MID-AMERICA TRANSPORTATION CENTER

Safety and Mobility Impacts of Winter Weather - Phase 3

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Safety and Mobility Impacts of Winter Weather Phase 3

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Final Report
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16. Abstract

Highway agencies spend millions of dollars to ensure safe and efficient winter travel. However, the effectiveness of winter-weather maintenance practices on safety and mobility are somewhat difficult to quantify. Safety and Mobility Impacts of Winter Weather - Phase 1 investigated opportunities for improving traffic safety on state-maintained roads in Iowa during winter-weather conditions. In Phase 2, three Iowa Department of Transportation (DOT) high-priority sites were evaluated and realistic maintenance and operations mitigation strategies were also identified.

In this project, site prioritization techniques for identifying roadway segments with the potential for safety improvements related to winter-weather crashes, were developed through traditional naïve statistical methods by using raw crash data for seven winter seasons and previously developed metrics. Additionally, crash frequency models were developed using integrated crash data for four winter seasons, with the objective of identifying factors that affect crash frequency during winter seasons and screening roadway segments using the empirical Bayes technique.

Based on these prioritization techniques, 11 sites were identified and analyzed in conjunction with input from Iowa DOT district maintenance managers and snowplow operators and the Iowa DOT Road Weather Information System (RWIS) coordinator.

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EXECUTIVE SUMMARY

Problem Statement

Highway agencies spend millions of dollars to ensure safe and efficient winter travel. However, the effectiveness of winter-weather maintenance practices on safety is somewhat difficult to quantify. When crashes are viewed over multiple years, some locations appear to have an overrepresentation of crashes.

Background

Safety and Mobility Impacts of Winter Weather - Phase 1 investigated opportunities for improving traffic safety on state-maintained roads in Iowa during winter weather conditions. The primary objective was to develop several preliminary means for the Iowa Department of Transportation (DOT) to identify locations of possible interest systematically with respect to winter weather-related safety performance based on crash history.

Specifically, four metrics were developed to assist in identifying possible habitual winter weather-related crash sites on state-maintained rural highways in Iowa. In addition, the current state of practice, for both domestic and international highway agency practices, regarding integration of traffic safety- and mobility-related data into winter maintenance activities and performance measures was investigated.

In Phase 2, a combination of the Phase 1 results and Iowa DOT maintenance field staff input were employed to evaluate three Iowa DOT high-priority sites. Winter-weather crash-mitigation analysis procedures were developed and applied for three sites. Realistic maintenance and operations mitigation strategies were also identified.

Objectives

The three primary objectives of the Phase 3 project were as follows:

- Develop and investigate a more systematic site prioritization protocol
- Develop crash frequency prediction models
- Analyze winter weather and crash history at the prioritized sites

Research Description and Methodology

Site prioritization techniques, for identifying roadway segments with the potential for safety improvements related to winter-weather crashes, were developed through traditional naïve statistical methods by using raw crash data for seven winter seasons and previously developed metrics.

Crash frequency models were developed using integrated crash data for four winter seasons, with the objective of identifying factors that affect crash frequency during winter seasons and screening roadway segments using the empirical Bayes technique. Empirical Bayes accounted for the regression to the mean (RTM) phenomenon by overcoming the limitations introduced by traditional methods.

Safety performance functions (SPFs) were developed for three types of roadways in Iowa to predict winter weather-related crashes as a function of several factors related to winter-weather conditions such as visibility, pavement temperature, air temperature, and wind speed.

The empirical Bayes approach was used to combine the predicted number of crashes from the SPFs with the observed crash counts at a location to produce an improved estimate of the expected number of crashes.

The difference of the empirical Bayesian adjusted crash frequency and the predicted crash frequency from an SPF is referred to as the potential for safety improvement (PSI). The higher the PSI value for a road segment, the higher potential for improving safety on that road segment.

Considering the PSI, the roadway segments were ranked or prioritized so that highest possible safety improvement can be achieved.

Based on these prioritization techniques, 11 sites were identified for more in-depth analysis in conjunction with input from Iowa DOT district maintenance managers and snowplow operators and the Iowa DOT Road Weather Information System (RWIS) coordinator.

Key Findings

Weather factors such as visibility, wind speed, and air temperature were found to have statistically significant effects on crash frequency along different types of roadways.

The ranking of roadway segments for PSI also differed from the ranking produced by simple crash frequency, which does not take into account the RTM; however, similarities did exist among the techniques.

While crash data served as a foundation for site analysis meetings, insight from Iowa DOT maintenance field staff was invaluable, particularly with respect to their maintenance practices, observations of events under various conditions, possible mitigation strategies, and impacts of the roadside environment. While some of the feedback may have been anecdotal in nature, maintenance staff are uniquely qualified to discuss winter-weather safety, given their nearly exclusive experience in maintaining the roadways and sharing them with motorists during a wide array of different weather conditions.

Additionally, site analysis meetings serve as a forum to increase awareness as well as facilitate open discussion of concerns, mitigation alternatives, and opportunities for coordination and improvement. The final project report provides details on the following issues that were identified:

- A prominent issue among all sites, through their entire extent or in localized areas, was blowing snow
- Poor roadway condition and/or macro texture of pavements along several sites may contribute to winter weather-related crashes
- Challenges in maintenance operations focused on snowplow runs and potential solutions, but were also reflected in crash experience as follows:
  - Glazing of wheel tracks between 8:00 a.m. and 10:00 a.m.
  - Refreeze between 4:00 p.m. and 6:00 p.m.
  - Slushy road conditions between 25 and 32 degrees Fahrenheit, intermittently moving in out and out of a frozen state
  - Roadways typically do not become icy or slick at low temperatures, such as between 10 and 15 degrees Fahrenheit

Implementation Readiness and Benefits

Identifying, or prioritizing, sites for additional safety review or improvement within a road network is an essential task for engineers in state agencies to ensure efficient allocation of limited resources for mitigating possible safety issues. In this study, a primary objective was prioritizing segments for additional analysis to determine if, and what types of, safety improvements may be feasible.

The PSI ranking produced by employing the empirical Bayes technique can be useful to identify roadway segments to consider for PSI and allocate agency resources in an effective manner to mitigate winter weather-related crashes. SPFs developed in this research can be used to produce a ranking based on PSI by using crash observations made over a specific number of years for winter-weather crashes.

There are multiple benefits associated with identification and analysis of locations with the potential for safety improvements related to winter-weather crashes. In general, the effort supports the Iowa DOT's safety and mobility initiatives.

Possible Mitigation Strategies

Several possible mitigations strategies were identified and discussed in the site meetings. Strategies may be considered broadly as roadway or roadside-related, informational, or operational in nature. Some of these strategies, and possible limitations, are covered in more detail in the final project report.

Expansion of snow fence installation was a commonly recommended strategy, including entirely new installation, filling in of gaps, and increasing heights. Limited right-of-way (ROW) availability may impact the ability to implement this strategy at all locations. But, standing stalk programs were suggested as a viable alternative, if participation can become more attractive.

From an operational standpoint, reevaluation of snowplow run turnaround locations, length of snowplow runs, snowplow run overlap, dedicated ramp trucks, cooperation or partnering with neighboring maintenance garages, and material use during different conditions were suggested mitigation strategies. Lastly, improving driver information, particularly in advance of locations prone to rapidly changing or different conditions, was proposed as a possible mitigation strategy. Information may be conveyed via permanent or portable dynamic message signs (DMSs). Locations of devices (specifically, portable DMSs), appropriate activation protocol, and message content would need to be established. Consistency among locations throughout the state may be an additional consideration.

CHAPTER 1. INTRODUCTION

Highway agencies spend millions of dollars to ensure safe and efficient winter travel. However, the effectiveness of winter-weather maintenance practices on safety and mobility are somewhat difficult to quantify. Safety and Mobility Impacts of Winter Weather – Phase 1 (Hans et al. 2011) investigated opportunities for improving traffic safety on state-maintained roads in Iowa during winter-weather conditions. The primary objective was to develop several preliminary means for the Iowa Department of Transportation (DOT) to identify locations of possible interest systematically with respect to winter weather-related safety performance based on crash history.

Specifically, four metrics were developed to assist in identifying possible habitual, winter weather-related crash sites on state-maintained rural highways in Iowa. In addition, the current state of practice, for both domestic and international highway agency practices, regarding integration of traffic safety- and mobility-related data in winter maintenance activities and performance measures were investigated. This investigation also included previous research efforts.

In Phase 2, a combination of the Phase 1 results and Iowa DOT maintenance field staff input were employed to evaluate three Iowa DOT high-priority sites. Winter-weather crash mitigation analysis procedures were developed and applied for these three sites. Realistic maintenance and operations mitigation strategies were also identified.

The three primary objectives of this project, Safety and Mobility Impacts of Winter Weather – Phase 3, were as follows:

- Develop and investigate more systematic site prioritization protocols
- Develop crash frequency prediction models
- Analyze winter weather and crash history at the prioritized sites

This report consists of six additional chapters. Chapter 2 presents a summary of factors affecting winter-weather safety and past methodologies for modeling winter-weather crash frequency. Chapter 3 discusses development of two site prioritization techniques, based on previously computed metrics. Chapter 4 introduces the various data sets, sources, and processing steps used to develop safety performance functions (SPFs) for winter-weather crashes in Iowa. Chapter 5 outlines the development of crash frequency prediction models for empirical Bayes analysis. Chapter 6 discusses use of the Chapter 3 and 5 analyses results to identify locations for more detailed review and the resulting evaluation of these sites. Chapter 7 provides conclusions and recommendations from the research project.

CHAPTER 2. LITERATURE REVIEW

This chapter provides a thorough literature review of the factors affecting winter-weather safety and methodologies used to analyze crashes related to winter weather from previous studies. It provides a comprehensive review of literature on the impact of weather-, traffic-, and maintenance-related attributes on winter-weather safety.

Past studies related to modeling winter-weather crash frequencies using both aggregate- and disaggregate-level crash data are also discussed in this chapter. While most of the studies focused on the effect of weather, traffic, and maintenance parameters on road safety, development of a site prioritization technique for improving winter-weather safety using available crash data and maintenance crew–reported weather data was scarce in the literature.

This study concentrates on developing a comprehensive site prioritization technique for identifying highway locations potentially prone to winter-weather crashes, as detailed in the following chapters.

2.1 Factors Affecting Winter-Weather Safety

2.1.1 Effect of Weather on Safety

Some of the weather-related factors affecting safety on the roadway include freezing precipitation, frozen precipitation, liquid precipitation, severe and major storms, temperature, visibility, and wind speed (Edwards 1998, Feng 2001, US Department of Commerce 2002, Strong et al. 2010).

Correlation and regression analysis was performed by Andreescu and Frost (1998) between daily accidents with weather-related variables (temperature, rain fall, and snowfall) using three years of crash data (1990 through 1992) from Montreal, Quebec. Differences in the daily number of crashes and the mean number of crashes over a week was used as the number of daily crashes for the three years of the study period to reduce the variation in the number of accidents per day. The study results found that the number of crashes increased with an increase in snowfall or rainfall intensity, but no significant relationship with respect to temperature was found.

Aggregated data by intervals of six hours was used by Andrey et al. (2003) to analyze the crash and precipitation data of six Canadian cities from 1995 to 1998 employing a matching pair technique. Using this technique, the researchers compared crashes in periods of days under adverse weather conditions with crashes in periods of similar days under normal weather conditions. The results indicated a 75 percent and 45 percent increase in frequency of overall collisions and injury severity collisions, respectively, due to precipitation, with snowfall effects being more pronounced than rainfall effects in collisions.

Andrey and Knapper (2003) found that the crash risk associated with rainfall is mainly due to visibility, with crash rates dropping quickly near to normal once the rain stopped. The study results also revealed that high winds and fog are responsible for a small proportion of crashes.

More recently, Andrey (2010) investigated the effects of weather on crash severities using data from 1984 to 2002 for 10 Canadian cities. Using a match-paired technique, Andrey showed that the risk of minor injury crash increased by 74 percent and 89 percent due to rainfall and snowfall, respectively, whereas the increase in major/fatal injury crash risk was 46 percent and 52 percent due to rainfall and snowfall, respectively.

Using 25 years of weather, traffic, and crash data for the 48 continental US states, Eisenberg (2004) developed a set of state-level daily and monthly collision models that followed a negative binomial distribution. The estimated monthly models showed a reduction in fatalities and an increase in non-fatal crashes with snow precipitation. The estimated daily models showed a positive relationship between snow precipitation and total number of crashes and revealed that fatalities increased with heavy precipitation.

Eisenberg and Warner (2005) conducted an analysis using the same data set to investigate the relationship between snowfall and crash rate and calibrated negative binomial models with number of crashes as the dependent variable and precipitation, traffic exposure, and other factors as independent variables. The findings revealed that the number of non-fatal injury crashes and property damage crashes increased during the snowfall, but the number of fatal crashes decreased.

Sherif (2005) attempted to establish a link between road surface temperature, surface moisture, and road safety using data for one winter season from the city of Ottawa, Ontario, Canada. A pavement moisture risk factor (PMRF) was developed using the ratio of crash rate on wet surface to that on dry surface. The results from the study indicated that wet surfaces were found to be more hazardous when the temperature ranges from +1 to -2 degrees Celsius. However, some of the major limitations of the study were the large aggregation of crash and weather data at a high level, masking the variations within different types of highways, and consideration of wet and icy surfaces to be equal in terms of their effect on safety.

Hermans et al. (2006a) investigated the effect of weather factors on road safety by using data collected in the Netherlands in 2002 and considering a number of factors related to wind, temperature, precipitation, and visibility. The collected data included hourly data on cloudiness, precipitation duration, precipitation amount, relative humidity, presence of precipitation, presence of fog, snow, thunderstorms, black ice, hail, and visibility. The researchers estimated negative binomial models and found that the duration of precipitation and wind gust speed were associated with higher crash frequency, while the presence of light was associated with a lower number of crashes.

Hermans et al. (2006b) also analyzed frequency and severity of crashes based on monthly data collected from 1974 to 1999 in Belgium using a state space approach considering several weather variables. The state space approach is based on describing a time-varying process by a

vector of quantities. The percent of days with thunderstorms and precipitation were found to be positively associated with minor injury risk with statistical significance. Both minor and major fatal injury risk was found to be higher on days with precipitation and with increased sunlight hours. On the other hand, risk for both types of injuries was found to be lower on days with freezing temperatures.

A meta-analysis on past studies from 1967 to 2008 was conducted by Qiu and Nixon (2008) to illustrate the weather-related factors affecting road safety. According to that review, it was found that snow precipitation was likely to increase the total number of crashes by 73 percent, 85 percent, and 100 percent on average in the US, Canada, and the UK, respectively. Rain was likely to increase the total number of crashes by 58 percent, 73 percent, and 24 percent. Injury crashes also followed the same pattern. However, the estimates considered in this meta-analysis from different studies were the gross averages in different countries in different time spans so many factors, such as driving behavior, exposures, and maintenance operations, attributed to the variations in the percentages. Therefore, the findings from this study cannot be generalized without considering specific traffic, maintenance, and weather characteristics of a specific region.

2.1.2. Effect of Traffic-Related Factors on Safety

Knapp and Smithson (2000) investigated the impact of winter storm events on traffic volumes. Sixty-four winter storm events occurring between 1995 and 1997 on Interstates in Iowa were considered that met certain traffic volume, storm duration, and snowfall intensity criteria set by the researchers. Road weather information system (RWIS) data from seven sites near the Interstates were used to collect roadway and weather condition data. Automatic traffic recorders (ATR) located near the RWIS were used to collect the hourly traffic volumes to approximate storm and non-storm event traffic volumes.

In that study, multiple regression analysis was conducted to investigate the relationship between the reduction in the percentage of traffic volumes during winter storm events, snowfall intensity, total snowfall, and other weather-related variables. The percent reduction in traffic volume during a winter storm event was derived by calculating the percent reduction in volume from the average traffic volume during a non-storm event. The analyses indicated that the percent reduction in traffic volume during winter storm events had a statistically significant and positive relationship with total snowfall and the square of maximum gust wind speed.

Knapp et el. (2000) also studied the impact of winter storms on crash frequency and reduction in traffic volume using a standard Poisson regression count model, as there was no evidence of the presence of overdispersion in the crash data. Hourly data were collected for crashes, traffic volume, and weather variables in Iowa for a 30-mile segment of the Interstate highway from 1995 to 1998, and 54 winter storm events were identified based on freezing temperature, precipitation, and non-dry pavement surface. The model results showed an increase in crash frequency with the increase in exposure (million vehicle miles), snowstorm duration, and snowfall intensity.

Knapp and Smithson (2001) investigated the change in vehicle speed during winter-weather events using mobile video data collection equipment to collect traffic flow data (i.e., speed and volume), weather conditions, and road surface conditions during seven winter-weather events from 1998 to 1999 at an Interstate location in Iowa. The researchers discussed the effectiveness of and concerns related to using mobile video data collection equipment during winter weather.

Exploratory data analysis revealed a 16 percent reduction in the average winter-weather vehicle speed compared to the typical average speed at the same location during non-winter conditions. A 307 percent increase in the variability of vehicle speed during winter-weather events was also found when compared to the typical speed variability. The multiple regression model developed as part of the study revealed that the off-peak average winter-weather vehicle speed would increase with the square of traffic volume, decrease with the decrease in visibility below 0.25 mile, and decrease when snow began to affect or cover the roadway lanes. That study assumed that traffic volume was a surrogate for the weather characteristics affecting variable speed and, as such, weather data were not collected during the winter-weather events.

Padget et al. (2001) conducted a study to investigate winter-weather speed variability in sport utility vehicles (SUVs), pickup trucks, and passenger cars. The authors collected and analyzed the speeds of SUVs, pickup trucks, and passenger cars on five different winter-weather pavement surface conditions in Ames, Iowa. The analysis results revealed that all three types of vehicles had similar average speeds during normal conditions, with passenger cars having the highest average speed, but this pattern reversed during winter-weather conditions, with SUVs having the highest average speed and passenger cars having the lowest average speed.

The researchers concluded that passenger car drivers generally traveled more slowly than SUVs during winter-weather conditions but faster during normal conditions. The researchers found there was a difference between the normal and winter-weather speed choice of SUV, passenger car, and pickup truck drivers. However, the variability in the speed of SUVs, pickup trucks, and passenger cars increased during winter-weather periods compared to the variability during normal conditions regardless of the time of day.

The researchers found nighttime speeds for all three types of vehicles to be significantly lower than daylight speeds. The analysis results also revealed that the average vehicle speed for all three types of vehicles decreased with poorer roadway surface conditions during the winter-weather periods.

Lee and Ran (2004) developed a winter-maintenance performance measure based on speed recovery duration (SRD) during snow events using speed data collected from ATRs and winter storm report data in Wisconsin. The authors defined SRD as the time between the stopping of the snow event and the recovery of vehicle speeds to normal. The SRD was proposed as a measure of winter-maintenance performance in lieu of the total cost of operations or salt usage. A regression model developed in the study showed that vehicle SRD to the normal condition was significantly associated with snow duration and maximum speed reduction during the snowstorm.

Lee et al. (2008) conducted a follow-up study involving a larger sample size to validate the findings of the Lee and Ran (2004) study. The follow-up study involved the investigation of vehicle speed changes during winter-weather events using data extracted from Wisconsin winter maintenance logs.

The study conducted a regression tree analysis with SRD, which the authors defined as the time required to regain the normal average speed from minimum speed during a winter storm event, as the dependent variable. SRD was found to be a promising factor to evaluate winter maintenance activities using vehicle speed data.

According to the developed models, the authors found that SRD would increase with the quick reduction of vehicle speed to the minimum speed during the winter storm events. A longer SRD would also be expected with a percentage increase of the maximum speed reduction. The study confirmed that vehicle speeds could be a good measure for indicating driving conditions during a winter-weather event.

2.1.3 Effect of Winter Maintenance on Safety

Adams et al. (2006) developed regression tree models for estimating labor, equipment and material resources, cleanup cost, and percent overtime cost associated with winter-weather maintenance activities during storm events in Wisconsin. The researchers focused on estimating the required resources using regression tree models, which are independent from unit costs of labor, maintenance, and equipment that change over time and vary from county to county.

Models were developed for 72 counties in Wisconsin that were divided into four service groups depending on the percent of highway coverage received by those counties during winter-weather events. The regression models captured the effect of precipitation depth, storm duration, air and pavement temperature at the start of the storm, time of the day, and service level on resource requirements for winter maintenance.

The analysis showed that temperature influenced labor and equipment requirements as well as materials usage for winter maintenance. This type of model is used by Wisconsin for estimating resource requirements in case of an impending storm. These models are also applicable to different counties for estimating resource requirements with varying unit labor, material, and equipment costs.

In another study, Ye et al. (2009) investigated and evaluated the effect of weather information on winter-weather maintenance costs. For this purpose, a general winter maintenance cost model was presented, and neural networks and sensitivity analysis were used to identify key variables that had a significant effect on cost.

The analysis revealed that enhanced accuracy and frequent use of weather information could reduce winter maintenance costs significantly. The cost-benefit analysis conducted as part of the

study revealed that weather information can be a promising way to improve winter maintenance and reduce agency costs.

Russ et al. (2008) conducted a study focused on addressing the pretreatment protocol for winter maintenance of roadways in Ohio. The study was conducted in four parts consisting of surveys of personnel in state departments of transportation and county managers in Ohio, field durability studies of various applications of brine on Portland cement concrete (PCC) and asphalt concrete (AC) pavements in Ohio, pretreatment inspections during three winter seasons, and laboratory tests on PCC and AC cores. Integration of the findings from these tasks resulted in a decision tree to aid in operational planning and pretreatment.

Blomqvist et al. (2011) combined an empirical model developed in Sweden with data on residual salt, road surface wetness, and traffic from 18 Danish field case studies to predict salt on road surfaces during winter weather. Results showed that the decay of residual salt could be modeled with traffic as an independent variable with a fair to quite good (R^2 value ranging from 0.64 to 0.99) fit. Road surface wetness was positively related to the rate of residual salt loss from the wheel tracks, meaning a wetter surface would expedite the process of salt leaving from the wheel tracks. While only a couple of hundred vehicles passing over a wet road surface would result in almost no salt in the wheel track, it would take a couple of thousand vehicles to pass on a moist road to achieve the same result.

2.2 Review of Past Methodologies for Modeling Winter-Weather Crash Frequency

2.2.1 Winter-Weather Crash Frequency Models

Usman et al. (2010) conducted a study to quantify the safety benefits of winter-weather maintenance and operations employing event-based crash frequency models. Using crash and weather data from different sources in the province of Ontario, Canada, the authors developed event-based models for predicting winter crashes, controlling for visibility, road surface [condition] index (RSI), traffic exposure, site specificity, and precipitation under snowstorm events.

The novelty of this research lay in introducing an RSI, which was assumed to reflect the maintenance operations during snowstorm events. RSI was defined for major classes of road surface conditions having ordered categories in terms of the severity. RSI was introduced as a surrogate measure of the commonly used friction level, and RSI was assumed to be similar to road surface friction values and varied from 0.1 (poorest, e.g., ice-covered) to 1.0 (best, e.g., bare and dry). RSI was defined as a range of surface friction values assigned to different major classes of road surface conditions based on the literature.

Three types of modeling techniques were used to investigate the association of crash frequency during a snowstorm event with road surface conditions and the other controlling factors mentioned previously. Results showed that the generalized negative binomial (GNB) model offered the best fit for the data over the negative binomial and the zero inflated negative binomial

models. The RSI was found to be a statistically significant influence on crash occurrence during a snow event.

Using disaggregate hourly data from the same winter snowstorm events as those used by Usman et al. (2010), Usman et al. (2011) developed a GNB model for predicting winter crash frequency. This model was compared to the model calibrated from using aggregate event-based data to examine the impact of data aggregation (from event-based data to hourly data) on modeling results.

Results showed that data aggregation ignoring data correlation could result in loss of information and models with biased parameters. Some important factors were significant in the disaggregate model while insignificant in the event-based aggregate model.

The same study also developed two Poisson-lognormal (PLN) models using an hourly winter crash data set with multilevel (event-hour structure) and single-level data structures. The multilevel data structure accounted for the within-event correlation of the observations at different hours. The single-level and multilevel PLN models based on hourly data were very similar, indicating that event-level correlation in the specific data set used in this study was weak.

After establishing the effectiveness of calibrating a model with a disaggregate data set over aggregated data for predicting winter crash frequency, Usman et al. (2012a) developed winter crash frequency models using a disaggregated hourly data set in a bid to investigate the link between winter road collision occurrence, weather, road surface conditions, traffic exposure, temporal trends, and site-specific effects.

Results showed that both the GNB model and the PLN model had a better fit when considering site-specific effects than without considering these effects. The PLN model considered the multilevel (event-hour level) structure of the data, while the GNB model was developed using the hourly data for winter crashes and the other factors mentioned above. The GNB model also had the ability to account for data heterogeneity through varying the overdispersion parameter. The authors found that GNB provided a better goodness of fit compared to the PLN model because within-event correlation was weak for the PLN model.

Using the same data set, Usman et al. (2012b) developed crash-injury severity models to take into consideration the multilevel or hierarchical nature of crash data. The authors developed three types of models using each of the following: occupant-based data, vehicle-based data, and collision- or crash-based data. The aim was to consider the possible intra-class correlation of occupant- or vehicle-level observations.

Multilevel multinomial logit, multilevel binary logit, and multilevel ordered modeling structures were adopted to develop models using the winter crash data having an occupant-, vehicle-, and crash-level hierarchy. The study compared these three alternative logistic models in a multilevel modelling framework.

The authors found that the multilevel multinomial logit model had a better fit to the occupant-level and vehicle-level data, while binary logit and ordered logit performed better for collision-level data. Overall, multilevel multinomial logit models offered better predictions. The authors also found that aggregation of crash data at the collision level affected the parameter estimates significantly.

Qin et al. (2006) developed a negative binomial model for predicting crashes during winter storm events from 2000 to 2002 relating to winter storm severity in regard to duration and intensity, wind speed, deicing units used per lane mile, and salt used per lane mile. The analysis was conducted for the Wisconsin State Trunk Highway system.

Results revealed that early deployment of winter maintenance operations could significantly reduce crash occurrence, with the model showing a negative relationship between crash frequency and the time crews spent out before the beginning of a storm. An inverse relationship between crash occurrence and the amount of deicing material used indicated a reduction in the number of crashes associated with the deployment of more deicing material. However, a positive relationship between salt units used and crash occurrence was found; this was explained by the fact that there is a time lag between salting and snowplowing that can result in a slurry period, during which the bare pavement might be slippery and more crashes could occur.

Storm duration and wind speed were found to be positively associated with the crash frequency. Temporal distribution of the crashes during a snowstorm revealed that a large percentage of the crashes occurred during the initial stages of snowstorms. Although the temporal patterns for the percentage of crashes during snowstorms were similar for both state and local roads, a higher percentage of crashes occurred on local roads during the later stage of the snowstorm, reflecting the different level of maintenance activities and usage of deicing materials.

2.2.2 Development of Winter Severity Index

Nixon and Qiu (2005) developed a storm severity index using 252 winter storm events in Iowa. The storm severity index can provide a measure of the severity of any given storm based solely on a meteorological description of that storm. Storms were classified by six factors: storm type, in-storm road surface temperature, in-storm wind condition, early storm behavior, post-storm temperature, and post-storm wind condition.

A multiple regression model was estimated to produce a storm severity index between 0 and 1, with 0 indicating a very mild storm and 1 indicating a very severe storm. Winter maintenance personnel (maintenance garage supervisors) from the Iowa DOT were asked to rank the severity of 10 representative storms (out of the 252 storm events considered for developing the multiple regression model) according to the level of difficulty that these events would pose in their maintenance activities.

The authors found that, although there was general agreement between the supervisors' ranking and the initial severity index, there were areas of disagreement. The scores for the different

factors considered in the regression model were adjusted according to the supervisors' ranking. This type of severity index for winter storm events can be helpful in assessing the performance of maintenance agencies because the severity of the storms they face can be quantified.

2.2.3 Comparison of Crash Injuries during Winter and Non-Winter Events

Khattak and Knapp (2001) conducted a study to compare the winter snow event crash injury and non-injury crash rates with comparable winter non-snow event crash rates on selected Interstate highway locations in Iowa.

Winter snow events were defined based on the definition in Knapp et al. (2000), and the same data set and location was used for this study. The authors also compared the crash injury occurrence during winter snow event periods and comparable winter non-snow events along with an assessment of the impact of snow event elements on snow event crashes using binary logit models. Comparable non-snow periods were identified and extracted for the same hours on the same weekdays within the same month of the winter snow events.

Results revealed a significant increase in injury and non-injury crash rates during winter snow events compared to those rates during comparable winter non-snow events. However, the modeling results indicated that crashes during snow events involved fewer injuries than crashes during comparable non-snow periods. The study also revealed that snow event elements such as higher wind gust speed tended to result in more injury crashes during snow events, while higher snowfall intensity resulted in crashes involving fewer injuries during snow events.

CHAPTER 3. DEVELOPMENT OF SITE PRIORITIZATION TECHNIQUES

This chapter discusses the development of various comprehensive, systematic site prioritization techniques for identifying locations of possible interest with respect to winter weather-related safety performance based on crash history.

In the first phase of this project, four metrics were developed and computed for one-mile road segments to assist in identifying possible habitual, winter weather-related crash sites on state-maintained rural highways in Iowa. These metrics included winter weather-related crash density, winter-weather crash proportion (the proportion of all winter crashes that are winter-weather related), winter-weather person-level injury severity (injuries on each roadway segment by frequency and severity), and a composite metric representing an equal combination of the three metrics into one overall rating.

Each of the metrics was evaluated within a common road type—freeway, expressway, or two-lane highway—and categorized based on relative magnitude within the appropriate road type and analysis period. Specifically, the total mileage of a given road type was computed and categories were created based on percentage of mileage ranges, following the U.S. Road Assessment Program (usRAP) risk-mapping protocol (Hans et al. 2011). Table 3.1 shows the categories with the corresponding percentage of system mileage.

Table 3.1 Mileage category ranges (for each road type) by relative magnitude

Category	Metric value among percentage of system mileage
1	Lowest 40 percent
2	Next 25 percent
3	Next 20 percent
4	Next 10 percent
5	Highest 5 percent

The analysis results were presented visually within a series of maps, allowing users to quickly identify and confirm possible locations of interest as well as compare locations on a system-wide basis—both within the same metric and among all metrics (Hans et al. 2011).

This chapter discusses the development of two more-systematic site identification and prioritization techniques. These techniques—standard deviation-based analysis and moving average analysis—employed the Phase 1 data sets to identify sites for potential in-depth analysis. An additional technique, empirical Bayes site prioritization, is presented in Chapter 5.

3.1 Standard Deviation–Based Analysis

The first systematic site prioritization technique employed was based on the standard deviation of each of the four metrics from Phase 1—crash density, crash proportion, crash severity, and composite—for the winters of 2002/2003 through 2008/2009. This technique served not only to prioritize sites but also to observe metric sensitivity with respect to the standard deviation.

The standard deviation of each metric, by road type, was first computed. The original metric value for each one-mile road segment was then divided by the standard deviation corresponding to the metric and type of roadway.

For visual presentation and mapping purposes, road segments were categorized by metric value and road type based on a combination of percentage of system mileage and logical numeric breaks. As a result, the mileage within each category did not always equal that presented in Table 3.1 Given that each road segment possessed a discrete value, segments were ranked using this value, with higher-value segments ranked higher for consideration, within their respective road type.

Figures 3.1 to 3.6 present the standard deviation-based analysis for all metrics on Interstate/freeway roadways. Figures 3.1 to 3.4 present the analysis results on a statewide basis and Figures 3.5 and 3.6 present the statewide analysis results on more of a corridor level.
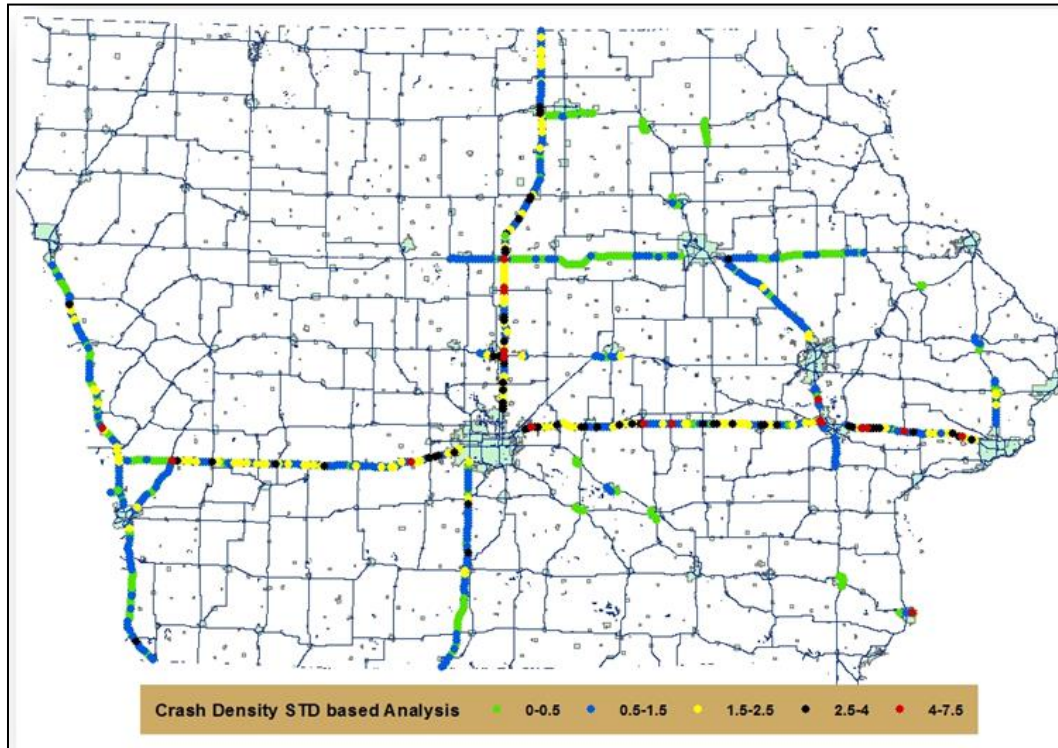
Figure 3.1 Standard deviation-based analysis of crash density for Interstates/freeways
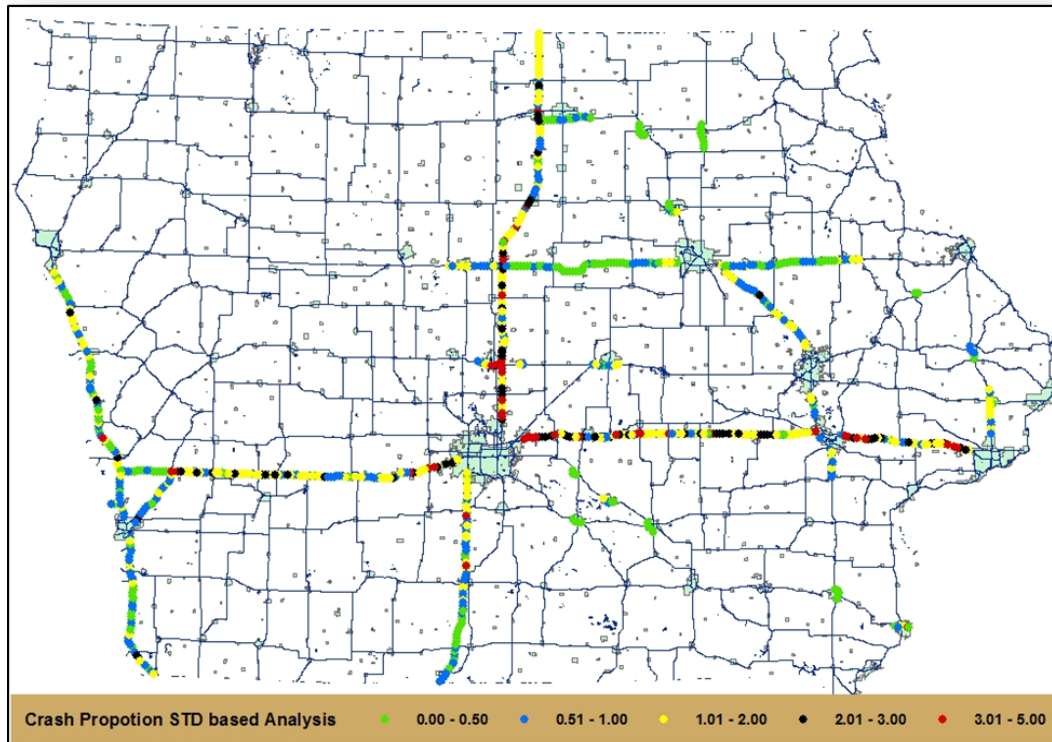
Figure 3.2 Standard deviation-based analysis of crash proportion for Interstates/freeways
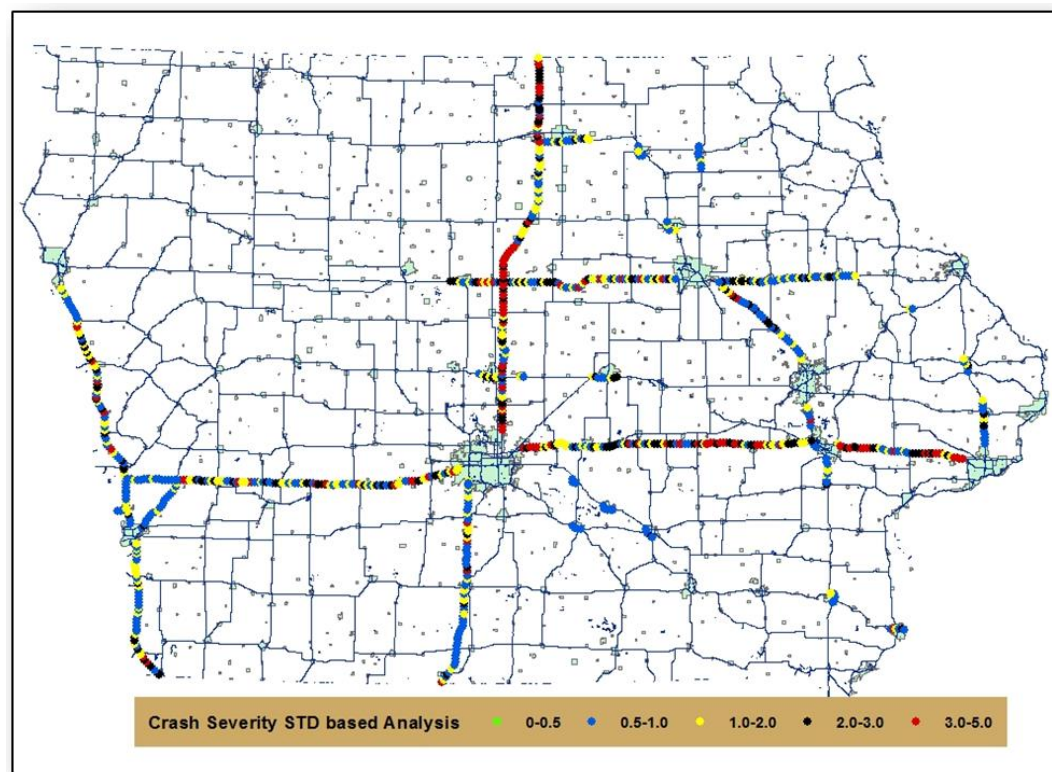
Figure 3.3 Standard deviation-based analysis of crash severity for Interstates/freeways
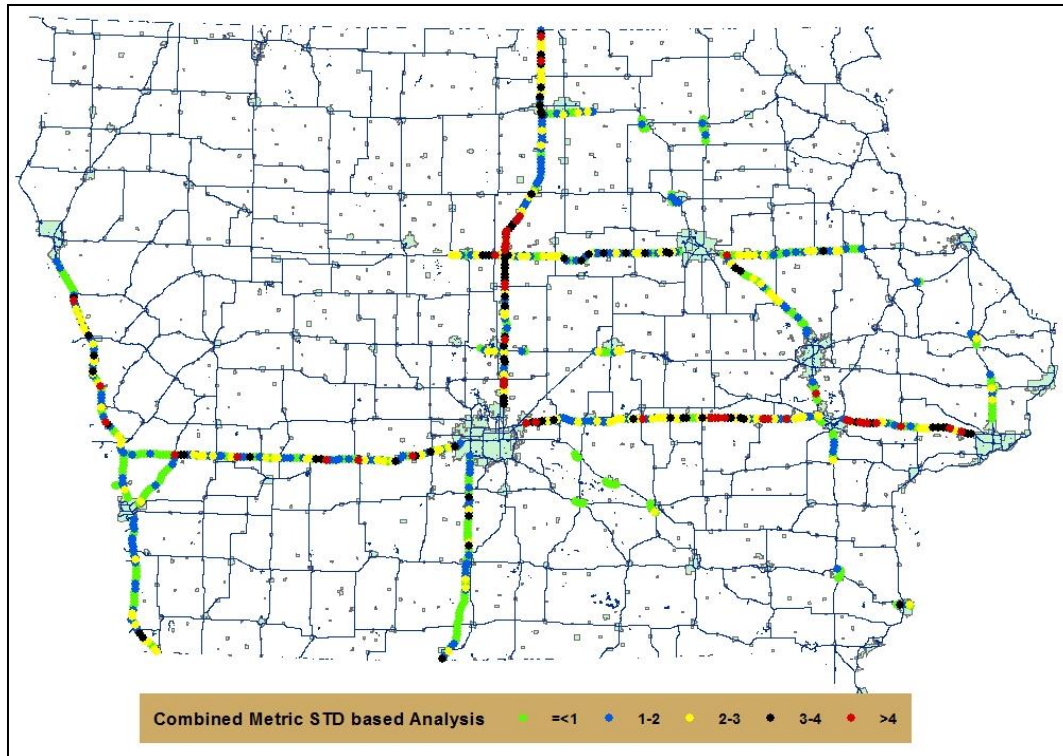
Figure 3.4 Standard deviation-based analysis of composite metric for Interstates/freeways
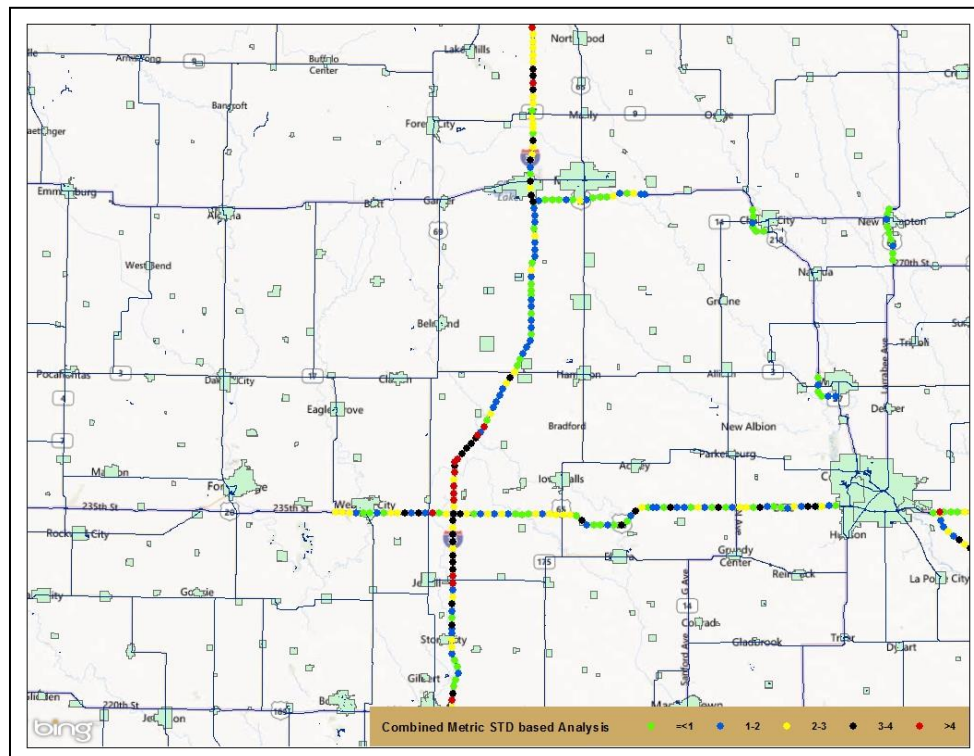
Figure 3.5 Standard deviation-based analysis of composite metric for I 35 and US 20
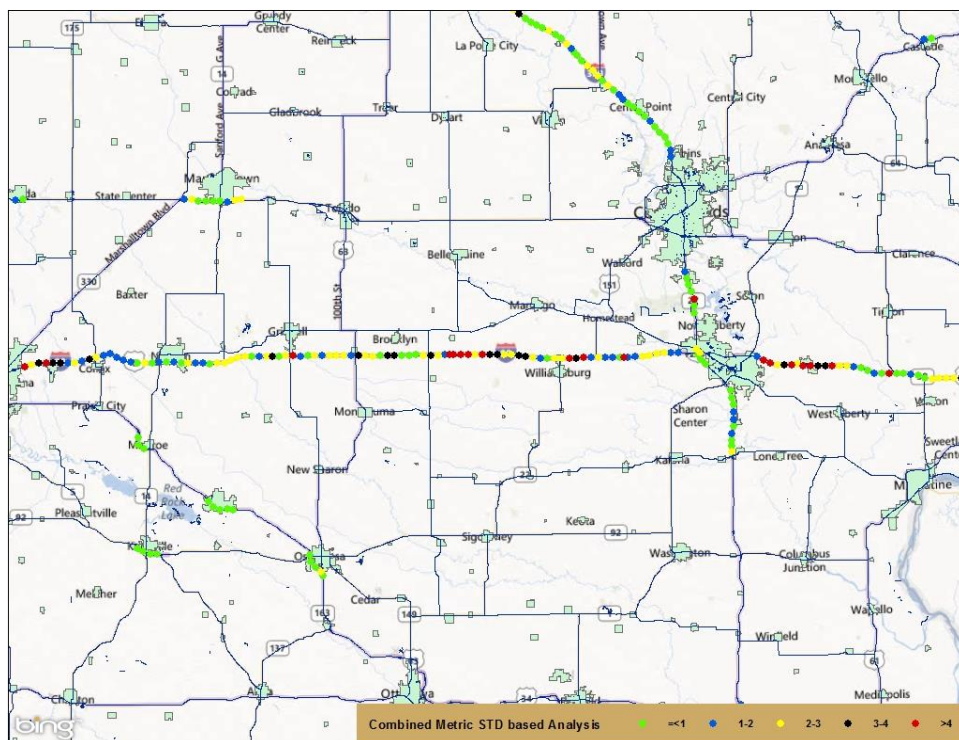
Figure 3.6 Standard deviation-based analysis of composite metric for I 80 and I-380

While differences can be observed among the various metrics, many segments were ranked or categorized highly by multiple metrics. Interestingly, both high and low traffic-volume locations were represented among the top categories, suggesting that the rankings were not driven by traffic volumes.

Several high traffic-volume locations, such as those located near urban areas or along commuter corridors, or both, were consistently ranked highly among all metrics. For example, locations near the Des Moines and Iowa City metropolitan areas were often prominently represented. Conversely, several lower traffic-volume rural, non-commuter locations were also prominently represented, such as Interstate 35 near US 30 and Interstate 80 west of Iowa City.

Additionally, many of the highly categorized locations were adjacent to, or near, other highly categorized sites. Therefore, the analysis results cannot only facilitate targeted site investigation, specifically along the individual one-mile segments on which the metrics were computed, but also investigation of multiple continuous segments.

Figure 3.5 more clearly conveys a several-mile section of Interstate 35 near US 20 consistently ranked in the top two categories of the composite metric. Comparatively, many of the proximate sections immediately to the north and south were ranked in the lowest two categories.

While highly categorized sites may be of primary interest, visual presentation of the standard deviation-based analysis also conveys locations along which winter-weather conditions have not

historically had a significant impact on crash experience. This is not to suggest that winter-weather conditions are not of concern at these locations. Conditions, such as traffic, terrain, roadway alignment, alignment, operations, and roadside safety features, may simply be different at these sites.

Figures 3.7 and 3.8 present the standard deviation-based analysis for two-lane road segments.
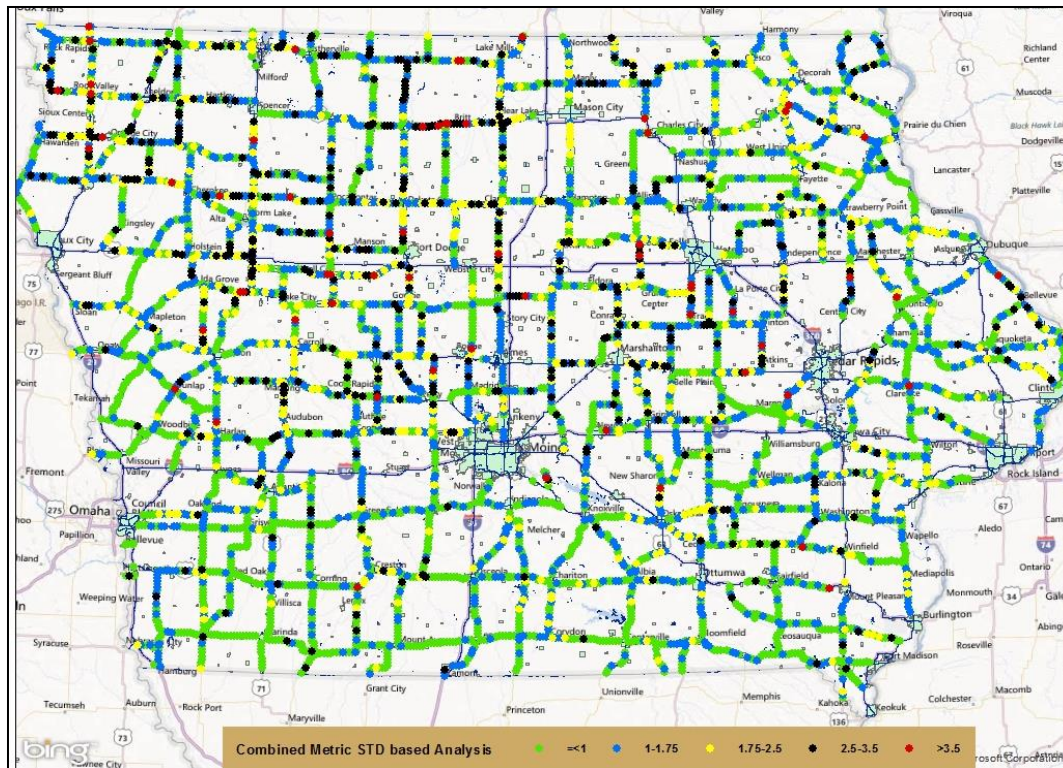
Figure 3.7 Standard deviation-based analysis of composite metric for two-lane roadways

16
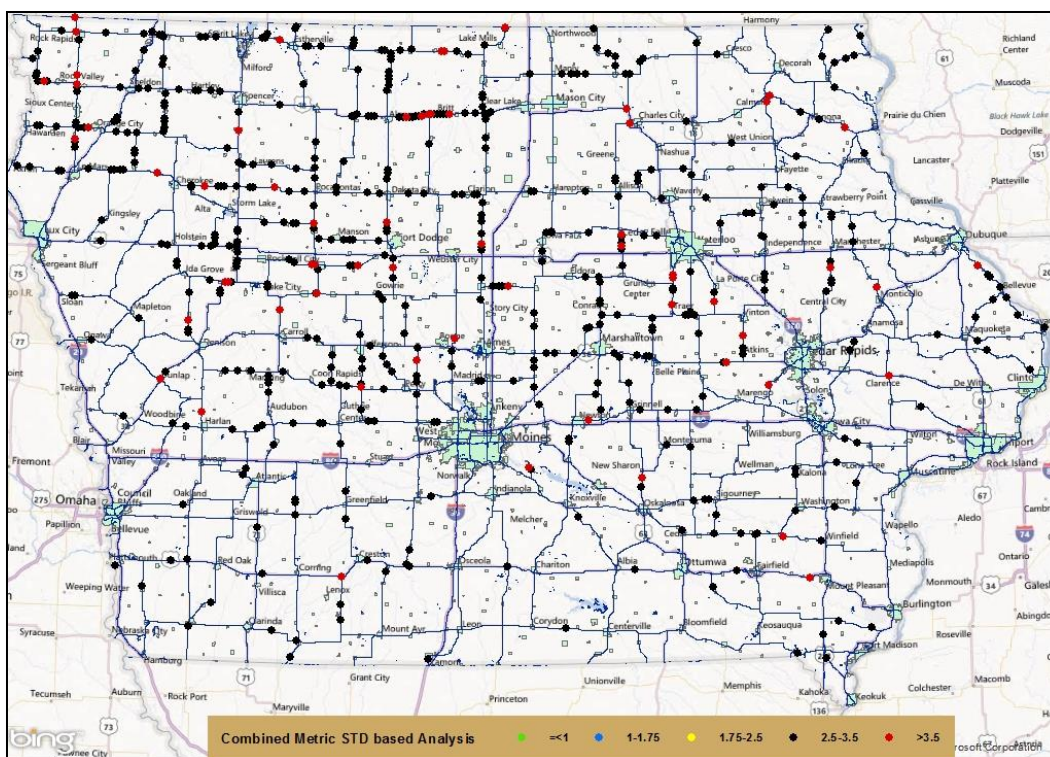
Figure 3.8 Standard deviation-based analysis of composite metric for two-lane roadways – top categories

The two-lane roads represent about 80 percent of the rural primary system, compared to the approximately 11 percent represented by Interstates/freeways. However, the vehicle miles traveled on each is nearly equal, indicating that the traffic volumes on the two-lane roads are much lower.

Given the extent of the two-lane network, variability among traffic volumes and roadway or roadside conditions increases as well as the spatial distribution of highly ranked sites. Additionally, the winter-weather crash frequency on a per site basis is much lower compared to the Interstate/freeway system; in other words, highly ranked two-lane sites may possess a relatively low winter-weather crash frequency.

Figure 3.7 presents the comprehensive statewide analysis using the composite metric. Presentation of all categorized sites in this manner can make it challenging to identify the more highly ranked sites visually. Figure 3.8 contains only the highly ranked road segments. The spatial distribution of highly ranked sites is evident; however, several multi-segment locations are also apparent.

While the standard-deviation analyses were conducted independently for each metric, the results should be used in conjunction with each other to identify and prioritize sites for detailed investigation. The composite metric, in part, addresses the need to consider the individual metric analysis results collectively, and was the preferred metric of the Iowa DOT.

In addition to the standard deviation-based results, the underlying, original metric values may be utilized to further refine site selection and prioritization. This may be of more significance on the two-lane road system, where winter-weather crash experience on a site-by-site basis is comparatively lower.

3.2 Moving Average Analysis

The primary objective of the moving average analysis was to utilize the spatial proximity of adjacent one-mile segments to expand the minimum length of locations of interest from one to three miles systematically. This analysis was performed on rural Interstates/freeways in Iowa by computing a moving average composite metric for three-mile sections.

An initial three-mile section was created at the beginning of each route and moved at an increasing one-mile increment until the end of the route. The composite metric value for each constituent one-mile segment was averaged to yield the average composite metric for the three-mile section.

For example, for a route beginning at mileage 0.0, the first three consecutive one-mile roadway segments represented mileages of 0.0 to 1.0, 1.0 to 2.0, and 2.0 to 3.0. The composite metric values for these segments were averaged to yield the new average composite value for mileage 0.0 to 3.0.

The three-mile section was then incremented by one mile to now represent mileage 1.0 to 4.0. The corresponding segments were combined, and their composite metric values averaged. This process was repeated until the end of each route.

Figure 3.9 presents the road segments categorized by the resulting moving average composite metric.
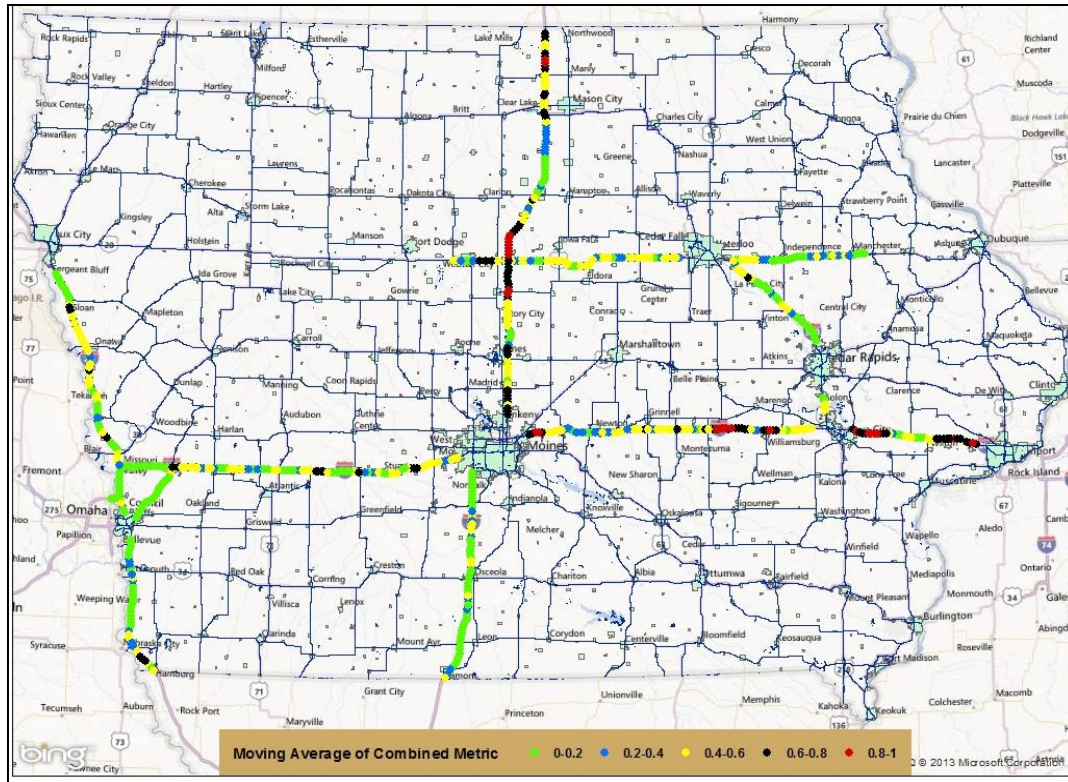
Figure 3.9 Moving average analysis of composite metric for Interstates

Figure 3.10 limits the sites presented to only those within the highest categories.
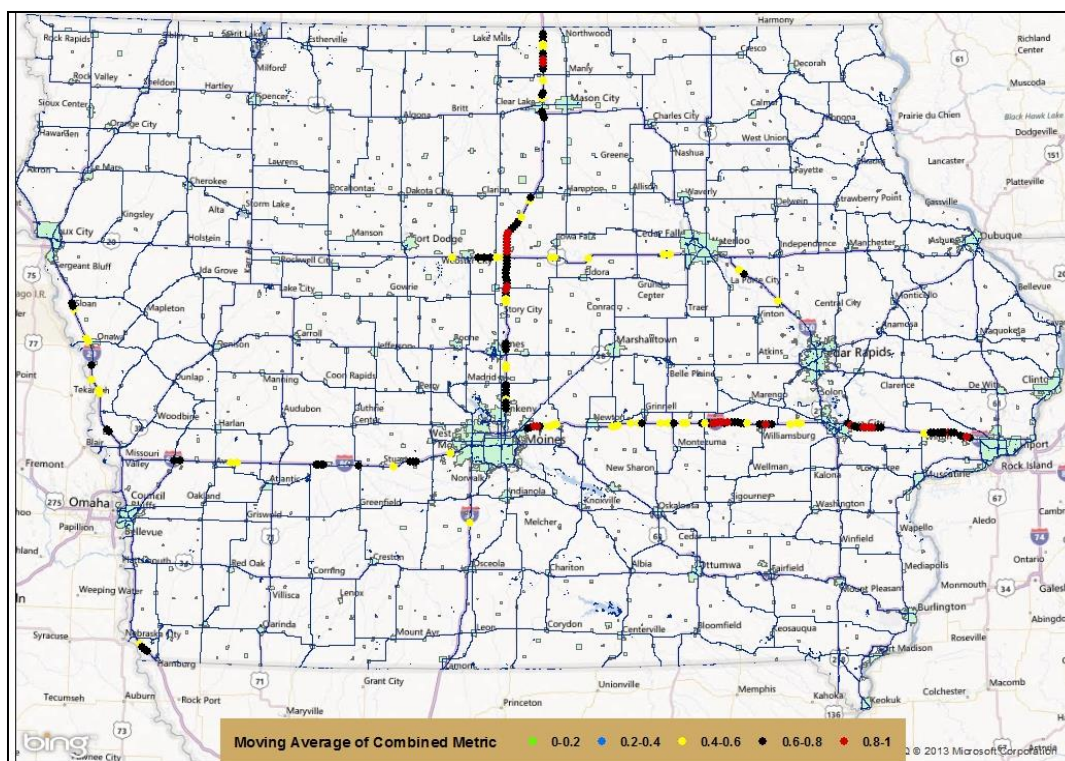
Figure 3.10 Moving average values of the composite metric – top categories

Several continuous collections of three-mile sites are apparent on Interstate 35 north of Des Moines and Interstate 80 east of Des Moines. As was observed in the standard deviation-based analysis, sites near urban areas, along commuter corridors, and almost entirely rural in nature are represented.

A benefit of the moving average analysis is that longer analysis sections, and a more extensive set of locations, may be considered for additional analysis. While unique, localized issues may exist on one-mile road segments, and definite benefits exist in identifying and addressing these issues; performing detailed analysis on more expansive sections facilitates addressing more of the network and may reveal common maintenance and operational practices.

3.3 Comparison of Standard Deviation and Moving Average Analyses

A comparison of the top 25 Interstate/freeway road segments identified in each of the analyses— standard deviation-based analysis of crash density, crash proportion, crash severity, composite metric, and moving average composite analysis—are presented in Table 3.2. These segments represent about 3 percent of the total rural, Interstate, and freeway network.

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Table 3.2. Site prioritization analysis results comparison

Rank	Density (D)				Proportion (P)				Severity (S)				Composite (C)				Composite Moving Average (M)			
	P	S	C	M	D	S	C	M	D	P	C	M	D	P	S	M	D	P	S	C
1		20	7	4	7			24										6		9
2					11		3										20		13	
3					17		8	10					11	2						
4			23	8							24	18					1		20	7
5							6							12				22		12
6							9	1		15				5				16		
7	1			24			10	12					1		20	4				13
8							19	16				20	17	3		10	4			23
9														6		1		10		
10								9						7		12	17	3		8
11	2		3											13		13				
12							5							22		5		7		10
13							11	13	20		2					7		13		11
14							16						21					18		
15						6														17
16								6						14				8		19
17	3		8	10												15				
18								14											4	24
19														8		16				
20		13		2					1		7	4							8	
21			14																	
22							12	5												
23													4			8				
24															4	18	7	1		
25																				

Table 3.2 reveals that the highest segment rankings among the different methods may differ. No segment is identified within the highest 3 percent of Interstate/freeway mileage by all the methods.

Rankings based on the composite moving average analysis and standard deviation-based composite analysis share the most common segments (11) within the top 25. This is to be expected, because the same metric was employed, simply over different linear extents.

Ranking based on standard-deviation analysis of crash proportion had 10 road segments in common with the composite metric-based rankings (both standard deviation and moving average), but only three and one in common based on density and severity, respectively. One possible reason for this difference is non-consideration of traffic volume in developing these two metrics.

Roads with high volumes typically experience more crashes and, therefore, have a higher crash density. The severity metric also does not account for the changes in total injuries resulting from different vehicle occupancies and traffic volumes. Exposure-based metrics, considering traffic volume, were not derived for this study because availability of traffic volume data during winter-weather conditions was limited. Only average annual daily traffic (AADT) was comprehensively available, which may not accurately represent travel during winter events, with localized variations.

CHAPTER 4. DATA

This chapter outlines the various data sets, sources, and processing steps used to develop SPFs for winter-weather crashes in Iowa. The general data sets employed were crash, roadway, and weather for the winter seasons—defined as October 15 through April 15 by the Iowa DOT—of 2008/2009 through 2011/2012. These winter seasons were selected primarily based on the availability of the data.

4.1 Data Sets

To consider the factors for developing SPFs, crash, roadway/traffic and weather-related data sets were acquired. These data were obtained from different sources and integrated to establish a suitable data set for model development.

4.1.1 Crash Data

The Iowa DOT maintains a geospatial database of all reportable crashes occurring on all public roadways in the state. The crash database contains detailed information about each crash event as well as the individuals and vehicles involved. Each crash possesses a unique crash identifier, and the time of crash occurrence and location are also maintained and may be used for data aggregation over time and space.

Winter weather-related crashes were extracted from the comprehensive crash database for the winter seasons from 2008/2009 through 2011/2012. Winter weather-related crashes were defined as those in which any of the following were reported for the crash event or for any driver or vehicle involved in the crash (Hans et al. 2011):

- Weather conditions: Sleet/hail/freezing rain or Snow or Blowing sand/soil/dirt/snow
- Surface conditions: Ice or Snow or Slush
- Vision obscurement: Blowing sand/soil/dirt/snow

The winter weather-related crashes were limited to those occurring on state (primary) roadways, corresponding to the one-mile segments previously utilized in analysis. However, in contrast to the previous analyses, both rural and urban roadways were considered.

4.1.2 Weather Data

Weather-related information for each crash was obtained for the Iowa DOT maintenance garages (cost centers) responsible for winter maintenance of the roadways. Specifically, cost centers represent Iowa DOT maintenance garages containing maintenance materials and equipment. Crews are dispatched from these garages to perform winter-weather maintenance activities. Each cost center possesses a specified set of roadways on which the maintenance crews associated with that particular cost center perform the maintenance activities during winter weather.

The Iowa DOT supplements crew-reported information with proximate RWIS data to yield information such as air temperature, pavement temperature, wind speed, visibility, and precipitation type while performing the maintenance activities. Specific types of maintenance activities were also reported. The analysis period was, in part, driven by the more recent and comprehensive availability of integrated weather-related information.

4.1.3 Roadway and Traffic Volume Data

Roadway geometry-related attributes and traffic volume data for each road segment, maintained through a geographic information management system (GIMS), were obtained from the Iowa DOT Office of Research and Analytics, Division of Planning and Programming. Several roadway geometry-related attributes such as surface width, lane width, number of lanes, shoulder width, and shoulder type are reported in the GIMS database along with the most recent AADT for the corresponding segments of roadways.

Roadway geometry and traffic volume data were collected for one-mile road segments for the four winter seasons analyzed. Each one-mile road segment was assigned a unique identifier.

4.2 Data Processing

Typically, SPFs have been developed to estimate crash frequency using site or roadway characteristics such as lane width and traffic volume expressed as AADT. Incorporating weather-related attributes representing the crash conditions in SPFs is more complex and labor intensive. It was necessary to integrate weather data with crash data to develop SPFs to predict winter-weather crashes as a function of variables related to winter-weather conditions such as visibility, pavement temperature, air temperature, and wind speed.

The primary challenge in processing the data was integrating the weather information with the crashes occurring on the one-mile road segments of different road types. Using a geographic information system (GIS), and specifically Esri's ArcGIS, crashes were assigned to the appropriate one-mile road segments and cost centers based on spatial location and proximity. Iowa DOT weather information was integrated with each crash based not only on location, but also common dates and times.

Multiple crew reports were obtained for many of the crashes, because there were multiple crews reporting weather information on the same day the crashes occurred. Only one crew report was retained for each crash based on two criteria.

Precipitation intensity was considered to screen crew reports. If precipitation intensity for multiple reports was the same for a crash, precipitation duration was taken into consideration. The crew report with greater precipitation duration was retained.

Once the integration processes were completed, 92 percent (13,859) of the winter-weather crashes occurring during the four winter seasons were found to be associated with crew-reported

weather. These crashes were assigned to the one-mile road segment according to the road type of Interstate/freeway, other multilane, or two-lane roadway. Details on the steps involved for data processing and integration are shown in Figure 4.1.
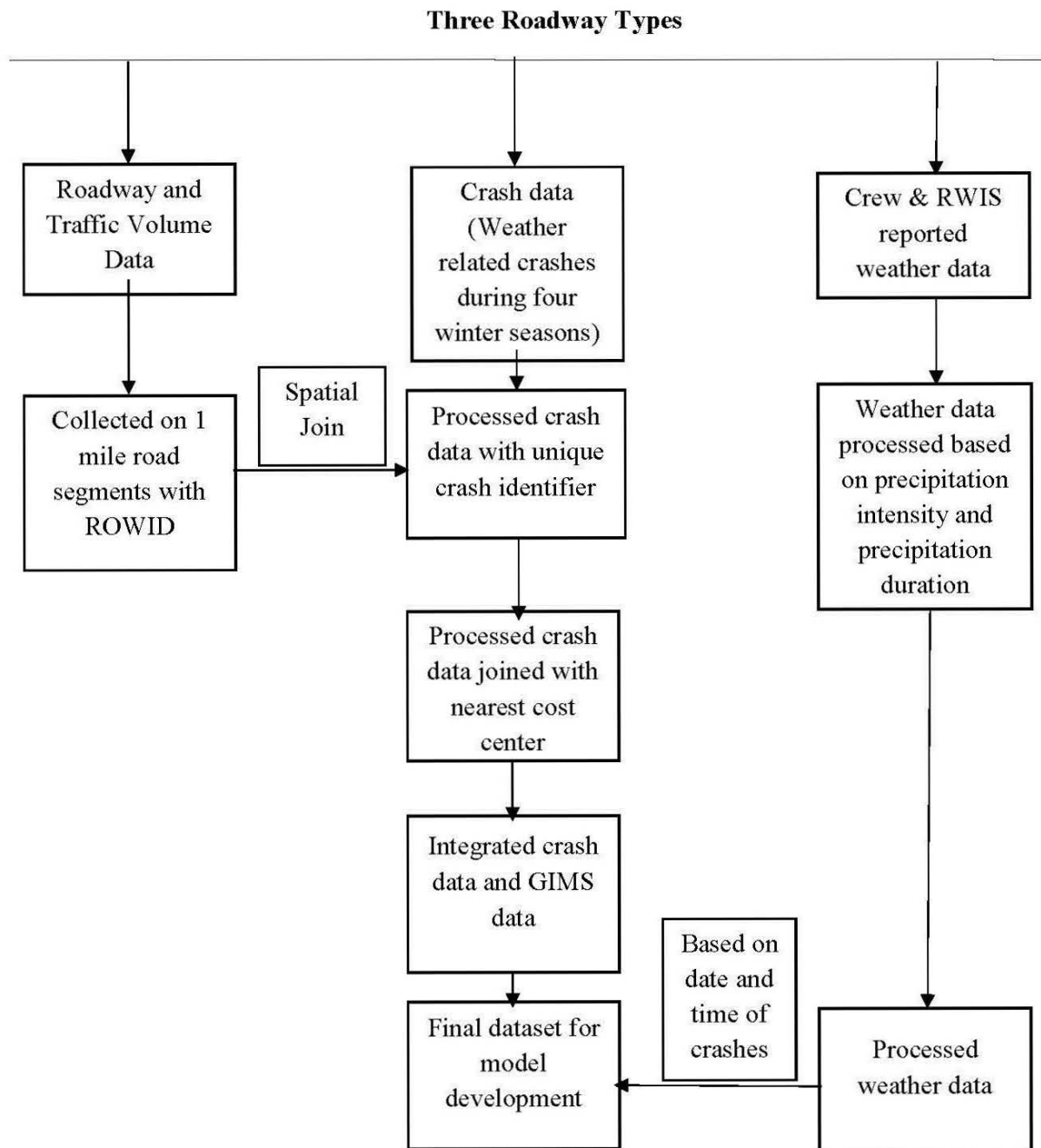
Figure 4.1 Crash data, weather data, and roadway data integration steps

4.3 Descriptive Statistics

Of the 13,859 winter weather-related crashes included for analysis, 6,210 crashes occurred on Interstates/freeways, while 3,898 crashes occurred on multilane roadways (divided and undivided roadways), and 3,751 crashes occurred on two-lane roadways. Descriptive statistics for the weather-related factors considered for the model development process for each class of roadway are presented in Tables 4.1 through 4.3.

Table 4.1 Descriptive statistics of weather attributes for crashes on Interstates/freeways

Total number of crashes	N = 6,210			
Variable	**Interstate/freeway**			
	Min.	**Max.**	**Mean**	**SD**
Air Temp (°F)	-25	51	20.46	10.4
Pavement Temp (°F)	-21	54	22.46	8.9
Wind Velocity (mph)	0	117	14.96	8.7
Visibility (miles)	1	5	3.65	1.31
Snow Amount (inches)	0	12.5	2.01	2.13

Table 4.2 Descriptive statistics of weather attributes for crashes on multilane divided/undivided roadways

Total number of crashes	N = 3,898			
Variable	**Multilane divided/undivided**			
	Min.	**Max.**	**Mean**	**SD**
Air Temp (°F)	-29	42	19.6	10.9
Pavement Temp (°F)	-31	54	21.32	10.05
Wind Velocity (mph)	0	117	14.13	8.6
Visibility (miles)	1	5	3.77	1.31
Snow Amount (inches)	0	16	1.94	2.2

Table 4.3 Descriptive statistics of weather attributes for crashes on two-lane roadways

Total number of crashes	N = 3,751			
Variable	**Two-lane roadway**			
	Min.	**Max.**	**Mean**	**SD**
Air Temp (°F)	-29	50	22.01	9.86
Pavement Temp (°F)	-26	56	23	9.24
Wind Velocity (mph)	0	57	15.24	9.07
Visibility (miles)	1	5	3.79	1.3
Snow Amount (inches)	0	16	1.83	2.1

Once all the crashes and factors to be considered for modeling were prepared, the average number of crashes was computed for each one-mile road segment for the three roadway types for the four winter seasons. Average values for each segment for the weather-related factors were considered for developing the SPFs.

The total frequency of one-mile Interstate/freeway, multilane divided/undivided, and two-lane road segments along which at least one winter weather-related crash occurred during the four winter seasons in Iowa were 995 (~87 percent of segments), 887 (~73 percent of segments), and 2,325 (~33 percent of segments), respectively. Tables 4.4 through 4.6 show the descriptive statistics for the average values of the factors considered for final modeling. In some cases, the minimum and maximum values may represent outlying values, arising from data coding or assignment issues, particularly with respect to AADT.

Table 4.4 Descriptive statistics of factors for SPF development (Interstate/freeway)

Number of roadway segments	N = 995			
Variable	**Interstate/freeway**			
	Min.	**Max.**	**Mean**	**SD**
Segmental Crash Frequency	1	54	6.24	6.6
Segmental Air Temp (°F)	-25	37	21.67	6.54
Segmental Pavement Temp (°F)	-9	38.8	22.28	7.21
Segmental Wind Velocity (mph)	0	37.57	14.03	5.9
Segmental Visibility (miles)	0	5	3.35	1.36
Segmental Snow Amount (inches)	0	10	1.97	1.36
Segmental AADT	90	113,600	23,958	17,056
Segmental Surface Width	16	90	30	10
Segmental Posted Speed Limit (mph)	35	70	67	4.68

Table 4.5 Descriptive statistics of factors for SPF development (multilane divided/undivided)

Number of roadway segments	N = 887			
Variable	**Multilane divided/undivided**			
	Min.	**Max.**	**Mean**	**SD**
Segmental Crash Frequency	1	27	4.4	4.36
Segmental Air Temp (°F)	-18	38	20.5	7.43
Segmental Pavement Temp (°F)	-8	54	21.28	7.82
Segmental Wind Velocity (mph)	0	50	13.64	6.67
Segmental Visibility (miles)	0	5	3.22	1.63
Segmental Snow Amount (inches)	0	12.5	1.9	1.52
Segmental AADT	50	34,225	11,023	5,891.44
Segmental Surface Width	12	72	32	11
Segmental Posted Speed Limit (mph)	20	65	52	13

Table 4.6 Descriptive statistics of factors for SPF development (two-lane roadway)

Number of roadway segments	N = 2,325			
Variable	**Two-lane roadway**			
	Min.	**Max.**	**Mean**	**SD**
Segmental Crash Frequency	1	12	1.61	1.26
Segmental Air Temp (°F)	-15	50	21.85	9.43
Segmental Pavement Temp (°F)	-12	56	22.23	9.54
Segmental Wind Velocity (mph)	0	50	14.18	8.81
Segmental Visibility (miles)	0	5	3.1	1.81
Segmental Snow Amount (inches)	0	14.5	1.84	1.92
Segmental AADT	50	52,700	3,345	2,652
Segmental Surface Width	14	76	26.3	6.56
Segmental Posted Speed Limit (mph)	20	70	52.71	6.75

CHAPTER 5. DEVELOPMENT OF CRASH FREQUENCY PREDICTION MODELS FOR EMPIRICAL BAYES ANALYSIS

5.1 Overview of Site Prioritization Techniques and Empirical Bayes Method

Identifying, or prioritizing, sites for additional safety review or improvement within a road network is an essential task for engineers in state agencies to ensure efficient allocation of limited resources for mitigating possible safety issues. There are various methods, mostly relying on historic traffic crash records, to obtain an estimate of safety for various traffic entities. The majority of these traditional methods use raw crash data, namely the crash frequency method, the crash rate method, the rate quality control method, the crash severity method, and the safety index method.

Problems associated with these naïve statistical methods to identify hot spots for safety improvements are manifold, with the regression to the mean (RTM) problem as the most prominent. Analysts or engineers must take into account this phenomenon when identifying potential safety issues for a single site or a group of sites.

RTM reflects the tendency of the observed crashes to regress or return to the mean in the year following an unusually high or low crash frequency (counts). The effect of RTM can arise when sites with high short-term crash counts are selected as candidate sites for safety improvements or treatments.

In this case, the counts of the crashes at these sites would decrease due to the RTM and regress toward their long-term mean irrespective of the implementation of the treatment. The safety effectiveness of the implemented treatment could be overestimated if the RTM was not taken into account.

Because of the random variation in crash occurrences, the sites with the highest numbers of crashes in one period are very likely to experience lower crash frequencies in the next period, and vice versa. So, relying solely on crash records and using one of the traditional methods does not warrant the analysis to account for the RTM and evaluate the effectiveness of a particular treatment aimed at improving safety at particular sites. Despite their simplicities, naïve statistical methods using raw crash records have serious limitations for screening road networks for safety improvements when evaluating the effectiveness of a treatment to trigger safety improvements at particular sites.

In recent years, techniques for screening road networks to identify crash locations have become more sophisticated and require more data as inputs. SPFs are frequently used in the network screening and evaluation process and can be used to reduce the effects of RTM. Those can be used to estimate the expected safety of a roadway segment or location based on similar facilities.

Typical SPFs have been developed to estimate crash frequency using site or roadway characteristics such as lane width and traffic exposure expressed as AADT. These typical SPFs

normally do not incorporate additional weather-related variables, because this would be more complex and labor intensive.

This study developed SPFs for three types of roadways in Iowa to predict winter weather-related crashes as a function of several factors related to winter-weather conditions such as visibility, pavement temperature, air temperature, and wind speed.

The empirical Bayes approach was used to combine the predicted number of crashes from the SPFs with the observed crash counts at a location to produce an improved estimate of the expected number of crashes.

Because crashes are random in nature, the empirical Bayes method takes into account the phenomenon of RTM. Extensive research has also shown that the empirical Bayes approach is the most consistent and reliable method for identifying sites with potential for safety improvement (Cheng and Washington 2008).

The implementation of the empirical Bayes method is connected with the results from the modeling performed during the development of SPFs. Using the overdispersion parameter found during modeling (crashes fitting a negative binomial model), a weight can be determined as follows:

$$w = \frac{1}{1+k(n*E(\lambda))} \tag{5.1}$$

where k is the overdispersion parameter derived from the SPFs modeled from negative binomial distribution and $E(\lambda)$ is the predicted number of crashes for a given roadway, with n being the number of years crash observations are made for.

According to the empirical Bayesian procedure, the weight factor is then applied to the predicted number of crashes (calculated from SPFs) and actual observed number of crashes to determine the estimated number of crashes as follows:

$$\lambda = w. E(\lambda) + (1 - w)k \tag{5.2}$$

where λ is the improved estimated number of crashes and k is the total number of crashes observed in n years.

The difference of the empirical Bayesian adjusted crash frequency and the predicted crash frequency from an SPF is referred to as the potential for safety improvement (PSI). Figure 5.1 represents the graphical definition of the PSI.
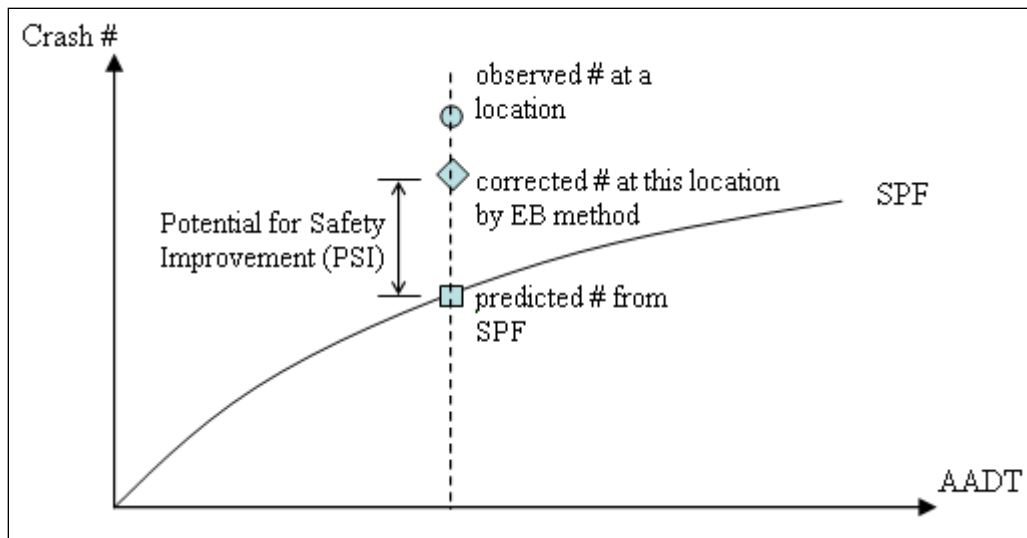
Figure 5.1 Calculation of PSI using empirical Bayes method (Source: Illinois DOT)

The higher the PSI value for a road segment, the higher potential exists for improving safety on that road segment. Considering the PSI, the roadway segments are ranked or prioritized for investing resources at those locations so that highest possible safety improvement can be achieved.

In this study, a primary objective was prioritizing segments for additional analysis to determine if, and what types of, safety improvements may be feasible.

5.2 Development of Crash Frequency Models for Winter Weather-Related Crashes

After the integration of the crash data for the 2008/2009 through 2001/2012 winter periods, crash frequency was modeled as a function of the geometric and traffic characteristics of different roadway types and weather-related variables derived from crew-reported and proximate RWIS weather information. Three frequency models were developed for Interstates/freeways, multilane divided/undivided roadway, and two-lane roadways.

Poisson distribution is normally assumed for modeling the probability of crash frequency on road segments. Overdispersion was present in the crash frequencies for Interstates/freeways and multilane divided/undivided roadway segments. As such, a negative binomial modeling approach (with variance greater than mean of crashes) was taken to estimate the frequency of crashes on these two types of roadway segments. Although the value of the overdispersion parameter was not very high, it was statistically significant for both classes of roadways.

For two-lane roadways, the variance and mean of crash frequencies for the road segments were the same, and, as such, a Poisson regression model was developed to estimate the probability of the number of crashes on this type of roadway.

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5.2.1 Poisson Regression Model

Generalized linear models (GLMs) are the most commonly employed models for predicting collision or crash frequency. A GLM could be applied to model both continuous and discrete variables. For the purpose of this research, it was assumed that the number of crashes over a period of time follows a count process such as Poisson distribution. Mathematically, if the number of crashes (Y) is assumed to follow a Poisson distribution, the probability of crash frequency can be expressed as shown in this equation:

$$P(Y = K) = \frac{e^{-\mu}\mu^{k}}{k!}, \ K = 0, 1, 2, 3 \ \ldots\ldots \tag{5.3}$$

where P (Y = K) is the probability of having k crashes over a period of time, Y is the number of crashes over a period of time, and μ is the expected number of crashes over a period of time, known as the Poisson parameter.

The Poisson regression models are estimated by specifying the Poisson parameter as a function of explanatory variables (geometric conditions of roadways, traffic exposure, pavement conditions, visibility, etc.) potentially having significant impact on the occurrence of crashes over a period of time. The model parameter μ in equation 5.3 is commonly assumed to be a function of these different factors using a non-linear link function g(.), as shown in the following equation:

$$g(\mu) = \ \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \tag{5.4}$$

where, β_0 is the intercept, β_k is the coefficient of explanatory variable X_k, and $X_k = k^{th}$ is the explanatory variable that could be related to road, traffic, or weather characteristics.

The most commonly used non-linear link function in road safety modeling is the log link function ensuring positive estimates for the mean. It can be expressed mathematically as follows:

$$\ln(\mu) = \ \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k \tag{5.5}$$

which can also be expressed as

$$\mu = \exp(\beta_0 + \sum_{k=1}^{n} \beta_k X_k) \tag{5.6}$$

Coefficients of the explanatory variables can be estimated using the maximum likelihood method (ML) by using the following equation:

$$LL(\beta) = \ \sum_{i=1}^{n}[y_i \ln(\mu_i) - \mu_i - \ln(y_i!)] \tag{5.7}$$

where $LL(\beta)$ is the log of the likelihood function.

Exposure, which can be represented by traffic volume, segment length, or the cross product of them, is one of the most important factors affecting crash frequency. The exposure can be included in a crash frequency model either as a variable or as an offset. For the latter case, equation 5.5 can be written as follows:

$$\ln(\mu) = \beta_0 + \sum_{k=1}^{n} \beta_k X_k + \gamma \ln(EXP) \tag{5.8}$$

where *EXP* is the exposure and γ is the exponent of the exposure.

5.2.2 Negative Binomial Regression Model

One limitation of the Poisson model is that the mean of the crash frequency is assumed to be equal to the variance. However, in practice, the variance of crash frequency is normally greater than its mean, which is known as the overdispersion problem.

Overdispersion affects the standard error estimates of the parameters (Cameron and Trivedi 1998), making some insignificant variables significant and drawing incorrect inferences from the model estimation. Negative binomial distribution can address this problem. The negative binomial model can be derived from the Poisson model by adding a gamma distributed error term to equation 5.5 as follows:

$$\ln(\mu) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon \tag{5.9}$$

where exp (ε) is assumed to follow a gamma distribution with both of its parameters equal to φ. The resulting crash frequency (Y) should have a variance that is a function of the mean and φ, as given by the following equation:

$$Var = \mu + \varphi \mu^2 = \mu + \frac{\mu^2}{\alpha} \tag{5.10}$$

where $\alpha = 1/\varphi$ is known as the overdispersion factor.

5.3 Model Results

Table 5.1 and 5.2 show the negative binomial regression estimation results for Interstate/freeway and multilane divided/undivided roadway segments. Table 5.3 shows the Poisson regression model estimation results for two-lane roadway segments.

Table 5.1 Negative binomial model for Interstate/freeway road segments

Variables	Estimates	Std. Errors	Pr
Intercept	-4.72	0.48	<0.001
Log of AADT	0.65	0.038	<0.001
Air temperature (°F)	-0.02	0.005	<0.001
Pavement Temperature	0.017	0.005	<0.001
Surface Width (feet)	0.02	0.003	<0.001
Visibility (miles)	0.03	0.016	0.053
Posted Speed Limit (mph)	-0.01	0.005	0.091
Null Deviance	1915.33		
Residual Deviance	961.79		
Overdispersion Factor	0.2343		

Table 5.2 Negative binomial model for multilane road segments

Variables	Estimates	Std. Errors	Pr
Intercept	-5.42	0.41	<0.001
Log of AADT	0.73	0.041	<0.001
Visibility (miles)	0.04	0.015	0.004
Air Temperature (°F)	-0.006	0.003	0.0853
Posted Speed Limit (mph)	-0.011	0.002	<0.001
Surface Width (feet)	0.02	0.002	<0.001
Null Deviance	1622.93		
Residual Deviance	797.63		
Overdispersion Factor	0.16		

Table 5.3 Poisson model for two-lane road segments

Variables	Estimates	Std. Errors	Pr
Intercept	-3.04	0.22	<0.001
Log of AADT	0.37	0.03	<0.001
Wind Speed (mph)	0.005	0.002	0.0156
Visibility (miles)	0.023	0.009	0.0109
Surface Width (feet)	0.0162	0.002	<0.001
Null Deviance	1493.6		
Residual Deviance	1143		

5.4 Model Interpretation

Poisson and negative binomial models are of exponential functional form; a measure of sensitivity of crash frequency to the corresponding variable can be attributed to the exponent in the model. Thus, elasticity for the variables in the models were computed to measure the sensitivity of crash frequency to the corresponding variables. Elasticity is defined as the percentage change in the dependent variable resulting from a 1 percent change in an explanatory variable. Table 5.4 shows the elasticity values for the variables considered when developing models for the three different classes of roadways.

Table 5.4 Estimated elasticities

Variable	Elasticties (for Interstate/freeway)	Elasticties (multilane)	Elasticties (two-lane)
Log of AADT	6.4	6.74	2.93
Air Temperature	-0.43	-0.12	
Pavement Temperature	0.38		
Road Surface Width	0.58	0.71	0.43
Visibility	0.06	0.13	0.07
Posted Speed Limit	0.66	0.53	
Wind speed			0.07

The following specific observations can be made from the modeling outcomes for the three functional classes of roadways. The results for the Interstate/freeway class and multilane divided/undivided class are discussed together because the findings from the models were similar for these two functional classes of roadways.

5.4.1 Interstate/Freeway and Multilane Divided/Undivided Roadways

Traffic Volume

As expected, traffic volume, represented by AADT for each specific road segment, was found to be significant with a positive sign, suggesting that an increase in traffic volume would result in an increase in the mean number of winter weather-related crashes expected to occur on the road segment during the winter season. The value of the coefficient associated with the traffic volume is 0.65, which is less than one and suggests that the moderating effect of traffic volume is non-linear with a decreasing trend. A similar value was found for road segments belonging to multilane divided/undivided roadways. Previous literature also reports similar effects of traffic volume on speed and weather-related crash frequency (Monsere et al. 2008). Traffic volume represented by AADT in the current study has a considerable impact on safety, as an increase in traffic volume (ranging from 90 to 113,600 during the winter seasons) by 1 percent would cause the mean number of crashes to increase by 6.4 percent on Interstates/freeways. The elasticity value for volume reveals that a 1 percent increase in AADT (ranging from 50 to 34,225 during

the winter seasons) will result in a 6.74 percent increase in the mean crash frequency on multilane divided/undivided roadway segments.

Air Temperature

Air temperature was found to be significant with a negative sign, suggesting that the mean number of weather-related crashes will increase with the decrease in the air temperature. The elasticity value for the air temperature reveals that a 1 percent increase in air temperature during the winter season would decrease the mean number of crashes by 0.43 percent on Interstate/freeway roads for air temperatures ranging from -25 to 37 degrees Fahrenheit. This result is in agreement with some of the previous findings (Fu et al. 2006). The elasticity value for multilane divided/undivided roadways indicates a 0.12 percent decrease in the mean number of crashes with a 1 percent increase in air temperature (from -18 to 38 degrees Fahrenheit) during the winter season.

Pavement Temperature

Modeling results reveal a significant relationship between average pavement temperature and mean number of crashes during the winter season on Interstate/freeway road segments. The elasticity value for the pavement temperature shows that a 1 percent increase in pavement temperature would cause the mean number of weather-related crashes to increase by 0.38 percent when pavement temperature ranges from -9 to 38.8 degrees Fahrenheit. Although the finding seems counterintuitive, it is possible that the increase in pavement temperature might result in different levels of variation in road surface conditions affecting crash frequency. Pavement temperature was not found to be statistically significant with crash frequency on multilane divided/undivided roadway segments.

Road Surface Width (in Feet)

Road surface width (measured from edge line to edge line) was found to be statistically significant, and the positive sign indicates that roadway segments with a wider surface were associated with a higher number of winter weather-related crashes. Results revealed that a 1 percent increase in the roadway surface width (from 16 to 90 feet) would result in 0.58 percent increase in the mean number of crashes on Interstate/freeway and 0.71 percent on multilane divided/undivided road segments (from 12 to 72 feet) during the winter seasons. On Interstate/freeway roadways, wider roadways may make drivers feel safer, and they may not adequately drive to the environmental and surface conditions. This result may also suggest that drivers drive more cautiously during winter weather on narrower roadways. Drivers are also prone to changing lanes on multilane roadway segments, which may increase the potential for a greater number of crashes on road segments with larger surface widths. Previous studies have also found similar results in developing crash frequency models for speed and winter weather-related crashes (Monsere et al. 2008).

Visibility (in Miles)

Visibility was found to be significant with a positive relationship, suggesting that the mean number of winter weather-related crashes during winter seasons will increase with better visibility. Although this finding might seem counterintuitive, the increase in the frequency of crashes during winter seasons might be attributed to the risk compensating behaviors of drivers due to increased visibility. Previous research findings showed a decrease in average vehicle speeds during winter weather with a decrease in visibility below 0.4 kilometers (Knapp and Smithson 2001). The elasticity value for visibility indicates that a 1 percent increase in visibility (ranging from 0 to 5 miles) during winter seasons will increase the mean number of winter weather-related crashes expected along Interstate/freeway road segments by 0.06 percent. The elasticity value for visibility (ranging from 0 to 5 miles) was found to be 0.13 for multilane divided/undivided roadway segments. These results are similar with those of a past study, Hermans et al. (2006a), which used data from 37 sites. However, the results of this study are different from those of the study conducted by Usman et al. (2011), which found a negative relationship between visibility and crash frequency during a storm event. The models developed in this research are not winter storm event–based models but rather consider all the weather-related crashes that occurred during the winter seasons. Large aggregation of data at the temporal level may have masked the effect of visibility in the current model.

Posted Speed Limit

Posted speed limit was found to be significant with a negative sign, suggesting that the mean number of winter weather-related crashes would increase with a decrease in posted speed limits along roadway segments during winter-weather seasons. This finding is in agreement with a previous study (Monsere et al. 2008). The elasticity value for the posted speed limit variable reveals that a 1 percent increase in posted speed limit (35 to 70 mph for Interstate and 20 to 65 mph for multilane roadways) will result in a 0.66 percent and 0.53 percent decrease in the mean number of winter weather-related crashes on Interstate/freeway road segments and multilane divided/undivided roadways segments, respectively. The greater variability of vehicle speeds during winter-weather conditions compared to non-winter conditions (Knapp and Smithson 2001) may contribute to this finding. The literature also shows evidence of a decrease in the average winter-weather speed compared to the typical average speed at the same location during non-winter-weather conditions (Knapp and Smithson 2001). In general, actual speed data, in contrast to posted speed limit, may be more appropriate for consideration but was not comprehensively available for this study.

5.4.1 Two-Lane Roadways

Traffic Volume

Traffic volume, represented by AADT, was found to have a statistically significant relationship with the mean number of crashes. The sign of the value of the coefficient was positive, suggesting an increase in the mean winter weather-related crash frequency with an increase in traffic volume. The elasticity value for the AADT suggests that a 1 percent increase in the traffic

volume will result in a 2.93 percent increase in mean crash frequency for AADT ranging from 50 to 52,700 on two-lane roadways.

Road Surface Width (in Feet)

Road surface width was also found to have a significant effect with a positive sign on winter-weather crash frequency for two-lane roadway segments. A similar effect was also found for weather-related crashes occurring on Interstate/freeway and multilane divided/undivided roadway segments during the winter season. A 1 percent increase in road surface width (ranging from 14 to 76 feet) would result in a 0.43 percent increase in weather-related mean crash frequency.

Visibility (in Miles)

Visibility was found to have an effect on mean winter-weather crash frequency for two-lane roadway segments similar to that for Interstate/freeway and multilane divided/undivided roadway segments. Results reveal that a 1 percent increase in visibility (0 to 5 miles) would result in a 0.07 percent increase in the mean number of weather-related crashes on two-lane roadway segments.

Wind Speed

While wind speed was not found to be significant for the frequency models developed for Interstate/freeway and multilane divided/undivided roadway segments, it was found to be statistically significant for two-lane roadways. The positive sign indicates that higher wind speeds were associated with a higher number of crashes. The elasticity value for wind speed (0 to 50 mph) shows that a 1 percent increase in wind speed would result in a 0.07 percent increase in mean weather-related crash frequency along two-lane roadway segments. The results appear intuitive, because higher wind speeds may cause blowing snow effects, which may impair driver performance. This result is in agreement with previous research findings (Knapp et al. 2000, Usman et al. 2011).

5.5 Ranking Results of Roadway Segments Using Empirical Bayes Technique

For demonstration purposes, Tables 5.5 and 5.6 present the top 25 Interstate/freeway and other multilane road segments based on PSI.

Table 5.5 Top 25 roadway segments for potential safety improvements (Interstate/freeway)

Rank	Observed	Predicted	Weight	Adjusted	PSI	Ranking Comparison				
						D	P	S	C	M
1	50	8.65	0.03	48.93	40.28					
2	35	10.93	0.02	34.5	23.57					
3	48	26.56	0.01	47.82	21.26					
4	36	16.3	0.01	35.73	19.42					
5	24	3.21	0.07	22.61	19.4		12		5	
6	29	9.74	0.02	28.56	18.82					
7	26	8.93	0.03	25.57	16.65	22				
8	24	7.11	0.03	23.47	16.36		4			
9	30	13.98	0.02	29.74	15.76					
10	20	3.84	0.06	19.09	15.24		7		10	12
11	21	5.11	0.04	20.31	15.21					
12	27	11.57	0.02	26.7	15.13					
13	22	6.45	0.03	21.46	15.02			8		20
14	23	7.69	0.03	22.56	14.86					
15	30	15.12	0.01	29.78	14.66					
16	21	5.87	0.04	20.43	14.56			10		
17	22	7.13	0.03	21.53	14.41	7	1			24
18	24	9.62	0.02	23.66	14.05					
19	50	36.19	0.01	49.91	13.73					
20	25	11.01	0.02	24.71	13.7					
21	20	5.98	0.04	19.48	13.5	1		20	7	4
22	20	6.7	0.03	19.56	12.86					
23	44	31.26	0.01	43.91	12.65					
24	17	4.24	0.05	16.34	12.1					
25	38	26.81	0.01	37.9	11.1					

Key to Ranking Comparison Columns in Table

D: Standard deviation-based winter-weather crash density
P: Standard deviation-based winter-weather crash proportion (the proportion of all winter crashes that are winter-weather related)
S: Standard deviation-based winter-weather person-level injury severity (injuries on each roadway segment by frequency and severity)
C: Standard deviation composite metric, representing an equal combination of the three metrics into one overall rating
M: Three-mile moving average of composite metric

Table 5.6 Top 25 roadway segments for potential safety improvements (multilane divided/undivided)

| Rank	Observed	Predicted	Weight	Adjusted	PSI
1	27	9.78	0.02	26.73	16.94
2	26	11.76	0.01	25.81	14.05
3	26	12.25	0.01	25.82	13.58
4	27	13.68	0.01	26.85	13.17
5	23	10.60	0.01	22.82	12.22
6	24	11.76	0.01	23.84	12.08
7	25	13.08	0.01	24.86	11.78
8	26	14.47	0.01	25.88	11.41
9	17	5.41	0.03	16.67	11.26
10	19	7.55	0.02	18.77	11.21
11	18	6.67	0.02	17.74	11.07
12	21	9.76	0.02	20.82	11.06
13	21	10.05	0.02	20.83	10.78
14	17	6.83	0.02	16.77	9.94
15	14	3.79	0.04	13.59	9.81
16	16	5.98	0.03	15.74	9.77
17	19	9.09	0.02	18.83	9.75
18	19	9.70	0.02	18.85	9.15
19	19	9.72	0.02	18.85	9.13
20	13	3.72	0.04	12.62	8.91
21	14	4.82	0.03	13.71	8.88
22	16	6.98	0.02	15.80	8.82
23	16	7.01	0.02	15.80	8.79
24	16	7.56	0.02	15.83	8.27
25	16	7.73	0.02	15.83	8.11

Both tables also present the observed, predicted, and adjusted crashes, while Table 5.5 also includes a ranking comparison to the standard deviation-based and moving composite average analyses previously discussed. The top 25 segments represent about 2 percent of the entire Interstate/freeway network.

In Table 5.5, three or four road segments are in common for the ranking produced using PSI and the analyses based on the other metrics. However, the standard deviation-based and moving composite average analyses only considered rural road segments, while the empirical Bayes analysis included both rural and urban locations. The empirical Bayes-adjusted frequency and observed frequency produced similar rankings. This is expected because crash counts are included in the empirical Bayes adjustment. Four winter seasons of crash counts were incorporated into the empirical Bayes adjustment, and as a result more weight was put on observed crash counts than the expected crash counts predicted from the SPFs. A similar result was also reported in the literature (Monsere et al. 2008). If fewer seasons of crash data would

have been considered, more weight would be assigned to the predicted crash frequency from the SPFs.

The table also shows that the ranking based on PSI is different from the ranking produced by empirical Bayes-adjusted crash frequency or the observed crash frequency. For example, the 25th ranked segment experienced 38 (observed) crashes during the four winters compared to 24 crashes experienced by the fifth ranked segment. However, the fifth ranked segment was ranked higher when PSI was considered. The predicted crash frequency from the SPF was low for this segment compared to the observed number of crashes. On the other hand, the predicted crashes for the 25th ranked segment were close to the observed number of crashes. More weight was put on the predicted crashes for the fifth ranked segment in comparison with the weight put on predicted crashes for the 25th ranked segment.

Figures 5.2 and 5.3 show the roadway segments with positive PSI values calculated based on the empirical Bayes technique. Many locations with positive PSI values generally correspond to the more highly ranked (categorized) locations from the more naïve analyses. Similarly, segments without positive PSI values tended to be among those ranked lower by the more naïve analyses.
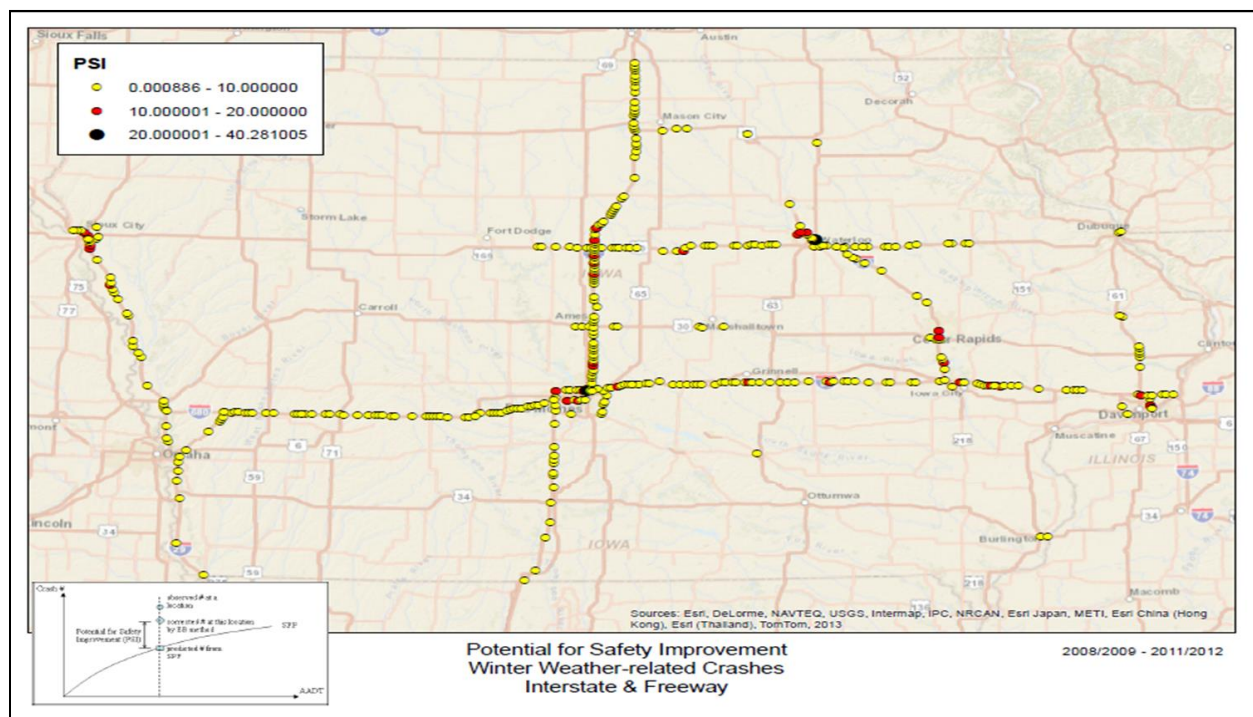
Figure 5.2 Roadway segments with positive PSI values (Interstate/freeway) (Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2013)
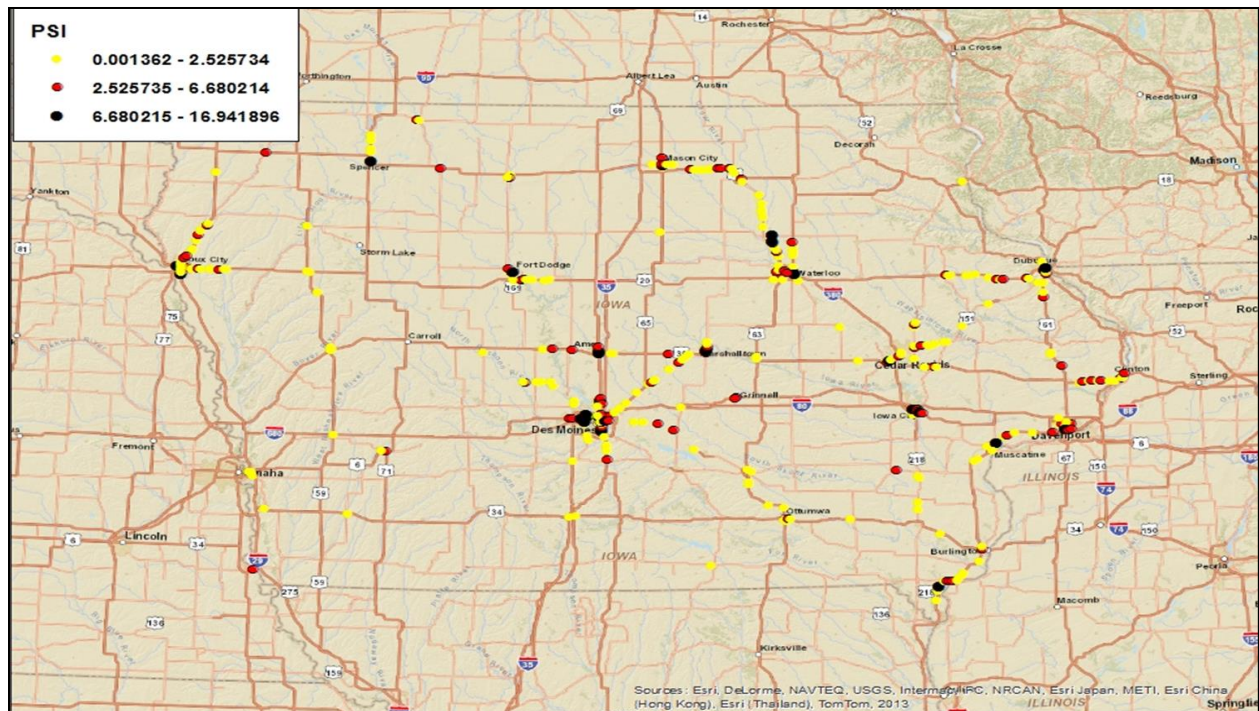
**Figure 5.3 Roadway segments with positive PSI values (multilane divided/undivided)
(Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI,
Esri China (Hong Kong), Esri (Thailand), TomTom, 2013)**

CHAPTER 6. SITE REVIEW AND EVALUATION

This chapter discusses the use of the Chapter 3 and 5 analyses results, in part, to identify locations for more detailed review and to explain the resulting evaluations.

6.1 Background

In Phase 2 of this study, three rural Interstate sites were identified for analysis of winter weather-related crash experience, conditions, and characteristics. These sites were identified primarily based on input from Iowa DOT district maintenance managers and then later confirmed as being within the top 5 percent to 10 percent of sites from the Phase 1 analysis. These sites are indicated by Ph. 2 in Figure 6.1.
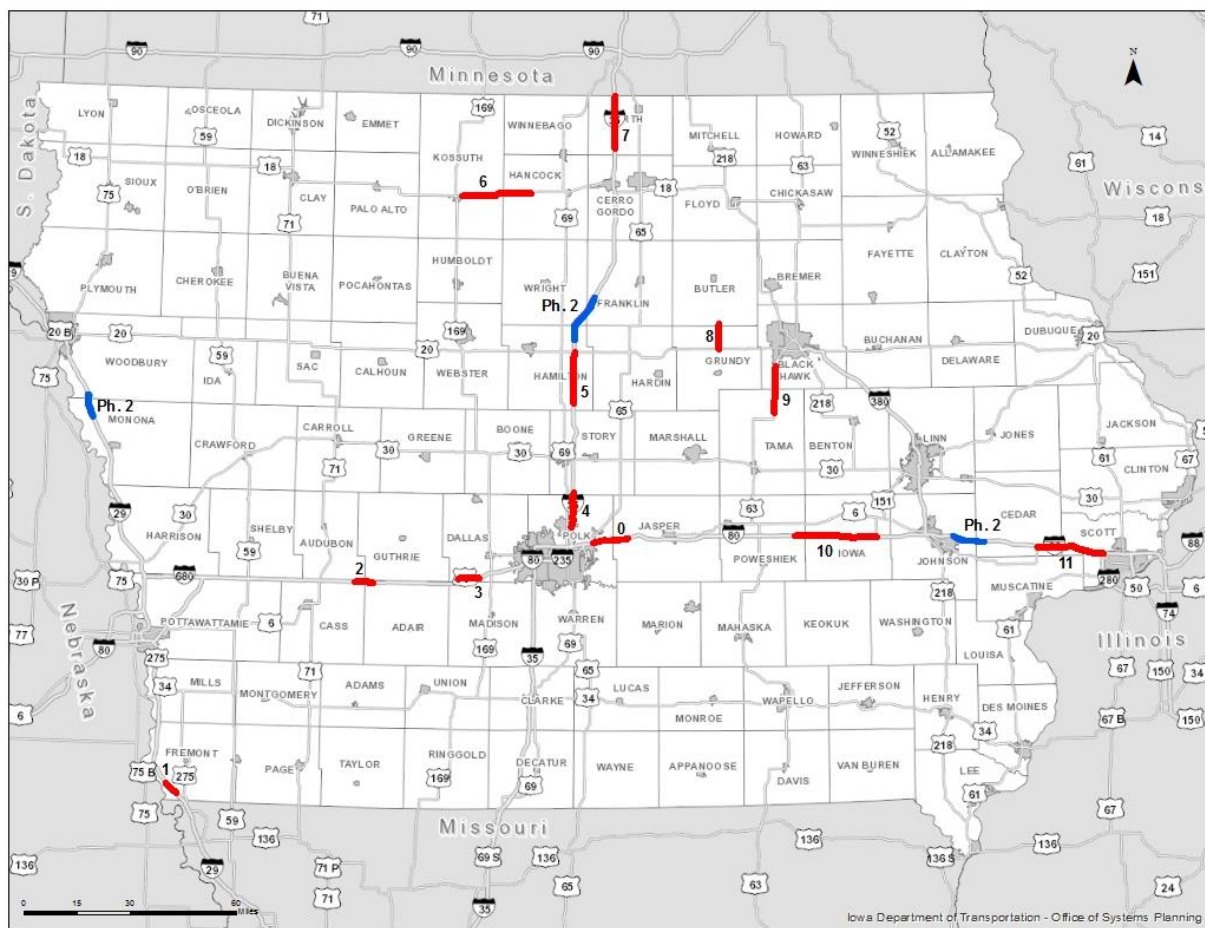
Figure 6.1 Analysis sites

The results of the site reviews, completed in conjunction with Iowa DOT district maintenance managers, snowplow operators, and the Iowa DOT RWIS coordinator, indicated that wind and visibility were issues at two of the sites, with conditions often markedly different immediately

upstream and downstream of the sites. Driver information was increased at the upstream and downstream locations through existing dynamic message signs (DMSs) and the addition of portable DMSs near the sites. The third site possessed no distinct weather characteristics; however, possible opportunities were identified for changing some existing operational procedures.

Based on the analysis results of the three sites, the Iowa DOT Office of Maintenance requested that additional sites be identified, driven by winter weather-related crash experience, and reviewed. Consideration of maintenance and weather data, not previously included in the analysis, was also promoted.

6.2 Site Selection

Using Chapter 3 results and preliminary Chapter 5 results, the Iowa DOT and the research team identified 11 sites for additional investigation and analysis. These sites represented a collection of the original one-mile analysis sections. Sites were identified and defined based on several factors, including generally consistent high ranks among the various analysis approaches and proximity of similarly ranked one-mile sections. Additionally, to introduce and ensure diversity among the sites, locations of different urban, suburban, and rural characteristics were identified, as well as roadways of different types, such as Interstate/freeway and two-lane roadways. Judgment was used to define site length and termini. Sites were not limited to those ranked in the top 25, and not all top 25 sites were selected. Lastly, some sites were selected because their prominence among the ranking of the one-mile analysis sections was unexpected.

Table 6.1 presents some general information about each of the sites, including the weighted AADT, winter weather-related crash frequency, winter weather-related crash density, and estimated winter weather-related crash rate.

Table 6.1 Descriptive statics of winter-weather crash analysis sites, 2003/2004 through 2011/2012

Site	1	2	3	4	5	6	7	8	9	10	11
Route	I-29	I-80	I-80	I-35	I-35	US 18	I-35	IA 14	US 63	I-80	I-80
Approximate Milepost	3-7	70-76	100-107	93-103	128-143	132-152	204-218	138-145	140-153	202-225	271-290
Total Length (miles)	4	5	6	10	15	20	15	7	14	23	19
Weighted AADT	13,000	19,976	26,313	42,254	20,341	2,630	17,721	2,458	3,889	27,597	31,377
Crash Frequency	22	64	77	234	304	34	154	18	31	321	224
Density (crashes/ mile/winter)	0.60	1.36	1.37	2.57	2.33	0.19	1.15	0.27	0.25	1.54	1.31
Rate (crashes/ 100M VMT)	25.38	37.30	28.46	33.28	62.67	39.51	35.63	60.51	35.82	30.60	22.89

The crash rate estimate was based on winter months only but does not account for the actual number of days with winter-weather conditions. Figure 6.1 presents the location of these sites, as well as sites evaluated in Phase 2 of the project.

Sites 6, 8, and 9 are predominantly rural, two-lane undivided roadways, while the remaining sites are located on the Interstate system. The winter weather-related crash frequency on the two-lane sites was relatively low compared to the Interstate sites; however, the estimated crash rate was generally similar. Sites 4 and 5 provide an interesting comparison. Both sites are located on Interstate 35, with Site 4 possessing a combination of suburban and rural characteristics and Site 5 being entirely rural. The winter weather-related crash density for both sites is nearly equal, but the traffic volume along Site 4 is more than twice that of Site 5. Conversely, the crash rate for Site 5 is nearly double the rate along Site 4. A discussion of the analysis of all sites follows.

6.3 Site Analysis Demonstration

Prior to comprehensive data integration and site-level analysis, a demonstration effort was initiated. Emphasis areas of this demonstration effort were data availability, ease of integration, and applicability and usefulness of results.

A set of summary Office of Maintenance data sets, from a combination of crew reports and RWIS sensors, were first obtained. Within these data sets, most attributes were reported at the cost center level. Attributes provided included event date, precipitation start/end times, precipitation type, air and pavement temperature, wind direction and velocity, visibility, snow amount, material usage, maintenance crew type of operation, and crew on/off road time/date. Crash data for 2002 through March 2012 were also obtained. With Iowa DOT guidance, a corridor was selected (labeled as 0 in Figure 6.1). This corridor is about nine miles long, with two different cost centers each responsible for about half of the corridor. It is predominantly rural, but given its proximity to the Des Moines metropolitan area, it has an AADT ranging from about 33,000 to 35,000.

6.3.1 Data Integration

Maintenance crew and weather attributes were first assigned to the respective crashes. Assignment was based primarily on spatial and temporal components. Specifically, the cost center of each crash location was derived to correspond with the reporting level of the maintenance/weather data. Then, common cost center and time/date of occurrence, typically discreet on the crash level and interval-based on the maintenance level, were used to integrate the data sets. Several additional considerations included the possible presence of multiple maintenance records, particularly crew based, during the same time interval, presence of crash data with no corresponding maintenance record (and vice versa), the normalized nature of the maintenance/weather data, and somewhat limited maintenance data prior to the winter of 2006/2007. Therefore, integration of crash and maintenance data was only possible after October 2006.

6.3.2 Analysis

An initial attempt at analyzing the maintenance data was made by comparing the number of unique days with a maintenance operation to the corresponding number of days with a reported winter weather-related crash. As noted previously, since the maintenance data are presented at the cost center level, an assumption must be made that the maintenance operation occurred at the crash location. Preliminary results indicated that about 8 percent to 19 percent of the days on which a maintenance operation occurred experienced at least one winter weather-related crash along the corridor. Excluding days with only frost run operations, which are typically limited to bridges, the results increased to 11 percent to 25 percent. Similar results were found when evaluating days with a reported precipitation (by type). This is to be expected because the precipitation type information is also reported by the maintenance crews. In general, these results seem to suggest that, not considering the intensity or duration of winter-weather events, winter weather-related crash experience is limited compared to winter maintenance activities.

Descriptive statistics (for 2002 through partial 2012) were prepared for a variety of crash characteristics—winter weather-related and non-winter weather-related—along the corridor. Summaries were also produced by cost center, direction of travel, and nearest milepost. The proportion of winter crashes along the corridor is 62 percent, which is slightly higher than the statewide rural Interstate average of 59 percent. However, of the winter crashes, the percentage of winter weather-related crashes is 63 percent, compared to the statewide rural Interstate average of 46 percent.

While investigating the direction of travel, reporting issues made it difficult to definitely assess whether winter weather-related crashes were more prevalent in one direction of travel; however, westbound appeared more prevalent. Somewhat surprisingly, reporting issues appeared more prevalent for non-winter weather-related crashes. Additionally, the western portion of the corridor, near the metropolitan area, had a higher proportion of weather-related crashes (70 percent) compared to the eastern portion of the corridor.

A test of proportions, with a 0.05 level of significance, was performed for a variety of crash characteristics along the corridor for the nearly 600 winter crashes. The test of proportions conducted for winter weather-related and non-winter weathe-related crashes were as follows: major cause, manner of crash/collision, location of first harmful event, severity, time of day, vehicle action, extent of vehicle damage, vehicle configuration, initial impact, driver age, and initial direction of travel.

Of the 26 possible crash major causes, five proportions were found significantly different between the sets of crashes. Higher proportions for non-winter weather-related major causes were observed for the following: animal, followed too close, and operating vehicle in an erratic/reckless/careless/negligent/aggressive manner. Animal, which represented nearly one-third of the non-winter weather-related major causes, is somewhat expected, given animal behavior in inclement weather conditions. Followed too close and operating vehicle in an erratic/reckless/careless/negligent/aggressive manner were somewhat unexpected but may be explained by more aggressive driver behavior during normal conditions and more cautious

behavior in poor surface and atmospheric conditions. Driving too fast for conditions and ran off road left were proportionally higher for the winter weather-related crashes.

Excluding non-reported manner of crash/collision, four proportions were statistically different. Rear-end crashes were proportionally higher for non-winter weather-related crashes, while the head-on, non-collision, and sideswipe (same direction) proportions were higher for winter weather-related crashes. Similarly, proportionally higher median and roadside locations of the first harmful events of winter weather-related crashes were observed and are consistent with the proportionally higher ran of road left major cause and non-collision manner of crash. Additionally, the proportionally higher driver side – middle point of initial impact of winter weather-related crashes is consistent with the higher proportion of sideswipe (same direction) collisions.

No statistically significant differences in proportions were observed for crash severity. In other words, crash severities were generally consistent between non-winter weather-related and winter weather-related crashes. Involvement of drivers of ages 25 through 29 was proportionally higher, and significantly different, for winter weather-related crashes. Sport utility vehicle involvement was also proportionally higher and significant for winter weather-related crashes. Winter weather-related crashes were proportionally higher during the morning hours of 8:00 a.m. to noon but proportionally lower for 4:00 a.m. to 6:00 p.m. and 4:00 p.m. to 6:00 p.m. Lastly, nearly 60 percent of the winter weather-related crashes occurred in the westbound direction, which was statistically higher than non-weather-related crashes. However, since nearly one-third of the non-weather-related crashes had unknown or not reported directions of travel, the accuracy of these results may be somewhat suspect.

GIS-based crash severity maps of the corridor were also produced and reviewed. General distribution of crashes as well as individual crash locations were investigated with respect to roadway and roadside characteristics, such as terrain and presence/size/maturity of living snow fences. These characteristics were assessed through use of both GIS tools and Google Earth, providing aerial imagery and roadway-level Street View.

6.4 Site-Level Analysis

A primary emphasis of site-level analysis was to facilitate discussion among Iowa DOT district maintenance managers, snowplow operators, and the Iowa DOT RWIS coordinator. While crash data were necessary to support these discussions and introduce findings to maintenance staff, maintenance crew feedback was of equal or greater importance. Therefore, site analysis meetings were somewhat loosely structured to provide the most opportunities for information sharing, which could include discussions of other locations of interest. Such flexibility was facilitated, in part, by use of the Iowa DOT Crash Mapping and Analysis Tool (CMAT), to be discussed later. The basic meeting structure was as follows, with the last two items often occurring during the course of the meetings:

- Project overview and meeting objective
- Overview of crash experience at the site

- Review of specific crash locations through CMAT, Google Earth, and hard copy maps
- Discussion of maintenance observations and experience
- Discussion of possible mitigation strategies and possible limitations to their implementation

6.4.1 Crash History

Based on Phase 2 experience and the previously discussed demonstration effort, a series of bar graphs were created using CMAT to present an overview of crash experience at each site, including the following:

- Crash frequency by crash severity, year, month, day of week, and major cause—regardless of time of year and weather contributing circumstances
- Total, non-animal-related crash frequency by month—regardless of time of year and weather contributing circumstances
- Total, non-animal- and non-winter weather-related crash frequency by month—regardless of time of year
- Total crash frequency by month, limited by vehicle configuration—regardless of time of year and weather contributing circumstances
- Total, non-animal crash frequency by month and by year—limited by surface conditions of ice, snow, and slush
- Total, non-animal crash frequency by month and by year—limited by weather conditions of blowing snow, sleet/hail/freezing rain, or snow

One of the benefits of the histograms was their ability to easily convey the predominance of winter and winter weather-related crashes along the site of interest. For example, Figure 6.2 presents the monthly crash experience along Site 5 during the calendar years of 2003 through 2012.
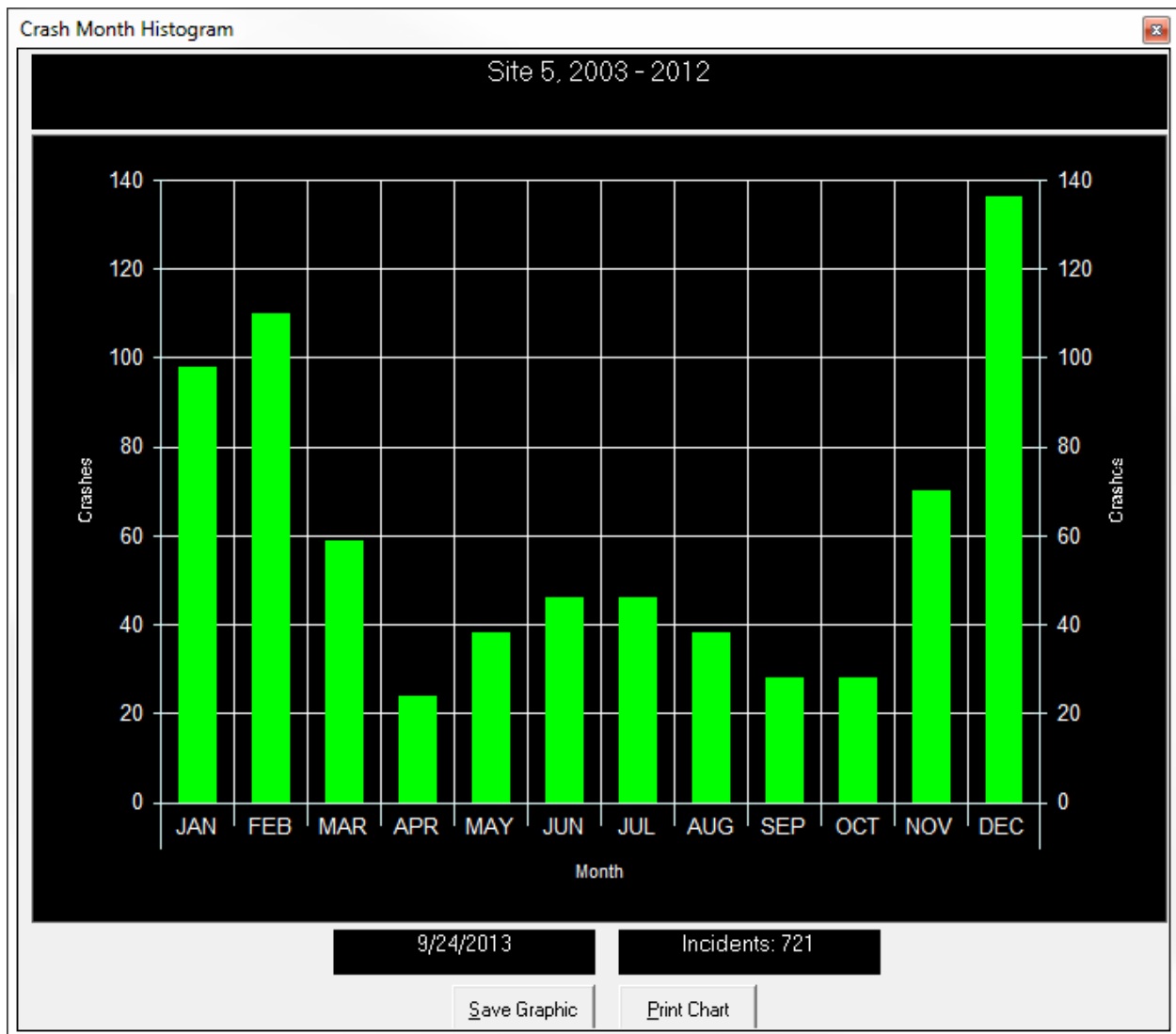
Figure 6.2 Total crash frequency by month for Site 5, 2002 through 2012

Removing the animal crashes, Figure 6.3 conveys the same, if not more pronounced, experience.
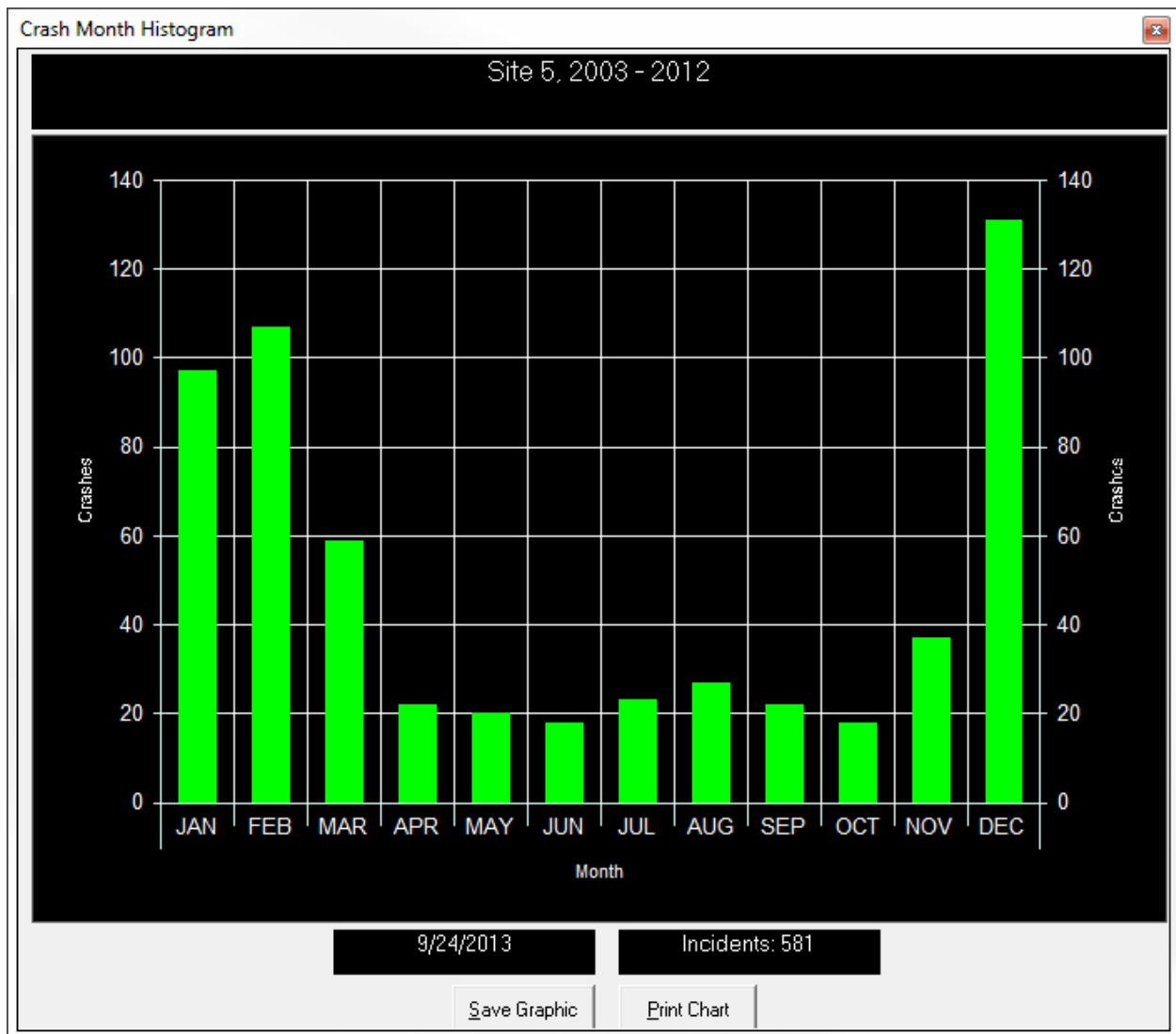
Figure 6.3 Total non-animal crash frequency by month for Site 5, 2002 through 2012

Furthermore, limiting the crashes to those of certain vehicle configurations, such a heavy trucks, can relay whether there may be an overrepresentation of certain vehicles during certain times of the year as shown in Figure 6.4.
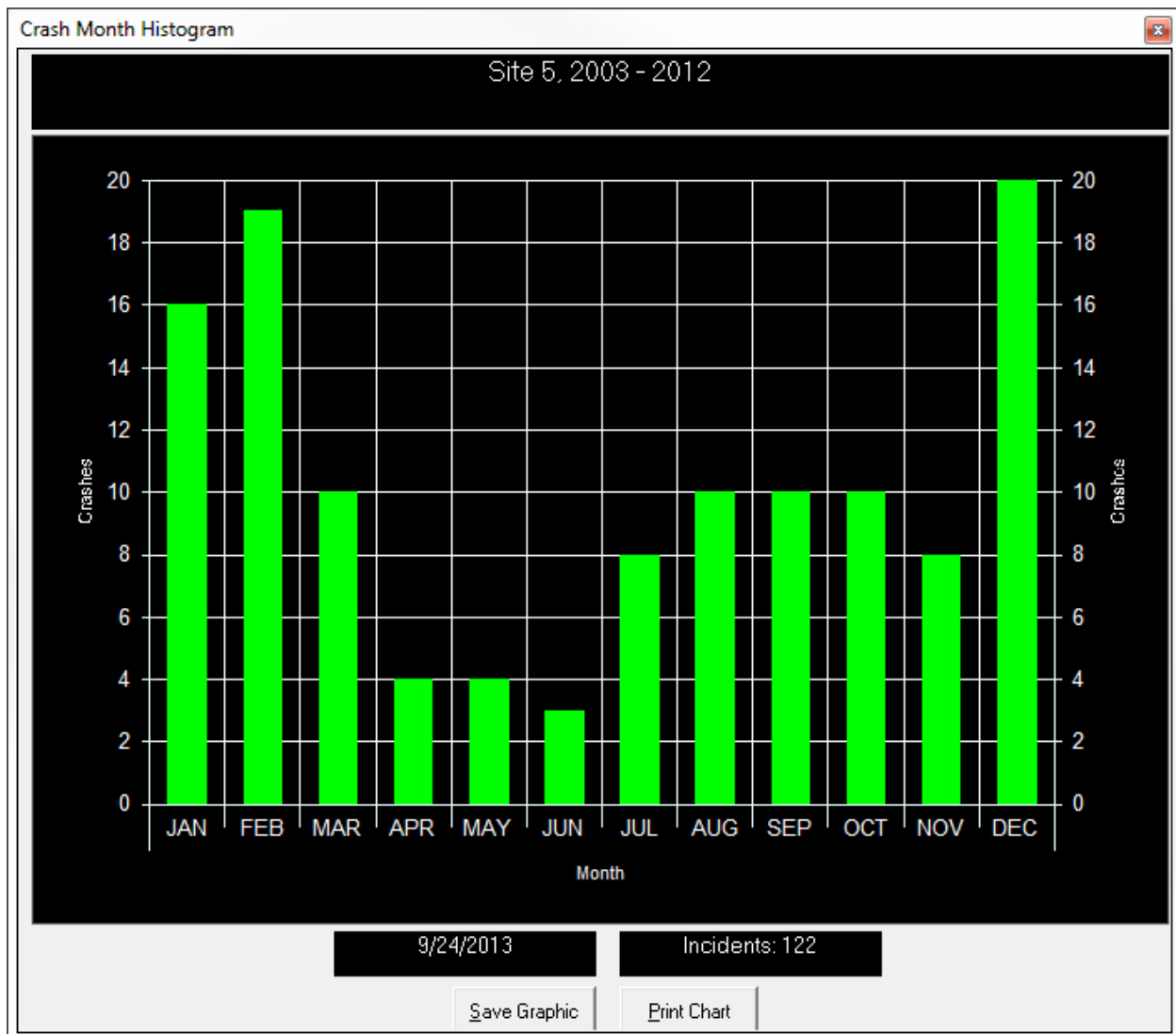
Figure 6.4 Total heavy-truck crash frequency by month for Site 5, 2002 through 2012

A series of additional bar graphs were prepared based only on the winter weather-related crashes, including the following:

- Daily winter weather-related crash experience
- Winter weather-related crash frequency by direction of travel and time of day
- Distribution of winter weather-related crashes by direction of travel
- Winter weather-related crash frequency by manner of crash/collision
- Winter weather-related crash frequency by major cause
- Winter weather-related crash frequency by weather conditions (crash report based)
- Winter weather-related crash frequency by surface conditions (crash report based)
- Winter weather-related crash frequency by air temperature
- Winter weather-related crash frequency by pavement temperature
- Winter weather-related crash frequency by visibility

- Winter weather-related crash frequency by wind velocity
- Winter weather-related crash frequency by pavement temperature and wind velocity
- Winter weather-related crash frequency by precipitation type (maintenance crew reported)

These bar graphs were created to better understand the characteristics of the crashes of primary interest and determine whether there were any discernable patterns, such as consistent time of day or direction of travel. Assessing daily winter-weather crash experience was somewhat different. Specifically, because each winter is different with respect to the number of weather events and their corresponding duration and intensity, an attempt was made to broadly and simply determine if most of the winter weather-related crashes resulted from a few events or if these crashes were distributed among many events. Using the crash data only, the total number of individual days during which a winter-weather crash occurred was first computed. Then, any day, noted as "prominent day," during which at least 10 percent of the annual winter weather-related crashes occurred was determined. Figure 6.5 presents a comparison of these two totals.
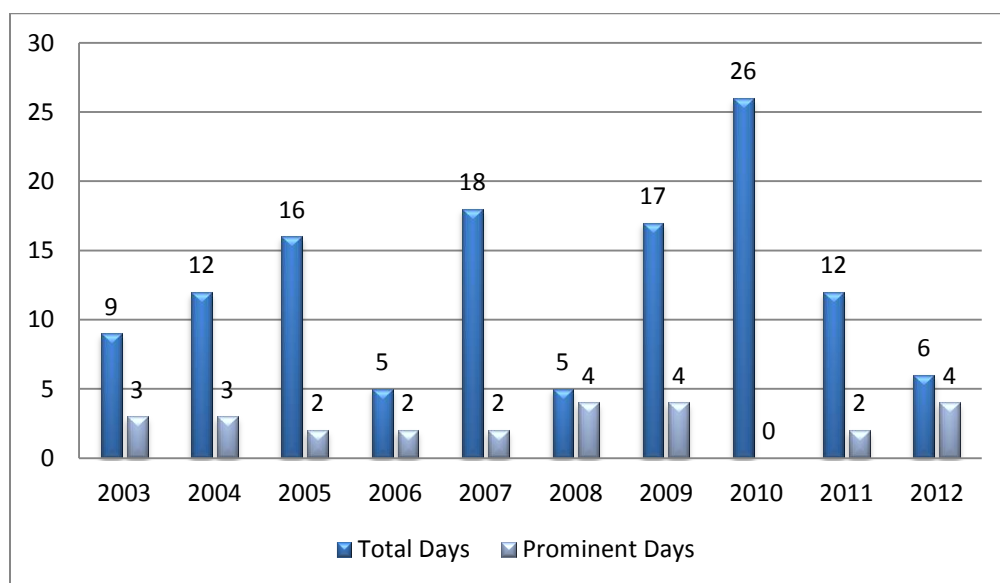
Figure 6.5 Daily winter weather-related crashes for Site 5, 2003 through 2013

In 2007, there were 18 days with a winter weather-related crash and only two days on which at least 10 percent of the total crashes occurred. By contrast, winter weather-related crashes only occurred on five days in 2008, and at least 10 percent of the total annual crashes occurred on four of the five days. Figure 6.6 presents the total number of winter weather-related crashes compared to the number of winter weather-related crashes occurring on "prominent days."
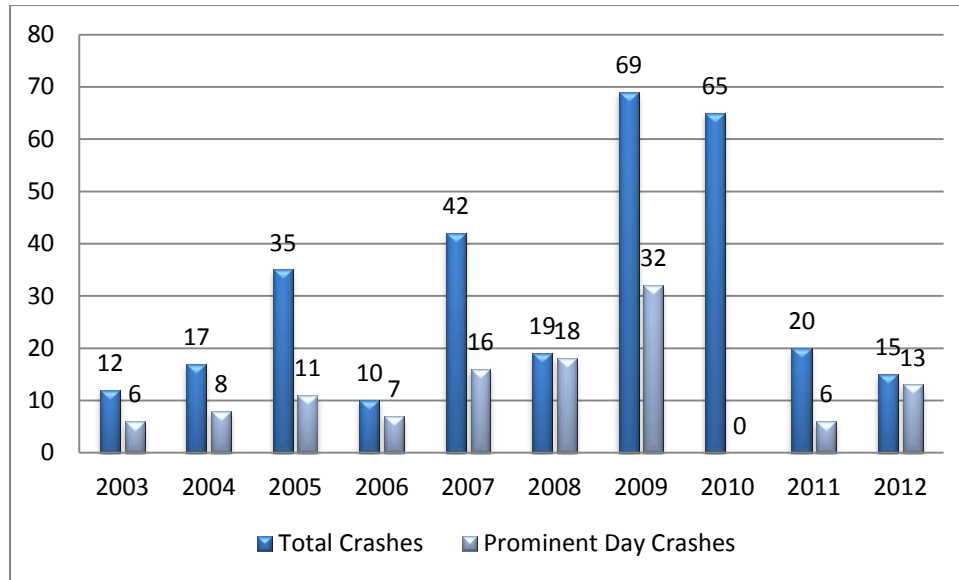
Figure 6.6 Winter weather-related crashes by day for Site 5, 2003 through 2013

In 2007, a total of 42 winter weather-related crashes occurred, with 16 of those crashes occurring on the "prominent days." In other words, 26, or more than 60 percent, of the crashes occurred on days when fewer than 10 percent of the annual crashes occurred. In general, the greater the difference between the total days/crashes and prominent days and corresponding crashes likely suggests a broader impact of winter-weather conditions in general, beyond a few events. Smaller, consistent differences likely indicate that a site is most impacted by more major events. These figures may also be used in concert. For example, in 2009, 32, or half, of the annual crashes occurred during only four days. By presenting the data annually, it can also become apparent whether a limited number of high-frequency years may have driven the site rankings and whether these years were early or late during the analysis period. More elaborate analyses, through integration of weather-specific event days, could be a future consideration in such analyses.

Following are a few other sample bar graphs that were prepared for presentation and discussion in the site analysis meetings. Figure 6.7 presents a distribution of crashes by direction of travel and time of day. This figure may be used to identify possible temporal and directional characteristics; however, it does not take into consideration time, duration, and intensity of weather events.
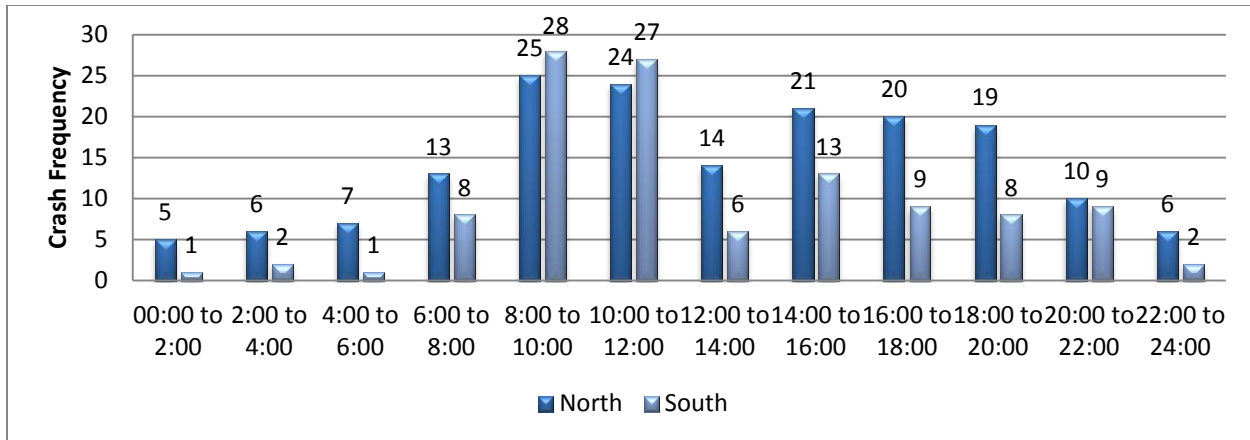
Figure 6.7 Winter weather-related crashes by time of day and direction of travel for Site 5, 2003 through 2013

Figure 6.8 presents the number of crashes occurring at different pavement temperature and wind velocity combinations.
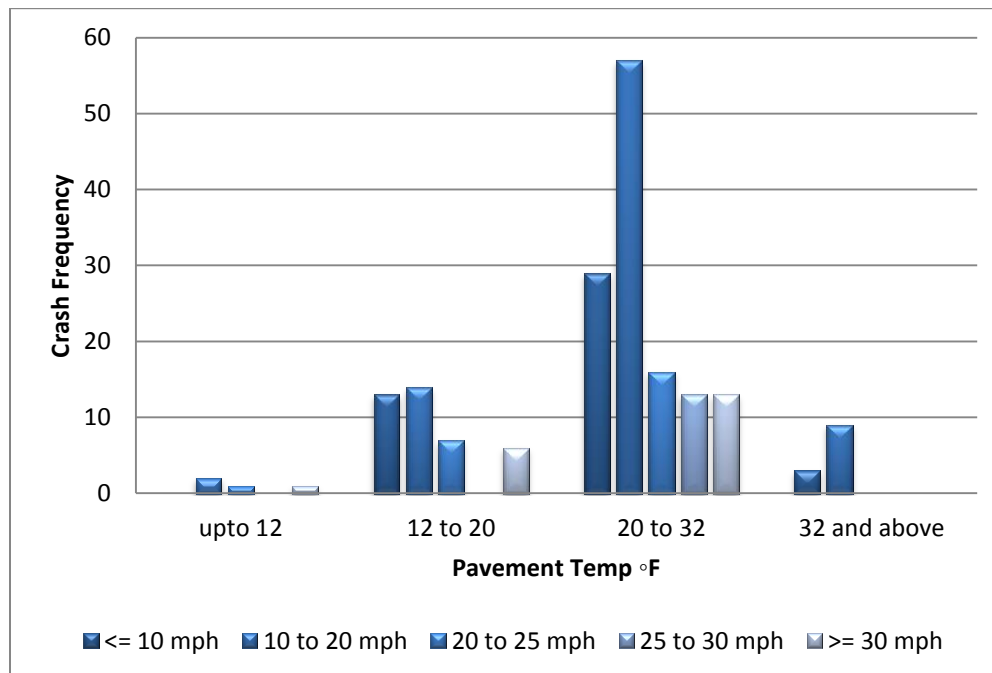
Figure 6.8 Winter weather-related crashes by pavement temperature and wind velocity for Site 5, 2003 through 2013

This information could be beneficial in identifying conditions of most risk. However, while the figure accurately represents the crash frequencies for different velocity and pavement temperature combinations, the distribution presented may simply mirror the general winter conditions. To more confidently utilize these data, it may be appropriate to determine such conditions as a baseline for comparison.

Figure 6.9 presents the crew-reported precipitation type corresponding to the time of the crash.
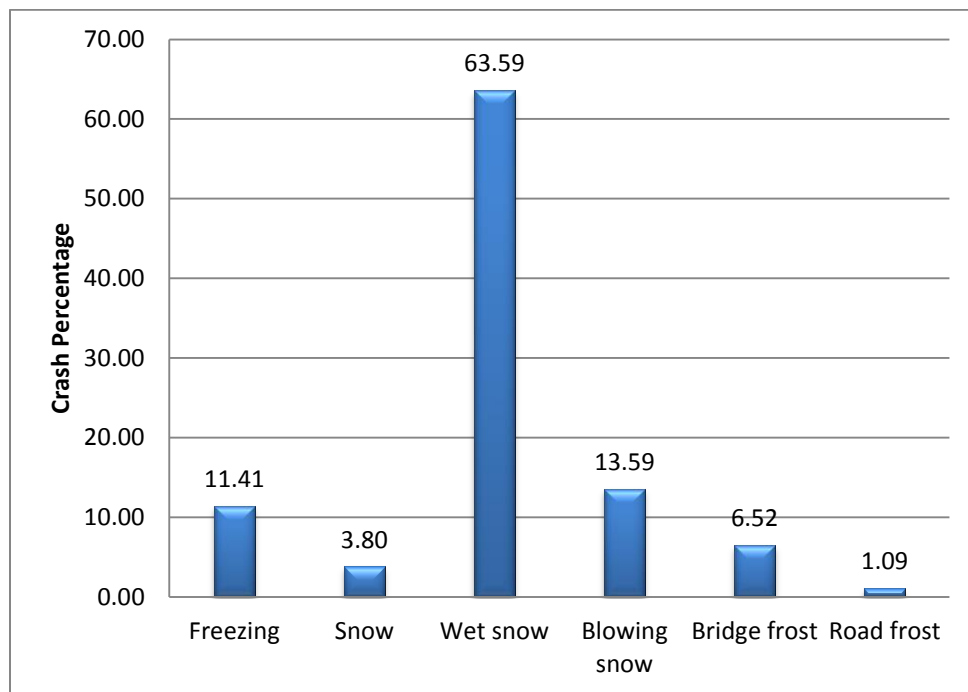
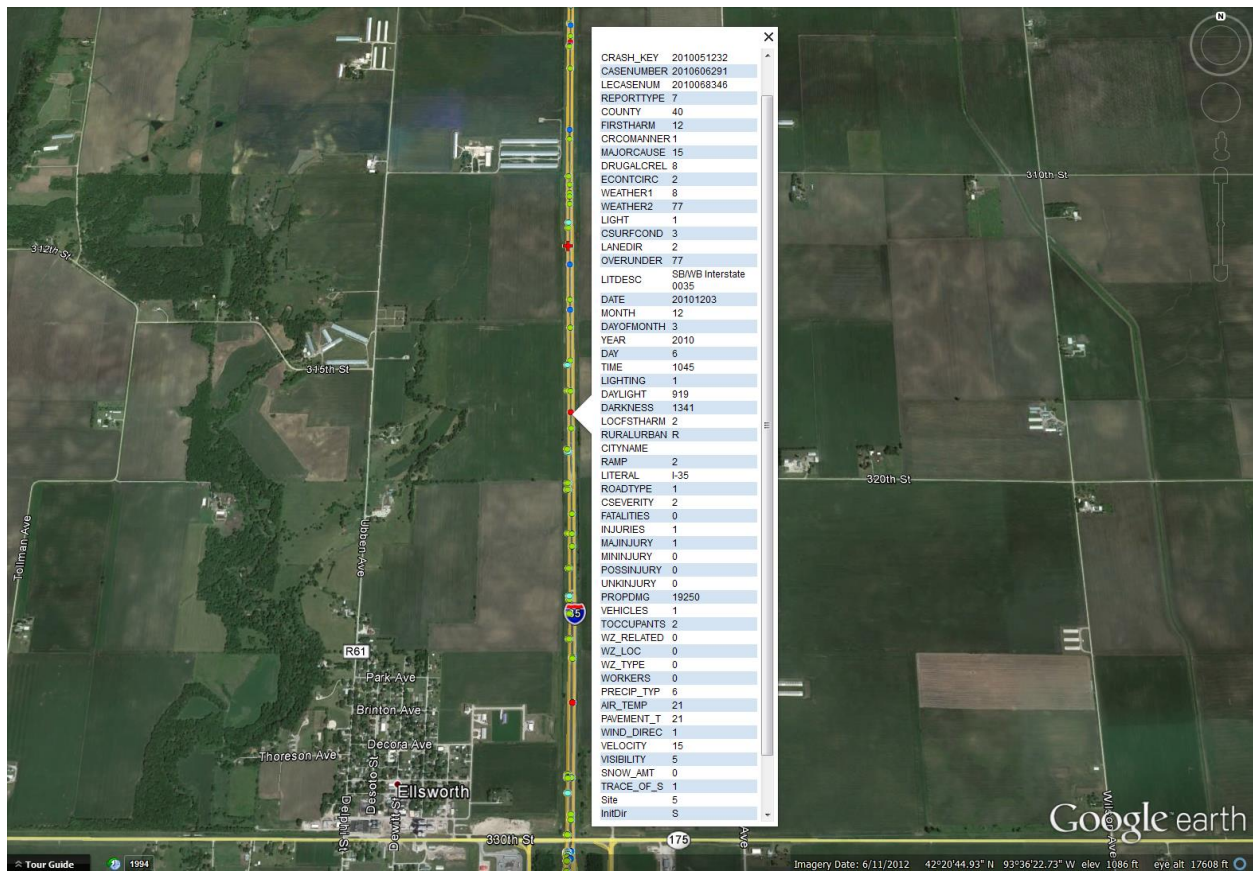**Figure 6.9 Winter weather-related crashes by precipitation type for Site 5, 2003 through 2013**

For nearly all sites analyzed, wet snow represented the prominent precipitation type, often at 60 percent or greater. At Site 9, wet snow only represented about 30 percent of the precipitation, compared to about 40 percent for blowing snow. That said, the wind velocity at the time of crashes was consistent with Site 5. Therefore, even though atmospheric conditions may be similar among sites, the impacts of these conditions may vary.

6.4.2 Crash Locations

As mentioned previously, CMAT was employed during meetings, allowing dynamic attribute and location-based selection, filtering, and reporting of crash experience at not only the selected sites but other locations, if deemed appropriate. For example, if Iowa DOT maintenance staff were interested in crash experience at another location, based on their experience, CMAT was used to investigate pertinent crash history in real time.

Hard copy, winter weather-related crash severity strip maps and Keyhole Markup Language, Zipped (KMZ) files were prepared for each site presenting winter weather-related crashes by severity. Figure 6.10 presents an example of one of the KMZ files presented in Google Earth.

Figure 6.10 Winter weather-related crash severityfor Site 5 in Google Earth

Each crash was clickable in Google Earth, with various crash and weather characteristics available. Additionally, Street View within Google Earth could be used to explore the roadway and roadside characteristics along the corridor and proximate to each crash location (see Figure 6.11). This was particularly valuable because a fair amount of variation may exist along each site and even within the original one-mile analysis sections.

Figure 6.11 Site 5 winter weather-related crash location in Google Earth using Street View (©2014 Google)

Both the hard copy and KMZ maps were primarily used as reference material in discussions. Pertinent site characteristics, history, and infrastructure were recorded on the hard copy maps during the course of the meeting. Observations from the crash analyses were also discussed and various crash and weather condition characteristics interactively explored, as well as locations of interest.

6.4.3 Findings

Insight from Iowa DOT maintenance field staff was immeasurably valuable, particularly with respect to their maintenance practices, observations of events under various conditions, possible mitigation strategies, and impacts of roadside environment. This section will include a discussion of the collective findings for the 11 sites investigated.

Blowing Snow

A prominent issue among all sites, through their entire extent or in localized areas, was blowing snow. While blowing snow is a common issue, its characteristics and impacts may vary. For example, maintenance staff noted that in some locations blowing snow may primarily impact a single direction of travel. Depending on roadway alignment, it may also travel along the roadway and, in some cases, shift directions as well as violate driver expectations. Maintenance staff observed that certain locations appeared more susceptible to blowing snow issues. These locations included diagonal roadways, horizontal and vertical curves, roadways in cuts or with a ditch back slope higher than the roadway, and areas without adjacent protective natural geographic features, like river valleys. Several of these characteristics can change along a roadway, resulting in marked differences within limited distances. Locations of blowing snow issues were also observed to change over time as the roadside changes due to natural disasters, such as floods, and manmade alterations.

Maintenance staff observed that poor visibility, while significant, is not the only impact of blowing snow. Impacts beyond visibility can include poor surface conditions, resulting from ground blizzards and low-profile blowing, and drifting. Drifting was observed as an issue in protected areas, at intersections on undivided roadways, near roadside safety features like guardrails, and near other roadside physical features. Drifting was observed to worsen with an increased presence of snow in the median and ditch, particularly near the end of the winter season. Through the course of a winter, these areas may retain falling, blowing, and plowed snow and eventually reach capacity. All additional blowing snow drifts into the roadway. Additionally, vehicles may no longer have the ability to leave the roadway if they lose control, creating additional hazards in the roadway. At one site with such issues, 70 percent of all surface condition–related crashes occurred from February to mid-April, with nearly six times as many occurring in February compared to December. Furthermore, no snow events were recorded in one month, but blowing snow issues, created solely from existing snow, resulted in several winter weather-related crashes.

While the consensus was that blowing snow is detrimental to driving conditions, a possible unexpected benefit was suggested by several maintenance staff. Specifically, they felt that

motorists appeared to decrease their speed in poor visibility conditions but overdrive in similar roadway conditions where visibility was not a significant issue. This observation could potentially be quantified through use of real-time traffic and visibility data.

Snow fences were identified as the primary solution for blowing snow issues. Many locations with blowing snow issues had no snow fence, discontinuous snow fence, or short/immature living snow fence. Expanding the extent of snow fences, particularly living snow fences, is viable in many circumstances, and the Iowa DOT has been attempting to accomplish this over time. Placement, and/or growing, of taller snow fences may also be a solution. However, a primary challenge related to placement of snow fences is a limited or narrow state-owned right of way (ROW) that does not accommodate proper fence placement. Acquisition or easement of additional ROW, which is typically valuable farmland, is often not feasible. A possible alternative suggested was expansion of the standing stalk programs, entered into with farmers of existing fields, but this may require increasing payment for participation is the program.

There were a few concerns regarding snow fences. For example, improper placement, particularly of living snow fences, in the past resulted in snow being dropped at poor locations. In fact, a site analyzed in the Phase 2 effort removed a living snow fence for such a reason. Another concern was that the effectiveness of snow fences was limited after a point of substantial snow build-up as well as along roadways with diagonal alignment.

Beyond snow fences, an additional strategy to address blowing snow related to surface maintenance is blade and material usage in an attempt to limit refreeze.

Roadway Characteristics

Maintenance staff suggested that the poor roadway condition and/or macro texture of pavements along several sites may have contributed to their winter weather-related crash experience. In fact, some sites did show crash reductions after resurfacing or reconstruction; however, winter conditions could have also influenced the reduction. Similarly, it was also suggested that reductions at a site coincided with installation of shoulder rumble strips.

As previously discussed, maintenance staff observed issues at locations of horizontal and vertical curvature. Additionally, it was suggested that, in some locations of horizontal or vertical alignment changes, the presence of parallel or adjacent roadways can create visual traps, resulting in motorist confusion regarding appropriate navigation of the roadway in inclement weather conditions. Narrow bridges and cable median barriers were also noted as possible influencing factors in winter weather-related crash experience, given their presence as a fixed object near the traveled way. At some sites, the existing placement of cable median barriers was being adjusted to a position farther from the roadway.

Maintenance Operations

The length of snowplow runs, both in time and distance, was considered when evaluating crash experience. Crash experience at the end of runs was of particular interest, as well as transitions between states. Maintenance staff suggested that, at some locations, reductions in run times, if possible given staff and equipment resources, would be ideal.

Overlapping snowplow runs may also be beneficial in improving surface conditions and minimizing differences in surface conditions. Dedicated snowplows for specific lanes and ramps and limiting deadhead were both considered desirable. A "worst first" approach in maintaining roadways during winter-weather events was viewed as somewhat practical and understandable but could result in poorer conditions on other portions of the system.

During one site review, maintenance staff were unaware of the winter weather-related crash experience along the corridor of interest. Through the discussion, they realized that the attention provided to another route due to some problem areas, and the manner in which the corridor was accessed, potentially led to a delayed response and worsening conditions. A proposed solution was to request assistance from neighboring cost centers nearer to the corridor of interest.

Some challenges in maintenance operations, which were also reflected in crash experience, included the following:

- Glazing of wheel tracks between 8:00 a.m. and 10:00 a.m.
- Refreeze between 4:00 p.m. and 6:00 p.m.
- Slushy road conditions between 25 and 32 degrees Fahrenheit, intermittently moving in out and out of a frozen state

Conversely, maintenance staff observed that roadways typically do not become icy or slick at low temperatures, such as between 10 and 15 degrees Fahrenheit. This observation was also supported by the crash data.

Other Observations

Through site analysis, maintenance staff conveyed that, for some of the locations, direction of travel and time of day of crashes were contrary to their expectations, which introduced potentially new information to those responsible for maintaining roadways during inclement winter conditions.

Staff were also able to share important insights, given their nearly exclusive experience of maintaining the roadways and sharing them with motorists during a wide array of different weather conditions. Staff suggested that some of the differences observed by time of day and direction of travel may be influenced by commuter traffic and weather event–level driver experience.

For example, at sites transitioning from urban to rural in nature, motorists traveling from the urban area will have less experience, and may be less aware of the poor conditions, compared to those who have been traveling in such conditions for some time. This could explain the apparently higher frequency of crashes exiting the urban area.

Maintenance staff suggested that driver behavior appears to become more cautious, and speeds decrease, after drivers observe the first crash or vehicle on the roadside.

Lastly, significant citizen band (CB) radio communication among commercial motor vehicles (CMVs) during winter-weather events had been observed, which increases driver awareness of conditions. CMVs may, however, create additional issues for general motorists due to snow and ice coming off their large vehicles.

Possible Mitigation Strategies

Several possible mitigations strategies were identified and discussed in the site meetings. Strategies may be considered broadly as roadway/roadside-related, informational, or operational in nature. Some of these strategies, and possible limitations, have been introduced in previous sections of this report.

For example, expansion of snow fence installation was a commonly recommended strategy, including entirely new installation, filling in of gaps, and increasing heights. In several cases, living snow fences had been planted along the site during the analysis period but simply had not matured to the point of having the desired impact.

As previously stated, limited ROW availability may limit the ability to implement this strategy at all locations. The standing stalk programs were suggested as a viable alternative, if participation can become more attractive.

From an operational standpoint, reevaluation of snowplow run turnaround locations, length of snowplow runs, snowplow run overlap, dedicated ramp trucks, cooperation/partnering with neighboring maintenance garages, and material use during different conditions were suggested mitigation strategies.

Several of these strategies may require reallocation of or additional resources, which may require coordination and assistance from the Iowa DOT Office of Maintenance. While investigating these alternatives, it is important to understand that winter-weather events are unique, and maintenance staff must remain flexible in addressing all possible conditions and situations.

Lastly, improving driver information, particularly in advance of locations prone to rapidly changing or different conditions, was proposed as a possible mitigation strategy. Information may be conveyed via permanent or portable DMSs. Locations of devices (specifically, portable DMSs), appropriate activation protocol, and message content would need to be established. Consistency among locations throughout the state may be an additional consideration.

Based on the site analysis meeting results, no immediate, specific mitigation actions were identified by the Iowa DOT. In general, field maintenance staff became more cognizant of areas of interest and the crash experience at these locations. Iowa DOT staff may informally address operational alternatives on a case-by-case basis, and continued expansion of snow fence installation was justified.

In the future, for sites with clearly identifiable mitigation strategies, development of an implementation plan is recommended. The plan should consist of the recommended site-specific mitigation strategies, with the Iowa DOT responsible for identifying which recommendations to pursue and developing the more detailed implementation plans.

Responsibilities should be clearly defined for the entirety of the implementation plan—from initiation through operation, if appropriate. Responsibilities may include but not be limited to construction, roadside modification, equipment acquisition, deployment, and operation, and maintenance practices and policies. Furthermore, a methodology for evaluating the effectiveness or performance of the site-based mitigation strategies should be established.

Data sets of interest should be identified, as well as the means by which they may be obtained. Data acquisition may require deployment of additional equipment and/or coordination with other agencies, such as the Iowa State Patrol. Data acquisition and analysis responsibilities should be clearly defined. Given the data sets of interest, an evaluation protocol should be established, specifically addressing the manner(s) in which data will be utilized to assess the effectiveness of the mitigation strategies. This may include creation of new evaluation metrics and measures of effectiveness.

CHAPTER 7. CONCLUSIONS

There are multiple benefits associated with identification and analysis of locations with the potential for safety improvements related to winter-weather crashes. In general, the effort supports the Iowa DOT's safety and mobility initiatives. Additionally, site analysis meetings serve as a forum to increase awareness as well as facilitate open discussion of concerns, mitigation alternatives, and opportunities for coordination and improvement.

Site prioritization techniques for identifying roadway segments with the potential for safety improvements related to winter-weather crashes were developed through traditional naïve statistical methods by using raw crash data and previously developed metrics.

Crash frequency models were also developed using integrated crash data for four winter seasons, with the objectives to identify factors affecting crash frequency during winter seasons and screen roadway segments using the empirical Bayes technique.

Empirical Bayes accounts for the RTM phenomenon by overcoming the limitations introduced by traditional methods. Weather factors such as visibility, wind speed, and air temperature were found to have statistically significant effects on crash frequency along different types of roadways.

The ranking of roadway segments for PSI also differed from the ranking produced by simple crash frequency, which does not take into account the RTM; however, similarities did exist among the techniques. The PSI ranking produced by employing the empirical Bayes technique can be useful to identify roadway segments to consider for potential safety improvement and allocate agency resources in an effective manner to mitigate winter weather-related crashes. SPFs developed in this research can be used to produce a ranking based on PSI by using crash observations made over a specific number of years for winter-weather crashes.

While crash data served as a foundation for site analysis meetings, insight from Iowa DOT maintenance field staff was invaluable, particularly with respect to their maintenance practices, observations of events under various conditions, possible mitigation strategies, and impacts of the roadside environment. While some of the feedback may have been anecdotal in nature, maintenance staff are uniquely qualified to discuss winter-weather safety, given their nearly exclusive experience in maintaining the roadways and sharing them with motorists during a wide array of different weather conditions.

Through these meetings, possible mitigation strategies were identified, ranging from roadway or roadside-related, informational, or operational strategies. In the future, for sites with clearly identifiable mitigation strategies, the researchers recommend development of an implementation plan, as well as a methodology for evaluating the effectiveness or performance of the site-based mitigation strategies.

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