

Weather Information and Road Safety

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Executive Summary

Each year road crashes drain over \$10 billion from the Canadian health care system and result in nearly 3,000 fatalities and one injury for every 135 citizens. Furthermore, despite large reductions in injury rates per unit of travel, the injury risk per capita is at a similar level as it was three decades ago.

Weather is one environmental risk factor that is known to affect collision rates. Weather-related collision costs in Canada are estimated to be approximately \$1 billion per year.

This report summarizes empirical research on this topic and assesses the state of knowledge pertaining to the role of weather information provision in road safety improvement.

Physical Effects

The state of knowledge on the engineering aspects of weather-related driving risks is quite advanced. In particular, the physical effects of weather on road surface friction and driver visibility are reasonably well understood. Road surface friction can be predicted with a fair degree of accuracy given detailed information on the storm, road, vehicle, and traffic conditions. Similarly, a number of factors are known to affect driver visibility— especially precipitation/fog intensity, but also droplet size, ambient illuminance, blowing snow, snow bank obstructions at intersections, wiper speed, and splash and spray from other vehicles.

However, converting estimates of frictional change or impaired visibility into collision risk is much more difficult. Although there is evidence of an inverse, statistically significant relationship between collision incidence and reduced friction/visibility, the stochastic nature of collisions and heterogeneity of driver response (both physiological and intentional) limit the utility of statistical models in explaining collision risk for small spatial or temporal units.

Empirical Estimates of Weather-related Road Collision Risk

Despite the modest achievements of modeling efforts, there is ample evidence that weather, especially in the form of rain and snow, is a serious risk factor in road transportation. A synthesis of empirical studies indicates the following:

- Collision risk usually increases from 50 to 100 percent during precipitation.
- Snowfall has a greater effect than rainfall on collision occurrence; however snowfall-related collisions tend to be less serious than other collisions. Canadian studies are consistent in finding that injury rates increase during snowfall relative to normal driving conditions.
- Risk varies according to both the form and intensity of precipitation. Risk appears to be greatest for freezing rain/sleet and the first snowfalls of the season, and lowest for light drizzle or snow flurries.
- Elevated risk during rainfall appears to be related to visibility, since collision rates quickly return to near-normal after the rain has stopped, even if roads continue to be wet. Snowfall-

related risk often remains elevated for an extended period, suggesting that frictional effects dominate.

- High winds and fog are associated with a small proportion of crashes but generally increase the risk of a traffic collision, whether acting alone or in combination with precipitation.
- Few studies have considered the effects of sunlight glare, heat stress and barometric pressure on collision risk, and the evidence is too sparse to draw any definitive conclusions.
- Few studies consider the interaction between inclement weather and other risk factors, but there is some evidence that weather effects are particularly acute at night and on roadways with a gradient and/or curve.

Weather Information and Driver Adjustment

Near real-time road condition information is available on television and radio broadcasts, and through telephone services and the Internet. Recent surveys of the Canadian public indicate that information on reduced visibility and the occurrence of precipitation are especially valued. Wind information is considered more useful in the winter, presumably because of its implications for wind chill and snow drifting. Despite the widespread availability of official weather reports, many experts believe that drivers use mostly personal observations, particular to an instant in time and a specific location, when making driving decisions.

A range of adjustments is possible when a motorist is faced with sub-optimal weather conditions. These occur on a temporal continuum. There is virtually no evidence that the public seriously considers the road safety implications of long-term decisions that affect exposure to risk, such as residential location. There is, however, evidence that motorists make adjustments just before and during trips. Trip cancellation is the most studied pre-trip response, and is usually inferred from traffic volumes. Seasonal patterns indicate reduced travel in northern countries during the winter but only minor changes in traffic volumes due to weather variations within a season, with the exception of some winter storms and freezing rain events. Minor adjustments also dominate decisions made by motorists during travel. Speed reduction is the primary adjustment, and estimates vary substantially; reductions of 15 to 50 percent during intense precipitation have been reported, but travel speeds typically remain above the posted speed limit during light precipitation and on wet roads. These actions are insufficient to completely offset weather hazards, in part because of the low magnitude of adjustments but also because of the variable responses of drivers, which increase traffic conflicts.

Road Weather Information for Drivers

Public surveys indicate that there is modest interest in receiving improved road-specific weather information. The most useful information for motorists who are in transit is real-time, site-specific information on visibility and road conditions. Intelligent transportation systems (ITS) offer the potential to deliver such information through roadside variable message signs, highway advisory radio and, in the future, message relays to in-vehicle navigation systems.

While it is unclear from the literature exactly how and to what extent ITS will improve safety, weather warning sub-systems within ITS may be useful in three general ways.

- *Risk perception may be increased.* Studies indicate that drivers can easily identify weather scenarios that increase driving risk, but surveys also indicate that most drivers believe that they are personally capable of accommodating this risk. The challenge then is to develop messages that make the safety risk more credible than the driver's own perception.
- *Hazard detection may be improved.* The premise of most fog warning systems is to notify drivers of a situation that they are likely to respond to, and to warn them far enough in advance for the appropriate adjustments to be made. Preliminary evidence indicates that warning systems for fog and other site-specific hazards have safety benefits.
- *Specific advice may be given to drivers.* ITS may bring about more consistent responses to a hazard, and preliminary investigations are encouraging.

Winter Road Maintenance: Safety Impacts

Canadian provincial and municipal government agencies have a long tradition of winter road maintenance (WRM), are continually refining operations, and spend in the order of \$1 billion annually on this activity. Despite these efforts, winter conditions remain a substantial hazard to drivers. This raises questions about the effectiveness of WRM programs, and of their relative influence on mobility versus safety.

Surprisingly, few studies have attempted to quantify the safety benefits of routine WRM activities such as plowing or salting; but the limited examples are consistent in showing safety improvement for salted versus unsalted roads. Estimates vary, however, and there is an insufficient basis for even approximating the magnitude of the effects for different driving circumstances.

In terms of specific WRM activities, some evidence suggests that casualty collisions may be inelastic to moderate changes in the rate of salt application. Also, there is growing evidence that anti-icing (i.e. application prior to precipitation or freezing conditions) improves safety relative to traditional salt-application (i.e., de-icing) practices.

Weather Information and Winter Road Maintenance Decisions

There are various dimensions of WRM—planning and evaluation (e.g., budgeting, performance measurement), winter season and event preparedness (e.g., procurement of equipment, salt, aggregate; staff/contractor call-in), and event response (e.g., routing and treatment decisions)—but most of the interest in ITS relates to event-response because guidelines often identify very specific temperature (related to road salt effectiveness) and precipitation accumulation (various thresholds for plowing) criteria for action. Advances in weather prediction, remote sensing, and computer, telecommunications, and engineering technologies since the mid-1980s have facilitated the development of new tools (e.g., ARWIS) that provide the specified data. However, more emphasis should be placed on the quality/usability of information from the perspective of the road maintenance operator.

1. Introduction

Road transportation is important to both the Canadian economy and the Canadian way of life. As a result, governments spend approximately \$11 billion annually on road construction, maintenance, traffic control and policing (Nix 1995); and the average Canadian household spends 13 percent of its budget on road transportation (Transport Canada 1998a).

Despite the many advantages of road mobility, there are several negative spinoffs, including road collisions. In Canada, over the past decade, approximately 8 million road transportation collisions and 40,000 related deaths were reported (Transport Canada 1998a and 1998b), the true costs of which are estimated to be in the order of \$200 to \$300 billion (Andrey 2000).

Safety gains have been achieved, however, especially if one uses the standard metric of casualties per unit of travel. In the early 1970s there were approximately 8 million passenger automobiles and nearly 11 million licensed drivers in Canada. The annual number of fatalities was approximately 6,000. By the mid-1990s, the number of vehicles and drivers had increased by approximately 65 percent and 75 percent, respectively, and the amount of auto travel per person had increased by almost 40 percent. Nevertheless, the annual number of fatalities declined to approximately 3,000 and the number of injured persons more-or-less stabilized at one-quarter million. These patterns translate into much lower risk per unit of travel (Andrey 2000), a trend that continues into the 21st century and has been repeated in virtually every developed nation. The reasons for the improved safety record are many and collectively indicate a maturation of the highway system--better vehicle and roadway engineering, a broad evolution in social norms related to driving, and advances in health care and emergency response.

Still, traffic crashes continue to be a major health problem in Canada. In fact, the casualty rate per capita is at a similar level as it was three decades ago. Two sets of factors affect the number and severity of crashes; the first set relates to transport demand (i.e. the volume and characteristics of traffic), which determines risk exposure, while the second set relates to the unsafe operation of vehicles on public roadways. Factors contributing to the unsafe operation of vehicles include driver, vehicular, roadway and other environmental factors, while measures taken to improve the safety of driving are often categorized into the three E's: engineering, enforcement and education.

Weather is one environmental risk factor that is known to affect collision rates in Canada and elsewhere. Weather that reduces road friction, impairs visibility and/or makes vehicle handling more difficult creates a safety threat. Weather-related driving risks can be reduced by better engineering and maintenance of roadway infrastructure and motor vehicles; enforcement of speed limits and other traffic laws; and education-based strategies. Education-based strategies can be divided into two groups—information provision and driver (skill) training.

2. Research Objectives and Methods

The goal of this research is to summarize and critically assess our state of knowledge as it relates to the role of weather information provision in road safety improvement. The research is timely given the increased availability of real-time weather data and improved local forecasts, and also the poorly tested assumption that such information will directly or indirectly improve road safety (reduce injuries and fatalities), reduce collision costs (reduce frequency and severity of weather-related crashes) and also improve mobility.

Specific questions to be addressed pertain to both roadway users and winter road maintenance operators/managers.

Roadway Users

- To what extent are collision rates increased during times of reduced road friction (wet, snowy, icy roads), reduced atmospheric visibility (precipitation, fog, blowing snow) and increased wind speed? Do rates vary according to driver, vehicular and roadway characteristics? What are the health and economic costs associated with these crashes?
- What types and sources of weather information are used by drivers in making travel decisions? What types of adjustments are made in light of such information? What are the safety implications of these adjustments?
- Do drivers want more or improved weather information? How might this information be used? What is the value of this information?

Winter Road Maintenance

- To what extent are crash rates reduced by winter road maintenance? What types and sources of weather information are used by those involved in winter road maintenance decisions and operations? How is this information used? What types of information would improve the efficiency and effectiveness (mobility and safety) of winter road maintenance operations?

The report is based primarily on peer-reviewed literature in the fields of transportation engineering and planning; risk assessment and accident analysis; and applied climatology and hazards. Other related literature including government documents, industry/consultant reports, theses, conference proceedings, and web pages are used to fill in gaps, where appropriate.

3. Roadway Users: Road Safety

3.1 To what extent are collision rates increased during times of reduced road friction (wet, snowy, icy roads), reduced atmospheric visibility (precipitation, fog, blowing snow) and increased wind speed?

3.1.1 *Physical Effects*

The most significant weather-related changes to the road transport operating system are the physical changes in road surface friction that result from precipitation. Considerable

experimental research on precipitation-related changes in tire-pavement friction has been conducted over a span of more than three decades. Most research has focussed on wet road conditions that result from rainfall. The two critical aspects of wetness are depth of water on the road surface and the length of time that the road is wet. In both cases, models exist to estimate these parameters (e.g., Dunlap *et al.*, 1976; Harwood *et al.*, 1988). Information on road wetness has in turn been related to road surface friction. These models consider not only wetness but also pavement texture, travel speed, tire tread and pressure, and ambient temperature (e.g. Proceedings of the Second International Skid Prevention Conference 1977; Rose and Galloway 1977; Henry 1998). Therefore, if detailed information on the storm, road, vehicle and traffic conditions is available, it is possible to predict the effect of rainfall on road surface friction with a fair degree of accuracy. This in turn can be translated into information on stopping distance and guidelines for reducing hydroplaning (e.g. Huebner *et al.*, 1999).

The problem of vehicle performance on roads covered by snow or ice has also been studied for several decades, but much of this work has been done by tire manufacturers and is proprietary. The snow/ice issue is somewhat more complex than rainfall because of the greater importance of temperature, traffic, and maintenance activities. Still, current knowledge does allow for estimates of stopping distance, providing that detailed site-and-time-specific data on weather, road and vehicle conditions are available.

However, the next step in this logical sequence is to translate friction or increased stopping distance into crash risk, a much more difficult task and outside the controlled experimental setting. There is evidence of an inverse, statistically significant relationship between collision incidence and friction. However, regression models are limited in their capability to explain wet-weather collision incidence (Herman, 1984; Xiao *et al.*, 2000). One reason why predicting wet weather collisions for small spatial and temporal units is so difficult is because they are stochastic events. Also of great importance, however, are human factors--the multitude of driver decisions made prior to and during trips.

Although based on a relatively smaller body of literature, a similar conclusion may be drawn about driver visibility during inclement weather, i.e., the physical effects of various weather conditions on driver visibility are fairly well understood, but there are no comprehensive models that translate changes in physical condition into collision risk. In terms of the physical effects, available evidence indicates that driver visibility decreases (approximately linearly) with increased rainfall intensity, due mainly to the film of water on the windshield rather than to the reduction in atmospheric visibility; this reduction is accentuated by low ambient illuminance, slow wiper speed, small droplet size, and splash-and-spray from other vehicles (OECD 1976; Morris *et al.*, 1977; Bhise *et al.* 1981; Ivey and Mounce 1984). The effects are similar for snowfall, but, for a given precipitation rate, the visibility during snowfall is much lower than during rainfall, largely because of density differences. In addition, visibility impairment may be associated with blowing/drifted snow, snow banks obstructing visibility at intersections, snow cover obscuring roadway markers, and the reduced contrast within the field of view due to snow on the ground/road (OECD 1976), although these are not as well documented. Finally, fog sensing devices are able to provide real-time information on the presence and density of fog,

which can be translated into visibility distances. However, once again, knowledge of human factors--both physical responses (e.g. lower arousal levels and drowsiness or fatigue (OECD 1976; Ranney *et al.* 1999) and driving decisions--are the missing pieces of the puzzle.

A third atmospheric hazard that affects road transportation safety is wind. Although wind is rarely the primary reason for a collision, it commonly adds to already unfavourable driving situations. High winds can overturn vehicles, make steering difficult, and blow obstacles such as snow, sand, or debris onto the roadway. The effects of wind on vehicles are dependent on several variables, such as wind speed, the angle at which the wind strikes the vehicle, roadside aerodynamic obstructions, the aerodynamics of the vehicle, the spatial curvature of the vehicle path, and the coefficient of surface friction (Watkins *et al.* 1995; Sigbjornsson and Snaebjornsson, 1998). The critical wind speed for vehicle stability/turnovers tends to be quite high for most vehicle makes; however, collision data indicate that much lower speeds can be problematic for vehicle handling or snow drift. Overall, compared to precipitation and fog, less attention has been paid to wind-related driving risks.

3.1.2 Empirical Estimates of Weather-related Road Collision Risk

A number of studies provide empirically derived estimates of weather-related driving risks, as summarized in Appendix A. Based on the results of these studies, the following conclusions can be drawn. Note that most studies focus on precipitation events whereby the effects of reduced friction, impaired visibility and sometimes other hazards are confounded.

- Collision risk usually increases during precipitation, from negligible amounts to several hundred percent, although the typical estimate in more rigorous studies is 50 to 100 percent. Variations are due in part to differences in methods and weather conditions, but may also reflect urban/rural or regional/contextual differences in sensitivity.
- There is considerable evidence that snowfall has a greater effect than rainfall on collision occurrence, although snowfall-related collisions tend to be less serious than other collisions. There is a debate in the literature about whether snowfall is associated with a net increase or net decrease in injuries, but Canadian studies are consistent in finding that injury rates increase during snowfall, although to a lesser extent than property damage collisions. The picture is less clear for fatal collisions, mostly because of the small numbers involved, but some studies note fewer fatalities during snowfall, probably because of reduced speed.
- Based on available evidence, risk increases appear to be greatest for freezing rain/sleet and the first snowfalls of the season, and lowest for light drizzle or snow flurries. Also, there is a positive relationship between precipitation intensity and collision risk.
- Much of the elevated risk during rainfall appears to be related to visibility, since collision rates quickly return to near-normal after the rain has stopped, even if roads continue to be wet. For snowfall, however, risk often remains elevated for an extended period, suggesting that frictional effects dominate.

- High winds and fog, either alone or in combination with precipitation, increase the risk of a traffic collision, although estimates vary from study to study, and in most cases only a small proportion of crashes are related to either condition.
- A few isolated studies have considered the effects of sunlight glare, heat stress and barometric pressure on collision risk, but the evidence is too sparse to draw any definitive conclusions.
- Only a few studies consider the interaction between inclement weather and other risk factors, such as roadway geometrics.

In summary, weather, especially in the form of rain and snow, is a serious risk factor in road transportation.

3.2 Do rates vary according to driver, vehicular and roadway characteristics?

It appears that the safety of all driver and vehicular groups are compromised by inclement weather, although there are differences in the types of crashes that occur during inclement weather as compared to 'normal' weather. For example, recent work by Andrey *et al.* (under review) shows how urban collisions that occur during rainfall relative to dry conditions tend to be less serious; are more likely to involve three or more vehicles, are more likely to occur at night, on gradients or curved sections of roadway, at signalized intersections and on roads with speed limits of 60 kilometres per hour (kph); and are more likely to involve a rear-end collision. The patterns for snowfall are similar when it comes to collision severity, light conditions and road alignment. However, snow events are associated with disproportionately more single-vehicle crashes; more collisions at locations without traffic controls and on roads with speed limits of 60 kph or higher; and they are less likely to involve a turning manoeuvre than 'normal' driving. Some of the same patterns were found in earlier work by Mercer (1986) and Andrey (1989).

3.3 What are the health and economic costs associated with these crashes?

Across Canada, 2,927 deaths and 217,614 injuries were caused by motor vehicle collisions in 1998, roughly one injury for every 135 citizens (Transport Canada, 1998b). Motor vehicle collisions account for 16 percent of all injury admissions to acute care hospitals in Canada— injuries being the leading cause of death among Canadians (and in most developed countries) aged 1-44 years (Health Canada *et al.*, 1999, p.243). CCMTA (2000) reports that the cost of casualty collisions to the Canadian health care system exceeds \$10 billion per year. Property damage sustained during all collisions in 1999 is estimated to be in excess of \$1.25 billion for Ontario alone¹.

¹ based on a \$5800/collision cost estimate derived from Doherty (1994, p.2) and MTO (1994).

National summaries of accident statistics for 1998 indicate that 18 percent of fatal collisions and 21 percent of personal injury collisions occurred during impaired weather conditions (rain, snow/freezing rain/hail/sleet, fog/mist/smog/dust/smoke) (Transport Canada, 2000). Ontario collision data for 1999 support these estimates but also suggest that over 25 percent of property-damage-only collisions occurred during inclement weather that impaired visibility (MTO, 1999).

While there are no firm estimates of the true costs of weather in road collisions, it is possible to derive an approximation based on aggregate data. Given the incidence of collisions during inclement weather (as shown in the preceding paragraph) and the relative risk of being involved in a collision during inclement weather (based on Canadian studies summarized in Table 1: 1.0 for fatal, 1.5 for injury and 2.0 for property damage), it is estimated that approximately 7 percent of injury collisions and 12 percent of property damage collisions are directly attributable to inclement weather. Based on average collision costs (health and property damage), this translates into a conservative estimate of \$1 billion per year as indicated by the following calculations:

Injuries: Approximately 21 percent of injury collisions occur during inclement weather. The relative risk ratio for injury during inclement weather is approximately 1.5. Therefore 2 in 3 injuries would likely have occurred even in good weather; 1 in 3 can be attributable to the weather. Thus 7 percent of all injury collisions are attributable to weather. The total health costs associated with road collisions are approximately \$10 billion. Seven percent of \$10 billion is \$700 million.

Property Damage: Approximately 25 percent of property damage collisions occur during inclement weather. The relative risk ratio for collision during inclement weather is approximately 2.0. Therefore one-half of property damage collisions would likely have occurred even in good weather; the other half can be attributable to weather. The total property damage associated with collisions in Canada is approximately \$3.5 billion (\$1.25 billion in Ontario; Ontario accounts for 35 percent of collisions in Canada). Twelve percent of \$3.5 billion is approximately \$400 million.

The combined cost estimate is \$1.1 billion.

4. Roadway Users: Weather Information

4.1 What types and sources of weather information are used by drivers in making travel decisions?

The Canadian public has virtually continuous access to weather information from a variety of sources and at a variety of temporal and spatial scales. Not surprisingly, national public surveys show that the overall use of weather information is quite high (Goldfarb, 1977; Ipsos-Reid 2001a). More specifically, the Goldfarb survey indicates that eight in ten Canadians access a weather forecast in the morning, and on average people listen to 2.3 forecasts a day. Both surveys indicate that television (especially *The Weather Network*) is the most popular medium

overall for weather information, although newspapers are used in a general way, and radio use increases for weather warning and work-related decisions. Use of the Internet, phones and other devices is not as prevalent, and only a small proportion of Canadians use Environment Canada's delivery systems (Goldfarb 1997). However, a subset of the population is interested in making greater use of cell phones and email (Ipsos-Reid 2001a).

In terms of road/driving conditions, near real-time information is available on television and radio broadcasts, and through telephone services (e.g., MTO²) and the Internet (e.g., B.C. Ministry of Transportation³, Washington State⁴). The Goldfarb (1997) survey indicates that the public perceives this type of information to be useful. More specifically, in both winter and fall/spring forecasts, the item that people find most useful is information on reduced visibility, and in all seasons knowing if it is going to rain or snow is seen as being important. Wind information is considered more useful in the winter, presumably because of its implications for wind chill and snow drifting.

Despite the widespread availability of official weather reports, many experts believe that drivers use mostly personal observations when making driving decisions, e.g. visual cues, that are particular to an instant in time and a specific location (Pisano and Nelson, 1997). This speaks to the temporal and spatial dimensions of information needs, a topic which will be further developed in section 5.2.

4.2 *What types of adjustments are made in light of weather information?*

A range of adjustments is possible when a motorist is faced with sub optimal weather conditions. These occur on a temporal continuum as illustrated in Table 1.

Table 1. Examples of driver adjustments to weather conditions.

<i>Timing</i>	<i>Types of Adjustments</i>	<i>Relevant Weather Information</i>
Months to Years Before Trip	Consumer and lifestyle decisions that affect travel patterns and type of vehicle, and thus exposure to risk during adverse weather	Long-term records of climate
Just Before Trip	Travel plans or modifications, e.g. cancellation, route selection, timing, mode, vehicle preparation	Short- and medium-term weather forecasts
During Trip	Instantaneous driving decision, e.g. speed, caution	Site and time-specific weather conditions that affect vehicle handling, visibility, friction

² Ontario Ministry of Transportation road information toll-free line (1-800-268-1376)

³ B.C. Ministry of Transportation Provincial Road Reports (<http://www.th.gov.bc.ca/bchighways/roadreports/roadreports.htm>)

⁴ The Washington State Department of Transportation has developed a web-based real-time statewide road and weather information system that provides access to real-time data from approximately 350 weather stations, traffic surveillance cameras, and other reporting mechanisms (<http://www.wsdot.wa.gov/Rweather/>).

In terms of decisions that are made months to years in advance of a particular trip, there is virtually no evidence that the public seriously considers the road safety implications of decisions such as residential location or employment choice. This is probably because of competing/overriding concerns and also the general sense that driving risks are both ubiquitous and not a serious personal threat. Perhaps the one exception is that safety ratings are considered in vehicle purchases, but even here safety appears to be secondary to performance and appearance variables.

In terms of adjustments made just before a trip, some motorists report leaving earlier and/or preparing their vehicles for the trip (OECD 1976, Doherty *et al.* 1993, Guerriero 1995, Knapp 2001), while others report trip cancellation or mode change. Trip cancellation is the most studied pre-trip response, and is usually inferred from traffic volumes. Seasonal patterns indicate reduced travel in northern countries during the winter but only minor changes in traffic volumes due to weather variations within a season. For example, Doherty *et al.* (1993) found that traffic counts at major intersections in Kitchener-Waterloo dropped by two percent on rain versus dry days. Other studies confirm the tendency for limited reductions in auto traffic during rainfall, but suggest greater changes during winter storms and freezing rain (OECD 1976; Andrey and Knapper, 1993; Hanbali and Kuemmel, 1993; Hassan and Barker, 1999; Knapp *et al.* 2000; Ipsos-Reid 2001a; Knapp, 2001; Perrin *et al.*, 2001). Also, a few studies show small increases in auto travel during inclement weather as people switch from other modes (e.g. pedestrian, bicycle, motorcycle) to auto (OECD, 1976; Bertness, 1980; Guerriero, 1995).

Minor adjustments also dominate decisions made by motorists during travel. Self-reported adjustments include increased concentration, alertness and caution, manifested as increased following distance or greater care in turning/cornering manoeuvres (Andrey and Knapper 1993; Doherty *et al.* 1993). However, the main adjustment--as indicated in surveys and confirmed by roadside observations and collision severity analysis--is reduced speed. Estimates of speed reduction vary substantially from one study to another, depending on a number of factors: the type of weather, roadway conditions, driving circumstances, and driver and vehicle characteristics (OECD 1976; Andrey and Knapper 1993; Doherty *et al.* 1993; Ibrahim and Hall 1994; Shepard 1996; Knapp 2001; Kyte *et al.* 2001). For wet roads and light rain/snow, adjustments are usually minimal (a few kph) and travel speeds typically exceed the posted speed limit. For more intense precipitation and for situations where compound hazards are present (e.g., slippery roads and reduced visibility), average speed reductions of 15 to 50 percent have been reported.

However, the elevated crash risk during inclement weather, as reported in section 3.1.2, indicates that adjustments are not sufficient to completely offset weather hazards. One reason why crash risk remains elevated is the high threshold for adjustments; for example Shepard (1996) notes that motorists do not significantly alter their speeds until visibility in fog is below 150 metres. Other reasons are the low magnitude and nature of adjustments (e.g., minor speed reductions and general reluctance to alter trip plans) and the fact that individuals respond in variable ways, which increases the potential for conflict, i.e., some drivers pull off to the side of the road and others continue to travel, but at varying speeds, as occurred in the September 1999 fog incident

on Highway 401 east of Windsor (Armstrong and Hibbert, 2001). In fact, the US National Transportation Safety Board has determined that the single greatest cause of poor visibility crashes is non-uniform response of the drivers (Center for Urban Transportation Research, 1997).

In terms of driving circumstances, there is limited related research, but Doherty *et al.* (1993) found that drivers are more inclined to slow down on highways than on city streets and that volume decreases due to bad weather were minimized during the peak traffic times. Also Elvik (1999) states that drivers adjust their driving behavior, depending on what type of tires they have on their car. People with worn tires generally travel slower and slow down more in adverse weather conditions.

Adjustment to weather also appears to vary with driver characteristics, although again there are only a few studies to draw on. These studies indicate that older drivers appear to compensate more for unfavorable roads, while younger drivers have a decreased hazard awareness, and therefore make fewer adjustments (Doherty *et al.* 1993). Safety studies by Andrey (1989) and McGwin and Brown (1999) provide some support for the above conclusion on older drivers in that they found that seniors are generally involved in disproportionately fewer collisions during inclement weather, probably because of trip cancellation.

4.3 What are the safety implications of these adjustments?

Much has been written about the importance of human behavior feedback or risk compensation in the field of road safety. Evans (1991), in his book, *Traffic Safety and Driver*, developed a framework and provided examples of different types of safety outcomes associated with changes to the road operating system.

Table 2. Safety outcomes associated with changes to the road operating system

Outcome	Changes Made to Increase Safety	Changes Expected to Decrease Safety
Safety changes in the direction that is expected, but the effect is more than is expected	The 55 mph speed limit imposed in the US in 1974	The 1987 decision to increase speed limits to 65 mph
Safety changes as expected	Use of seat belts	Repeals of mandatory motorcycle helmet legislation
Safety changes in the direction that is expected, but the effect is less than expected	Use of studded tires and anti-lock braking systems	Driver fatigue
No (minimal) change in safety	Vehicle inspection programs	Drivers with only monocular vision
Perverse effect, i.e. the opposite effect to what was expected	Some pedestrian crosswalks	Sweden's change from driving on the left- to the right-hand side of the road

Source: Evans (1991)

Studies on weather-related collision risk suggest that, in most cases, inclement weather (which is expected to decrease safety) changes safety in the direction that is expected, but the net effect is less than expected because of driver adjustments. For very severe weather, where mobility is greatly reduced, a perverse effect can occur, e.g., injury collisions declined slightly during the 1999 Toronto snow emergency (Mills *et al.* 2001).

5. Roadway Users: Information Needs

5.1 Do drivers need or want more or improved weather information?

It is commonly assumed that the public wants more timely and road-specific weather, but recent public surveys suggest that the majority of Canadians are satisfied with both the accuracy of forecasts (Goldfarb, 1997) and also with the amount of information and delivery media for weather warnings (Ipsos-Reid, 2001a). Still, there is evidence that a minority want improved weather forecasts to inform travel decisions. More specifically, 7 percent of respondents in the Goldfarb survey (and 12 percent of those who use weather information in work-related decisions) want information on road/highway conditions in their forecasts. There is also an interest in hearing more about changing conditions including knowing when the temperature will cross zero. Also, the experiences of recent winter storm events illustrate that extreme conditions do generate a large surge in demand for both weather information and related advice. For example, during the 1999 Toronto Snow Emergency, CablePulse 24 (part of CITY-TV), a live 24-hour news, traffic and weather information service, estimated that its viewership during the week of January 11 increased by almost 40 percent over the previous and subsequent weeks (Mills *et al.* 2001).

One possible explanation for why the public is not more interested in improved weather information may relate to risk perceptions. Two recent polls show that the majority of Canadians do not feel that hazardous weather is a risk to them where they live (Ipsos-Reid, 2001b). Still, the same survey shows that the specific weather types that are associated with the greatest perceived levels of personal risk are freezing rain and major winter storms, and for these weather scenarios concerns relate primarily to transportation. Other surveys on risk perceptions also show that drivers are generally concerned about being involved in a traffic collision (Fischer *et al.*, 1991) and that they do recognize the elevated risk associated with particular weather conditions (e.g., freezing rain, fog, and winter roads) (Andrey and Knapper, 1993). Thus, in summary, weather information is far from being near the top of the public's agenda, but there does appear to be some interest in receiving improved road-specific weather information.

5.2 How might more or improved weather information be used?

As discussed in Section 4.2, the most useful information for motorists who are in transit is real-time, site-specific information on visibility and road conditions. Because of this, there is considerable interest in the design and implementation of hazard detection and warning systems, which fall under the umbrella of intelligent transportation systems⁵ (ITS).

ITS are intended to offer a variety of technological solutions to surface transportation problems, by improving mobility, promoting economic efficiency and growth, reducing energy use and emissions, and improving safety. Literature indicates that improved safety is a high priority goal among transportation experts when they consider ITS (e.g., Levine and Underwood, 1996). But, because ITS technologies are new and untested, it is difficult to make reliable quantitative estimates as to their safety benefits.

From a weather hazards perspective, the most interesting developments in ITS relate to active motorist information/warning systems that today typically use roadside variable message signs, sometimes in conjunction with highway advisory radio (e.g., for fog warnings, see Shepard, 1996); in the future this type of messaging could be relayed via onboard navigation systems.

Warning signs on roads have a long history, but have traditionally used fixed messages. Changeable message signs have a shorter history, and have the advantages of being both portable and less likely to result in advertising wear-out. However, their benefits are less well established, both generally and more specifically for weather detection/motorist warning systems, as noted by the Center for Urban Transportation Research (1997). Still, several jurisdictions are opting for such warning systems over the alternative of public service announcements, especially for fog (see Shepard, 1996; Centre for Urban Transportation Research 1997), but also for wet/slippery roads (Collins and Pietrzyk, 2001) and high winds (Perry and Symons, 1991; ADI, 1994).

⁵ Also sometimes referred to as intelligent vehicle and highway systems (IVHS) or telematics. See www.itscanada.ca for an overview of overview.

In addition to warning signs, other approaches have been attempted. For example, MacIver and Auld (2000) describe a community-led road weather watch program in southern Ontario and Chen *et al.* (1994) elaborate on a 'road sense index' for travelers. The effectiveness of such programs has not been fully assessed—the first example may prove as important for developing a common sense of community (i.e., social benefit) as for providing direct safety or mobility benefits.

5.3 What is the value of more or improved weather information?

According to the "information is power" principle, increased weather information should improve the safety of the traveling public. However, according to Pisano and Nelson (1997), weather uncertainties (presumably due to lack of information) are not the primary cause of poor driving decisions. Furthermore, there is little discussion on exactly how these elevated safety levels are to be achieved by ITS. There are, however, three general purposes for weather warning systems—to increase risk perception, improve hazard detection, and advise drivers--and each of these will be discussed in turn.

In terms of risk perceptions, studies show that drivers' subjective assessments of the relative danger associated with driving during various weather scenarios are reasonably consistent with collision studies (Andrey and Knapper, 1993; Doherty *et al.* 1993). Therefore, educating the public on the dangers of driving during inclement weather would appear to be unnecessary, and could increase stress in already wary drivers. On the flip side, though, many studies have shown that drivers believe themselves to be capable of handling most situations, and the majority of drivers believe that they are better-than-average drivers. Thus the challenge is to develop message signs that make the safety risk more credible than the driver's own perception (The Weather Team, 1998).

In addition to changing risk perceptions, ITS can aid motorists in hazard detection. This is the premise of most fog warning systems--to notify drivers of a situation that they are likely to respond to, and to warn them far enough in advance for the appropriate adjustments to be made. In this case, although evidence is still very preliminary (Shepard 1996), it appears that warning systems for fog, and other site-specific hazards such as drifting snow, road/bridge icing, or wind gusts, will have safety benefits.

Finally, it is worth considering the role of ITS in providing drivers with specific advice (such as the "reduce speed now" signs at curved sections of U.K. roads). This type of intervention is intended to bring about more consistent responses to the hazard, and again preliminary investigations indicate that this technique achieves some of the intended effects during inclement weather (Russam, 1984). A variation on the theme is to use ITS to direct traffic off highways during unsafe driving conditions, as has been implemented by the Minnesota Department of Transportation (BRW, 1999).

Before leaving this discussion, it is important to consider the possibility that warning systems could have perverse effects, i.e., they could increase risk, due primarily to the distraction that is

created by this intervention. A number of studies have identified a link between transient distractions (e.g., cell phones, passengers, smoking/eating), especially those that are visual, and unsafe driving (US DoT, 2000 as cited in Abernethy, 2001; Yang and Fricker, 2001).

Also, there is a need to consider the circumstances under which ITS will have the greatest safety benefits, and also the relative merit and complementarity of ITS with other efforts to reduce weather-related collisions, e.g. through driver skills training programs or improved road design.

In summary, ITS appears to hold considerable promise for reducing weather-related road collisions, but it would be naive to assume that these programs will produce the exact results that are intended, given the complexity of the system and the variable results of other safety interventions that have been introduced over the past three decades. It is therefore imperative that the use and value of existing and improved weather information products and media be assessed, both generally (e.g., Pielke *et al.*, 1997), and more specifically vis-à-vis road safety.

6. Winter Road Maintenance

6.1 To what extent are collision rates reduced by winter road maintenance?

The previous discussion (see section 3.1.2) demonstrates how weather, especially during the winter season, can be hazardous for road transportation, despite the fact that winter road maintenance (WRM) programs have been established and are continuously being refined by virtually every provincial and municipal government agency in Canada. This raises questions about the overall effectiveness of WRM programs, and of their relative influence on mobility versus safety.

WRM programs have traditionally involved snow and ice clearing activities through a combination of plowing, salting, sanding and snow-fencing in response to the immediate effects of blowing or accumulating snowfall and icing conditions on roadways. The aggregate expenditure on winter road maintenance for public roads in Canada is estimated to have exceeded \$890 million in 1998 (Jones, 2001). Approximately \$2 billion is spent annually in the United States (The Weather Team 1998).

These and many other WRM practices and technologies have been proposed, tested and/or implemented on the basis of three assumed transportation outcomes:

- improvements to road safety (fewer casualty collisions);
- mobility benefits for the traveling public, emergency service providers, and freight or passenger carriers; and
- WRM efficiency benefits (lower collision costs/claims; reduced salt, aggregate, fuel use; lower labour costs; less damage to the natural environment, steel-reinforced infrastructure and vehicles—corrosion, etc.).

The section is particularly concerned with the first benefit.

The assumed benefits of WRM are widely touted in introduction sections of many technical research reports or fact sheets about winter road maintenance. Typical quotes are noted below:

“Accurate road ice sensing is very important for both road agencies and the travelers. For road agencies, accurate road sensing is highly associated with efficient management of labor, equipment and materials. For travelers, on-time accurate ice sensing capabilities assist safe driving and injury prevention.” (Sisiopiku and Oh, 2001, p. 3).

“New technologies can improve information systems, maintenance tools, and road weather management practices. This will help transportation officials reduce weather-related costs, provide more accurate and up-to-date information to the public, and decrease the number of weather-related traffic injuries and fatalities.” (U.S. DoT, 2001, p.1)

Upon examination of the literature, however, information demonstrating the benefits for even basic WRM activities such as plowing, salting and sanding is weak or absent. This is surprising, given the level of public investment. Other reports, including a White Paper produced by The Weather Team (1998), acknowledge that insufficient research has been conducted to address the benefits of improved road weather information and other WRM technologies; and that the data and methods to distinguish between weather and other influences on collisions or delays, and to evaluate the benefits of additional weather information, are virtually nonexistent (The Weather Team 1998).

There are, however, a few published studies that have assessed the safety benefits of WRM programs, including two from Scandinavia. In particular, The Norwegian Directorate of Public Works (as reported in TAC 1999, p.1-13) assessed the safety benefits of salting previously unsalted roads (11 percent reduction in reported collisions observed) and compared salted roads against otherwise similar unsalted highways (26 percent fewer collisions on salted roads; casualty collisions during winter reduced by 20 percent). Benefits were higher for serious injury collisions relative to minor injury collisions and greater during daytime, where speed limits exceed 70 kph, and for roads that exhibited poor horizontal geometrics. In a second study, Kallberg (1996) reports results from an experimental salt reduction program during 1992-1994 in the Kuopio road district of south-central Finland. Salt application rates were reduced on experimental road segments from the typical 10 tonnes/road km to 1-2 tonnes/road km. The frequency of slippery conditions on these roads attributable to snow and ice increased by 30-40 percent and casualty collision frequencies increased by about 20 percent on most road sections (Kallberg, 1996, pp.33,36). Interestingly, a public survey revealed that about 75 percent of people wanted reductions in the amount of salt applied to roads both before and after the experiments (Kallberg 1996, p.37).

The Salt Institute (2001) web site also provides information on a range of salt-related issues, and summarizes findings from a 1992 analysis by the Marquette University Department of Civil and Environmental Engineering. The Salt Institute draws the following conclusions from this study:

- collision frequency is 8 times higher before de-icing than after on a two-lane roadway (4.5 times higher for multi-lane freeways),
- casualty-collision frequency is 9 times higher before application (7 times higher for multi-lane freeways), and
- collision severity is reduced by 30 percent after application of road salt.

Other sources of information are specific to applications of new forms of WRM technology making results even more difficult to generalize. For instance, Stowe (2001) outlines the projected benefits associated with equipping a problematic section of highway in Washington State with an automatic anti-icing system; an 80 percent reduction in snow- and ice-related collisions was estimated in the benefit-cost analysis. Wirtz and Moritz (1993) measured benefits for a similar technology (thawing agents spraying system) employed over 6 km of German highway—collision frequencies were reduced by almost 58 percent following installation. C-SHRP (2000) reports that after two years of implementing anti-icing trials over 161 lane-km of roadway in the City of Kamloops, British Columbia, the number of collisions was reduced by up to 73 percent. A Swedish study reported a 30 percent reduction in early morning crashes after deploying “special overnight road de-icing patrols” (Bjorketun, 1983 as cited in TAC, 1999).

While relatively little evidence was found that demonstrates the safety benefits of WRM activities, especially in Canada, the limited examples were consistent in showing some level of safety improvement. Unfortunately, the paucity of such studies and the questionable rigour of the analyses makes these results difficult to generalize. The size, continuity and widespread geographic coverage of public investment in WRM is by itself an indication of societal benefit. It is also known that specific WRM practices such as salting/sanding or snow-fencing have measurable impacts on road conditions that are thought to influence collision occurrence (i.e., salting increases road surface friction, Salt Institute, 2001; snow-fencing and other drift-control measures improve visibility, Perchanok, 1998). It remains unclear how these potential benefits vary by location and how specific WRM practices and resulting conditions affect driver behaviour and collision rates.

6.2 What types and sources of weather information are used by those involved in winter road maintenance decisions and operations? How is this information used?

Weather information has always been an important and recognized input to WRM decision-making, although historically the reliance has been on the observations and experience of maintenance staff. Since the mid-1980s advances in weather prediction, remote sensing, computer, telecommunications, and engineering technologies have spawned the development of new tools for understanding and predicting the road surface condition (hazard). These technologies were first pioneered in Europe and then later imported to the U.S., Canada and Japan (for example see Rayer, 1987; Smith, 1988; Thornes, 1989) and include:

- road weather sensors to measure visibility, road surface temperature and condition (icy, snow-covered, wet, bare, etc.), chemical concentration (brine), and ambient conditions (wind direction/speed, air temperature, humidity, precipitation, etc.);
- in-vehicle mobile sensors;

- thermal mapping of road segments;
- road weather numerical prediction models; and
- advanced road weather information systems (ARWIS) that integrate many of the components listed above.

Together these sources of weather information can conceivably be incorporated into many aspects of a WRM program. An attempt to summarize some of the essential weather inputs is provided in Table 3.

Greater emphasis is placed on the lower two rows in Table 3, both in the academic and especially in government literature. Each organization has slightly different weather information needs pertaining to its particular transportation context and road maintenance practices, the latter of which is often documented in government publications. Maintenance criteria most commonly refer to a temperature range, type of precipitation, road condition, maintenance activity, and suggested treatment timing (TAC 1999). For example, the following weather-related criteria were derived from the guidelines used by the Ontario Ministry of Transportation (MTO, 1990):

- temperature (-18, -12, -7, 0°C; rising/falling)
- precipitation accumulation on road (snow, ice pellets/freezing rain; snow accumulation of 0.5, 2, 2.5, 5cm)
- wind speed and direction (related to drifting snow)

Based on figures noted in C-SHRP (2000), the actual use of information derived from new technologies such as ARWIS appears skewed towards agencies with substantive budgets and staff—provincial transportation departments and large regional urban municipalities (e.g., former Regional Municipality of Ottawa-Carleton, Cities of Calgary and Winnipeg). This suggests that there may be financial and other obstacles to incorporating ARWIS technologies into WRM decision-making. However, because of the population distribution patterns in Canada, this also means that the majority of the travelling public could potentially receive the benefits of these new initiatives.

6.3 What types of information would improve the efficiency and effectiveness (mobility and safety) of winter road maintenance operations?

The *Road Salt Management Guide* (TAC, 1999, p.3-41) suggests general types of information that will assist road maintainers in making improved decisions, including:

- *“sensor based data, including fixed pavement sensors as well as mobile infrared thermometers;*
- *pavement forecasts which predict trends in pavement temperature and chemical dilution to better enable the timing of the next salt application; and*
- *decision guides and expert systems which will incorporate the best wisdom in a decision tree format to help the decision makers to choose their action plan.”*

TAC (1999) also recommends the development of more value-added types of information beyond traditional weather service forecast or climatological products, including the frequency of plowable snow events, the number of saltable events, and intensity-duration figures. TAC (1999) acknowledges the need for indexes and similar longer-term indicators that could be used to baseline operations.

It is not clear as to whether the needs are leading the search for better information products, or whether it is the other way around. Boselly (1992) hints that more information is not necessarily better for the road manager. A case might be made that ARWIS technologies are in fact ahead of their time, that they are solutions for problems that have yet to be defined and that more emphasis might be placed on the quality/usability of information from the perspective of the road maintenance operator. On the other hand, TAC (1999) and others argue that new approaches to maintaining roads, including the incorporation of additional road weather information, will not be readily adopted until the method has been proven reliable and useful.

Table 3. Examples of weather-related WRM decisions and potentially inputs for weather information

Types of WRM Decisions	Weather-specific questions	Types of information	Sources of Information
Planning and program evaluation <ul style="list-style-type: none"> • budgeting • equipment/capital stock turnover • performance measurement and baselining 	What is average or normal for this jurisdiction/region?	Climatic data <ul style="list-style-type: none"> • precipitation (seasonal amounts and event frequencies for snowfall, freezing rain, etc.; mean and variability) • temperature (daily means and extremes; variability) • wind • visibility • winter severity indexes that incorporate multiple climate variables and relate to historic patterns of WRM activity 	<ul style="list-style-type: none"> • Research community (e.g., Hulme, 1982; Cornford and Thornes, 1993; Andrey <i>et al.</i> 2001a) • Staff experience
Season Preparedness <ul style="list-style-type: none"> • equipment and material (salt, sand) planning 	What is the outlook for this month and season? Will it be abnormally cold or warm, snowy or dry or rainy?	<ul style="list-style-type: none"> • monthly and seasonal forecast products 	<ul style="list-style-type: none"> • Staff experience • Public and private weather service providers (e.g., Environment Canada, Canadian Institute for Climate Studies)
Event preparedness <ul style="list-style-type: none"> • call in additional staff/contractors • prepare equipment, load trucks, salters, sanders, etc. 	What is the expected weather for the next 6-24 hours?	<ul style="list-style-type: none"> • standard 6-hour modelled weather forecast products • road weather forecasts 	<ul style="list-style-type: none"> • Staff experience • Public weather forecasts provided by Environment Canada • Weather forecasts/model output provided by private or academic organizations (e.g., Intellicast, The Weather Network, Unisys)
During the event <ul style="list-style-type: none"> • routing decisions • treatment decisions (plow, salt, sand, etc.) 	What is happening now and over the next few hours? What areas need immediate treatment?	<ul style="list-style-type: none"> • current road and weather conditions • RWIS station data • remote cameras • ambient weather station data • weather radar 	<ul style="list-style-type: none"> • Staff and driver observations (central office and patrols) • Owners/operators of RWIS and remote cameras (municipalities, provinces, private contractors) • Environment Canada

Regardless, the authors' experience in working with operational road maintenance staff suggest that ARWIS may represent a form of automation and threat to employment or at least a diminishing of the role that operator experience has traditionally played, especially in many rural jurisdictions. This implies that a significant training effort is required as is more common in Europe. For instance, all winter maintenance service employees in Switzerland are required to undertake training in meteorology every 3 years while a facility in France has been specifically designed for winter service training (National Cooperative Highway Research Program 1999). Using a survey instrument over three winter seasons, Conger (2001) observed a strong learning curve among Utah 'maintenance shed supervisors' as they became accustomed to using ARWIS-based road weather forecasts in their operations.

While the focus has been on weather information, it should also be stressed that road maintenance authorities might influence safety and mobility through indirect means. TAC (1999) recommends conveying WRM information to the public as part of a broader education strategy. Various media, including web sites, utility bill flyers, radio, T.V., billboards, and changeable message signs, might be used to communicate snow route and service delivery maps, explanations of WRM procedures, winter survival safety tips, conditions/locations at greater risk of freezing/drifted (exposed areas, bridges, curves, hills, shaded areas), and reminders about vehicle maintenance and driver adjustments to road conditions.

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APPENDIX 'A'

Appendix A: Empirical Research on the Relationship Between Weather and Traffic Accident Risk

Reference and Author Affiliation	Spacial and Temporal Context of Study	Main Conclusions
Andrey, Mills, Leahy & Suggett, 2001 Geography, U. of Waterloo	6 Canadian cities 1995-1998	Precipitation was associated with a 75% increase in traffic collisions and a 45% increase in related injuries.
Khattack & Knapp, 2001; Knapp, 2001; Knapp, Smithson & Khattak, 2000 Iowa State University	Iowa interstates 1995-1998	Crash rates increased by approximately 1000% during severe winter storms.
Suggett, 1999 U. of Regina	Regina, Canada 1991-1994	Driving during a snow event was twice as likely to result in a crash, and 70% more likely to result in injury. The risks of collision and injury were lower for rain than for snow. Periods of elevated risk caused by residual snow lasted up to a week after measurable snow had fallen.
Edwards, 1996 U. of Wales College	England and Wales 1980-1990	In most counties of England and Wales, 4% of road collisions occurred in high winds, 1 to 2% in fog, and less than 1% in snowfall.
Lane, McClafferty, Green & Nowak 1995, Victoria Hospital and U. of Western Ontario	401 Highway and feeder highways near London, Ontario. 1984-1990	8% of fatal accidents and 9% of injury accidents occurred during rain. 12% of fatal accidents and 16% of injury accidents occurred during snow. 13% of fatal crashes and 16% of injury accidents occurred on wet roads, while 13% of fatal accidents and 18% of total injury accidents occurred on snow covered roads.
Levine, Kim & Nitz, 1995 University of Hawaii	City and County of Honolulu 1990	For every inch of rainfall, there were approx. 13 more collisions per day.
Shankar, Mannering & Barfield, 1995	I-90 in east Seattle, USA	A 1% increase in the number of rain days resulted in a 0.26%

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Reference and Author Affiliation	Spacial and Temporal Context of Study	Main Conclusions
University of Washington	1988-1993	increase in collision frequency. A 1% increase in the number of snow days resulted in a 0.10% increase in collision frequency. There is an interaction between weather and roadway geometrics.
Edwards, 1994 U. of Wales College	England and Wales 1980-1990	The presence of high winds (>22 knots) appeared to double collision risk.
Andrey and Yagar, 1993 University of Waterloo	Calgary and Edmonton, Canada 1979-1983	Collision risk during precipitation increased by 70%.
Pike, 1992 Meteorological Magazine	United Kingdom March 29th, 1986	3 major traffic collisions occurred on motorways when drivers reacted in variable ways to heavy hail showers.
Perry and Symons, 1991 Geographical Magazine	Wind storms in England Especially January 1990	Winds storms can result in death, injury and structural damage. Strong winds effect vehicle steering and can cause overturn. Wind can also cause instability in bridges, due to static and dynamic forces.
Andrey & Olley, 1990 Geography, U. of Waterloo	Edmonton, Canada 1983	2% of summer accidents occurred on wet roads, while 40% of winter accidents occur on wet/snowy/icy roads.
Brodsky and Hakkert, 1988 Geography, U. of Maryland	Israel, 1979-1981 United States, 1983-1984	Rain is responsible for approx. 14% of injury accidents.
Campbell, 1986 City of Winnipeg	Winnipeg, Canada 1974-1984	Temperatures below -15°C contribute to greater rates of vehicle collisions than do temperatures between 0 and -15°C.
Mercer, 1986 CounterAttack Program, BC	British Columbia, Canada 1984	Weather related traffic accidents constituted 11.1% of total accidents. Of these, it was raining 42% of the time and snowing 19% of the time.

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Reference and Author Affiliation	Spacial and Temporal Context of Study	Main Conclusions
Jovanis & Delleur, 1983 Engineering, Northwestern U., Illinois	Indiana tollways, USA	Collisions increased significantly on snow vs. clear days 1987 but there was no significant change on rain days.
Mather, Gossette & Mack, 1983 Geography, U. of Delaware	Connecticut & S. Carolina, USA 1975-1976	On average there were disproportionately more fatal collisions during precipitation.
Scott, 1983 T.R.R.L., Britain	Great Britain 1970-1978	Collisions increased during the rain.
Mende, 1982 Engineering, U. of Toronto	Metropolitan Toronto, Canada Winter 1980-1981	Significant snowfalls resulted in daily accident rates 1.3-2.4 times the average daily rate.
Smith, 1982 Geography, U. of Strathclyde	Glasgow, Scotland 1978-1979	Collisions increased during precipitation, anywhere from 2% to 250% depending on methodology employed.
Bertness, 1980 Illinois State Water Survey	Chicago area, USA Summers 1976-1978	On average collisions more than doubled on rain vs. dry days.
National Transportation Safety Board, 1980	United States 1970's	The risk of a fatal accident is 3.9 to 4.5 times greater on wet than on dry pavement. 13.5% of fatal highway accidents occur on wet pavement.
O'Leary, 1978 Geography, Wilfrid Laurier U.	Kitchener, Canada 1978	Collisions increased by up to 250% on snow vs. average days.
Sherretz & Farhar, 1978 Human Ecology Research Studies	St. Louis area, USA Summers, 1971-1975	Collisions increased by 1.5-3.5 times on rain vs. dry days.
Clissold, 1977 Ministry of Transport., New Zealand	New Zealand 1973	Almost 4 times as many collisions occurred during rain versus dry conditions.

Appendix A: Empirical Research on the Relationship Between Weather and Traffic Accident Risk

Reference and Author Affiliation	Spacial and Temporal Context of Study	Main Conclusions
Emanalo, Puustelli, Ciampi & Joshi 1977, U. of Zambia	Zambia, 1954-1974	Traffic casualties decreased by 5% during the rainy season.
Roosmark Anderson & Ahlquist, 1976 (as cited in Smith, 1982a)	Sweden	Collisions were 88% higher on snow vs. non-snow days.
OECD, 1976 (as cited in Perry, 1981)	Britain	The collision rate was twice as high during snow than normal conditions.
OECD Road Research Group, 1976	Various countries over the globe Various time spans	4.5 to 21% of Canadian road accidents occur in rain. 15 to 20% of accidents occur when rain is falling in Ireland, the United Kingdom, Germany, France, and Italy. Between 1 and 3% of all accidents occur during fog.
Satterthwaite, 1976 Traffic Studies Group, U. College	State Highways, CA, USA	Daily accident totals were higher when raining than on clear or cloudy days.
deFreitas, 1975 Geography, University of Queensland	5 Canadian cities 1968-1969	Snow accumulation, mean wind speed and air temperature affected the degree of disruption to society (and the transportation system).
Codling, 1974	Britain 1969-1970	Injury collision rates were approximately 50% higher during rain.
T.R.R.L., 1974	Britain 1972	Injury collisions increased by approximately 50% under snowy or icy, or wet conditions and during fog as compared with clear weather.
Haghighi-Talab, 1973	2 cities in England 1966-1967	Accident rates increased during rainfall, especially at night but the two cities show very different patterns.
Sabey, 1973	Britain	Injury collisions at nighttime were 20% more frequent under

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Reference and Author Affiliation	Spacial and Temporal Context of Study	Main Conclusions
T.R.R.L.	1969	wet vs. dry conditions.
Orne & Yang, 1972 Dept. of Highways, Michigan	State trunkline hwys, MI, USA 1968	Of 8 weather variables examined, the hourly accident rate was affected more by the presence of precipitation than any other variable.
Campbell, 1971 Dept. of Highways, West Virginia	West Virginia, USA 1969	Site by site analysis suggests that there are disproportionately more collisions under wet vs. dry conditions.
Rooney, 1967 Geography, Clark University	Several USA cities 1950's through 1960's	This hazard study showed that collisions increased by at least 200% on 3-12 snow days per year.
Robinson, 1965 (as cited in Maunder, 1970)	Melbourne, Australia	There were 30% more injury collisions during rain.