Effects of Adverse Weather on Traffic Crashes

Systematic Review and Meta-Analysis

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Adverse weather obviously has an impact on vehicle crash rates on roads and highways. However, it would be valuable to quantify the extent to which weather conditions affect the crash rate. To do that, a meta-analysis has been conducted to generalize research findings on this subject and attempt to quantify the impact of weather on traffic crashes. Studies between 1967 and 2005 that examined the interaction of weather and traffic safety were reviewed. Thirty-four papers and 78 records that meet the predetermined criteria were included in the analysis. Crash rates from each study were normalized with respect to effect size for meta-analysis generalization. Results indicate that the crash rate usually increases during precipitation. Snow has a greater effect than rain does on crash occurrence: snow can increase the crash rate by 84% and the injury rate by 75%. Further results also suggest that variations in study results can be explained by study design, date of the study, and region or countries included in the study.

Adverse weather conditions are known to be a major factor affecting traffic safety and mobility. A number of studies have attempted to quantify this impact, although study results are not consistent. The increased crash rate ranges from less than 100% to more than 1,000% during snowfall. There has also been debate on whether injury rate decreases during snowfall. Andrey et al. noted that injury rate increased more than 20% in Ottawa, Canada (*1*). Brown and Baass found fewer crashes involving injuries during winter in the province of Quebec, Canada (*2*). The impact of severe weather on fatal crashes is even harder to quantify, owing to the lower number of events involved and other confounding factors. Eisenberg and Warner (*3*) estimated the effects of snowfall on U.S. traffic crash rates between 1975 and 2000, and they concluded that fatal crash rate decreased during snow days compared to dry days, but nonfatal-injury crash rate and property damage only (PDO) crash rate increased, which seems to be in agreement with the study by Knapp et al. in the state of Iowa (*4*).

USE OF META-ANALYSIS

To present a clear idea of how weather affects traffic safety, the method of meta-analysis has been applied to examine the impact of adverse weather on crash rates. The basic idea of meta-analysis is to identify relevant studies by a systematic search and then use effect size standardizing on each study result. In addition, this approach corrects sampling error and other artifacts, and it can present an estimate of the total effect with minimized subjectivity (*5*). Further, since different studies might be influenced by methodologies, time span, and regions, hierarchy meta-analysis has been applied using these factors as grouping variables. Separate analyses are conducted for each group.

The process used in the meta-analysis is outlined in Figure 1. After careful review of the included articles, two separate meta-analyses were conducted separately for comparison studies and regression studies.

For regression studies, measures of weather conditions were taken as the continuous variable. Effect size and percent change in crash rate were both applied to standardize the research results. However, due to space limitations of this paper, those results are not presented; they may be found in Qiu (*6*).

For the comparison studies, measures of weather conditions were considered as a binary variable (such as snow versus nonsnow). In addition to the overall meta-analysis carried out for each weather category (snow, rain, etc.), hierarchy meta-analyses were conducted separately for the comparison studies stratified by decades (time span) and by countries.

METHOD

Literature Search

A literature search for relevant studies published from 1970 to 2005 was conducted for both peer-reviewed literature and unpublished technical reports and theses. Search strategies used ensured this study contained enough primary studies for meta-analysis, because meta-analysis based on a large number of studies with a small sample size has been shown to be more accurate than that based on a small number of studies with large sample sizes (*5*).

Following the search, 376 papers and reports were selected for further examination, of which 108 were determined to be pertinent. From those reports, 34 that provided 78 result records were selected for meta-analysis.

Study Inclusion Criteria and Coding

Previous studies that explored the association between weather conditions and traffic safety have investigated diverse variables. These studies have also applied a variety of methods and were based on

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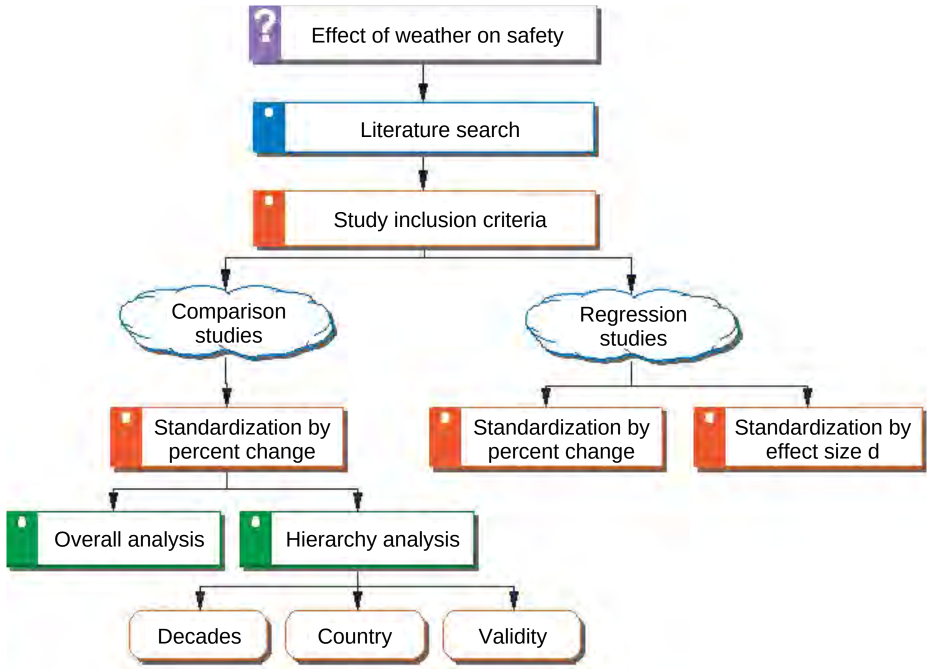

FIGURE 1 Process used in meta-analysis.

different types of data. To ensure that the included studies were comparable, the following study inclusion criteria were used:

Subject

Only studies that explored the associations between traffic safety and weather factors were included.

Study Design and Method

This paper reports on studies that used some form of comparison between adverse weather and normal weather conditions. Matched-pair study design was commonly used to control for extraneous factors in these studies considered. The studies identified the pairs similar in all respects (study area, time of a day, week or weekend), except for the weather factors being studied, so the other confounding factors were controlled. The studies then compared the crash rate during the precipitation days (events) to comparable nonprecipitation days (events) to obtain an averaged relative risk ratio (*7–9*). (Typically, in such studies, the many accident rate ratios are averaged to produce a single value.) Similar approaches include the wet pavement index method, and the difference-in-means method, which are variations to the matched-pair method.

Studies that investigated only the effect of weather conditions on crash frequency were excluded. Studies that investigated only the proportion of crashes with different levels of severity were also excluded, because the results are only informative about the relative frequencies of different types of crashes (*7, 9, 10*).

Outcome Measures

To be included, a study must have used an appropriate outcome measure such as counts or rates of traffic crashes, injuries, or fatalities; or measures of crashes likely to be affected by adverse weather, such as winter crashes or summer crashes. Examples of appropriate measures include crash counts defined by number of crashes during a certain time unit (*11*); and crash rate defined by the ratio of crash counts to traffic exposure or crash risk (also called relative accident risk ratio) as estimated by crash rate during precipitation events divided by crash rate during nonprecipitation events (*12*).

Measures of Weather Conditions

Snow and rain were the primary weather conditions among the identified studies. The commonly used measure in the comparison studies for the precipitation is whether it is a snow (rain) day (event) or not, which is mainly based on the precipitation type and total precipitation amount. For example, Andrey et al. (*13*) defined a snow event as a snow or ice precipitation event of 6 h, in which the total precipitation amount was greater than 0.4 mm (water equivalent).

Data

Only studies that provided sufficient quantitative data to permit the calculation of the effect of adverse weather on crashes were included.

Data Extraction

For each study that met the inclusion criteria, variables were coded into two tables (*6*). General information included document type, authors, publication year, country, study design, data source, and data on traffic volume. Study results information included sample size, weather category, weather specification, crash category, and percent change in crash rate.

Each of the selected studies was assessed for validity. A complete description of this process is in Qiu (*6*). For each study, scores were assigned to each study on the basis that the validity of each study could be estimated by assigning a validity score in each of three categories: study design, traffic volume data, and level of aggregation (*14*). The total validity score of a study is then the sum of these three scores. Qiu investigated the relationship between validity score and confidence interval (CI), and found that as validity score increased, the CI decreased (*6*).

Statistical Analysis to Generalize Research Findings

The major objective of this study was to quantify the effect of weather conditions on crash rate. As mentioned, separate meta-analyses were conducted for two types of studies.

Comparison Studies with Percent Change as Standard Measure

It had been planned to calculate an effect size d as the standard measure for each study (*5*):

$$\text{Cohen's } d = \frac{M_1 - M_2}{\sigma_{\text{pooled}}}$$

To compute an effect size, there was need for a parameter estimate and its standard error or variance estimation. However, not all comparison studies consistently report those parameters. Thus, an alternative, percent change of crash rate (number of crashes per million vehicle miles traveled), was used to standardize outcome variables.

For comparison studies using relative crash risk ratio (risk_i) as outcome variables, or for studies providing crash rate (rate_i) during precipitation versus nonprecipitation conditions ($\text{rate}_{\text{control}}$), percent change ($P_i$) was computed directly as shown in Equations 1 and 2:

$$P_i = \text{risk}_i - 1 \tag{1}$$

$$P_i = \frac{\text{rate}_i - \text{rate}_{\text{control}}}{\text{rate}_{\text{control}}} \tag{2}$$

where i represents different adverse weather conditions.

For some of the regression studies, information was extracted to compute the percent change in crash rate during adverse weather. These computations were based on the expert knowledge of weather conditions; a certain range of weather factor was selected on the x-axis, and from this the corresponding crash rate change was computed.

Correction of Traffic Volume Reduction

To ensure all the percent changes are comparable, it is necessary to correct those studies that did not control for the reduced traffic volume associated with adverse weather. For studies that used relative accident risk ratio (crash count ratio) as outcome variables or studies that did not take traffic volume reduction into consideration owing to insufficient traffic volume data, the effect of reduced traffic volume on the crash rate was incorporated.

Two assumptions were made to do this correction as used in the study by Fridstrom et al. (*15*). First, exposure is proportional to traffic volume. This assumption is made because for a specified segment of road, the exposure measure, vehicle miles traveled (VMT), is normally estimated by multiplying traffic volume on each road segment with the length of road segment and then summing them together to get an entire area VMT. Second, percent traffic volume reduction compared to the nonadverse weather condition can be defined as P_{vi}. Though traffic volume reduction data are not available for each study, comparable literatures indicate that the estimations are similar.

Doherty et al. suggested that during rain, traffic volume in Canada reduced 2% in comparison with non-precipitation days (*16*); this estimation is the same as a study conducted in London (*17*). Keay and Simmonds showed that the traffic volume decreased 1.35% to 2.11% on wet days in winter and spring, and it can decrease up to 3.43% for heavier precipitation (2 to 10 mm) (*18*). In regard to snow, traffic volume has a substantial reduction range from 7% to 56% (*19*) and 10% to 50% (*20*). Khattak and Knapp also estimated the average traffic volume reduction is 29% during heavy snow for Interstate highways (*20*). From these studies, traffic volume reductions, as shown in Table 1, for a variety of precipitations were used.

Accordingly, the percent change (P_i) of each study that needs traffic volume correction has been modified by Equation 3 to provide the corrected percent change in crash rate ($P_{\text{icorrected}}$).

$$P_{\text{icorrected}} = \frac{1}{1 - P_{\text{vi}}} * \left(P_i + 1\right) - 1 \tag{3}$$

Weight Each Study by Sample Size and Correct Sampling Error Variance

The occurrence of crashes is subject to random variation (*15*). Thus, studies with small sample size tend to have great variability and may lead to biased results. Computing the mean percent change across studies can reduce the impact of sampling error because of the large sample size obtained in this manner.

Because studies based on a large sample size normally provide a better estimation, each study was weighed by its sample size. Also, in many areas of scientific research, sampling error has been found to account for most of the observed variance; thus, the sampling error variance was corrected by the Hunter-Schmidt method (*5*).

The sample size (N_i) and the percent change in crash rate (P_i) during adverse weather events are available for each study. For each

TABLE 1 Traffic Volume Reduction P_{vi} Due to Different Weather Conditions

Precipitation Type	Light Precipitation	Precipitation	Rain	Light Snow	Snow	Heavy Snow
Percent deduction in traffic volume, P_{vi}	1.35%	1.65%	2%	10%	15%	29%

weather factor category, the mean percent change was computed as shown in Equation 4:

$$\bar{P} = \frac{\sum n_i P_i}{\sum n_i} \tag{4}$$

The observed variance is given in Equation 5:

$$\frac{\sum n_i \left(P_i - \bar{P}\right)^2}{\sum n_i} \tag{5}$$

Thus, the sample-size-weighted mean was obtained and the sample-size-weighted variance of observed crash rate change for each weather factor was calculated. The formula for the sampling-error variance of proportions is shown in Equation 6:

$$\frac{P_i * Qi}{n} \tag{6}$$

where $Qi = 1 - Pi$.

A sample-weighted mean of the sampling-error variance of proportions to be cumulated was then obtained as shown in Equation 7:

$$\frac{\sum P_i * Qi}{\sum n_i} \tag{7}$$

Then sampling error variance was corrected by subtracting the sampling-error variance from the observed variance, providing an estimate of the true variance plus variance due to other artifacts. Because of the lack of necessary information to allow for correction due to other artifacts, this estimation is used as an approximation for the true variance and also used to compute the confident interval.

RESULTS FOR COMPARISON STUDIES

General Results

In total, this study considered 29 comparison studies that provided 41 records, of which 23 record crashes, 5 record fatalities, 13 record injuries, and 4 record PDO crashes. Table 2 presents the estimated crash rate change during various weather conditions using 95% CI. Most of the percent changes were positive, indicating that during adverse weather conditions, all types of crashes (fatality, injury, and PDO) exhibit some kind of increase in crash rate. Results also indicate that most precipitation events are associated with considerable increased crash risk, a somewhat lesser increase in injury crash risk and minor increase in fatal crash risk. Generally, as the precipitation intensity increases, all levels of crash risk increase. High winds are also associated with an increase in the traffic crash rate.

The wet pavement index method was used in most of the studies that explored wet pavement related crashes. This method tends to overestimate the real crash risk (*21*). Also, wet pavement included in this analysis indicates all wet pavement events during winter month or cold temperature conditions, so the wet pavement in fact represents various undesirable road surface conditions during winter. As indicated in Table 2, on average, the wet pavement conditions would increase both crash rate and fatal crash rate by more than 300%. The significant impact of road surface condition on crash rates has also been found by Norrman et al. (*22*) and various papers by Andrey and coworkers (publication series from the University of Waterloo and the University of Western Ontario). Andrey and Knapper showed the relative injury risk was 1.70 on the slippery road surface without precipitation present (Department of Geography publication series, University of Waterloo). Norrman et al. suggested the highest crash risk was associated with road slipperiness due to rain or sleet on a frozen road surface, and the estimated increase of crash rate can be over 1,000% (*22*).

As shown in Figure 2, the average percent change in crash rates for rain and snow is 71% and 84%, respectively. Compared with rain, snow has a more significant impact on crashes and injuries.

Contrary to some research findings that the fatal crash rate would decrease in the adverse weather condition, the result shows that those who travel on the road during snow experience an 9% increase in fatality rate in comparison with that on dry days. Eisenberg suggested precipitation is negatively associated with fatal crashes (3.73% reduction per 10 cm of precipitation) (*23*). However, he acknowledged that the reduced traffic volume was not controlled in that study. Indeed, in this meta-analysis study, before controlling for the reduced exposure, the estimated fatality rate has a decrease of 7% during snow similar to the result found by Eisenberg (*23*). However, once the results have been corrected for traffic volume reduction, the fatality rate does still increase with precipitation. This estimation suggests that decline in the traffic volume may result in less car crashes, but for those who traveled in adverse weather, the risk of a fatal crash is still increased. However, this result needs to be further investigated.

TABLE 2 Crash Rate Change Compared with Rate in Nonadverse Weather Conditions

	Fatalities			Injuries			Crashes		
	N	Estimate (%)	95% CI (%)	*N*	Estimate (%)	95% CI (%)	*N*	Estimate (%)	95% CI (%)
Snow	1	9	9	4	75	54–96	8	84	68–99
Rain	1	8	8	7	49	28–70	10	71	31–111
Wet pavement	3	384	308–459	\	\	\	3	380	249–511
Heavy snow	\	\	\	2	420	350–490	\	\	\
Heavy rain	\	\	\	\	\	\	1	93	93
High wind	\	\	\	\	\	\	1	100	100

NOTE: Heavy snow = hourly precipitation intensity above 5 mm; snow = total 6-h precipitation amount above 4 mm; rain = total 6-h precipitation amount above 0.4 mm; high wind = wind speed above 15 mph. There were no data available for the particular conditions denoted by the backward slash.

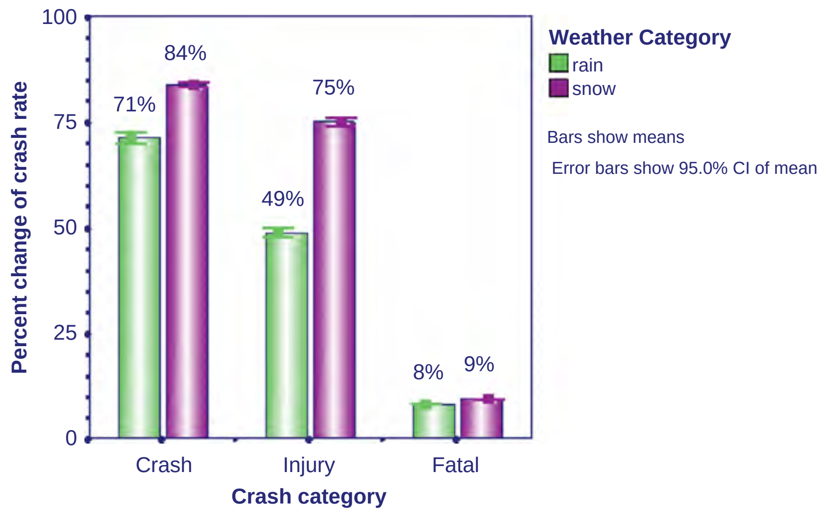

FIGURE 2 Effect of snow and rain on crash rates.

Results of Evaluating Studies by Decades

Since the previous studies have spanned several decades, hierarchy meta-analysis were conducted to assess to what extent patterns have changed over time. Three subgroups were formed, with study decades used as the grouping variable. Separate analyses were conducted for each subgroup.

As shown in Table 3, the percent change of crash rates during snow has a decreasing tendency over decades. It dropped from 113% during the decades 1950–1979 to 47% during 1990–2005. This conclusion can be further confirmed from the 95% CI of the percent change as shown in Figure 3. From 1950 to 1979, the estimated percent change of crash rate has a CI from 76.6% to 146%, while after 1990, the CI is from 33% to 62%.

One possible explanation for the result is that winter maintenance methods and technologies have improved over time. For example, the proactive technology of anti-icing has been introduced into the United States since the early 1990s (*24*). While this strategy is not yet used throughout the United States, clear evidence exists that anti-icing reduces crashes in winter weather (*25*). It would be useful to know which snow and ice control strategies are the most effective at reducing crashes. This, however, lies beyond the scope of the current study.

In contrast, there is no statistically significant variation in the crash rate under rain conditions over this same time period (1950s to 2005). This tentatively suggests that any technological improvements related to safety in rain (e.g., improved tire design) have been overwhelmed by other factors.

TABLE 3 Percent Change of Crash Rate, by Decade (fatal, injury, and PDO)

	Percent Change of Crash Rate Related to Snow			Percent Change of Crash Rate Related to Rain		
Study Decade	*N*	Mean (%)	95% CI (%)	*N*	Mean (%)	95% CI (%)
All decades	8	84	68–99	10	71	31–111
1950–1979	3	113	77–146	4	80	43–118
1980–1989	2	71	71–72	2	29	10–49
1990–2005	3	47	33–62	4	70	30–111

Results of Evaluation Studies by Country

Since the previous studies have spanned a number of countries, hierarchy meta-analysis was conducted to assess how much results vary with country. United States, Canada, and Great Britain tree subgroups were selected. Table 4 indicates how the change in crash rates varies across countries.

In Figure 4, the impact of rain and snow on injury and crashes are shown for the United States, Canada, and United Kingdom. When studies were evaluated by countries, there was considerable difference in the crash rate change, but there is no a clear pattern. Explanations for the differences might be different transportation policies, climate, and whether drivers accustomed to a specific weather driving condition.

The average crash rate under snowfall conditions in the British studies has a higher increase than in the other two counties. One explanation for the difference might be that snowfall is less frequent in the United Kingdom than in the United States and Canada, so drivers in the United Kingdom are not as experienced at driving under snow condition as drivers in regions with frequent snow precipitations. Thus, the crash rate might be expected to have a higher increase. However, further work would be needed to clarify the finding.

RESULTS

Extremes

Before starting the data analysis, the researchers checked whether there were extreme values in percent change for each study. Significant differences exist between study results. Most of the inconsistency in percent changes is due to variation in the study design.

Eisenberg's study produced a very low estimation of the effect of snow on safety (*23*). The crash records he used in his estimation are

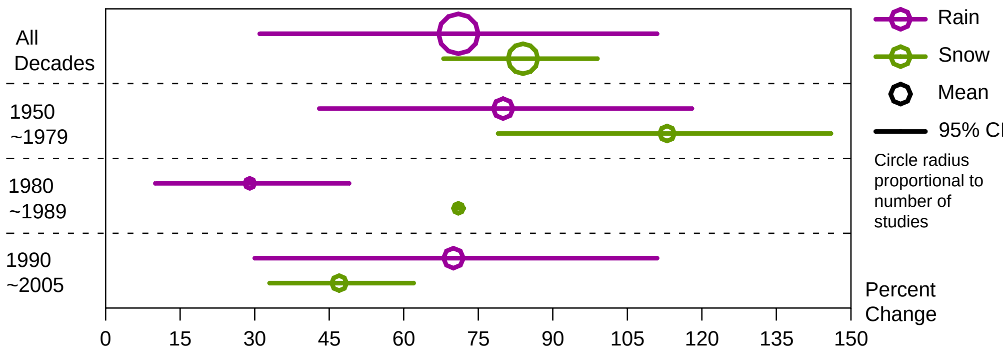

FIGURE 3 % change in crash rate, by decade.

from 1975 to 2000. The large sample size provides a fairly reliable estimation; however, the study is compromised by the high level of aggregation of the exposure measure, which is the FHWA annual estimation of state-year VMT. Even though traffic volume fluctuation of state, year, and month is controlled by introducing fixed effects into the model, the traffic volume reduction due to adverse weather is not able to be considered. The author also acknowledged that deficiency in his paper. His estimation is an 8% increase in rain related crashes, which is the lowest estimation in comparison to the other studies.

Contrary to Eisenberg's study, the study by Knapp et al. produced a significantly high result. Knapp evaluated the snow impact on traffic volume and safety (*26*). In the Knapp et al. study, matched-pair analysis is applied, and the authors specified the snow event as a very severe condition, with the average for each snow event duration of about 9 h, a snowfall rate above 1 cm/h, and wind speed range from 10 km/h to 66 km/h. Compared to the matched-pair studies conducted before, Knapp et al. focused the study only on selected segments of Interstate highways with roadway weather information systems located nearby (*26*). Thus, the weather data are more accurate than are weighted weather station data throughout the state, and the study area is on a specified highway, so the produced results should be representative for the state of Iowa Interstate highway system. However, due to the limited sample size, during the study period, no fatal crash and few injury crashes happened.

Another study evaluated highway and freeway crashes in Connecticut (*27*). The relative risk ratio approach was used to estimate real time crash risk under a combination of weather conditions and hourly traffic flow rate. The estimated crash risk of snow varies depending on the traffic volume rate, and it reached its peak when traffic flow rate (vehicle per hour per lane) was around 1,500.

If those extreme values are excluded, the estimated injury crash rate would increase by 52% and 78% for rain and snow condition, respectively (in comparison with 71% and 84%, respectively, if the extremes are included).

Future Research

The many factors that influence driving safety under adverse weather conditions demand further research and analysis. Traffic speed and volume are significantly correlated with crash rates. Weather also has a significant influence on traffic speed and volume. However, the effect of reduced traffic volume is not normally considered in most of the studies considered, and neither is reduced speed. Thus, further studies need to explore how drivers interact with adverse weather to make their trip decision or reduce their driving speed, and as a result determine how these behaviors influence the crash rates.

Weather interaction with other factors might be another area to explore. Some of the studies have explored the interactions of weather variables with other factors, for example, interaction with lighting [(*17*) and Andrey and Knapper, University of Waterloo], grade and curve (*28*), and urban versus rural roads (*7*).

Most studies focused exclusively on the effect of precipitation on crashes, while few estimated crash risk during other adverse driving

TABLE 4 Percent Crash and Injury Rate Change for Snow and Rain, by Country

		Injury			Crashes		
Country	Weather Category	*N*	Estimate (%)	95% CI (%)	*N*	Estimate (%)	95% CI (%)
United States	Snow	1	45	45	2	73	72–73
	Rain	1	21	21	3	58	28–88
Canada	Snow	2	79	61–96	4	85	69–100
	Rain	2	50	39–61	5	73	32–113
Britain	Snow	1	50	50	1	1.00	100
	Rain	2	42	28–56	1	0.24	24

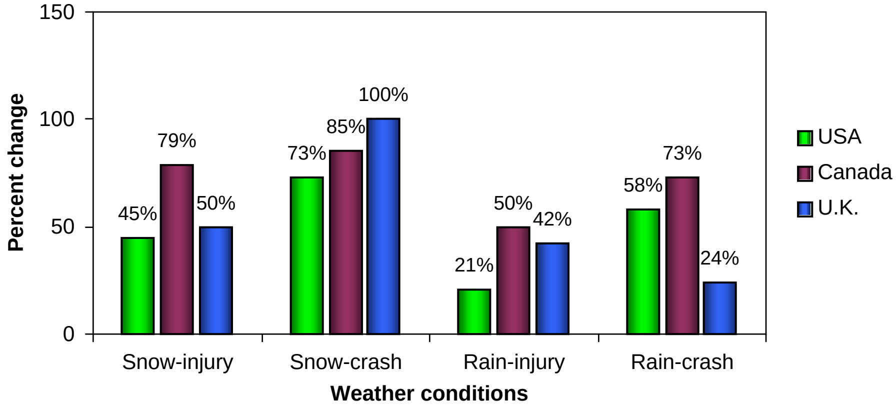

FIGURE 4 Effect of snow and rain on crash rate.

conditions, such as high winds, fog, low temperature, and interactions of these other weather conditions with precipitation.

Precipitation and undesirable pavement condition together constitute a greater hazard to traveling public than each alone (*29*), and the effects are a joint result of winter highway maintenance, weather, and traffic. Thus, further research is needed to explore to what extent winter highway maintenance can reduce crashes, and which types of winter highway maintenance produce the greatest reduction in crash rates (i.e., the greatest increase in safety).

CONCLUSION

The generalized results from studies that compared daily crash rates during adverse weather and those during nonadverse weather indicate a number of points. Most precipitation events are associated with a considerable increase in crash rate and injury rate. Snow has a greater effect than rain. It can increase the crash rate by 84% (95% CI = 68%, 99%), and the injury rate by 75% (95% CI = 54%, 96%), while rain can increase the crash rate by 71% and the injury rate by 49%. As precipitation intensity increases, the crash risk also increases. Undesirable road surface conditions (icy, slushy, etc.) have an even more significant impact on crash risk.

However, the association between precipitation and the fatal crash rate is not that definitive. From limited evidence, when the effect of reduced traffic volume on the crash rate was considered, the fatal crash rate increased 9% during snow and 8% during rain compared with rates in nonadverse weather conditions.

Further results from hierarchy meta-analysis indicate that the effect of snow on crash rates has a decreasing tendency over decades. The percent change of crash rate dropped from 113% during 1950 to 1979 to 47% during 1990 to 2005. Also, the percent change of crash rate during rain does not have the same decreasing tendency. Overall improvements in safety may be the reason, but improvement in winter maintenance methods might be also an explanation.

REFERENCES

1. Andrey, J. C., B. N. Mills, and J. Vandermolen. Temporal Analysis of Weather-Related Collision Risk for Ottawa, Canada: 1990–1998. Presented at 82nd Annual Meeting of the Transportation Research Board, Washington, D.C., 2003.
2. Brown, B., and K. Baass. Seasonal Variation in Frequencies and Rates of Highway Crashes as Function of Severity. In *Transportation Research Record 1581,* TRB, National Research Council, Washington, D.C., 1997, pp. 59–65.
3. Eisenberg, D., and K. E. Warner. Effects of Snowfalls on Motor Vehicle Crashes, Injuries, and Fatalities. *American Journal of Public Health,* Vol. 95, No. 1, 2005, pp. 120–124.
4. Knapp, K. K., D. Kroeger, and K. Giese. *The Mobility and Safety Impacts of Winter Storm Events.* Iowa State Center for Transportation Research and Education, Iowa State University, Ames, 2000. www.ctre.iastate.edu/reports/winstorm.pdf. Accessed May 2008.
5. Hunter, J. E., and F. L. Schmidt. *Methods of Meta-Analysis: Correcting Error and Bias in Research Findings.* Sage Publications, Thousand Oaks, Calif., 2004.
6. Qiu, L. *Performance Measurement for Highway Winter Maintenance Operations.* Ph.D. thesis. University of Iowa, Iowa City, 2008.
7. Bertness, J. Rain-Related Impacts on Selected Transportation Activities and Utility Services in the Chicago Area. *Journal of Applied Meteorology,* Vol. 19, 1980, pp. 545–556.
8. Andrey, J., and S. Yagar. A Temporal Analysis of Rain-Related Crash Risk. *Accident Analysis and Prevention,* Vol. 25, 1993, pp. 465–472.
9. Sherretz, L., and B. Farhar. An Analysis of the Relationship Between Rainfall and the Occurrence of Traffic Crashes. *Journal of Applied Meteorology,* Vol. 17, 1978, pp. 711–715.
10. Edwards, J. B. The Relationship Between Road Crash Severity and Recorded Weather. *Journal of Safety Research,* Vol. 29, No. 4, 1998, pp. 249–262.
11. Andreescu, M. P., and D. B. Frost. Weather and Traffic Crashes in Montreal, Canada. *Climate Research,* Vol. 9, No. 3, 1988, pp. 225–230.
12. El Dessouki, W., and J. N. Ivan. *Using Relative Risk Analysis to Improve Connecticut Freeway Traffic Safety Under Adverse Weather Conditions.* Project UCNR14-5. Final report. Region 1 Urban Transportation Center, U.S. Department of Transportation, 2004.
13. Andrey, J., B. Mills, M. Leahy, and J. Suggett. Weather as a Chronic Hazard for Road Transportation in Canadian Cities. *Natural Hazards,* Vol. 28, 2003, pp. 319–343.
14. Elvik, R. Area-Wide Urban Traffic Calming Schemes: A Meta-Analysis of Safety Effects. *Accident Analysis and Prevention,* Vol. 22, 2001, pp. 327–336.
15. Fridstrom, L., J. Ifver, S. Ingebrigtsen, R. Kulmala, and L. K. Thomsen. Measuring the Contribution of Randomness, Exposure, Weather, and Daylight to the Variation in Road Crash Counts. *Accident Analysis and Prevention,* Vol. 27, No. 1, 1995, pp. 1–20.
16. Doherty, S. T., J. C. Andrey, and J. C. Marquis. Driver Adjustments to Wet Weather Hazards. *Climatological Bulletin,* Vol. 27, 1993, pp. 154–164.
17. Codling, P. Weather and Road Crashes. In *Climatic Resources and Economic Activity* (J. Taylor, ed.), G. and J. Chesters, Tamworth, United Kingdom, 1974, pp. 205–222.

18. Keay, K., and I. Simmonds. The Association of Rainfall and Other Weather Variables with Road Traffic Volume in Melbourne, Australia. *Accident Analysis and Prevention,* Vol. 37, No. 1, 2005, pp. 109–124.
19. Hanbali, R. M. Economic Impact of Winter Road Maintenance on Road Users. In *Transportation Research Record 1442,* TRB, National Research Council, Washington, D.C., 1994, pp. 151–161.
20. Khattak, A., 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,* Washington, D.C., 2001, pp. 30–36.
21. Brodsky, H., and A. S. Hakkert. Risk of a Road Crash in Rainy Weather. *Accident Analysis and Prevention,* Vol. 20, No. 3, 1988, pp. 161–176.
22. Norrman, J., M. Eriksson, and S. Lindqvist. Relationships Between Road Slipperiness, Traffic Crash Risk, and Winter Road Maintenance Activity. *Climate Research,* Vol. 15, 2000, pp. 185–193.
23. Eisenberg, D. The Mixed Effects of Precipitation on Traffic Crashes. *Accident Analysis and Prevention,* Vol. 36, No. 4, 2004, pp. 637–647.
24. Ketcham, S. A., L. D. Minsk, R. R. Blackburn, and E. J. Fleege. *Manual of Practice for an Effective Anti-Icing Program: A Guide for Highway Winter Maintenance Personnel.* Report FHWA-RD-95-202. FHWA, U.S. Department of Transportation, 1996.
25. Breen, B. D. *Anti-Icing Success Fuels Expansion of the Program in Idaho.* Idaho Department of Transportation, Ames, 2001. www.transportation.org/sites/sicop/docs/US-12%20Anti%20Icing%20Success.pdf. Accessed March 2008.
26. Knapp, K. K., L. D. Smithson, and A. J. Khattak. The Use of Multiple Data Sources to Evaluate the Volume and Safety Impacts of Winter Storm Events. *Proc., ITE Annual Meeting,* Nashville, Tenn., Aug. 6–8, 2000, p. 11.
27. 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, Washington, D.C., 2005.
28. Shankar, V., F. Mannering, and W. Barfield. Effect of Roadway Geometrics and Environmental-Factors on Rural Freeway Crash Frequencies. *Accident Analysis and Prevention,* Vol. 27, No. 3, 1995, pp. 371–389.
29. Goodwin, L. *Weather-Related Crashes on U.S. Highways in 2001,* 2003. www.ops.fhwa.dot.gov/weather/docs/2001CrashAnalysisPaperV2.doc. Accessed Jan. 27, 2004.

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