Snowstorm Event-Based Crash Analysis

Article *in* Transportation Research Record Journal of the Transportation Research Board · January 2006
DOI: 10.3141/1948-15

4 authors, including:

Xiao Qin
Syracuse University

David A. Noyce
University of Wisconsin–Madison

Chanyoung Lee
University of South Florida

Snowstorm Event–Based Crash Analysis

Xiao Qin, David A. Noyce, Chanyoung Lee, and John R. Kinar

This study investigated the impact of snowstorms on a roadway system and assessed winter maintenance efforts in improving highway safety from a macroscopic perspective. The Wisconsin State Trunk Highway System was used as the data source. An inverse relationship between deicing material consumption and crash counts during snowstorms is reflected in the analysis; it also implies multiple causes of snowstorm crashes. Primary factors considered in this research were the effects of various weather conditions and winter maintenance. Results showed a mixed influence of both the snowstorm severity and winter maintenance investment on road safety. That is, severity of the snowstorm in regard to duration, intensity, and wind speed increases traffic crashes and casualties with simultaneous consumption of more deicing materials and labors. The research also explicitly proves that a proactive winter maintenance effort significantly improves traffic safety. Temporal distribution of crash occurrence during a snowstorm shows that a large percentage of crashes occurred during initial stages of the snowstorms, probably because snow removal activities had not yet begun. The pattern is quite similar for state-maintained highways and local roads, except that in the second half of a snowstorm, a higher percentage of crashes occur on local roads than on state highways, possibly suggesting that the different level of maintenance and use of deicing materials may play an important role. Additional research is required to quantify the effects of deicing materials specifically, particularly in regard to application rate and frequency, on highway safety.

Travel in winter, especially when one encounters a snowstorm, may not be a safe driving experience. Snowstorms may not only extend travel time but 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 more than 500 million h 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. Fatalities, injuries, and property damage from weather related-crashes cost an average of $42 billion in the United States 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 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, that is, average vehicular acceleration or deceleration and normal friction coefficient.

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

CHALLENGES FROM WINTER WEATHER

Wisconsin and other Upper Midwestern states face 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 in. (101.6 cm) in the south to as much as 160 in. (406.4 cm) 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 22.8523 billion, almost 40% of the annual VMT (Wisconsin highway traffic volume data, unpublished data from the Wisconsin Department of Transportation, 2004).

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

Crashes due to weather are of critical concern for Wisconsin transportation professionals. Significant effort has been invested to mitigate snowstorm hazards, to keep roadways passable, or to recover roadways to traversable lanes as early as possible. Meanwhile, as in most other states, tighter winter operations budgets make the challenge more difficult. Winter maintenance costs continue to increase because of higher costs of anti-icing and deicing materials and higher costs of labor and equipment. In the winter spanning 2003 and 2004, the total cost of winter operations in Wisconsin was $40,184,200, a 9% increase over the previous 5-year average (*2*).

Wisconsin faces the challenge of how to improve travel conditions during winter snowstorm events while maintaining the safe standard expected by the traveling public, and with a decreasing budget. This research investigated the relationship between snowstorm crashes and snowstorm severity, winter operation, and maintenance cost. First, this paper explores snowstorm impacts on road safety along with relevant weather variables contributing to the snow-related crashes and available safety assessment of winter road maintenance. Next, a data collection method is described to yield a meaningful approach to connecting the snowstorm information with crash data. The exploratory

X. Qin, Traffic Operations and Safety (TOPS) Laboratory, and D. A. Noyce and C. Lee, Department of Civil and Environmental Engineering, University of Wisconsin–Madison, 1415 Engineering Drive, Madison, WI 53706. J. R. Kinar, Wisconsin Department of Transportation, 4802 Sheboygan Avenue, Room 501, P.O. Box 7986, Madison, WI 53707-7986.

Transportation Research Record: Journal of the Transportation Research Board, No. 1948, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 135–141.

data analysis (EDA) procedure was used to examine the data set from two important aspects: data characteristics and a temporal analysis of snow-related crashes. The paper concludes with negative binomial (NB) statistical analysis of the snowstorm crash data, providing an in-depth analysis on snowstorm crashes and crash risk factors. Then there is a discussion of results, offering a thorough explanation and future research needs.

BACKGROUND

Numerous studies have assessed the negative impact of weather on the transportation system in regard to delay and traffic safety. Nevertheless, many studies are quite dated. Of various 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. Although the previous results vary, their conclusions are fairly consistent. Research conducted at Clark University in 1968 showed that collisions increased by at least 200% on 3 to 12 snow days per year (*3*). Similarly, a British study indicated that injury collisions increased by approximately 50% under snowy, icy, wet, or fog conditions, compared with the rate in clear weather (*4*). 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 h per lane (vphpl) under snow conditions (*5*). Drivers must endure the deteriorated safety condition not only during the precipitation phase of the event but also for some time thereafter. This safety concern is addressed by in 2003 by Suggett, who indicated that collision risk was elevated for both the precipitation period and for several days following measurable snowfalls, due to the slippery roads (*6*). Supporting evidence can be found in a 2001 Canadian report presenting a wide range of road weather safety studies (*7*).

Other than simply documenting the fact that snowstorm and adverse weather fatalities continue to rise, researchers have sought to identify the weather variables that directly or indirectly cause safety problems. Studied weather parameters include, but may not be limited to, pavement temperature, air temperature, atmospheric visibility, wind speed and direction, snow intensity, duration, and coverage. For 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 (*8*). Several other studies show that wet or slippery roads reduce friction by 30% to 40% and snow- and ice-covered roads by up to 75% (*6, 9*). Because snow- and ice-covered roads can reach skid number below 35, safety becomes more critical. AASHTO assumes a pavement skid number of 35 or more in the commonly used stopping sight distance model (*10*). Pavement temperature also has a significant effect on the surface frictional properties. Researchers found that pavement friction tended to decrease with increased pavement temperatures, also subject to vehicular velocity (*11*). Quantifying the 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 snowstorm threats more effectively and efficiently. The winter maintenance community realizes that this information is invaluable in policy making, program managing, and performance measuring.

Winter maintenance operations are to ensure, as reasonably practicable, safe and efficient movement of vehicles, especially on the principal road network. Efforts aim 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 states that experience significant snow events are simply to keep roadways passable or to recover travel lanes to the pavement surface within an acceptable time frame subject to highway priorities. However, information demonstrating benefits for even basic winter maintenance operations such as snowplowing, 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 (*7*). The Norwegian Directorate of Public Works study found that salted roads had 26% fewer collisions than did 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. In another study, Finnish researchers applied reduced salt rates on experimental road segments from the typical 10 tons/km each winter to 1 to 2 tons/km each winter. They discovered that the frequency of slippery conditions on these roads attributed to snow and ice increased by 30% to 40% and crashes increased by 20% on most road sections (*7*).

In the United States, Kuemmel and Hanbali summarized their study with the following findings: crash frequency was eight times higher before deicing than afterward on a two-lane highway and four and one-half times higher for multilane freeways; crash frequency was nine times and seven times higher before application of salt for two-lane and multilane roadways, respectively, and crash severity was reduced by 30% (*12*). Although the few examples show a consistent level of safety improvement on limited experimental sites, a large-scale study is needed to realize the general benefits of winter maintenance activities.

DATA COLLECTION AND PROCESSING

This research involved analysis of a large number of data from various resources. Data on winter snowstorm events have been carefully collected and archived by the Bureau of Highway Operations at the Wisconsin Department of Transportation (DOT) since 1998. Winter storm reports are designed for tracking the relationship between the winter operations and maintenance cost and severity of snowstorms. Snowstorm data are reported through the county highway maintenance authorities that contract with Wisconsin DOT to complete the anti-icing, deicing, and snowplowing activities on the Wisconsin State Trunk Highway System [or state trunk network (STN)]. Therefore, data for winter maintenance activities are recorded only 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 costs pertaining to labor, equipment, and material usage. One goal of winter maintenance is to achieve passable roadways within the limitations imposed by climatological conditions, availability of resources, and environmental concerns during a winter storm event. In the Wisconsin DOT 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. Also, it can be traveled safely at reasonable speeds—speeds at which a vehicle can travel without losing traction (*2*). Another use of the snowstorm data is to calculate the winter severity index for each county, which, in conjunction with winter maintenance cost data, could be used to compare the cost and effectiveness of snow and ice removal between counties.

TABLE 1 Summary Statistics for Snowstorm Crash Data Set

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 (°C)	–3.95	–13.15	–20.56	13.89
PTE	Pavement temperature end (°C)	–14.71	–11.46	–23.33	13.33
Sdur	Storm duration (h)	14.37	10.66	0.5	134
Cdur	Crew work duration (h)	15.41	12.34	0	232
Csout	Crew out prior to storm (h)	2.58	3.67	–16	46
Csin	Crew in after storm (h)	3.63	6.01	–24	39.5
Depth	Snow depth (cm)	6.50	7.65	0.25	190.50
Unit	Deicing units used (unit)	13	9.28	1	208
Hrs	Deicing unit hours (h)	125.29	146.60	1	2,023
AT	Air temperature in degrees (°C)	–3.97	–12.78	–23.33	20.56
SPD	Wind speed (km/h)	15.38	8.37	5.60	55.20
Salt	Salt used (tons)	228.57	357.97	0	5,935
Sand	Sand used (m^3)	13.68	49.96	0.00	709.51
CHM	Chemical for prewetting sand [L(1000 cm^3)]	978.68	2,896.33	0.00	57,871.35

The basic source of crash data in Wisconsin is the motor vehicle traffic accident form completed by the reporting law enforcement personnel. Every crash report has a description of the weather and surface conditions and location and time that 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 and slush, or ice. Provided that crash information is coded correctly by the officers, researchers are able to identify whether or not a crash is snowstorm related.

Because the snowstorm report records the weather service and Wisconsin DOT snowstorm start and end times, a crash can be linked to a specific snowstorm by location (county where the crash occurred) and by time (between the snowstorm start and end times). Considering the possibility of a temporal lag of a snowstorm from one side of the county boundary to another, a cross-validation was conducted to ensure that all the crashes are snowstorm related. Other data were used, such as weather condition, road surface condition, and crash contributing factors. After integration of the crashes with the snowstorm data, every snowstorm corresponds to a number of snowstorm-related crashes for each county. That enables researchers to take advantage of the information stored in the snowstorm report and explore the relationship between snowstorm and relevant crashes; to identify 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.

EXPLORATORY DATA ANALYSIS

Data Characteristics

Table 1 presents variables included in the snowstorm data and crashes. A total of 7,037 snowstorm events were reported by 72 counties in Wisconsin for the 2000 through 2002 winter seasons. More than 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. A common crash type in Wisconsin, deer–vehicle crashes, was excluded from this analysis.

Snowstorms vary by duration, severity, and coverage. For snowstorms with crashes, snow duration ranged from 30 min to 134 h, with a mean of 14.36 h. Snow depth ranged from a minimum of 0.1 in. (0.254 cm) to a maximum of 75 in. (190.5 cm), with an average of 2.5 in. (6.35 cm). If more than one type of precipitation occurred during a snowstorm, all were measured and recorded individually. Pavement temperatures were also collected at the beginning and the end of a snowstorm through either the fixed roadway weather information system (RWIS) stations on the roadside or the mobile sensors installed on maintenance vehicles. Wind speed and air temperature collected from the nearest airport were also included in the snowstorm report.

Winter maintenance operational efforts are also considered in Table 1. Winter maintenance staff schedule is recorded as crew out time and crew in time. As can be seen in the data, crew work time in a snowstorm is relatively consistent with snow duration. To evaluate the maintenance performance effect on traffic safety, two additional variables were calculated. One is the time that winter maintenance staff are out before a snowstorm, which is the difference between the crew out time and the 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. Evaluation of the numbers shows a large variation from county to county and from event to event. The most proactive maintenance starts 16 h before the snowstorm or does not end until approximately 40 h after the snowstorm stops. In contrast, the least aggressive snowstorm treatment does not start until 46 h after the snowstorm begins or ends 24 h earlier than the snowstorm stops. The average times for those two variables are 2.58 h and 3.36 h, respectively.

The snowstorm report provides abundant information for traffic safety analysis. Nevertheless, some information may be dependent,

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

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 snowstorm duration and amount. The Pearson Correlation Matrix for selected variables confirms the existence of the dependence among variables (Table 2). Pavement temperatures, for example, are randomly sampled by the mobile sensors installed on maintenance vehicles or locations with RWIS pavement sensors, and they may not reflect 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.

Temporal Effects

During a snowstorm, the highway system can no longer provide the same service as it does on a clear day. The real condition of the roadway is dynamically altered by the snowstorm, traffic volume, and 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 traffic is low and maintenance activities have not been fully carried out. Because it is quite difficult to monitor and collect both traffic data and maintenance activities for individual snowstorms, relative crash time only is employed to create histograms of the temporal variation of snowstorm crashes on state-maintained highway and local highways. Relative crash time is calculated as the ratio of crash time to the storm duration and is expressed in Equation 1.

$$\mathrm{RT}_i = \frac{T_i - T_{ss}}{T_{se} - T_{ss}} \qquad (1)$$

where

RT_i = relative crash time of crash i,
T_i = crash time of crash i,
T_{ss} = snowstorm start time, and
T_{se} = snowstorm end time.

Figure 1 shows that snowstorm crashes are uniformly distributed from the beginning to the middle of a snowstorm and then decrease rapidly when the end of a snowstorm is approaching. Crash distribution on local roads exhibits a similar but more gradual and steady decrease in comparison with that for state-maintained highways. The significant difference of crash percentage distributions between state-maintained highways and local roads can be recognized in the second half of a snowstorm. A higher percentage of crashes occurred during a period on local roads than on state highways, possibly suggesting 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 h or 24 h per day during a winter storm event, as conditions warrant. Local municipalities may have insufficient resources to operate winter maintenance. Wisconsin DOT winter maintenance guidelines also indicate that priorities are given to the highways with higher traffic volume and a higher functional classification (*13*).

MODELING OF SNOWSTORM CRASHES

The number of crashes that occurred during a snowstorm provides information on 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. In a 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

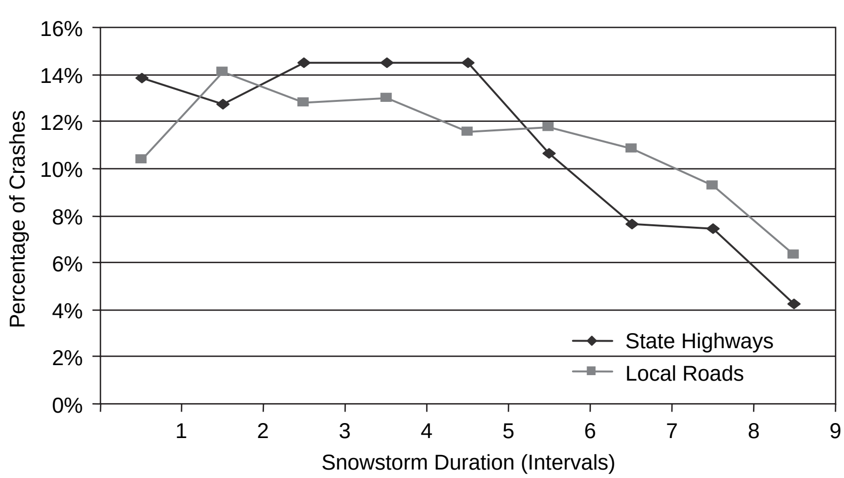

FIGURE 1 Crash occurrence by time of snowstorm.

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 NB distributions is widely employed to describe distinctive features of the crash data. The Poisson distribution assumption that the mean is equivalent to the variance restrains its popularity. Because computation of the snowstorm crashes shows a larger variance, suggesting an overdispersion of the crash data, NB distribution is more appropriate in describing this type of overdispersed count. The NB distribution has two parameters, the mean and a dispersion parameter.

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

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

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 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 as in 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, used as traffic exposure;
- $\boldsymbol{D}$ = vector of dummy variables such as precipitation and county factors;
- $\boldsymbol{\gamma}$ = vector of unknown coefficients of dummy variables;
- $\boldsymbol{X}$ = vector of explanatory variables in relation to crashes; and
- $\boldsymbol{\beta}$ = vector of unknown coefficients of variables.

After the log transformation, Equation 4 becomes a linear relationship. Within the GLIM framework, an NB regression analysis of these data is performed with the following log link function:

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

in which $\boldsymbol{\gamma}$ and $\boldsymbol{\beta}$ are unknown parameters and can be estimated by the maximum likelihood estimation method using the SAS procedure PROC GENMOD (a generalized linear model procedure) (*14*). The logarithm of lane mile is specified as an offset variable that serves as traffic exposure to normalize the fitted expected number of crashes. In addition to variables such as temperature, wind speed, and cost, which are continuous, precipitation type is used as a categorical variable in the model. A snowstorm could be one or more combinations of the following types of precipitation: dry snow, wet snow, freezing rain, and sleet.

RESULTS

Intuitively, more intense snowstorms require more salt per lane mile and deicing hours, the explanatory variables such as deicing hours (hrs), deicing units per lane mile (unit_di) and salt per lane mile (unit_salt) were normalized by using the storm intensity indicator—snow depth (depth) before the regression analysis. Considering the large number of input variables, the modeling was repeated by using a step-wise procedure. Variables with statistical significance remain, and insignificant variables are removed from the models. Also, as discussed earlier, the dependence between variables is 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 duration of maintenance staff work, storm duration and storm depth, and storm duration and deicing unit usage. Various models were tested, and regression results with the new interaction variables showed that all coefficient estimates for the interaction variables were too small to be meaningful. After comprehensive modeling, the following factors (also shown in Table 3) were statistically significant at the 95% confidence level:

- Freezing rain (no freezing rain);
- Crew out time before the storm (csout);
- Storm duration (sdur);
- Deicing units used per lane mile (unit_di);
- Salt per lane mile (unit_salt); and
- Wind speed (speed).

Lane mile is used as the offset and therefore does not appear in the NB regression model results.

TABLE 3 NB Regression Model Results

			95% Confidence Limits		
Variable	Estimate	Std. Err	Low Bound	High Bound	*P*-Value
Intercept	−5.402	0.051	−5.502	−5.303	<.0001
No freezing rain	0.221	0.035	0.152	0.291	<.0001
Csout	−0.045	0.004	−0.053	−0.037	<.0001
Sdur	0.033	0.001	0.031	0.036	<.0001
Unit_di	−0.013	0.003	−0.019	−0.008	0.0003
Unit_salt	0.001	0.0001	0.0004	0.001	<.0001
Speed	0.011	0.003	0.006	0.016	<.0001
Dispersion	0.345	0.013	0.324	0.376	

DISCUSSION OF RESULTS

The study provides useful information on various aspects of road weather safety in winter snowstorms. It is understandable that traffic operations are influenced when snowstorm occurs. Highway safety changes. The snowstorm interferes with traffic operations by affecting a driver's behavior, lowering speeds, and increasing speed variability; therefore, it escalates crash risk. In addition, pavement friction, visibility, and vehicle level of maneuverability are also reduced by adverse weather conditions. County highway departments are being asked to become more proactive in providing good winter driving conditions. In this case, snowplows and salt spreader trucks are sent out either before the start of the storm event or shortly after the event. Early deployment and quick dispatch have proved effective in regard to reducing the number of crashes. As shown in Table 3, crew out time before the beginning of the snowstorm (Csout), by hours, shows a negative relationship (–0.045) with crash frequency, indicating that early deployment of winter maintenance operations can significantly reduce crash occurrence. More data from various resources, including snowstorm reports, winter maintenance records, and crash database, have been integrated to demonstrate the relationship between snowstorm severity, winter maintenance investment, and highway safety.

Study results display a negative relationship (–0.013) between crash occurrence and deicing units normalized by snow intensity (Unit_di). It means that deployment of more deicing units improves road surface condition and thereby reduces the number of crashes. Study results also show an inverse relationship between deicing unit hours (Hrs) and the number of crashes, even though it is not statistically significant at the 95% confidence level, with a P-value of 0.0713. Obviously, more severe snowstorms that cause more crashes also cost more deicing unit hours.

However, the same philosophy cannot be fully employed to explain the functionality of salt in battling the snowstorm as well as the safety impact on the ice or snow-covered roadway. Study results display a positive relationship between crash occurrence and unit salt usage (Unit_salt), with a small coefficient of 0.001. It can be interpreted that the severity of a snowstorm increases salt usage, and on the other hand, it causes more crashes. Some information on traffic safety benefits of salting practice in combating snowstorms can be found at the Salt Institute website (*15*). A study conducted by Marquette University documented the use of salt and showed that proper salting can reduce injury crashes by 88.3% (*12*). Nevertheless, melted snow or ice will make pavement more slippery if not cleaned in time, and that in turn may increase crash risk.

Leggett testified in his study that when most anti-icing or deicing chemicals transition from liquid to solid, and from solid to liquid, a "slurry" phase is formed, producing a relatively short-lived reduction in coefficient of friction for most chemicals (*16*). In the current study, the average lapse between deicing action and snowplowing ranges from 1.5 h to 4 h, depending on traffic volume and 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 high speed and more easily lose control of their vehicles. The lack of data prevented further investigation of this issue for the data presented here. Although salt usage is confounded by the severity of the snowstorm, it is recommended that prudent applications be required to ensure that the deicer reduces slipperiness and the use of prewetting salt or salt alone be in conjunction with snowplows within a short time frame.

Other results of snowstorm impact on highway safety are consistent with previous research (*8*). For example, the estimate of the coefficient for wind speed is positive—that is, higher wind speed causes more crashes. Not surprisingly, blowing snow is a major reason for limited visibility. In regard to snowstorm duration, it also has a positive relationship with the crash occurrence with a coefficient of 0.033. One discovery is fairly counterintuitive. Experience tells us that freezing rain is considered as the most dangerous weather event because the ice, sometimes called "black ice," on pavement is both extremely low in friction and often difficult to detect. Nevertheless, the results show that freezing rain leads to crashes, but not at a higher rate than for nonfreezing 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 per event for the freezing rain events is far less than that of 5 crashes per event during the more common phenomena dry or wet snowstorms.

That reduced crash rate may be due to more aggressive and proactive winter maintenance efforts for treating freezing rain (versus other types of winter precipitation) or heightened public awareness and caution. One should recall that a large percentage of crashes are caused by human errors, especially when driving faster than is safe for the conditions. When drivers realize the potential hazards, greater 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 do not realize the need to slow down during freezing rain, owing to invisible black ice. As a result, collisions occur at a higher rate of speed, increasing severity.

Other atmospheric or road weather factors are also analyzed, such as the pavement temperature before and after the snowstorm, precipitation type, and so on. Generally, the amount of salt and chemicals consumed during the snowstorm is closely related to snowstorm severity and its features. When snow is dry with low moisture, it is difficult for salt to be blended with snow, and prewetting salt chemicals are usually added to facilitate the melting process. The low pavement temperature (below −10°C) also affects salting function, and sand is commonly used as an abrasive to increase pavement surface friction. The proper use of these materials not only can facilitate recovery to bare pavement but also can keep the road condition as passable for a longer period, which benefits highway safety. Unfortunately, the actual snowstorm maintenance, atmospheric data, and pavement temperature data indicate that the aforementioned principles are not well followed. One reason may be deficiency in data collection, because pavement temperature is collected at the snowstorm start 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 in regard to using deicing materials. Therefore, the dry or wet snow condition is not statistically significant in affecting crash occurrence; nor is pavement temperature, though presenting a positive relationship to the total number of crashes in a snowstorm.

CONCLUSION AND FUTURE RESEARCH NEEDS

This study investigated snowstorm impact on highway safety and assessed the winter maintenance effort in reducing the 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 crashes occurring during the same period. Results show a mixed influence of the snowstorm on road safety: severity of the snowstorm in regard to duration, intensity, and wind speed increase traffic crashes and casualties on the state highways, whereas a freezing rain event presents a reduction in crash counts, a result that is fairly counterintuitive. Further analysis reveals that freezing rain leads to a more severe consequence if a crash happens. Not only does weather interact with highway geometric features and traffic conditions but it also affects drivers' behaviors. Driving with caution in adverse weather can help drivers avoid dangerous situations.

Maintenance effort reflected the severity of the snowstorm. The more severe snowstorms consume more winter maintenance labor (number of staff hours in the field), units (number of times the maintenance unit has been used), and deicing materials, and they cause a higher number of crashes. The expected inverse relationship between the number of crashes and deicing units is obtained from the study. This study also implies that duration of the slurry period caused by the time lag between salting and snowplowing may lead to more crashes. Furthermore, the research explicitly proves that a proactive winter maintenance effort will significantly improve traffic safety, in that starting maintenance efforts before the snowstorm begins leads to fewer crashes.

The temporal distribution of crash occurrence during a snowstorm shows that a large percentage of crashes occurred during the initial stages of snowstorms. That result 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 quite similar for both state-maintained highways and local roads, except that in the second half of a snowstorm, a higher percentage of crashes occurred on local roads than on state highways, possibly suggesting that the different level of maintenance and use of deicing materials may play an important role in affecting traffic safety.

Additional research is required before definitive conclusions can be made about the use of deicing materials to improve highway safety, particularly about application rate and frequency on battling snowstorms to secure highway safety. Besides some atmospheric information applied in the study, other weather factors that are a detriment to driving condition, such as wind direction, freezing rain intensity or duration, and visibility are not available; nor available is a detailed winter maintenance record for appropriate snowplowing, salting, sanding activities, and routes. Hence, future research is planned to focus on a smaller scale, that is, one county or one winter patrol section, where more comprehensive analysis is feasible, on availability of more data. Ideally, a variety of snowstorm treatment strategies, including different working schedules or varying amount of deicing and sanding materials, will be evaluated to assist winter maintenance operations in optimizing cost without sacrificing winter mobility and safety.

ACKNOWLEDGMENTS

The authors acknowledge the Bureau of Highway Operations of the Wisconsin Department of Transportation for financial support. The authors also thank Ghazan Khan for processing the data.

REFERENCES

1. *Where the Weather Meets the Road: A Research Agenda for Improving Road Weather Services.* Committee on Weather Research for Surface Transportation: The Roadway Environment. National Academies Press, Washington, D.C., 2004.
2. Martinelli, T. J. *Annual Winter Maintenance Report 2002–2003*, Wisconsin Department of Transportation, Madison, 2004.
3. Rooney, J. T., Jr. The Urban Snow Hazard in the United States. *Geographical Review*, Vol. 57, 1967, pp. 538–559.
4. *Transport and Road Research Laboratory Leaflet LF 389: Road Wetness and Surface Characteristics.* Transport and Road Research Laboratory, Crowthorne, United Kingdom, 1974.
5. Zhang, C., J. N. Ivan, and E. N. Anagnostou. Relative Risk Analysis for Studying the Impact of Adverse Weather Conditions and Congestion on Traffic Accidents. Presented at 84th Annual Meeting of the Transportation Research Board of the National Academies, Washington, D.C., 2005.
6. Suggett, J. Weather-Related Collisions in Regina, Saskatchewan, Canada. *Weather and Transportation in Canada.* Department of Geography, University of Waterloo, Ontario, Canada, 2003, pp. 67–95.
7. Andrey, J. *Weather Information and Road Safety.* Institute for Catastrophic Loss Reduction, Toronto, Ontario, Canada, 2001.
8. Khattak, A. J., and K. K. Knapp. Interstate Highway Crash Injuries During Winter Snow and Nonsnow Events. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1746*, TRB, National Research Council, Washington, D.C., 2001, pp. 30–36.
9. Noyce, D. A., and J. Yambo. *The Effects of Asphalt Pavement Surface Friction on Traffic Safety.* Draft Final Report. Traffic Operations and Safety (TOPS) Laboratory, Report 2005-2, University of Wisconsin–Madison, Wisc., 2005.
10. *A Policy on Geometric Design of Highways and Streets*, 5th ed. AASHTO, Washington, D.C.
11. Flintsch, G. W., Y. Luo, and I. L. Al-Qadi. Analysis of Effect of Pavement Temperature on Frictional Properties of Flexible Pavement Surfaces. Presented at 84th Annual Meeting of the Transportation Research Board of the National Academies, Washington, D.C., 2005.
12. Kuemmel, D., and R. M. Hanbali. Accident Analysis of Ice Control Operations. *Public Works*, Vol. 124, No. 8, 1993, pp. 48–50.
13. Traveler Information. Wisconsin Department of Transportation. www.dot.wisconsin.gov/travel/road/18–24hours.htm. Accessed July 7, 2005.
14. *SAS/STAT9.1 User's Guide.* SAS Institutes Inc., Cary, N.C., 2004.
15. Highway Deicing and Anti-icing for Safety and Mobility. Salt Institute. www.saltinstitute.org/30.html. Accessed July 6, 2005.
16. Leggett, T. S. *Temperature and Humidity Effects on the Co-efficient of Friction Value After Application of Liquid Anti-icing Chemical.* Final Report. Forensic Dynamics Inc., Kamloops, British Columbia, Canada, Sept. 30, 1999.

The contents of this paper reflect the authors' personal opinions and do not necessarily reflect the official views of the Wisconsin Department of Transportation.

The Winter Maintenance Committee sponsored publication of this paper.