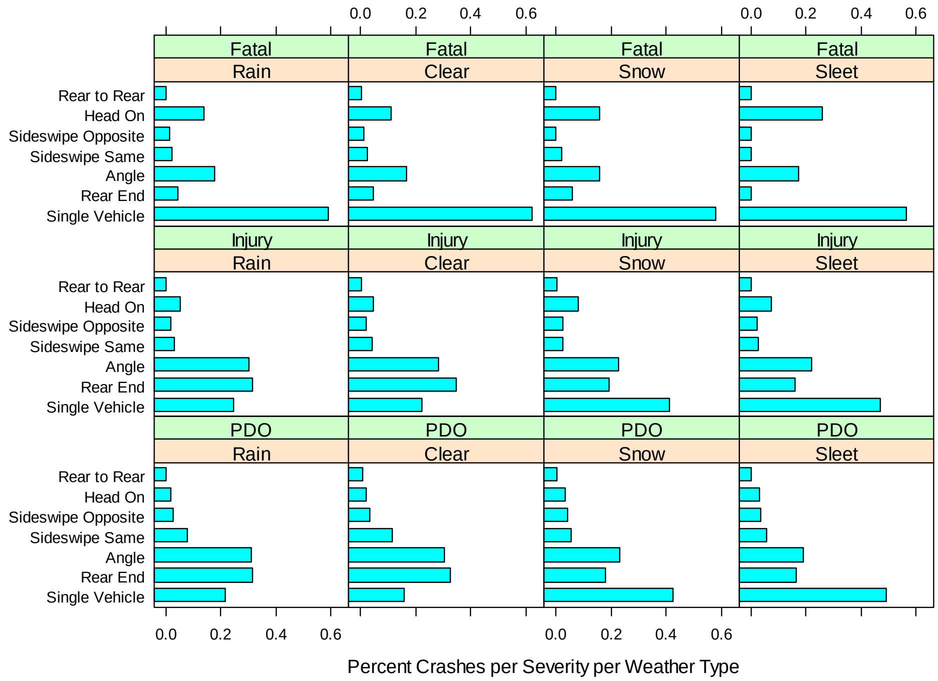


Figure 20 2004-2009 MA manner of collision percent crashes per severity per weather parameter

There were some factors that were discussed in previous research that were not included in this study. Roadway lighting was not included in the study because an overwhelming majority of the crashes occurred during daylight or on a lit roadway, between 92% of clear crashes and 77% of crashes that occurred during sleet occurred with adequate ambient light. Roadway surface condition was not taken as a substitute for weather conditions since the weather conditions were displayed, but a correlation between roadway surface condition and weather parameter was found in initial analysis. Driver contributing code, including speeding, drunk driving and other elements that the driver may have added to cause the crash are not included because they were not included in the initial data query. These would be interesting to investigate especially speed or driver contributing codes coupled with roadway junction type or manner of collision, weather parameter and severity.

CHAPTER 5

RESULTS OF DATA QUALITY ASSESMENT

The hope of the data quality assessment was to increase the comprehension of the affect weather has on traffic safety, but also to point out some areas that may need to be simplified or improved on the crash report form to help lessen enforcement recording errors. The data quality assessment was conducted in two parts the first was to check the accuracy of the weather-related fields on the crash form by the comparison and correlation of the weather-related field with captured NCDC weather data. The second was to gather information from the crash narrative from a sample of crash forms to determine the true impact of weather on the crash, if the crash simply took place during adverse weather or the crash was related to the adverse weather.

5.1 Weather data, crash report form weather field comparison

There were a few factors that were questioned in the Worcester data assessment portion of the study. The first was if both of the weather factor columns from the crash report form were necessary in the weather comparisons with the NCDC weather data. The second being if the daily weather data from the NCDC station was too broad for precipitation analysis. Figure 21 shows the crash report form weather factors from column one only as the columns bunched by the weather conditions from the NCDC weather station. This figure supports the initial analysis that both weather columns need to be included especially for the rain and snow/ sleet analysis.

The continued assessment included both the weather factor columns combined so that if there was any rain in either column it is displayed as rain unless there is snow in the other column then it is shown as rain or snow due to the warmed precipitation bucket at the site location. This combination is why there numbers in the

Table 14 rain or snow column that are greater than the sum of the rain column and snow column because they are instances of one crash report weather factor being rain and the other snow. The difference in the actual NCDC weather and the crash report recorded weather differs more the larger the radius away from the weather station. The “All” rows display all the crashes within the given radii and the “Clear” rows display crashes that occurred on days which had no precipitation at all.

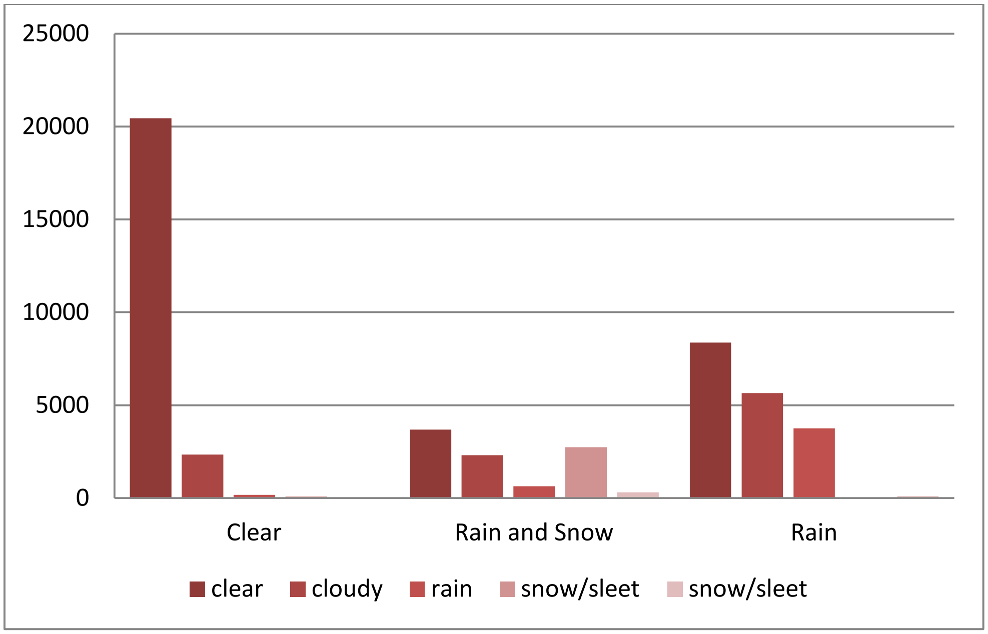


Figure 21 Worcester 12.5 Mile Radius Crash Form Weather Column One Only Versus NCDC Data

Table 14 2004-2009 Worcester Daily Weather Data versus Crash Report Form Weather Data

0.5 miles		Crash Form Columns 1 & 2		
		rain	snow	rain or snow
NCDC	All	2	4	6
	Clear	0	0	0
	Rain and Snow	0	4	4
	Rain	2	0	2

5 miles		Crash Form Columns 1 & 2		
		rain	snow	rain or snow
NCDC	All	4112	1923	5880
	Clear	187	85	269
	Rain and Snow	536	1721	2145
	Rain	3389	117	3466

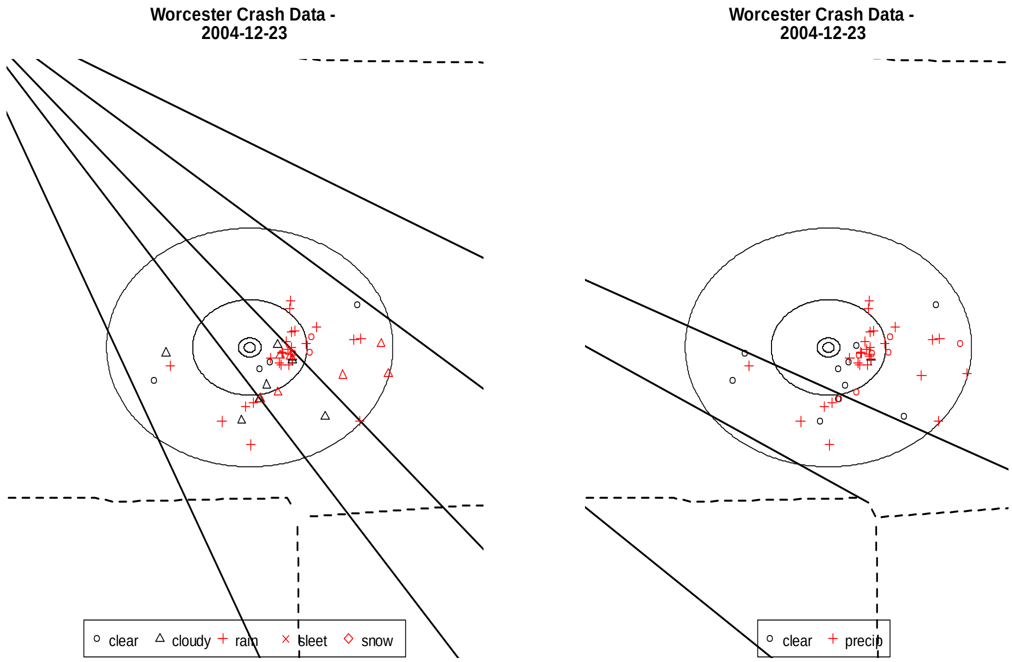
1 mile		Crash Form Columns 1 & 2		
		rain	snow	rain or snow
NCDC	All	49	31	78
	Clear	1	3	4
	Rain and Snow	8	28	34
	Rain	40	0	40

12.5 miles		Crash Form Columns 1 & 2		
		rain	snow	rain or snow
NCDC	All	7131	4170	11025
	Clear	306	160	462
	Rain and Snow	938	3798	4522
	Rain	5887	212	6041

Next, hourly weather data were compared against the time of crash. This was performed by locating the hour in by locating the hour in which the crash occurred and examining the hourly meteorological record from the Worcester from the Worcester Airport station. For example, if a crash occurred between 12 AM and 1 AM, it was compared against it was compared against the hour one record of the meteorological station.

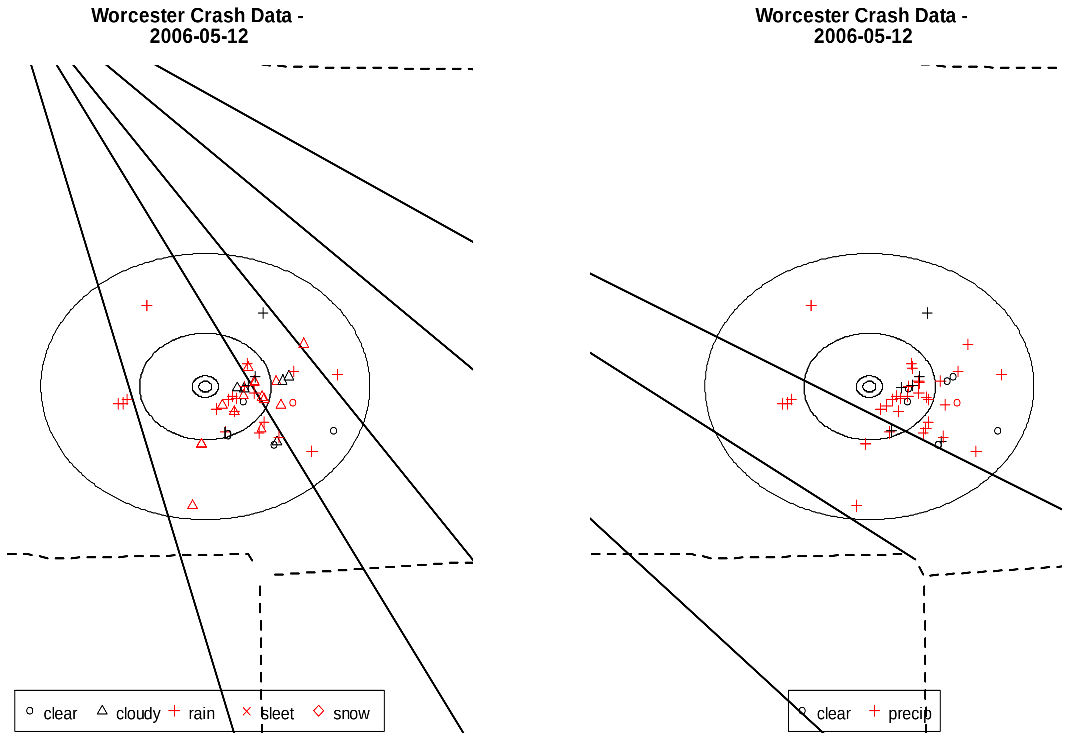
Figure 22 through

Figure 25 present crashes over the course of a day compared against hourly meteorological records and were created as a preliminary check to determine if the data was logical and whether hourly data and both columns weather fields could be utilized. If the symbol is grey there was some form of precipitation during the hour of the crash. The pane on the left plot the weather type recorded in column one of the crash report form, meaning that the indicator from column one of the crash report form is shown grey or black whether or not it was precipitating during the hour the crash occurred. The pane on the right plots crashes that had precipitation indicators recorded in either column one or column two of the crash report form. Based upon this preliminary analysis the hourly weather data tend to match the weather indicator recorded in the crash report more often than using the bulk daily weather numbers. This is evidenced by all the figures in that there are clear crashes that remain clear on an hourly basis, whereas in a daily analysis, any clear crash would be recorded as rain.



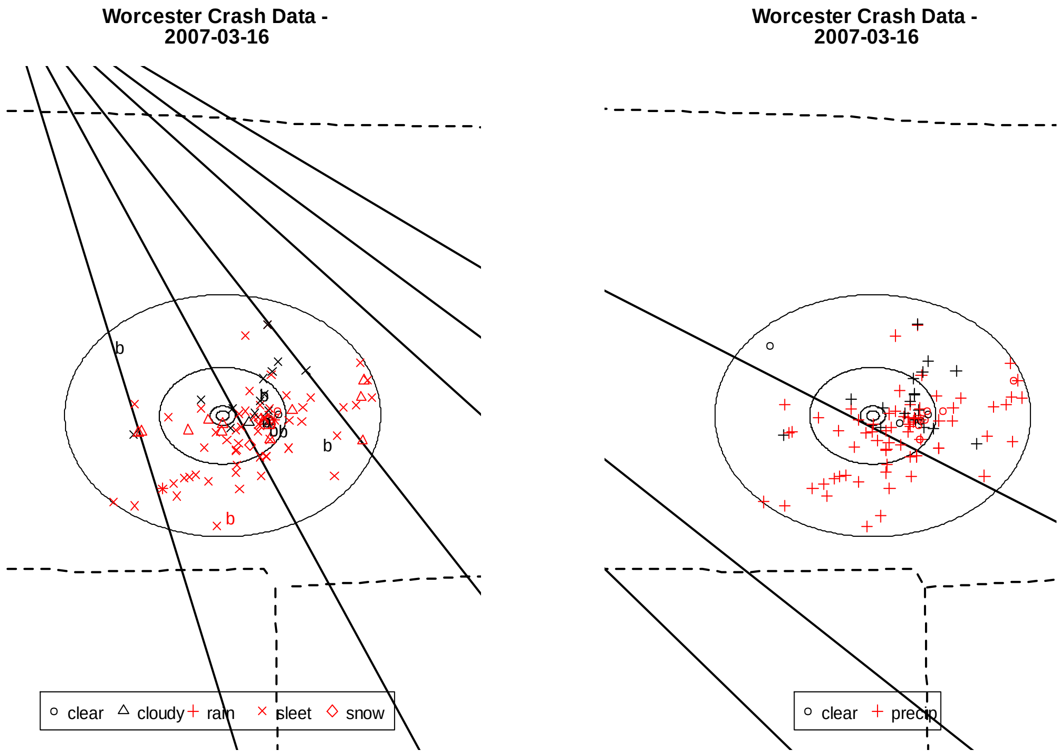
The left pane plots the weather type recorded in column one of the crash report form, meaning that the indicator from column one of the crash report form is shown grey or black whether or not it was precipitating during the hour the crash occurred. The right pane plots the crashes that had precipitation indicators recorded in either column one or column two of the crash report form and if the symbol is grey there was some precipitation.

Figure 22 12/23/2004 Hourly Worcester Crash Weather Data



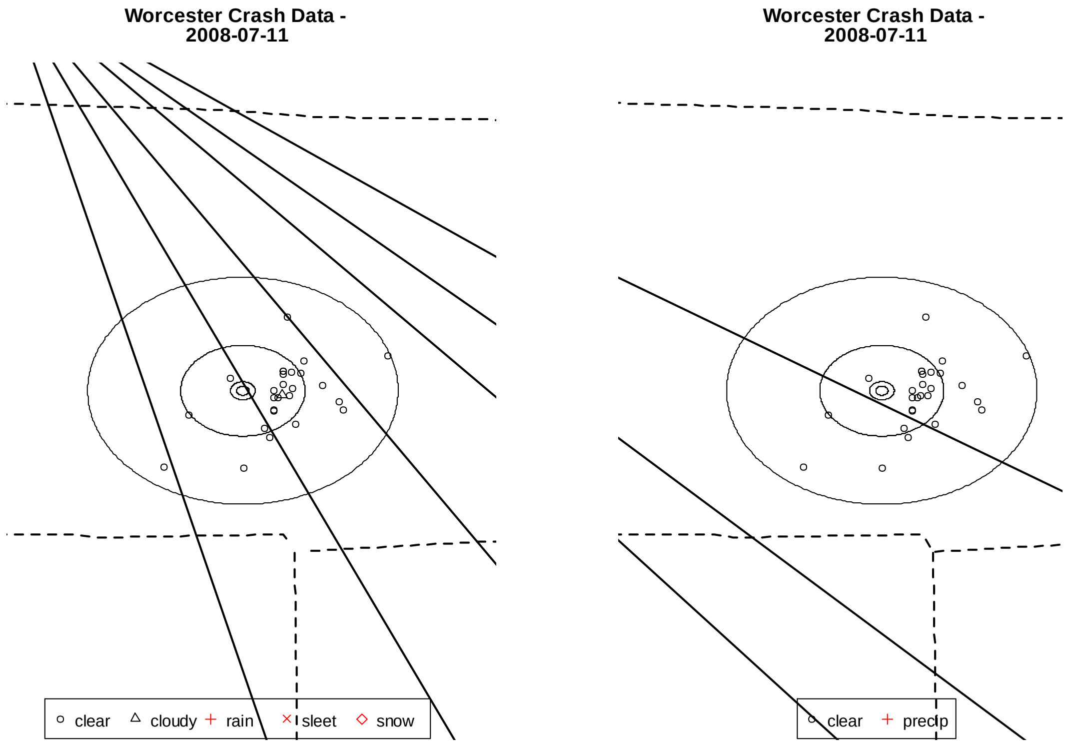
The left pane plots the weather type recorded in column one of the crash report form, meaning that the indicator from column one of the crash report form is shown grey or black whether or not it was precipitating during the hour the crash occurred. The right pane plots the crashes that had precipitation indicators recorded in either column one or column two of the crash report form and if the symbol is grey there was some precipitation.

Figure 23: 5/12/2006 Hourly Worcester Crash Weather Data



The left pane plots the weather type recorded in column one of the crash report form, meaning that the indicator from column one of the crash report form is shown grey or black whether or not it was precipitating during the hour the crash occurred. The right pane plots the crashes that had precipitation indicators recorded in either column one or column two of the crash report form and if the symbol is grey there was some precipitation.

Figure 24: 3/16/2007 Hourly Worcester Crash Weather Data



The left pane plots the weather type recorded in column one of the crash report form, meaning that the indicator from column one of the crash report form is shown grey or black whether or not it was precipitating during the hour the crash occurred. The right pane plots the crashes that had precipitation indicators recorded in either column one or column two of the crash report form and if the symbol is grey there was some precipitation.

Figure 25: 7/11/2008 Hourly Worcester Crash Weather Data

Table 15 and

Table 16 display the weather breakdowns for the daily and hourly NCDC weather data in matching with the combination column one and column two weather fields of the crash report form. If there was any precipitation at all, the day or hour was marked as not being clear. The categories are indicated by precipitation or no precipitation according to met gauge (NCDC weather data) by crash report form weather field. So within the 1 mile radius ring there were 327 crashes, 68 of them said rain on the crash report form and it was actually raining, 114 said clear and there was some amount of precipitation (even just trace amounts), 4 said there was precipitation and there was none and 141 said clear and there was no precipitation. In

Table 16, the hourly data is displayed with the daily data just for those days with hourly crashes for a more even comparison.

Table 15 Daily Weather Data and Crash Report Form Weather Breakdown

Radius (mile)	No. crashes	Daily			
		Rain/Rain	Rain/Clear	Clear/Rain	Clear/Clear
0.5	24	6	6	0	12
1	327	68	114	4	141
5	28749	5546	9971	265	12966
12.5	23581	4967	8030	193	10390

Table 16 Hourly Weather Data and Crash Report Form Weather Breakdown

Radius (mile)	No. hourly crashes	Hourly				Daily (just days with hourly data)			
		Rain/ Rain	Rain/ Clear	Clear/ Rain	Clear/ Clear	Rain/ Rain	Rain/ Clear	Clear/ Rain	Clear/ Clear
0.5	14	4	1	2	7	6	6	0	2
1	187	36	6	32	113	68	113	0	6
5	16019	3401	762	2161	9694	5546	9944	16	512
12.5	13365	3257	653	1718	7736	4965	8007	10	382

Table 17 sums up both Table 15 and

Table 16 with percentages of the comparisons. The hourly data has a more accurate matching between the weather and crash data than the daily. The hourly data also does not decrease in percent matching along with a larger radius as has been discussed in some proximity studies. The daily data has a 10% step down of matching after the half mile radius, but plateaus off there. The worst matches are the daily weather data with the crash report form weather fields for the days with the hourly data and this seems to be due to an overestimation of days that are rainy, due to any precipitation even trace amounts being counted.

Table 17 NCDC Weather and Crash Report Form Weather Comparisons

Radius	Daily		Hourly		Daily (just days with hourly data)	
	Match	No Match	Match	No Match	Match	No Match
0.5 mile	75.0%	25.0%	78.6%	21.4%	57.1%	42.9%
1 mile	63.9%	36.1%	79.7%	20.3%	39.6%	60.4%
5 mile	64.4%	35.6%	81.7%	18.2%	37.8%	62.2%
12.5 mile	65.1%	34.9%	82.3%	17.7%	40.0%	60.0%

5.2 Crash report form narrative analysis

To see if the weather had an impact on the crashes was more than analyzing checked boxes on the crash report form, the information had to be pieced together from multiple fields including the crash report form narrative. The crash narrative analysis focused on the three weather types that were the main emphasis of the data analysis section: clear, rain and snow/ sleet. The weather types were taken from the weather conditions chosen by the recording officer in the report form. Table 18 shows the breakdown of weather and road conditions mentioned in the crash report form narratives and if the mention of the weather correlated with the weather type and if the mention of weather gave any insight into if weather had an impact on the crash or the crash just occurred during a specific weather type.

Table 18 Narrative Weather Insight

Weather Type (% per weather type)	Narrative				
	no weather mentioned	mention of weather-no insight	mention of weather-insight- no correlation w/ weather fields	road conditions mentioned	mention of weather-insight-correlation w/ weather fields
Clear	93	0	0	7	0
	93.0%	0.0%	0.0%	7.0%	0.0%
Rain	67	4	1	24	21
	57.3%	3.4%	0.9%	20.5%	17.9%
Snow/ Sleet	28	3	0	69	27
	22.0%	2.4%	0.0%	54.3%	21.3%

The narratives were categorized into 5 groups, but occasionally the narrative could fit into two of the groups. The first group was "no weather mentioned" these narratives never had a mention of weather. An example of a clear weather type with no weather mentioned is

> "MV2 WAS STOPPED AT A RED LIGHT HEADING EAST ON TEATICKET HWY. MV1 WAS BEHIND MV2 AND WENT TO PASS MV2 IN A NO PASSING ZONE. IN DOING SO MV1 RIGHT PASSENGER SIDE THEN COLLIDED WITH MV2 FRONT LEFT SIDE. THERE WERE NO REPORT OF INJURIES AT THE SCENE. BOTH MVS SUSTAINED MODERATE DAMAGE AND WERE ABLE TO DRIVE FROM THE SCENE. MV1 DRIVER WAS GIVEN A CITATION FOR MARKED LANES."

The "no weather mentioned" group accounted for 93 percent of the clear weather types, 57.3 percent of the rain weather types and 22 percent of the snow/sleet weather types. For clear weather, it makes sense that the weather would not cause or specifically affect the crash. For the other two weather types “no weather mentioned” might mean varying things from weather was not an issue to just not recorded in the narrative due to being recorded in the crash report form weather fields, but can be taken as the weather did not impact or cause the crash enough for the recording officer to think it crucial for narrative mention.

The second group was “mention of weather—no insight” these narratives mentioned weather, but there was no insight given into whether or not the weather had an impact on the crash. There were no clear weather type narratives in the second group and only 3.4 percent of rain weather type and 2.4 percent of snow/sleet weather type. These crashes can be viewed as the weather in the narrative was noted to match the crash report form fields’ weather type, but weather did not have a specifically recorded impact on the crash. An example from the rain weather type of “mention of weather—no insight” is

> “HEAVY TRAFFIC AND RAIN. I WAS TRAVELING NORTH ON GARDNERS NECK RD., TURNING WEST ONTO WILBUR AVE.. A VEHICLE TRAVELING EAST AND WEST ON WILBUR AVE. STOPPED TO LET ME GO. AS I WAS PULLING OUT TWO VEHICLES TRAVELING WEST ON WILBUR AVE. WENT INTO THE BREAKDOWN LN TO GO AROUND THE VEHICLES. #1 SAW ME, SLAMMED ON HIS BRAKES AND WAS REAR ENDED BY #2. BOTH #1 AND #2 CITED FOR OPERATING IN A BREAKDOWN LANE”.

Most of the second group of narratives was also accounted for in the fourth group “road conditions mentioned”. The fact that some narratives fit into multiple categories created the percentage totals of each weather type to not necessarily sum to be 100%, but for rain and snow/ sleet more than 100%. The road conditions was not specifically looked at in this data analysis as it was in many weather and road safety studies (8, 20, 21, 22), but was taken into consideration for the narrative assessment due to the data quality nature of the assessment and the previously stated fact that the road conditions and weather at the time of the crash could in rare instances dramatically differ from those at the time that the crash report form was completed (14). The road conditions were mentioned in 7 percent of the clear crashes with some of the instances being adverse road conditions such as "BLACK ICE" or "SNOW AND ICE FROM PRIOR STORM" and two being "DRY ROADWAY SURFACE". The road conditions were mentioned at much higher rates in the rain and snow/sleet weather types with 20.5 percent in rain and 54.3 percent in snow/sleet. At times the road conditions and insight to the crash causation were both mentioned in the narrative, but not the weather. For example,

> "VEHICLE 1 WAS TRAVELING EASTBOUND ON TREMONT ST. DUE TO THE ICE COATED ROADWAY, VEHICLE 1 SLID OUT OF CONTROL AND OFF THE ROADWAY. VEHICLE 1 RESTED FACING WESTBOUND ON THE PASSENGER'S SIDE OF THE VEHICLE."

As Table 18 shows there was only one crash that the weather was mentioned in the narrative and the weather mentioned gave insight into the causation of the crash, but the weather was not the same as the weather type checked on the crash report form. This was a unique situation that occurred, but worth pointing out. The rain weather type narrative read:

> "VEHICLE #1 WAS IN THE 1ST TRAVEL LANE TRAVELING SOUTH ON ROUTE 93, TRAFFIC CAME TO A STOP IN FRONT OF HIM. VEHICLE #2

> WAS IN THE 1ST TRAVEL LANE TRAVELING STRAIGHT COMING UP ON VEHICLE #1, VEHICLE #2 THEN REAR ENDED THE VEHICLE #1. OPERATOR OF VEHICLE #2 STATES HE COULD NOT SEE BECAUSE OF THE GLARE FROM THE SUN. VEHICLE #2 WAS SECURED BY A&S TOW SERVICE.   VEHICLE: MA SM87834 2000   OPERATOR: PHILIP SINCLAIR 11/17/1949 S35672957   VEHICLE: MA 898BJ0 2008 FORD OPERATOR: PHILIP LANE 12/03/1979 S21832705".

This narrative was from the rain weather type, but specifically mentioned the driver crashed because he could not see due to the glare from the sun, which could possibly happen during a rare "sun shower," but normally sun would be in the clear weather type during no type of precipitation.

The fifth group of narratives mentions the weather, gives insight into whether or not the crash was impacted by the weather and the weather mentioned correlates to the weather type given in the weather fields of the crash report. No clear weather types were observed in this category which makes sense since if there is no specific weather element why would it affect the crash or be mentioned in the narrative. 17.9 percent of the rain weather type crashes and 21.3 percent of the snow/ sleet weather type crashes fell into the fifth group with all of those stating that weather (precipitation) had a direct impact on the crash. A snow/ sleet weather type example where the weather had an impact on the crash causation,

> "OPERATOR 1 STATED SHE WAS HEADING WEST ON ARTISAN WAY WHEN SHE ATTEMPTED TO STOP AT THE STOP SIGN BY ROUTE 130. SHE STATED SHE SLID COMPLETELY THROUGH THE INTERSECTION

AND COLIDED WITH A TREE IN FRONT OF #7 ROUTE 130. OPERATOR 1 STATES SHE WAS TRAVELING AT APPROXIMATELY 15MPH BEFORE SLIDING INTO THE TREE. SHE ALSO STATED SHE WAS UNABLE TO SEE THE INTERSECTION OR THE STOP SIGN DUE TO THE SNOW. THE WEATHER AT THE TIME OF THE ACCIDENT WAS HEAVY SNOW AND WIND. OPERATOR 1 CLAIMED NO INJURY. VEHICLE 1 WAS TOWED BY ALL CAPE TOWING TO THEIR YARD."

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

As noted throughout the primary objective of this research effort was to develop an improved understanding of the nature of the relationship between weather and traffic safety. A secondary objective aimed at evaluating the quality and applicability of available datasets for use in these types of analyses. Successful completion of the developed research tasks translated into the results presented in Chapters 4 and 5 as well as the associated conclusions and recommendations presented in the sections below.

The completed research did in fact result in an improved understanding of the relationship between weather and traffic crashes. The knowledge of this relationship will prove useful in future efforts to improve traffic sounding in and around weather events. Specific conclusions associated with the modeling of the weather and safety relationship include the following:

- An analysis of the injury severity associated with crashes under varied weather indications indicated that snow and sleet crashes resulted in a greater proportion of PDO crashes than crashes occurring in either clear or rain related events. This finding may be consistent with what may be expected, however it is interesting to note that the trend for rain crashes more closely resembled that of clear crashes across all injury severity levels. Nevertheless, it would be interesting to analyze the injury severity across weather levels with some measure of exposure (i.e., vehicle miles traveled).

- An analysis of the months in which weather related crashes occur proved to match with the weather itself. The rainiest months, April, May, October, November, have the most rain-related crashes. The snowiest months, December, January and February, have the most snow-related crashes. Clear crashes are relatively evenly broken out with approximately 8% of the clear crashes occurring in each month. This finding may be consistent with what is expected, but may prove more interesting if coupled with actual precipitation amounts.
- An analysis of the ambient light with weather-related crashes indicated that a higher percentages of rain and snow/sleet crashes occurred in dark ambient lighting situations, approximately a third, whereas only about a quarter of the clear weather crashes occurred in dark ambient lighting. There are also a higher proportion of clear crashes that occur during daylight than percentages of rain or snow/ sleet crashes that occur during daylight.
- An analysis of the first harmful event, the first event in the collision sequence, and where that event took place, show that clear and rain crashes are very similar with the majority of the crashes occurring on the road and with another vehicle. The snow/sleet related crashes differ the most with the majority of the crashes occurring off of the roadway and with a fixed object. For many of the other factors analyzed the rain crashes more closely mirrored the clear crashes with the snow and sleet crashes differing.
- The matching between the NCDC weather data and the crash-report form weather data identified a strong parallel between the data sources. The daily data had a 64 to 75% correlation and the hourly data had a 78 to 82% correlation, with the

correlations more similar within a closer proximity to the weather station for the daily data, but not the hourly. The hourly data had a better correlation which could be expected considering trace amounts of precipitation could occur during a 24-hour period, be recorded as an amount of precipitation for the day, but not occur at the same time as any crashes during that day, this was not the case for many of the daily crashes though.

- A quantifiable amount of additional insight into the impact of weather on traffic safety was provided by investigating the narratives on the police-recoded crash report forms. Although the quantifiable amount was limited with only approximately 18% of rain and 21% of snow crashes offering this information about the weather, that matched the weather-fields and gave insight into the relationship between the weather and the crash their narratives.

Even though the completed research resulted in an improved understanding of the relationship between weather and traffic crashes, there are some recommendations to improve the future research. While conducting this research certain elements which could not be improved on at the time were noted to enhance the future knowledge of the relationship between weather and traffic and safety. To improve on this study and develop a correlation between weather parameters and crashes, a number of additional factors and angles should be examined in further research:

- Jung, Qin and Noyce suggested that even though the effect of rainfall on crash severity has been looked into in previous studies, the weather-related factors lack the sophistication and accuracy to reflect real time visibility and pavement surface conditions (26). This leads into another aspect that should be investigated, which factor is more influential in the correlation between weather and crash factors, including severity, the roadway conditions, the visibility or the weather itself? The question should be investigated more thoroughly and the outcomes will help to provide quantitative support on improving road weather safety and maintenance.

- Maintenance and seasonal factors were not looked into in this study as this was a preliminary divulgence into the relationship between crashes and weather parameters. Both maintenance and seasonal factors are critical components in roadway safety especially during inclement weather, winter months, and areas with plowing and salting, and should be included in future research.
- Other research areas that should be included in further research are utilizing differing modeled relationships to determine best fit and modeling differing relationships with the inclusion of differing factors. The maximum number of combined factors in this study was three to four, but utilizing regression modeling many more factors can be incorporated and therefore the combination of factors effect on the safety and crash severity can be looked into. This would allow designers and safety officials to warn people to reduce the use of dangerous factor combinations especially during inclement weather.
- Regarding the crash report form narrative analysis interviews with the recording officers and the drivers could give greater insight into the weather's affect on the crash itself. All in all there were few staggering errors in the correlation between the narrative and the weather fields even though some of the crashes are recorded after a quick moving weather event has passed. To improve upon the crash report

form information regarding weather's causation or influence on the crash, a greater insight could also be gained by conducting a future study with specifically trained officers looking at weather parameters as they fill in the crash report form.

- To improve upon the data quality assessment, more sites can be investigated. The current problem is access to hourly weather data and the linkage of crash data to weather station data by proximity. Multiple sites investigated into weather data and crash data weather field information correlation as well as normalization of the crash data analysis by the weather data for that area. For example, how many rainy Sunday's days were there in the region that could have had an effect on the number and percentage of rain related crashes?

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