SNOWSTORM EVENT-BASED CRASH ANALYSIS

By

Xiao Qin[1] Ph.D., P.E.
Associate Researcher
Traffic Operations and Safety (TOPS) Laboratory
University of Wisconsin-Madison
1415 Engineering Drive
Madison, WI 53706
Telephone: (608) 262-3649
Fax: (608) 262-5199
E-mail: xqin@engr.wisc.edu

David A. Noyce Ph.D., P.E.
Assistant Professor
Department of Civil and Environmental Engineering
University of Wisconsin-Madison
1415 Engineering Drive
Madison, WI 53706
Telephone: (608) 265-1882
Fax: (608) 262-5199
Email: noyce@engr.wisc.edu

Chanyoung Lee Ph.D.
University of Wisconsin at Madison
Department of Civil and Environmental Engineering
1415 Engineering Dr
Madison, WI 53706
Phone: 608-265-8582
Fax: 608-262-5199
Email: chanyounglee@wisc.edu

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[1] Corresponding Author

ABSTRACT

This study investigated the snowstorm impact on Wisconsin state highway system and assessed the winter maintenance effort in improving highway safety from a macroscopic perspective. Though the inverse relationship between the de-icing material consumption and the crash counts during the snowstorms is not reflected in the analysis, it implies that causes of snowstorm crashes are multifold. The following main factors were investigated: weather, human factors, and winter maintenance. The results showed a mixed influence of both the snowstorm severity and winter maintenance investment on road safety. In other words, the severity of the snowstorm in terms of duration, intensity, and wind speed increases traffic crashes and casualties, while at the same time consuming more de-icing materials and labors. The research also explicitly proves that a proactive winter maintenance effort will significantly improve traffic safety.

The temporal distribution of the crash occurrence during a snowstorm shows that a large percentage of crashes occurred during the initial stages of the snowstorms, likely because snow removal activities had not yet commenced. The pattern is very similar for both state-maintained highway and local roads except that in the second half of a snowstorm, higher percentage of crash occurred on local roads than that of the state highways possibly suggesting that the different level of maintenance and the use of de-icing materials may play an important role. Additional research is required to specifically quantify the effects of de-icing materials, particularly with regards to application rate and frequency, on highway safety.

Key Words: Road Weather Safety, Snowstorm Crashes, Winter Maintenance, Negative Binomial Model.

INTRODUCTION

Travel in winter, especially when encountering a snowstorm, may not be a pleasant driving experience. The snowstorm may not only extend travel time, but may also place drivers in a dangerous position. According to the National Research Council, it is estimated (excluding delays due to rain and wet pavement) that drivers endure over 500 million hours of delay annually on the nation's highways and principal arterial roads because of fog, snow, and ice (*1*). Furthermore, 1.5 million vehicular crashes each year, accounting for approximately 800,000 injuries and 7,000 fatalities, are related to adverse weather. The injuries, loss of lives, and property damage from weather related-crashes cost an average of 42 billion dollars in the U.S. annually (*1*).

Mother Nature can have a significant physical impact on the transportation system: low friction pavement increases the difficulty of operating and maneuvering a vehicle; impaired atmospheric visibility limits driver sight distance and restricts driver ability to judge the unexpected conditions ahead; and the accumulating or drifting snow on the roadway obstructs vehicles as well as covers pavement markings, worsening the already deteriorated situation. The interaction between adverse weather and the highway system undermines the mobility, capacity, and safety of the system that is traditionally designed for ideal conditions, i.e., average vehicular acceleration or deceleration and normal friction coefficient.

Some drivers may underestimate the real weather threats or are overconfident of their ability by not complying with the actual conditions, which not only places themselves in a riskier position, but also endangers other travelers' safety. Therefore, a driver's comprehension of a snowstorm's influence on winter road maintenance and driver safety is beneficial in preventing unsafe driving behavior.

Wisconsin faces a wide array of challenges each year in battling the combined consequences of unavoidable snowstorms and a mobile society. Wisconsin's average snowfall ranges from approximately 40 inches in the south to as much as 160 inches along the shores of Lake Superior. On average, about 35 to 40 winter weather events occur in Wisconsin each winter. Total winter vehicle-miles-traveled (VMT) for the November 2003 to March 2004 winter season in Wisconsin was 22,852,300,000, almost 40 percent of the annual VMT (*3*).

Blowing snow or fog can cause severe visibility restrictions for drivers. While snow is the primary winter event with only a couple large freezing rain events each winter, the state experiences numerous freezing drizzle and freezing fog events that cause roads to ice over (*2*).

Crashes due to weather are a critical concern of transportation professionals in Wisconsin. Significant effort has been invested to mitigate snowstorm hazards, to keep the roadway passable or to recover the roadway to traversable lanes as early as possible. Meanwhile, like most states, tighter winter operations budgets make the challenge more difficult. Winter maintenance costs continue to increase due to the higher anti-icing and de-icing material cost and increased labor and equipment cost. In the winter spanning 2003 and 2004, the total cost of winter operations in Wisconsin was $40,184,200, a nine percent increase over the previous five year average (*2*).

Wisconsin is facing a challenge of how to improve travel condition during winter snowstorm events while maintaining a safe standard expected by the traveling public.

This study investigated the relationship between snowstorm crashes and snowstorm severity, winter operation, and maintenance cost. The first part of this paper presents a literature review of snowstorm impacts on road safety along with the relevant weather variables attributing to the snow-related crashes and available safety assessment of the winter road maintenance. Next, a collection of data is described to yield a meaningful approach to connecting the snowstorm information with crash data. The Exploratory Data Analysis (EDA) procedure was used to examine the dataset from two important aspects: data characteristics and a temporal analysis of snow-related crashes. The paper concludes with the Negative Binomial statistical analysis of the snowstorm crash data, providing an in-depth analysis on snowstorm crashes, and the crash risk factors. The follow-up discussion offers a thorough explanation of the results as well as the future research needs.

LITERATURE REVIEW

Numerous studies have assessed the negative impact of weather on the transportation system in terms of delay and traffic safety. Nevertheless, many of the studies are quite dated. Of a variety of weather conditions such as rain, snow, sleet, fog, and ice, snow has been of special interest in that it jeopardizes road safety from all critical aspects: reduced road surface friction, impaired driver visibility, and obstructed roadway. Though the previous results vary from one to another, the conclusions are fairly consistent. Research conducted at Clark University in 1968 shows that collisions increased by at least 200 percent on three to 12 snow days per year (*4*). Similarly, a British study indicates that injury collisions increased by approximately 50 percent under snowy, icy, wet, or fog conditions, as compared with clear weather (*5*). Taking traffic volume into consideration, Zhang, et al. found that the highest risk occurred at traffic flow rate from 1,200 to 1,500 vehicles per hour per lane (veh/hr/ln) under snow condition (*6*). Drivers have to endure the deteriorated safety condition not only during the precipitation phase of the event but also for sometime thereafter. This particular safety concern is addressed by Suggett in 2003 who indicated that collision risk was elevated for both the precipitation period and for several days following measurable snowfalls, due to the slippery roads (*7*). Supporting evidence can be found in a 2001 Canadian report which presents a wide range of road weather safety studies (*8*).

Other than simply documenting the fact that snowstorm and adverse weather fatalities continue to go up, researchers have been seeking to identify the weather variables that directly or indirectly cause the safety problems. Studied weather parameters include, but may not be limited to, pavement temperature, air temperature, atmospheric visibility, wind speed and direction, and snow intensity, duration, and coverage. In a study conducted in Iowa in 2000, detailed crash, weather, traffic exposure, and roadway geometry data were collected on seven different sections of the interstate highway system. The study found that higher wind speed (gusts) resulted in more injurious crashes, whereas higher snowfall intensity tended to result in less injurious crashes (*9*). Several other studies show that wet or slippery roads reduce friction by 30 to 40 percent and snow and ice-covered roads by up to 75 percent (*7, 10*). Since snow and ice covered roads can reach friction numbers below 35, safety becomes more critical because the American Association of State Highway and Transportation Official

(AASHTO) assumes a pavement friction value of 35 or more in the commonly used stopping sight distance model (*11*). Pavement temperature also has a significant effect on the pavement surface frictional properties. Researchers found that pavement friction tended to decrease with increased pavement temperatures and it was also subject to the vehicular velocity (*12*). Quantifying weather impact on road safety via a collection of weather variables reveals critical information to road weather safety professionals and offers great opportunities to respond to the snowstorm threats more effectively and efficiently. The winter maintenance community is realizing that this information is invaluable in policy making, program managing, and performance measuring.

Winter maintenance operations are to ensure, as far as reasonably practicable the safe and efficient movement of vehicles, especially on the principal road network, to minimize delays and crashes attributable to adverse weather conditions and to use resources efficiently. Existing guidelines and standards for winter maintenance activities in most snowbelt states are simply to keep the roadway passable or to recover the travel lane to the pavement surface within an acceptable timeframe subject to the highway priorities. However, information demonstrating the benefits for even basic winter maintenance operations such as snow plowing, salting, and sanding is scarce. Moreover, the absence of crash data as a performance measure in winter maintenance activities is inappropriate. A limited number of published studies cited by Andrey have assessed the safety benefits of winter maintenance. The Norwegian Directorate of Public Works study found that salted roads had 26 percent fewer collisions than similar unsalted highways. Benefits were higher for serious injury crashes than minor injury ones and greater during daytime and for roads that have poor horizontal alignment (*8*). In another study, Finland researchers applied different amount of salt on the similar road segments and discovered that the frequency of slippery conditions on these roads attributed to snow and ice increased by 30 to 40 percent and crashes increased by 20 percent on most road sections (*8*). In the United States, Kuemmel summarized his study with the following findings: crash frequency was eight times higher before de-icing than after on a two-lane highway and 4.5 times higher for multi-lane freeways; crash frequency was nine times and seven times higher before application of salt for two-lane and multi-lane roadways, respectively, and the crash severity was reduced by 30 percent (*13*). Though the few examples show consistent level of safety improvement on limited experimental sites, a large scale study is needed to recognize the general benefits of winter maintenance activities.

DATA COLLECTION AND PROCESSING

This research involved the analysis of a large number of data from a variety of resources. Winter snowstorm event data have been carefully collected and archived by the Bureau of Highway Operations in the Wisconsin Department of Transportation (WisDOT) since 1998. The Winter Storm report is designed for the purpose of tracking the relationship between the winter operations and maintenance cost and the severity of the snowstorms. The snowstorm data are reported through the county highway maintenance authorities who contract with WisDOT to complete the anti-icing, de-icing, and snowplowing activities on the State Trunk (highway) Network (STN). Therefore, data for winter maintenance activities is only recorded for the state-maintained highway system. Table 1 provides a selected list of data in the snowstorm reports, including atmospheric elements, pavement temperature, and maintenance cost in terms of labor, equipment, and material usage. One of the goals of winter maintenance is to achieve "passable roadways" within the limitations imposed by climatological conditions, the availability of resources, and environmental concerns during a winter storm event. Note that in the WisDOT snowstorm guidelines, a "passable roadway" is defined as a roadway surface that is free from drifts, snow ridges, and as much ice and snow pack as is practical and can be traveled safely at reasonable speeds, a speed that a vehicle can travel without losing traction (*2*). Another use of the snowstorm data is to calculate the Winter Severity Index (WSI) for each county, which, in conjunction with winter maintenance cost data, could be used to compare the cost and the effectiveness of snow and ice removal between counties.

The basic source of crash data in Wisconsin is the Police Report of Motor Vehicle Traffic Accident form. Every crash report has a description of the weather and surface conditions and the location and time the crash took place. Also, most reports give the police officer's opinion of possible contributing circumstances such as snowy, icy, or wet roadways. Weather conditions include rain, snow, fog, sleet (freezing rain or drizzle), blowing snow, sand, and so on; road surface conditions include wet, snow/slush, or ice. Provided that the crash information is coded correctly by the officers, researchers are able to identify whether or not a crash is snowstorm-related.

Since the snowstorm report records the weather service and WisDOT snowstorm start and end times, a crash can be linked to a specific snowstorm by location, the county where the crash occurred and by time, between the snowstorm start and end times. Considering the existence of a possible temporal lag of a snowstorm from one side of county boundary to another, a cross-validation was conducted to ensure that all the crashes are snowstorm-related using other factors such as weather condition, road surface condition, and crash contributing factors. After the integration of the crashes with the snowstorm data, every snowstorm corresponds to a number of snowstorm-related crashes for each county, which enable researchers to take advantage of the information stored in the snowstorm report and explore the relationship between snowstorm and relevant crashes; to identify the potential crash risk factors; to evaluate the snowstorm impact on traffic safety of the state highway system; and to assess the level of service of snowstorm mitigation.

EXPLOTORY DATA ANALYSIS

Data Characteristics

Table 1 presents features of the snowstorm data as well as crashes. A total of 7,037 snowstorm events were reported by 72 counties in Wisconsin for the 2000 through 2002 winter seasons. Over half of the snowstorms, 3,667, had crashes, resulting in 95 fatalities and 7,432 injuries on the STN. A total of 17,294 crashes were reported from the 3,667 snowstorms, ranging from a minimum of one crash/event/county to a maximum of 134 crashes/event/county with an average of almost five crashes/event/county. Note that all deer-vehicle crashes during snowstorm events were excluded. Snowstorms vary in terms of duration, severity, and coverage. For the snowstorms with crashes, snow duration ranged from 30 minutes to 134 hours, with a mean of 14.36 hours. Snow depth is from a minimum of 0.1 inch to a maximum of 75 inches with an average of 2.5 inches. If more than one type of precipitation occurs during a snowstorm, all are measured and recorded individually. Pavement temperatures are also collected at the beginning and the end of a snowstorm through either fixed Road Weather Information System (RWIS) stations on the roadside and the mobile or sensors installed on the maintenance vehicles. Wind speed and air temperature collected from the nearest airport are also included in the snowstorm report.

TABLE 1 Summary Statistics for Snowstorm Crash Dataset

Variable	Explanation	Mean	S.D.	Min	Max
Crash	Number of Crashes	4.72	7.14	1	134
Injury	Number of Injuries	2.03	3.32	0	42
Fatal	Number of Fatalities	0.03	0.18	0	3
PTS	Pavement Temperature-Start (F)	24.89	8.33	-5	57
PTE	Pavement Temperature- End (F)	5.52	11.37	-10	56
SDUR	Storm Duration (hrs)	14.37	10.66	0.5	134
CDUR	Crew Work Duration (hrs)	15.41	12.34	0	232
CSOUT	Crew Out Prior to Storm (hrs)	2.58	3.67	-16	46
CSIN	Crew In After Storm (hrs)	3.63	6.01	-24	39.5
DEPTH	Snow Depth (inches)	2.56	3.01	0.1	75
UNIT	De-icing Units Used (tons)	12.65	9.28	1	208
HRS	De-icing Unit Hours (hrs)	125.29	146.60	1	2023
AT	Air Temperature in degrees (F)	24.86	9	-10	69
SPD	Wind Speed (mph)	9.61	5.23	3.5	34.5
SALT	Salt Used (tons)	228.57	357.97	0	5935
SAND	Sand Used (Cubic Yards)	17.89	65.35	0	928
CHM	Chemical For Prewitting Sand (Gallons)	258.54	765.13	0	15,288

Winter maintenance operations cost is also listed in Table 1. Winter maintenance staff schedule is recorded as crew out time and crew in time. As can be observed in the data, the time that the crew worked in a snowstorm is relatively consistent with the snow duration. To evaluate the maintenance performance effect on traffic safety, two additional variables were calculated. One is the time that winter maintenance staff is out prior to a snowstorm, which is the difference between the crew out time and snowstorm start time. The other is the time that the maintenance workers come in after a snowstorm which is the subtraction of the snowstorm end time and the crew in time. The numbers display a large variation from county to county and from event to event. The most proactive maintenance starts 16 hours prior to the snowstorm or does not end until approximately 40 hours after the snowstorm stops. The least aggressive snowstorm treatment does not start until 46 after the snowstorm begins or ends 24 earlier than the snowstorm stops. The average times for the two variables are 2.58 hours and 3.36 hours, respectively.

The snowstorm report provides an abundance of information for the traffic safety analysis. Nevertheless, some information may be dependent, incomplete, inaccurate or unreliable and should be used with caution. For instance, there is a strong correlation between the maintenance labor hours, material unit cost, and the snowstorm duration and amount. The Pearson Correlation Matrix (Table 2) for selected variables confirms the existence of the dependence among variables. Pavement temperatures, for example, are randomly sampled by the mobile sensors installed on the maintenance vehicles or the locations with RWIS pavement sensors and may not reflect the true pavement conditions for the whole county. Other variables such as air temperature and wind speed reported from the adjacent airport at the beginning may not accurately capture the real situation over the course of a snowstorm. Nevertheless, the information more or less exhibits the severity of a snowstorm and its influence on traffic safety will be recognized in the following analysis.

TABLE 2 Pearson Correlation Matrix*

	SDUR	**CDUR**	**PTS**	**AT**	**UNIT**	**HRS**
SDUR	1					
CDUR	*0.863*	1				
PTS	-0.076	-0.126	1			
AT	-0.081	-0.138	*0.77*	1		
UNIT	0.132	0.218	-0.061	-0.054	1	
HRS	0.414	0.522	-0.123	-0.136	*0.715*	1

* The explanations of the acronyms are listed in the second column of the Table 1.

Temporal Effects

During a snowstorm, the highway system can no longer provide the service as it does on a clear day. The real condition of the roadway is dynamically altered by the snowstorm, traffic volume, and the level of maintenance effort. Therefore, the fundamental question is: "When is the worst time for people to travel in the course of a snowstorm given the current state of the winter maintenance practice?" Normally, snow accumulates more rapidly when the traffic is low and the maintenance activities have not been fully carried out. Because it is very difficult to monitor and collect both traffic data and maintenance activities for individual snowstorms, relative crash time only is employed to create the histograms of the temporal variation of the snowstorm crashes on the state-maintained highway and local highways. Relative crash time is calculated as the ratio of the crash time to the storm duration and is expressed in equation 1.

$$RT_i = \frac{T_i - T_{ss}}{T_{se} - T_{ss}} \tag{1}$$

where
RT_i is the relative crash time of crash i;
T_i is the crash time of crash i;
T_{ss} is the snowstorm starts time; and
T_{se} is the snowstorm ends time.

Figure 1 shows that snowstorm crashes are uniformly distributed from the beginning to the middle of a snowstorm and then decrease rapidly when approaching the end of a snowstorm. While the local roads crash distribution exhibits a similar but a more gradual and steady decrease. The significant difference of the crash percentage distributions between state-maintained highway and local roads can be recognized in the second half of a snowstorm. Higher percentage of crashes occurred during a time period on local roads than on state highways which suggests that the different level of maintenance may play an important role in affecting traffic safety. In fact, county highway departments maintain the state's highways for either 18-hours or 24-hours per day during a winter storm event, as conditions warrant. Local municipalities may have insufficient resources to operate winter maintenance. WisDOT winter maintenance guidelines also indicate that priorities are given to the highways with higher traffic volume and higher functional classification (*14*).

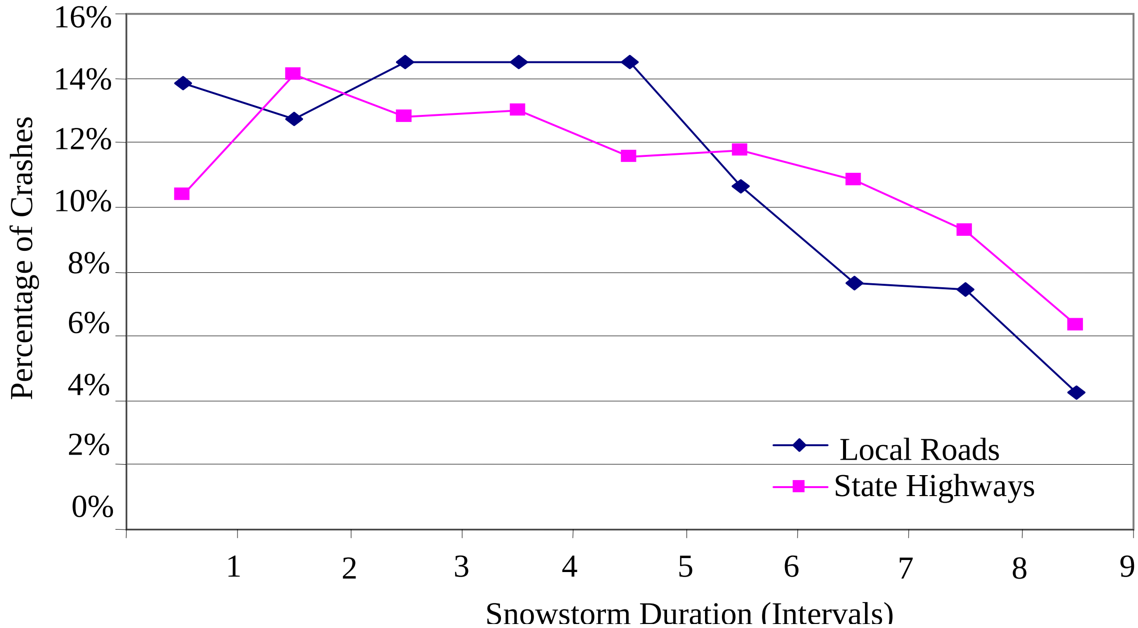

FIGURE 1 Crash Occurrence by Time of Snowstorm.

MODELING THE SNOWSTORM CRASHES

The number of crashes that occurred during a snowstorm contains information regarding the snowstorm characteristics and the level of winter maintenance effort. In traffic safety analysis, Generalized Linear Models (GLIM) have been frequently adopted to estimate or predict crashes as well as its relations to other factors. Following similar philosophy, snowstorm crashes are regarded as a dependent variable and other aforementioned factors are treated as explanatory variables. Crash counts, inherently discrete, positive numbers, illustrate a highly skewed distribution in that most snowstorms experience few crashes while a small number of snowstorms experience relatively more crashes. Therefore, a GLIM framework with underlying Poisson or Negative Binomial distributions is widely employed to describe the distinctive features of the crash data. The Poisson distribution assumption that the mean is equivalent to the variance restrains its popularity. Since the computation of the snowstorm crashes shows a larger variance, suggesting an overdispersion of the crash data, Negative Binomial (NB) distribution is more appropriate in describing this type of over-dispersed counts. The NB distribution has two parameters, the mean and a dispersion parameter.

The probability of the number of crashes in a snowstorm follows a NB distribution with parameters α and d (with $0 \le \alpha \le 1$ and $d \ge 0$) and can be seen in Equation 2.

$$P(Y_i = y_i; \alpha, d) = \frac{(y_i + d - 1)!}{y_i!(d-1)!} \frac{\alpha^{y_i}}{(1+\alpha)^{y_i + 1/d}}; \quad y_i = 1,2,3,... \tag{2}$$

where y_i is the number of crashes in storm ***i*** and ***d*** is the inverse of the dispersion parameter in the NB distribution. Instead of being equal to the mean, the variance of the NB distribution is shown in Equation 3.

$$Var(Y) = d\alpha + d\alpha^2 = \mu_i + \frac{\mu_i}{d} \tag{3}$$

In fact, the NB approaches to the Poisson distribution when the value of *d* is large enough. The relationship between the expected number of snowstorm crashes (μ) and a set of explanatory variables follows the exponential function (Equation 4).

$$E(Y) = \mu_i = d\alpha = L \cdot \exp(\boldsymbol{D} \cdot \boldsymbol{\gamma} + \boldsymbol{X} \cdot \boldsymbol{\beta}) \tag{4}$$

where

L: lane-mile of each county is used as traffic exposure;
D: the vector of dummy variables such as precipitation and county factors;
γ: the vector of unknown coefficients of the dummy variables;
X: the vector of explanatory variables in relation to the crashes; and
β: the vector of unknown coefficients of the variables.

After taking the log transformation, Equation 4 becomes a linear relationship. Within the GLIM framework, a NB regression analysis of these data is preformed with a log link function as shown in Equation 5

$$\ln(\mu_i) = \ln(L) + \boldsymbol{D} \cdot \boldsymbol{\gamma} + \boldsymbol{X} \cdot \boldsymbol{\beta} \tag{5}$$

in which the γs and *β*s are unknown parameters and can be estimated by the Maximum Likelihood Estimation (MLE) method using the SAS procedure PROC GENMOD (a generalized linear model procedure) (*15*). The logarithm of lane-mile is specified as an offset variable which serves as traffic exposure to normalize the fitted expected number of crashes. In addition to the variables such as temperature, wind speed, and cost which are continuous, the precipitation type is used as categorical variable in the model. A snowstorm could be one or more combination of the following types of precipitation: dry snow, wet snow, freezing rain, and sleet.

RESULTS AND DISCUSSION

Considering the large number of input variables, the modeling was repeated using a step-wise procedure. The variables with statistical significance remain and the insignificant variables are removed from the models. Also, as discussed in the Exploratory Data Analysis Section, the dependence between the variables are dealt with by either the use of only one of the two correlated variables or the addition of a new interaction variable. For instance, correlation exists between variables such as storm duration and maintenance staff work duration; the storm duration and storm depth; and the storm duration and de-icing unit usage. A variety of models were tested and the regression results with the new interaction variables showed that all coefficient estimates for the interaction variables were too small to be meaningful. After the comprehensive modeling, the following factors (also shown in Table 3) are statistical significant at 95 percent confidence level: freezing rain (NO FREEZING RAIN), crew out time prior to the Storm (CSOUT), storm duration (SDUR), de-icing hours (HRS), salt per lane mile (UNIT_SALT), and wind speed (SPEED). Note that the lane-mile is used as the offset and, therefore, does not appear in the NB regression model results.

TABLE 3 NB regression Model Results

Variable	Estimate	Std. Err	95% Confidence Limits		P-value
			Low Bound	High Bound	
Intercept	-5.704	0.069	-5.839	-5.568	<.0001
NO FREEZING RAIN	0.218	0.033	0.154	0.283	<.0001
CSOUT	-0.026	0.004	-0.034	-0.018	<.0001
SDUR	0.019	0.002	0.016	0.022	<.0001
HRS	0.063	0.013	0.038	0.087	<.0001
UNIT_SALT	0.005	0.003	0.002	0.006	<.0001
SPEED	0.007	0.003	0.002	0.012	0.007
Dispersion	0.345	0.013	0.324	0.376	

Discussion

The study provides useful information in various aspects regarding road weather safety in winter snowstorms. County highway departments are being asked to become more proactive in their approach to providing good winter driving condition. In this case snow-plowing and spreader trucks are sent out either prior to the start of the storm event or shortly after the event. This has been proved to be effective in terms of reduced number of crashes. As shown in Table 3, crew out versus the beginning of the snowstorm (CSOUT) in the unit of hours shows a negative relationship (-0.026) with crash frequency, indicating the fact that the early deployment of the winter maintenance operations can significantly reduce crash occurrence. The positive value of 0.063 between the de-icing unit hours (HRS) and the number of crashes might be confusing at the first impression because intuitively people think that more snowplowing, salting, and sanding unit hours improve road surface condition and thereby, reduce the number of crashes. In fact, HRS is recorded in a way that the units were used after the snow or freezing precipitation had begun falling. Obviously, more severe snowstorms which cause more crashes also cost more de-icing unit hours. In other words, the HRS emphasizes the severity of the snowstorm rather than the crash occurrence.

The same philosophy might be carried over to explain the functionality of the de-icing materials in battling the snowstorm as well as their safety impact on the ice or snow-covered roadway. Study results display a positive relationship between the crash occurrence and the unit salt usage (salt/lane mile). It means that the severity of a snowstorm increases the salt usage and on the other hand, causes more crashes. Similar to the total de-icing units and hours, it is an appropriate reflector of the severity of the snowfall. Generally speaking, the de-icing materials consumed during the snowstorm such as sand, salt, and other chemicals like CaCl, salt brine, $MgCl_2$, and agriculture based products also are closely related to the snowstorm severity and its features. When snow is dry with low moisture, salt is difficult to be blended with snow and prewetting salt chemicals are usually added to facilitate the melting process. The low pavement temperature also affects salting function. Especially, when pavement temperature drops below 15 degrees, salt does not function well and sand is commonly used as an abrasive to increase the pavement surface friction.

Unfortunately, the actual snowstorm maintenance cost data indicates that the aforementioned principles are not well followed. One reason may be the data collection deficiency since pavement temperature is collected at the beginning of the snowstorm and may change over the course of the snowstorm. Another important reason is that in practice, winter maintenance staff use their personal experience and judgment to decide the use of de-icing materials. The data exhibit that out of 3,667 snowstorms with crashes, sand was used only 900 times, prewetting salt was used in 1,742 snowstorms while salt alone was used in 3,640 occasions. The use of sand, salt, and prewetting salt covered a wide range of pavement temperature and appeared in both dry and wet snow events. Therefore, the dry or wet snow condition is not statistically significant in affecting crash occurrence. The pavement temperature, though presenting a positive relationship to the total number of crashes of a snowstorm, is difficult to be interpreted in that complicated situation.

Some information regarding the traffic safety benefits of the salting practice in combating the snowstorms can be found at the Salt Institute website (*16*). It is well known that salt prevents snow and ice from bonding to the pavement and thereby snowplows are able to remove accumulations quickly and efficiently. In this way, salt can keep highways passable and safe. A study conducted by Marquette University documented the use of salt and showed that proper salting can reduce injury crashes by 88.3 percent (*13*). Nevertheless, melted snow or ice will make pavement more slippery if not cleaned in time, which may increase crash risk. Leggett testified in his study that when most anti-icing or de-icing chemicals transition from liquid to solid, and solid to liquid, a "slurry" phase is formed and this produces a relatively short-lived reduction in co-efficient of friction for most chemicals. This reduction is anywhere from essentially non-existent 0.4 percent, (FreezGard with Ice Ban) to a substantial 29 percent, (LiquiDow) (*17*). In Wisconsin, the average lapse between the de-icing action and the snowplowing ranges from 1.5 hours to four hours, depending on the traffic volume and the priority of the highways. During the lagged time period, pavement may be bare under the traffic movement but remains slippery. Without noticing the difference, drivers may resume the high speed and are easier to lose control of their vehicles. The lack of data prevented further investigation of this issue for the data presented here. Although the salt usage is confounded by the severity of the snowstorm, it is recommended that prudent applications be required to assure the deicer reduces slipperiness and the use of prewetting salt or salt alone be in conjunction with snowplows within a short timeframe.

The other results of snowstorm impact on highway safety are consistent with the previous research (*9*). The estimate of the coefficient for wind speed is positive; in other words, higher wind speed causes more crashes. Not surprisingly, blowing snow is one of the major reasons for limited visibility. The snowstorm duration and depth also have a positive relationship with the crash occurrence, although latter is not statistically significant. One discovery is fairly counterintuitive. Experience tells us that freezing rain is considered as the most dangerous weather events because the ice, sometimes called “black ice”, on the pavement is both extremely low in friction and often difficult to detect. However, the results show that freezing rain leads to crashes, but not at a higher rate than non-freezing rain conditions. The crash facts are that 3,456 crashes occurred during the 898 snowstorm events with freezing rains, causing 1,630 injuries and 29 fatalities. The crash rate of 3.85 crashes/event for the freezing rain events is far less than five crashes/event during the more common phenomena dry or wet snowstorms. This may be due to more aggressive and proactive winter maintenance efforts for treating the freezing rain (versus other types of winter precipitation) or the raised public awareness and caution. Recall that a large percentage of crashes are caused by human errors, especially when driving faster than the safe conditions. Once drivers realize the potential hazards, increased caution may prevent loss of vehicle control and crashes. However, approximately two injuries per freezing rain event are the highest among all the precipitation types, indicating a more severe consequence if crash occurs. Perhaps drivers don’t realize the need to slow down during freezing rain because of the invisible “black ice”, thus collisions occur at a higher rate of speed increasing severity.

CONCLUSION AND FUTURE RESEARCH NEEDS

This study investigated the snowstorm impact on highway safety and assessed the winter maintenance effort in reducing number of crashes from a macroscopic perspective. County level snowstorm reports showing salting, sanding, and snowplowing activities in the 2000 to 2002 winter seasons are linked to the crashes occurring during the same time period. The results show a mixed influence of the snowstorm on road safety: the severity of the snowstorm in terms of duration, intensity, and wind speed increases the traffic crashes and casualties on the state highways while freezing rain event presents a negative relationship to the crash counts, which is fairly counterintuitive. A further analysis reveals that freezing rain leads to a more severe consequence if crash happens. Not only weather interacts with highway geometric features and traffic conditions but also affects driver behaviors. Driving with caution in adverse weather can help drivers avoid dangerous situations.

Maintenance cost reflected the severity of the snowstorm. The more severe snowstorm consumes more winter maintenance labor, units and de-icing materials and causes a higher number of crashes. Though the expected inverse relationship between the number of crashes and the de-icing material consumption is not obtained from the study, it implies that snowstorm-related crashes are complicated by the interaction between weather, human behavior, and winter maintenance. The study also implies that the duration of the “slush” period caused by the lag between the de-icing and snowplowing may lead to more crashes. The research also explicitly proves that a proactive winter maintenance effort will significantly improve traffic safety, in that starting maintenance efforts prior to the beginning of the snowstorm leads to fewer crashes.

The temporal distribution of the crash occurrence during a snowstorm shows that a large percentage of crashes occurred during the initial stages of the snowstorms. This may be due to reduced traffic volumes as the storm becomes more intense, intensified maintenance efforts throughout the event, or both. The temporal crash pattern is very similar for both state-maintained highway and local roads except that in the second half of a snowstorm, higher percentage of crash occurred on local roads than that of the state highways possibly suggesting that the different level of maintenance and the use of de-icing materials may play an important role.

Additional research is required before definitive conclusions can be made with respect to the use of de-icing materials to improve highway safety, particularly with regards to application rate and frequency, on battling snowstorm to secure highway safety. Future research is planned which will also target the combined real-time traffic information, winter maintenance activities and crash occurrence at a microscopic level (i.e., road segment or a maintenance patrol station). This future research will assist winter maintenance operations in optimizing the cost without sacrificing the winter mobility and safety.

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