Understanding the influence of weather and warning information on trip and activity decisions, behaviour, and risk outcomes

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Statement of Contributions

Exceptions to sole authorship of the contents of this thesis:

Chapter 2: Mills, B., J. Andrey, B. Doberstein, S. Doherty, and J. Yessis, 2019. Changing patterns of motor vehicle collision risk during winter storms: A new look at a pervasive problem, *Accident Analysis & Prevention*, 127:186-197. doi.org/10.1016/j.aap.2019.02.027.

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I declare that I was the lead author for both manuscripts, responsible for developing and applying the research methodologies, analyzing and interpreting data, crafting the text, and conceptualizing the broader dissertation to which these empirical pieces contribute. The research in these papers builds upon the matched-pair technique originally designed and applied by my Supervisor, Dr. Jean Andrey, who also facilitated acquisition of motor vehicle collision data for the research described in the *Accident Analysis & Prevention* article. All co-authors provided comments helpful in interpreting analytical research findings, and general editorial support.

Abstract

Winter storms present challenges to the safe design, operation and maintenance of transportation systems. Weather warning information, often originating from publicly funded meteorological services, is intended to support decision making in ways that reduce risk and disruption. Among the general public, the most frequent weather-sensitive decisions are those associated with personal mobility—routine trips that serve or facilitate social interaction, employment, business, shopping, recreation and leisure activities. While existing research examines hazard perceptions, driver adjustments, and the effects of weather on mobility and safety outcomes, few studies have explicitly investigated how weather and related warnings affect trip and activity decisions and behaviour, and risk outcomes, during winter storms. Gaps in the literature remain regarding: non-auto modes of winter mobility; dynamic aspects of individual hazard perception, information use, and trip and activity behaviour; effects of research design, method and measurement choices on insights about warning efficacy; and the applicability of current behavioural theory to enhance understanding.

These concerns were addressed in this dissertation using a mixed-methods approach that included: formal risk analysis of large secondary motor vehicle collision and fall injury data sets; semi-structured interviews with a purposive sample of households with high levels of everyday travel; experience sampling of the same cohort during multiple winter storms in near real-time; and analysis, evaluation, and interpretation of the Theory of Planned Behaviour. The research resulted in several important empirical findings, theoretical considerations, and methodological contributions. Empirical analyses showed that falls account for a greater proportion of the excess injury burden during winter storms than motor vehicle collisions. Further, no official government warning was issued in almost two-thirds of winter storm events that produced excess injuries. The interviews and winter storm surveys exposed more nuanced and detailed interpretations of factors thought to affect trip behaviour, including variable definitions and perceptions of winter storm hazards and a complex arrangement of elements that comprise concern. Empirical findings also supported a role for official warnings in raising participant awareness and increasing confidence in general storm expectations and concern, but highlighted people's reliance on informal sources to inform specific mobility intentions and behaviours as a storm progressed.

This dissertation is among the first to incorporate and evaluate a general behavioural theory—the Theory of Planned Behaviour (TPB)—to help explain the influence of weather information on trip and activity practices during winter storms. An interpretive analysis raised questions about the effectiveness of guidance offered through TPB, diagnosing a particular inability of the model to accommodate and discretize potential interaction, sequencing, or substitution among certain protective behaviours. Other contributions of the dissertation were methodological. They included development and successful application of new event definition criteria to capture the entire life cycle and evolution of discrete winter storms as might be perceived and experienced by the public; the design of a consistency analysis method to assess and interrogate TPB constructs using small samples; and the combination of pre-season interviews with a novel experience sampling procedure used to examine inter- and intra-storm effects, which shed unique light upon dynamic aspects of factors and TPB constructs thought to affect the influence of winter weather-related risk information on trip and activity behaviour. The multiple dimensions of temporal and within-participant variation in risk outcomes, exposure, beliefs, perceptions, and preferences revealed through this dissertation strongly points to a future of warning services that necessarily must be tailored to individual situations and circumstances at discrete points in time in order to increase efficacy and societal value.

Acknowledgements

As they say, “it takes a village”, a phrase as relevant to this dissertation as anything else. While my village included many great people, this decade-long journey would not have begun or successfully ended without the generous support and patience of my advisor, Jean Andrey. Jean, you are an exceptional scholar, teacher, leader, colleague and, most importantly, friend. Thank you.

Patience must also be a virtue of the other advisors on my Committee: Sean Doherty, Brent Doberstein, and Jennifer Yessis. Your valuable comments, encouragement, and willingness to stick with me over the years are much appreciated. Many thanks as well to the [external examiner]…

As an ‘older’ student I’ve had the luxury of years of “learning on the job” with exposure to a rich variety of research colleagues, directors, and practitioners around the globe. Too many to name but all have been very generous with their time and knowledge whenever needed, and are as passionate about weather and society as I am!

I remain forever indebted to the participants who wholeheartedly agreed to contribute their time, opinions and experiences to the study and to the officials who facilitated access to health, collision, and hydrometeorological data, including those from the Regional Municipality of Waterloo, Environment and Climate Change Canada, Grand River Conservation Authority, and the Canadian Institute for Health Information. The analyses, conclusions, opinions and statements expressed in this thesis remain my own and those of the manuscript co-authors, and not those of any of these organizations.

The ‘bookend’ to Jean, I would not have started or ended this voyage without the constant support and love from my family. Michelle, Alex and Cameron, you inspire me every day and I will never take for granted the time with me you have forgone in letting me pursue this selfish little endeavour called a PhD!

Dedication

To all that I owe so many debts
To the ones that I hold so dear
I beg your forgiveness in dedicating this life-changing experience
Solely to my Dad who, rest his soul, is no longer here
I miss you so much—brian

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List of Abbreviations

CA	Canada
CaPA	Canadian Precipitation Analysis
CI	Confidence Interval
CIHI	Canadian Institute for Health Information
DUI	Driving Under the Influence (of alcohol or drugs)
ECCC	Environment and Climate Change Canada
EDVF	Emergency Department Visits for Falls
$EDVF_{IS}$	Emergency Department Visits for same-level Falls involving Ice or Snow
$EDVF_{OTHER}$	Emergency Department Visits for other types of Falls
$EDVF_{TOTAL}$	Emergency Department Visits for all types of Falls
ESM	Experience Sampling Method
FSA	Forward Sortation Area
GRCA	Grand River Conservation Authority
IBWS	Impact-Based Warning System
ICD	International Classification of Diseases
IP	Ice Pellets
MTO	Ministry of Transportation of Ontario
MVC	Motor Vehicle Collision
NACRS	National Ambulatory Care Reporting System
NMHS	National Meteorological and Hydrometeorological Service
NZ	New Zealand
OR	Odds Ratio
P	Precipitation
PBC	Personal Behavioural Control
PDO	Property Damage Only
RMW	Regional Municipality of Waterloo
RR	Relative Risk
RWIA	Region of Waterloo International Airport
S	Snow
SE	Standard Error
T	Temperature
TPB	Theory of Planned Behaviour
TWN	The Weather Network
UK	United Kingdom
USA	United States of America
WMO	World Meteorological Organization
WS	Winter Storm
ZL	freeZing Drizzle
ZR	freeZing Rain

Preface

Motivation for this dissertation comes from the author's personal experience obtained over a 28-year career as a geographer and interdisciplinary scientist with Environment and Climate Change Canada (ECCC), the federal government agency responsible for meteorological research, warning and forecasting in Canada. It also stems in part from over a decade of collaborative work with international representatives of National Meteorological and Hydrometeorological Service (NMHS) organizations through the United Nations World Meteorological Organization (WMO). These roles have provided the author with unique insight regarding the rationale, operations and challenges associated with producing and delivering weather-related scientific information and knowledge services to the public. A recurring and troubling observation throughout the author's career—and a chief inspiration for this dissertation—has been the presence of gaps and inconsistencies among four aspects of service production and provision:

- awareness and knowledge of weather-related hazards and risks among members of the public and those providing weather warning services;
- expectations among service providers about the potency or efficacy of weather-related risk information at influencing public decisions, behaviours, and practices;
- actual decisions taken, behaviour conducted, or practices performed by members of the public; and
- social outcomes of individual decisions, behaviour, and practices.

The author's experience suggests that service providers tend to underestimate the public awareness and understanding of weather-related risks and coping strategies. Yet, at the same time, these same service providers seem to overestimate the potential influence of weather information on decisions made by members of the public and resultant outcomes. If correct, this has the effect of reinforcing an existing mantra that the issue at hand is merely one of providing more precise, timely, accurate, salient, and instructive weather and risk information (e.g., Shapiro et al. 2010). The research conducted through this dissertation allowed the author to explore and shed light on some of these assumptions and complexities beyond what would normally be possible working within a government institution.

Chapter 1: Research Problem Context and Framing

1.1 Problem context

Safety of citizens, protection of property, and economic benefits are the primary stated reasons that government organizations produce and disseminate weather observations, forecasts, advisories and warnings to the public (WMO 2015a). Such services are delivered by National Meteorological and Hydrological Service (NMHS) agencies through a variety of communication channels and outlets. Increasingly they are provided via public authority partners (e.g., a local public health office), non-government groups and organizations, or through private-sector enterprises, for example those in the mainstream and internet media. In the case of advisories and warnings, information is conveyed about risk—the likelihood of experiencing hazardous conditions and potential consequences—and often is accompanied by recommended protective actions, such as obtaining access to air conditioning during heat waves and avoiding driving during winter storms.

Public meteorological agencies expect that their information is effectively considered by individuals in making decisions that reduce or manage weather-related risks and take advantage of socio-economic opportunities (i.e., avoided losses, cost savings, and investments). The communication may therefore be conceived and framed as a deliberate intervention—it is explicitly intended to influence individual decisions, behaviour, and practices, with the aim of reducing the risk of personal injury, property damage, and disruption.

The extent to which the provided services and information actually affect public decisions and actions is subject to considerable interpretation and debate. Formal surveys and other consultations suggest that a majority of people in North America check a weather forecast at least daily and are generally satisfied with the information that they receive (Ekos Research Associates 2007, Harris/Decima 2011, Lazo et al. 2009). It is much less clear, however, whether this means that the information communicated about a particular hazard event and its potential consequences was received and understood by those at risk, considered in decision making, and translated into recommended behaviours to yield the expected, positive social outcomes (Morss et al. 2008, WMO 2015b). This disconnect among the response expected or intended by information providers, the actual decisions and behaviours of those targeted to receive a communication, and the outcomes of such actions has been a subject of interest among hazard geographers and other researchers for decades (White et al. 2001) and extends across health, consumer behaviour, environmental sustainability, and other fields as well. It is particularly relevant for applications related to mobility and transportation—the subject, content, and focus of this dissertation and many weather information services and products issued by government authorities. Most NMHS agencies were conceived or developed within sections of transportation ministries or departments (Thomas 1991) and the sector is arguably one of the most sensitive to weather and climate conditions, particularly during the winter season (Andrey et al. 2014).

Weather information, whether supplied by a publicly funded agency, private-sector enterprise, or internal staff meteorologist, gets factored into a vast array of transport policies and decisions, such as aircraft de-icing and payload constraints, routing for ships to avoid storms and ice, temporary speed restrictions (slow orders) for freight and passenger trains, and the design and maintenance of runways, railways, roadways, sidewalks, and bike lanes. Many of these arrangements are institutionalized through formal legal or procedural rules, regulations, guidelines, and processes (e.g., building codes, wind thresholds to shut down bridges, etc.). Relative to the public, this in effect makes them less prone, though certainly not immune, to expectation-knowledge-action gap concerns, as behaviour is usually directed or constrained by specific and often enforceable rules, monitoring, and accountability measures.

Among the general public, the most frequent weather-sensitive decisions are those associated with personal mobility—routine trips that serve or facilitate social interaction, employment, business, shopping, recreation and leisure activities. Included among these types of decisions are those related to: 1) acquisition and application of goods and services in preparation for expected conditions; 2) activity scheduling and rescheduling; 3) trip decisions within the traditional breakdown of destination, mode, route, and departure time choice as well as substitutes for short-term travel; and 4) in-transit choices such as driving speed or employing extra caution when crossing a street (Stern and Richardson 2005).

Typically taken at the individual or household scale, these mobility decisions and actions manifest into a complex dynamic picture of exposure, sensitivity, and behavioural response to weather that has been studied in two principal ways:

1) Statistical analyses of secondary data to determine the orientation and estimate the strength of relationships between certain weather or road weather conditions and traffic volume, motor

vehicle collisions (MVCs) and injuries, and transit ridership, revealing aggregate patterns in travel and safety at the highway, city or regional scale; and

2) Stated preference, choice and adaptation surveys about perceived weather-related hazards, specific choices and intentions to reduce individual travel risks, and the use and value of weather or travel information in making such choices.

Several studies have thoroughly reviewed and synthesized research regarding the relationships between weather conditions and indicators of mobility or safety at the aggregate scale (e.g., Andrey et al. 2001, 2003; Bocker et al. 2013; Khattak and DePalma 1997). Significant deviations in traffic or collision patterns can be interpreted as signals of behaviour change. Observed reductions in transit ridership during rainfall (e.g., a few percent, Doherty et al. 1993) are assumed to be related to modal switch, possibly forced by the inconvenience of getting wet; lower traffic volumes during heavy snowfall (e.g., up to 50%, Knapp et al. 2000) indicate a preference by some drivers to cancel or defer trips, or adjust route choices; and lower driving speeds on wet roads (e.g., 10%, Unrau and Andrey 2007) are likely driver reactions to perceived road and visibility conditions. Much of this work is focused on automobile travel—selected results for a much more limited literature covering other modes of personal transport are described in Table 1-1. A few studies have also analyzed the effects of fixed and variable road hazard message signs on driving speed with very modest reductions reported (Carson and Mannering 2001, Lind 2007, MacCarley et al. 2007). Despite evidence of adjustment, studies continue to show higher crash and injury rates during precipitation relative to normal or baseline conditions (e.g., Andrey 2010, Black and Mote 2015), suggesting an imperfect response to weather hazards, inflexibility of trip options, presence of skill or knowledge gaps, and a role for improved communication and application of weather-related risk information.

The general directions of relationships discovered through the analysis of traffic and collision data appear consistent with studies that survey travelers about their stated perceptions, preferences and intentions for dealing with adverse weather and road situations when presented with various scenarios of hazard (Andrey and Knapper 2003, Cools et al. 2010, Strawderman et al. 2018) or different types of weather and road weather hazard information (Cools and Creemer 2013, Elevant 2013, Kajiya et al. 2008, Kilpeläinen and Summala 2007, Matsuzawa et al. 2006, Khattak and DePalma 1997, Strawderman et al. 2018).

Table 1-1. Selected studies reporting relationships between adverse weather and travel.

Study	Mode/focus	Location	Main finding
Aultman-Hall et al. (2009)	Pedestrian	Single site in Vermont, USA	• Average daytime volume reduced by 13% (16% in winter) during precipitation
Walton-Sunseri (2010)	Pedestrian	Auckland and Wellington, NZ	• Up to 30% of hourly daytime count variance explained by weather • Noon-hour volume increases 1.5%/°C
Robertson-Wilson et al. (2008)	Pedestrian	Ontario, Canada	• Weekly average temperature and days with precipitation did not significantly explain variation in the active commuting choice/level of over 20,000 high school students
Nankervis (1999)	Cycling	Melbourne, Australia	• Daily bike counts are significantly reduced during extreme cold or warm temperature • Counts also reduced during rainfall, but results insignificant
Guo et al. (2007)	Transit	Chicago, USA	• Weekday bus ridership reduced 16-22,000 (~4% of average daily) per inch Weekday rail ridership falls 5-8,000 for rail (1-2% average daily) • Fog increases weekday rail bus ridership by 8-10,000 • Weekend trips more likely to be affected by weather than weekday trips
Kalkstein et al. (2009)	Transit	Chicago, San Fancisco, New York, USA	• Variation in air mass type (e.g., continental polar, moist tropical) can reduce or increase rail ridership up to 6% depending on season • Air mass effects much greater on weekend than weekday travel
Datla and Sharma (2008)	Automobile	Alberta, Canada	• 7-17% drop in daily volume per centimeter of snowfall • Up to 51% drop in volume during severe snowstorms • 30% drop when temperatures ≤ -25°C

The perception of risk and degree of adjustment, though, vary by study and are seemingly affected by socio-demographic (e.g., age), travel and hazard experience (e.g., driving, route familiarity, climate), and trip characteristics (e.g., purpose, activity, distance) (Bocker et al. 2013, Cools et al. 2010, Cools and Creemer 2013). Production and delivery aspects of the weather information (i.e., early warning, 'official' communications relative to exchange of information via social networks) also seem to be important (Elevant 2013) but are not as well-studied.

In the case of aggregate pattern studies, researchers have defined associations between weather and indicators of mobility and safety or exposure using secondary data, and have offered suggestions of the types of adjustments that might explain observed patterns. The work does not directly test or evaluate specific behavioural mechanisms operating at the individual traveler or household level where decisions are made nor does it address the influential social context within which people are embedded. While the survey-based research accesses information at the level of individuals, virtually all of the instruments used constrain responses to a limited set of hazard, trip adjustment, weather or traveler information, and contextual variables that are pre-determined by the investigators and typically informed (or simply repeatedly examined) by past empirical work. The designs are subject to being reactive and thus may overlook or misrepresent important attitudes and beliefs (Bostrom et al. 1994). These studies provide evidence of stated behavioural intent and associations or differences among various factors, but offer limited insight into the processes, thinking, or feelings behind the seeking, receiving, confirming, interpreting, and acting upon weather-related risk information by individuals in trip decision-making. Such information is needed to explain why, for instance, certain types of travelers in particular situations are more or less tolerant of risk and motivated to modify their behaviour.

As noted by Bocker et al. (2013), very few studies have explicitly examined the role of weather forecasts or weather-related risk information in affecting trip decisions and behaviour. Notable exceptions include: Barjenbruch et al. (2017), Brazil et al. (2017), Drobot et al. (2014), Elevant (2013), Li et al. (2018), Rutty and Andrey (2014), and Strawderman et al. (2018). Again, much of this work is empirical in nature and research designs typically do not incorporate theoretical or conceptual models and constructs that are rooted in the broader behavioural and social change literature, such as the Theory of Planned Behaviour (Ajzen 1991). Studies are often survey-based and cross-sectional with minimal attention paid to dynamic processes and variation in the determinants of behaviour and risk outcomes over time.

In summary, routine public mobility decisions, actions and practices offer a promising canvas for exploring the influence of weather-related risk information and to further the understanding and explanation of gaps and inconsistencies among service provider expectations, public knowledge, actual behaviour, and outcomes. The problem is societally relevant, especially during the winter season, with potential practical applications for NHMSs and other authorities engaged in risk communication. Despite a substantive base of research examining the effects of weather on mobility and safety outcomes, and stated hazard perceptions and adjustments among drivers, there remain several significant gaps and issues in understanding regarding:

- Pedestrian and other non-auto modes of winter mobility;
- Dynamic aspects of individual winter weather hazard perception, information use, and trip and activity behaviour;
- Effects of research design, method and measurement choices on findings; and
- Application, evaluation, and further development of existing behavioural theory.

These important limitations have not been adequately addressed in the few studies that have explicitly examined weather information and its effects on trip decisions and behaviour. Together, these concerns form the rationale for pursuing research described in this dissertation, with specific goals, objectives and aims further elaborated in the following section.

1.2 Dissertation purpose, objectives, and aims

The purpose of this dissertation is to critically explore the variable influence of weather and weather-related risk information (public warnings) on routine mobility decisions, behaviour, and risk outcomes during winter storms. Four research objectives, together with supporting aims, were established to realize the overall goal:

Objective 1: Develop and apply an improved approach for comprehensively estimating weather-related mobility risks for multiple modes.

Aim 1: Develop and apply a new event-based characterization of winter storms using multiple, complementary sources of weather information.

Aim 2: Estimate, compare, and combine estimates of relative and absolute injury risk during winter storms for two primary forms of mobility safety outcomes: motor vehicle collision and pedestrian fall-related injuries.

Objective 2: Determine the extent of behavioural response to winter storms and winter weather warnings by analyzing risk outcome data.

Aim 1: Stratify, analyze and compare relative risks by winter storm attribute (severity/magnitude, precipitation type), risk outcome (injury collisions, non-injury collisions), and presence/absence of winter storm related weather warnings.

Aim 2: Estimate, examine, and interpret temporal trends in estimated relative risks.

Objective 3: Understand the effects of different methods and timing of data collection on insights into the influence of winter storm-related risk information on routine trip and activity behaviour.

Aim 1: Informed by Objectives 1-2 and a review of literature, develop a robust, multi-method research design for the same case region.

Aim 2: Conduct semi-structured interviews and apply experience sampling techniques to establish and compare pre-season, within-storm, and between storm perceptions, beliefs, intentions, and behaviours for a common cohort of study participants.

Aim 3: Analyze and compare empirical findings with those found in the extant literature and identify practical implications for weather warning service providers.

Objective 4: Evaluate the relevance and utility of Theory of Planned Behavior constructs in explaining the influence of winter storm-related risk information on routine trip and activity behaviour.

Aim 1: Code and interpret pre-season semi-structured interview discourse for TPB constructs.

Aim 2: Inductively analyze experience sampling survey data to assess the strength and consistency of constructs in explaining behaviour and intent as per TPB theory.

Aim 3: Interpret a typical winter storm warning information product through the TPB lens and critically review the theory as a source of guidance for improving warning service interventions.

1.3 Dissertation structure

A manuscript-style has been adopted in this dissertation. The introductory chapter is followed by three manuscripts published in, or prepared for submission to, peer-reviewed journals (Chapters 2-4). Each chapter contains a thorough review of pertinent literature, description and rationale for the research methods employed, and documentation of findings and implications that are further considered and integrated in Chapter 5.

Chapter 2 presents an empirical study of the risk of injury and non-injury MVCs during winter storms relative to seasonal, dry conditions in a mid-sized urban community in Ontario, Canada. Published in *Accident Analysis and Prevention*, the analysis improved upon past studies by developing a new lifecycle definition of winter storm events using multiple sources of weather data to capture a greater portion of time during which drivers respond to hazardous weather and road surface conditions. Findings confirm that winter storm events are associated with large increases in both injury and non-injury collisions relative to dry, seasonal conditions. A statistically significant decline was observed in relative risk of injury and non-injury collisions during winter storms over the course of the 2002-2016 study period—a disproportionately greater reduction than for collisions in general. This manuscript addresses Objective 1 and Objective 2.

The second manuscript, presented in Chapter 4 and published in *Weather, Climate and Society*, extended the expected value approach from the first manuscript to an understudied mobility risk outcome—emergency department visitations for fall-related injuries. Relative risks were evaluated in terms of the presence of government-issued weather watches and warnings to empirically assess the influence of weather information. Both relative risks and absolute injury numbers suggested that same-level falls on ice and snow constitute a larger health burden than MVCs during winter storms. Findings raise important questions about the relative importance of falls in understanding the effects of winter storms on injuries, indirect impacts of weather on exposure and overall risk outcomes, and the limitations of population-level analyses in disentangling the effects of weather information from other forms of intervention. These limitations, in combination with a need to better understand fine-scaled risk variations within individual winter storm events, pointed to alternative methods and social theory-driven investigations of behaviour as complementary and more promising avenues for research. This manuscript addresses Objectives 1 and 2.

Lessons from Chapters 2-3 are taken up in Chapter 4, which examined the effects of methods and timing of data collection on insights into the influence of winter storm-related risk information on routine trip and activity behaviour. Prepared for submission to *Environment and Behavior*, the manuscript describes the design and execution of a mixed-methods approach, consisting of content analysis of pre-winter season semi-structured interviews and experience sampling surveys during three winter storms in near real-time, to collect rich, detailed information about the perceptions, beliefs, actions, and behaviour of study participants. Data and empirical findings were then reanalyzed through the lens of the TPB, which underscores the theory's utility, but also limitations, in providing guidance to improve the efficacy of warning information interventions. This manuscript addresses Objectives 3 and 4.

Chapter 5 is used to review and integrate the primary findings of the dissertation with critical discussion focused on the merits, limitations, and potential improvements to methods and theory, particularly with regard to the treatment of temporal stability in constitutive constructs. Implications for weather service providers and transportation agencies are discussed and recommendations made for future research directions and potential applications for NMHSs and the weather enterprise more broadly.

Chapter 2: Changing patterns of motor vehicle collision risk during winter storms

Mills, B., J. Andrey, B. Doberstein, S. Doherty, and J. Yessis, 2019. Changing patterns of motor vehicle collision risk during winter storms: A new look at a pervasive problem, *Accident Analysis & Prevention*, 127:186-197. doi.org/10.1016/j.aap.2019.02.027.

2.1 Synthesis

Past research has shown that winter precipitation is an important environmental factor that increases the frequency of motor vehicle collisions that cause personal injury and property damage. Questions remain about the magnitude of winter storm effects on collision occurrence, changes in risk over time, and the role of driver behaviour in conjunction with other factors (e.g., winter maintenance by road authorities) as it affects exposure and sensitivity to hazardous conditions. In response, a matched-pair, retrospective cohort method was used to estimate injury and non-injury collision risks for a mid-sized urban community based on a new definition of winter storm events that, relative to previous studies, captures a greater portion of time during which drivers respond to hazardous weather and road surface conditions. Winter storm definition criteria were applied to weather radar imagery and traditional surface station observations in a unique manner to classify and characterize a set of 196 variable-length storm events in terms of precipitation type and amount, visibility, temperature profile, presence of government-issued warnings, location, and temporal factors. Injury and non-injury collisions increased by 66 and 137 percent, respectively, during winter storms relative to dry weather conditions. Although these increases were higher than findings from similar studies of winter precipitation events conducted over the same timeframe (i.e., 2002-2016), they were found to have declined by a statistically significant amount over the course of the study period and disproportionately to collisions in general. Understanding why this is occurring, and then attributing improvements to specific winter road safety interventions and behavioural adjustments, is a key focus for future research and for informing future risk-mitigating investments.

2.2 Introduction

Winter weather is an important environmental factor that influences the frequency of motor vehicle collisions (MVCs) that cause personal injury and property damage. Reviews of the empirical evidence concerning weather-related crash risk have demonstrated the effect that winter precipitation, and associated slippery road surface conditions and/or low visibility have on increasing collision and casualty rates (Andrey et al. 2003, Eisenberg, 2004; Qiu and Nixon 2008, Koetse and Rietveld 2009, Strong et al. 2010, Theofilatos and Yannis 2014). Results documented in these papers are synthesized from research conducted across a variety of temporal (hourly, daily, monthly) and spatial (short highway or freeway segments, cities and city districts, counties, states/provinces, countries) scales covering a wide range of climates in primarily developed-world driving contexts, including Canada, Netherlands, Scandinavia, United Kingdom and the United States.

Research methods used in these papers are similarly varied, ranging from descriptive statistics that infer the significance of winter weather by the number or proportion of collisions reported during precipitation or poor visibility (e.g., Andersson and Chapman 2011) to more complex approaches such as regression, time series modelling (e.g., El-Basyouny et al. 2014) and matched-pair relative risk analysis (e.g., Andrey 2010). Despite the range of techniques applied, studies consistently find that collision risk is substantially elevated during winter precipitation (snowfall, freezing rain, ice pellets) or on slippery road surfaces, with estimates ranging from increases of five percent (El-Basyouny et al. 2014) to over 900 percent (Knapp et al. 2000). Winter precipitation is also associated with a greater increase in overall collision risk than rainfall, though this is not consistently the case for fatal collisions. A positive relationship exists between snowfall amount and crash risk although there is some evidence to suggest that this effect lessens for severe storms with high snowfall rates and accumulations as traffic volume decreases.

Some researchers suggest that variations in risk estimates across studies may be largely explained by methodological differences including the choice of temporal and spatial units of analysis, hazard event definition, treatment of exposure (i.e., traffic volume, speed), length and specific range of timeframes investigated, and the unique characteristics and driving contexts of the locations examined (Andrey 2010, Black and Mote 2015, Qiu and Nixon 2008, Strong et al.

2010). Calls for new research to better understand the implications of such choices and situational factors, thought to be critical for deciphering and evaluating the efficacy of safety and mobility interventions, have been advanced and acted upon in several recent studies (e.g., Andrey et al. 2013, Black and Mote 2015, Elvik 2016).

As part of a larger project examining the influence of winter storms and related risk information on trip and activity decisions and behaviour, this paper also contributes to the aforementioned call for new research. The primary aim of this paper is to develop a new approach to defining and characterizing storm events in order to better capture the complete 'life cycle' of winter storms using multiple data sources. Variations in relative risk were explored across several temporal, location and storm characteristic stratifications to reveal insight into short and long-term shifts in exposure and sensitivity that may signal evidence of behavioural change, including that associated with interventions such as the provision of weather warning information. Estimates based on this approach provide a sound historical baseline analysis of relative collision risk to inform and contextualize a complementary survey-based evaluation of mobility-related decisions and behaviour being conducted by the authors.

2.3 Study area and data

2.3.1 Study area

The Regional Municipality of Waterloo (RMW) is located in the Province of Ontario, Canada, about 100 km west of the City of Toronto. It covers an area of 1,369 km^2 (Statistics Canada 2017) and contains three cities (Cambridge, Kitchener, Waterloo) surrounded by four, largely rural, townships (North Dumfries, Wellesley, Wilmot, and Woolwich). The approximately 583,500 inhabitants (RMW 2017) rely upon a regional transportation network comprising 61 Regional roads, five provincial highways, and many local urban neighbourhood and rural roads. Personal automobile is the primary mode of travel for approximately 88 percent of all trips taken within the RMW with other modes, principally transit, walking and cycling, accounting for the remaining 12 percent (RMW 2011). RMW therefore remains very much an auto-reliant community.

Located in the mid-latitudes (roughly 43.5°N, 80.5°W) beyond the direct influence of oceans, the study area experiences a continental climate modified in all seasons by the moderating influence of the Great Lakes. Many snow and mixed precipitation events of varying intensities and durations affect the Region each year making it a particularly suitable area to study the effects of winter weather on collision risk. As shown in Figure 2-1, snowfall and temperatures below the freezing point are typically restricted to the months of November through April. Snowfalls that are measurable (≥ 0.2cm) and those that are greater than or equal to 5 cm are expected to occur about 61 and 10 days each winter season, respectively, based on historic (1981-2000) climate conditions (ECCC 2018).

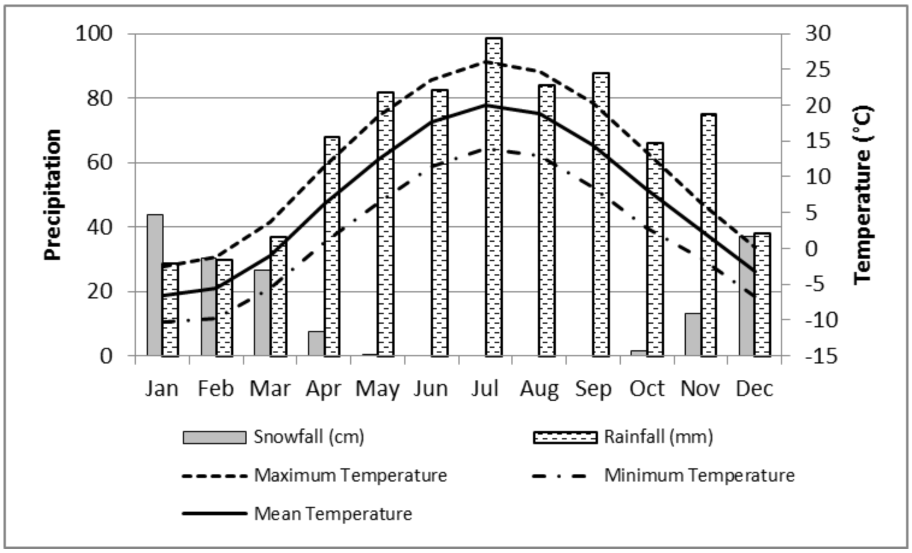


Figure 2-1. Average climatic conditions (1981-2000) for Waterloo-Wellington (ECCC 2018)

2.3.2 Data

Collision records

Collision records were obtained from the RMW Transportation Department covering all winter months (November-April) from 2002-2016, except for 2013-14 which was unavailable at the time of the analysis. The data included all incidents reported to the Waterloo Regional Police Service that occurred on roads managed by the RMW or at signalized intersections and pedestrian crossings on local streets. It excluded collisions on other sections of local streets and provincial highways under the jurisdiction of the local area municipalities or the Province of Ontario. Records contained information on collision severity, location, timing, and prevalent weather and road-surface conditions. Collison severity data were consolidated into injury and non-injury categories, the latter consisting of property-damage-only (PDO) and unreportable crashes (damage value threshold below that required for official reporting). The data were rolled up into hourly, daily, monthly and seasonal counts to facilitate analysis with weather-condition information.

Over 41,600 collisions were included in the dataset, averaging 17.7 collisions per day, with 3.8 of these involving one or more injuries. Winter season collision counts varied, ranging from a high of about 3,800 in 2002-03 to a low of almost 2,900 in 2009-10. Collision frequency, regardless of severity, was highest during the early winter month of November and lowest at the end of winter in March (injury collisions) or April (non-injury collisions). The majority (87%) of all collisions occurred in the three cities with the remainder (13%) in the townships—almost perfectly proportional to population. When one accounts for population growth in the Region—an average of 1.5 percent per annum—injury and non-injury collision rates per thousand residents have declined considerably over the course of the study period by about 26 and 33 percent, respectively (Figure 2-2). On an annual basis, injury and non-injury per capita collision rates were about nine and 32 percent lower than those for the Province of Ontario as a whole (MTO 2014, RMW 2014).

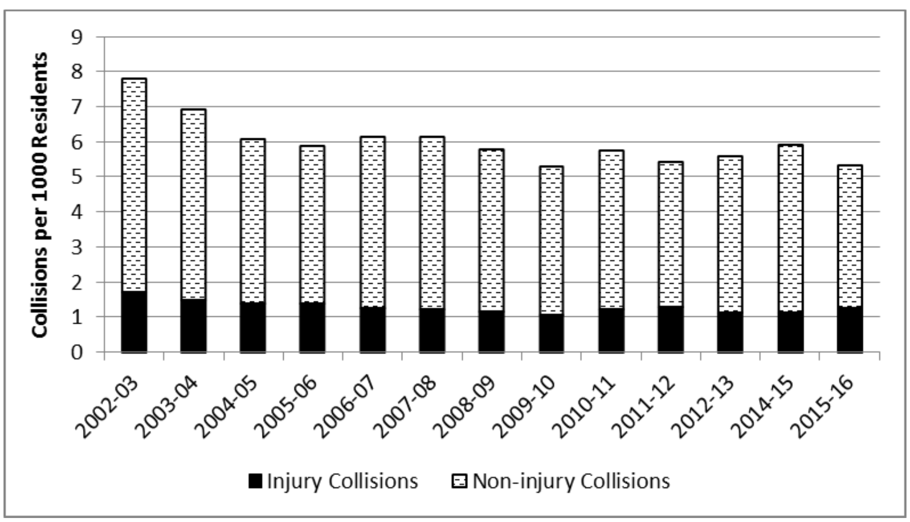


Figure 2-2. Winter season (November-April) RMW collision counts per thousand residents.

Strong day-of-week and hourly patterns, similar for both non-injury and injury collisions, were present in the data. The highest counts occurred on Fridays during the late afternoon while the lowest counts happened very early during Wednesday mornings. The highest weekday hourly collision count (Friday, 15:00) was over 42 times greater than the lowest count (Wednesday, 03:00) which reinforces the need to account for highly variable exposure in any analysis of risk at the sub-weekly scale.

Weather condition data

Multiple types and sources of weather data were utilized in the current study to define and characterize winter storm events and corresponding control periods, and to interpret findings from the analysis of relative risk. Summarized in Table 2-1, the weather data included hourly and daily observations from several stations across RMW and processed precipitation imagery from the Exeter (WSO) and King City (YKR) weather radar sites operated by Environment and Climate Change Canada (ECCC). The weather and road-surface information from the collision reports served as a secondary dataset to further verify conditions.

The most important source of weather data used in defining winter storm events was historical radar imagery. Radar technology involves actively sending a scanning beam of energy at various angles into the atmosphere. When the beam intercepts falling rain, ice pellets or snow, a portion of this energy is reflected back to the radar installation where it can be interpreted using well-tested algorithms to detect the 3-dimensional location, type, intensity, and motion of the precipitation. Recent applications in matched-pair analyses of MVCs confirm its value as a more comprehensive and representative picture of precipitation over large areas than offered by widely scattered surface meteorological station observations alone (Jaroszweski and McNamara 2014, Tamerius et al. 2016). A nearly complete record of processed hourly images depicting the location and intensity of precipitation was obtained through the public ECCC[1] web site for the period 2007-2016 and through an internal database accessible to the lead author as an ECCC employee for the period 2002-2007. Located approximately 50 km west of the RMW, the Exeter (WSO) radar site was the primary source of imagery; where data gaps occurred, supplementary imagery was obtained from the King City (YKR) radar site positioned about 80 km northeast of RMW.

Using the approach developed by the authors in previous research (Brenning et al. 2011), each processed radar image within the study period was examined to determine the extent of

[1] See http://climate.weather.gc.ca/radar/index_e.html

precipitation coverage across the study area. Radar images were saved and stored for every observed occurrence of precipitation in RMW. Additional images several hours prior to the initial precipitation and immediately following the last observed period of precipitation were added to ensure that entire events were documented. The following criteria were used to assign each hour into one of three classes of categorical precipitation coverage within the RMW:

Class 1. Precipitation observed to be just entering RMW, restricted to a very small part of the Region, or consisting of widely scattered precipitation of low intensity (<0.5 cm/h)

Class 2. Precipitation observed to affect two of the main cities (Cambridge, Kitchener, Waterloo)

Class 3. Precipitation observed over most of RMW and all three main cities

Additional weather data sources listed in Table 2-1 were used to define and characterize winter precipitation events by type (e.g., snow, mixed), amount of precipitation, visibility, and temperature profile (e.g., cold, warm, falling or rising temperature). The procedure for doing this is further explained in the methods section below. Weather watch, warning and advisory bulletins, obtained from ECCC, and regional media reports of winter weather events causing abnormally high motor vehicle collision rates, injuries and hospitalizations, and various forms of disruption to transportation systems and activities, were used as secondary sources to confirm the event classifications and establish suitable control periods. The warning information was also used as a surrogate for defining intense or severe storms.

Table 2-1. Sources and description of weather condition data used in the study.

Site/location	Source	Variable	Timestep	Length of Record
Exeter Radar (about 50 km west of ROW)	Environment and Climate Change Canada	• Processed colour images of precipitation coverage and intensity derived from reflectivity signal (snowfall detection mode, approx.. 1km resolution)	Hourly (10 and 30 minute imagery accessed to supplement as needed)	2002-2016
King City Radar (about 80 km northeast of ROW)	Environment and Climate Change Canada	• Processed colour images of precipitation coverage and intensity derived from reflectivity signal (snowfall detection mode, approx.. 1km resolution)	Hourly (10 and 30 minute imagery accessed to supplement as needed)	2002-2016
Region of Waterloo International Airport (RWIA) Observing Station (Township of Woolwich, just east of City of Kitchener)	Environment and Climate Change Canada	• Air temperature (°C) • Dewpoint temperature (°C) • Wind speed (km/h) • Wind direction (tenths of degrees) • Visibility (km) • Precipitation indicator (text: snow, rain, freezing rain, blowing snow, etc.)	Hourly	2002-2016
		• Maximum temperature (°C) • Minimum temperature (°C) • Rainfall (mm) • Snowfall (cm) • Total precipitation (mm)	Daily	2002-2016
University of Waterloo Weather Station (City of Waterloo)	University of Waterloo	• Air temperature (°C) • Relative humidity (°C)	Hourly	2002-2016
		• Maximum temperature (°C) • Minimum temperature (°C) • Total precipitation (mm) • Snowfall (cm) (measured offsite)	Daily	2002-2016
Shade Mills observing station (12285042) (City of Cambridge)	Grand River Conservation Authority (GRCA)	• Air temperature (°C) • Rainfall (mm) (when warm temperatures permit use of tipping bucket gauge)	Hourly	2002-2016
Laurel Creek observing station (12285042) (just NW of City of Waterloo)	Grand River Conservation Authority (GRCA)	• Air temperature (°C) • Rainfall (mm) (when warm temperatures permit use of tipping bucket gauge)	Hourly	2002-2016

2.4 Methods

A matched-pair, retrospective cohort method was employed as the primary means of estimating injury and non-injury collision risk. Winter storm event periods were matched to dry weather control periods by hour and day-of-week either one week prior to or following the event. The matching process made it possible to isolate the influence of weather from other factors that affect exposure such as traffic volume and underlying activity patterns that exhibit regular behaviour but for which there are limited data (e.g., work tends to be concentrated from 9:00-17:00 on weekdays; people stay out later to dine or socialize on Friday and Saturday evenings). This approach thus assumed that within-day and day-of-week travel patterns are similar when averaged over a large number of observations. Each event-control pair became a basic unit of the subsequent risk analysis.

The matched-pair technique is commonly adopted in health applications (e.g., Di Bartolomeo et al. 2009), for instance, when assessing the benefit or harm of a medical treatment, drug or other intervention. Matched-pair research designs are increasingly being used in MVC studies (e.g., Cummings and Grossman 2007, Cummings et al. 2006, Hijar et al. 2000, The SAM Group et al. 2008, Zheng et al. 2010) and have a long history of application in collision studies focused on inclement weather (Andrey 1989, Andrey 2010, Andrey et al. 2003, Black and Mote 2015, Changnon 1996, Keay and Simmonds 2006, Liu et al. 2017, Mills et al. 2011, Smith 1982, Tamerius et al. 2016).

Variable-length event and control periods were used in the current study to capture spatial and temporal qualities unique to each winter storm (e.g., onset, spread, duration, intensity, sequence, antecedent and subsequent conditions) and to better match scales of official warnings issued by government agencies, protocols of winter maintenance authorities, and the planned activity patterns and preparedness actions of the public. While the choice of variable-length events is not unique to this investigation (see Andrey 1989, Black and Mote 2015), most matched-pair studies define events and controls with fixed-period lengths. For example, three-hour, six-hour, and daily periods were used by Jaroszweski and McNamara (2014), Andrey et al. (2013), and Liu et al. (2017), respectively, yet each of these choices is problematic. There is some concern that sub-daily fixed periods may not fully account for the lagged effects of winter precipitation on relative risk since road surfaces may remain icy, snow-covered, or wet for up to several hours after precipitation has become scattered or ended (Andrey 1989, Jaroszweski and McNamara 2014, Tamerius et al. 2016). As multiple fixed-period events may be identified within a single winter storm, there may also be issues about independence between events (e.g., risk perceptions and trip decisions may be affected by conditions in the previous periods thus potentially affecting exposure and sensitivity). This concern is supported by research that demonstrates that relative risk during wet conditions increases as dry weather gaps between precipitation events lengthen (Eisenberg 2004). Criteria may be used to establish a minimum period between events; however, this may create a separate problem by artificially forcing an oversampling of the beginning parts of winter storms. Finally, although fixed periods are suitable for short-duration hazardous events (e.g., heavy convective rainfall during thunderstorms, frontal snowsqualls, flash freeze situations), periods greater than six hours may also have the unintended effect of bisecting winter storms resulting in partial coverage or missed events. For all of these reasons, the authors decided to use variable-length events and control periods in the analysis.

Variable-length events and corresponding controls were based on climatological storm factors and a conceptual definition of 'winter storm', using the criteria listed in Table 2-2. Winter storms in RMW are most often associated with developing, mature, or occluding mid-latitude cyclones. At their peak, as depicted in Figure 2-3, these cyclones have three principal areas (or times, as these systems are transient) of precipitation that usually occur within an 8 to 24 hour storm window: 1) ahead of the main area of developing low pressure along the warm frontal zone; 2) around the comma head of a passing mature cyclone and in active zones of deformation; and 3) along and immediately behind the cold front (Barry and Chorley 1987, Semple 2003). The extent, duration, intensity, and type of precipitation; surface wind speed and direction; and temperature profile, largely depend on the track, strength, maturity, and source region of a given cyclone as well as upper atmospheric features that govern the antecedent and post-storm air masses. Mesoscale phenomena within a given storm (e.g., banding, elevated convection) and following the passage of the main surface low pressure centre (e.g., lake effect snowsqualls) add to the complexity of winter storms in this region. In particular, the cold front, and subsequent shortwave troughs circulating around parent upper air lows, typically bring initial and reinforcing shots of cold arctic air, strong unidirectional wind, and elevated moisture that interact with surface heat and moisture from the Great Lakes to energize the development of localized but often very intense lake effect snowsqualls (Campbell et al. 2016, Villani et al. 2017).

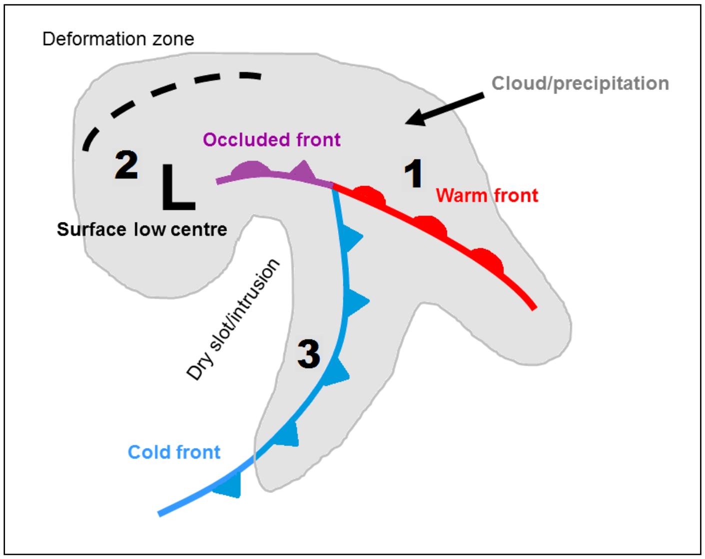


Figure 2-3. Generic simplified model of an occluded mid-latitude cyclone (winter storm) and areas of potential precipitation (based on Barry and Chorley 1987, Semple 2003).

Noteworthy are the potential ‘temporary breaks’ in winter precipitation that can occur at the beginning of storms as the atmospheric column saturates, immediately after the passage of the triple point (i.e., dry slot in Figure 2-3), and in the period between the passage of a cold or occluded front (i.e., end of synoptic system precipitation) and the commencement of lake-effect precipitation. Classifications intended to capture the entire ‘storm’ life cycle, as perceived and experienced by people in a particular location, should include such breaks in precipitation as well as the multiple zones of precipitation within a single event as they potentially influence decisions to travel and winter road maintenance practices.

Application of the event criteria resulted in the identification of 323 variable-length winter storms over the study timeframe. Given event durations of 12 to over 60 hours, it was difficult to find matching controls for every hour within a particular event. Complete coverage of event hours with suitable controls was obtained for 62 events, too few for any significant disaggregated estimations of relative collision risk. A sensitivity analysis conducted using thresholds of 50, 75, and 95 percent coverage of event hours with suitable controls revealed no significant difference in calculated relative risk, thus, the lower threshold (50 percent) was adopted yielding a total of 196 storm events for the analysis.

Table 2-2. Criteria used to define winter precipitation (storm) events and corresponding control periods.

Event Criteria	**Controls**
Duration and Coverage • ≥ 8 consecutive hours of radar-indicated precipitation of any coverage level (1,2,or 3); up to 1 precipitation-free hour permitted in sequence, but total hours of precipitation must be 8 or more (i.e., 9 hour event consists of 8 hours of precipitation and a 1 hour break) • event must include at least 4 hours of radar-derived precipitation of coverage level 2 or 3 • event must include at least 1 hour of radar-derived precipitation of coverage level 3 Precipitation Type • event must include confirmed hours of observed winter precipitation (S-snow, ZR-freezing rain/ZL-drizzle, IP-ice pellets) from collision data (S, ZR), hourly ECCC station observations (S,ZR,ZL, IP), and daily snowfall totals Capture of storm and post-precipitation effects • the hour before the precipitation commences is added to the event (to ensure capture of event start) • 3 consecutive precipitation-free hours following the last precipitation hour are added to event (to account for road surface condition lag)	Selection Process • Each hour within a defined event is matched to an hour exactly 1 week before and after the event hour • Only 1 control hour is selected for analysis. Preference is given to 'before' control period if both meet the precipitation and exposure criteria below (assumption is that the 'before' period is less influenced by the event being evaluated) Precipitation Criteria • no radar-derived precipitation coverage at any level (1,2,3) • no collision reports of precipitation (rain, snow, freezing rain, blowing/drifting snow) • no daily snowfall reported • no collision reports of wet or snowy/icy road surface conditions Exposure Criteria • no hours that are allocated to a storm event • no hours on a statutory holiday • no Environment and Climate Change Canada weather watch or warning in effect

Estimates of risk were based on the ratio of the odds of a crash occurring during one condition relative to the odds of a crash during another condition, an approach which is consistent with the theory elaborated in Fleiss (1973, 110-111), and similar to Johansson *et. al.* (2009) who studied accident risk associated with darkness. Mills et al. (2011) document the approach further, noting that each event-control pair produces four counts:

A: collisions or injuries during the event period

B: collisions or injuries during the control period

C: an estimate of the number of safe outcomes during the event period

D: an estimate of the number of safe outcomes during the control period

The odds ratio, *OR*, was thus calculated as:

$$OR = \left(\frac{A/C}{B/D} \right) \tag{1}$$

Note that in areas with large urban centres like RMW, where thousands of trips or driving maneuvers occur every hour, C and D are very large and therefore may be set somewhat arbitrarily. A log transformation of the sample odds ratio was applied to ensure that the predictions were approximately normally distributed. A statistical weight for each event-control pair, w_i, was calculated as shown in equations 2-3 based on a fixed-effects model for combining estimates of risk (as per Johansson et al. 2009:812).

$$w_i = \frac{1}{v_i} \tag{2}$$

where:

$$v_i = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D} \tag{3}$$

The following hypothetical example helps to illustrate the calculation process for one event-control pair. A snow event with falling temperatures began at 3:00 p.m. on Friday, February 10 and ended by 8:00 a.m. on Saturday, February 11. Forty collisions were reported during the event, thus (A) equals 40. Exactly one week earlier, the weather was clear and roads were dry and, over the same amount of time, only 20 collisions occurred, thus (B) equals 20. Assuming 10,000 outcomes for both the event and the control, (C) and (D) are the net safe outcomes accounting for the collisions that occurred. For this event-control pair, the *OR* is calculated as [40/(10,000-40)] / [20/(10,000-20)] = 1.996, and its weight (w_i) in the subsequent calculation of the overall risk estimate is 1/[1/20+1/40+1/10,000+1/10,000] = 13.298.

The weighted mean effect on a set of *g* event-control pairs, $\bar{y}$, was calculated as shown in equation (4) where y_i is the log of the OR. By taking the antilog of this value, the overall estimate of relative risk is obtained. The standard error (*SE*) of the risk estimate (equation 5) is used to calculate 95 percent confidence intervals for the weighted mean effect; again anti-logging provides lower and upper boundaries for the risk estimate.

$$\bar{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i} \right) \tag{4}$$

$$SE = \frac{1}{\sqrt{\sum_{i=1}^{g} w_i}} \tag{5}$$

This procedure was followed to obtain estimates of collision risk for all types of storm events and then repeated in a series of stratified analyses that are described in Table 2-3.

Table 2-3. Description of criteria used to develop stratified analyses.

STRATIFICATION	CRITERIA	ADDITIONAL CONTEXT
Winter Storm Characteristics		
Precipitation Type		
All	• All events included	
Snowfall	• Only events where precipitation consisted entirely of snowfall	
Mixed	• Events with winter precipitation other than snow (freezing rain/drizzle, ice pellets), OR where both snowfall and liquid rainfall were observed	• Mixed events were further stratified into those with and without reports of freezing rain/drizzle
Precipitation (P) Amount		
Very light	• $P < 2$ cm/mm	• Units are expressed in cm for snowfall and mm of liquid-equivalent *P* for mixed events
Light	• $2 \le P < 5$ cm/mm	• Event *P* estimated from maximum daily amounts recorded at area observation sites
Very light to Light	• $P < 5$ cm/mm	• Where storms covered partial days, hourly radar data were examined to determine the proportion of *P* that could be assigned to particular storms
Moderate	• $5 \le P < 10$ cm/mm	
Moderate to Heavy	• $P < 10$ cm/mm	
Heavy	• $P \ge 10$ cm/mm	
Visibility		
Good	• No hours with visibility ≤ 2km	
Fair	• 1-14% of event hours with visibility ≤ 2km	
Poor	• 15-29% of event hours with visibility ≤ 2km	
Very Poor	• ≥30% of event hours with visibility ≤ 2km	
Temperature (T) Profile		
Rising	• T warms from < -1°C to >0°C during event	• Events were assigned in the following order: Rising, Falling, Very Cold, Cold, Warm
Falling	• T falls from ≥ 0C to <-1C during event	• Events meeting both rising and falling criteria were assigned based on what occurred last in the event hour sequence
Stable - Very cold	• T ≤ -8°C throughout event	
Stable - Cold	• T < -1°C throughout event	
Stable - Warm	• T ≥ -1°C throughout event	
Weather Warnings		
Warned	• Event hours at least partially overlap an official winter weather watch or warning bulletin issued by Environment Canada	• Includes watches and warnings for winter storms, snowfall, snowsqualls, blowing snow, freezing rain or drizzle, and flash freeze
Unwarned	• No watches or warnings overlap any event hours	
Temporal and Location Factors		
Temporal		
Weekdays	• Events that occurred entirely on weekdays (Monday-Friday)	
Weekends	• Events included weekend hours (Saturday-Sunday)	
Month	• Events allocated to specific winter months (November, December, January, February, March, April)	
Season	• Events allocated to particular winter seasons (e.g., 2002-03, 2003-04)	• Analysis proceeded using a two-season unit due to limited sample size in individual seasons (i.e., 2002-03 to 2003-04, 2004-05 to 2005-06, etc.)
Location		
Townships	• Collision counts spatially restricted to those occurring in RMW Townships, City of Cambridge, City of Kitchener, and City of Waterloo, for respective categories	• Analysis also included a comparison of Townships with all cities, combined
City of Cambridge		
City of Kitchener		
City of Waterloo		

2.5 Results

2.5.1 Overall injury and non-injury collision risk

The 196 event-control pairs used in the analysis included 3,936 paired hours during which 4,650 event collisions (802 injury; 3,848 non-injury) and 1,904 (431 injury; 1,473 non-injury) control collisions occurred. The estimated relative risk (RR) for injury collisions during all winter storms was 1.66 (95% CI: 1.47, 1.88). This means that 66 percent more injury collisions happened during winter storm events than during comparable but dry winter conditions. The RR estimate for non-injury collisions was 2.37 (95% CI: 2.23, 2.53), just over twice the increase in RR observed for injury collisions. Additional insight into relative risk was obtained by conducting stratified analyses to examine the influence of winter storm characteristics (precipitation type, precipitation amount, temperature profile, visibility) and time and location factors (city, season, month, day-of-week).

2.5.2 Winter storm characteristics

Event-control pairs were disaggregated by precipitation type, precipitation amount, temperature profile, and visibility to evaluate the influence of weather-related storm characteristics on relative collision risk (Table 2-3). Snow events (n=117) consisted entirely of reports of snowfall, while mixed events (n=79) included any storm during which at least one observation of a winter precipitation type other than snow (freezing rain/drizzle, ice pellets) was made or in situations where the event consisted of both snowfall and liquid rain observations. Mixed events were further stratified into those with and without reports of freezing rain.

Hierarchy of relative risk

Figures 2-4 and 2-5 present a hierarchy of relative risk results for injury and non-injury collisions across the full set of weather-related stratifications. Estimates are ordered left to right from the lowest to highest mean relative risk values to indicate the relative importance of different storm characteristics; 95 percent confidence intervals are also shown for each estimate and their range generally increases as sample size decreases. The dotted line represents a relative risk of 1.00, the reference condition for which no additional effect of weather occurs relative to dry, seasonal conditions. Several statistically significant observations were apparent for the estimated relative risk of injury collision during winter storm events (Figure 2-4):

- All types of winter storms, except for minor snowfalls (less than 2 cm accumulation), substantially increased the risk of injury collision, typically from 50 to 80 percent;

- Very little difference was seen between the effects of snowfall (RR 1.68; 95% CI:1.41, 1.99) and mixed precipitation events (RR 1.65; 95% CI: 1.38, 1.97) on injury collision risk;
- Snowfall and mixed storm events with moderate accumulations (5-10 cm snow or 5-10 mm liquid-equivalent) or a higher proportion (≥ 15 percent) of poor visibility (≤ 2km) hours had the greatest effect on injury collisions, with relative risks roughly doubling; and
- The temperature profile of the storm, as defined in this analysis (Table 2-3), had little impact on injury collision risk.

Primary observations from the analysis of non-injury collision risks (Figure 2-5) include:

- All types of winter storms significantly increased the relative risk of non-injury collision, typically by 100 percent or more;
- Snowfall events (RR 2.55; 95% CI: 2.34, 2.78) had a greater influence on non-injury collision risk than mixed precipitation events (RR 2.17; 95% CI: 1.98, 2.38); and
- Snowfall events with large accumulations (≥ 10cm), a high proportion of (≥ 15 percent) of poor visibility (≥ 2km) hours, or with very cold or falling temperatures, had the greatest effect on non-injury collisions, producing increases of between 200-250 percent.

Storm intensity effects

Precipitation amount, visibility, and government-issued severe weather warnings were examined further to explore the relationship between winter storm intensity and collision risk. Figure 2-6 plots relative risks of injury and non-injury collisions during snow events for four categories of accumulation. Non-injury collision risk continued to increase with accumulation while injury collision risk peaked at 5-10 cm and then dropped slightly with greater snowfall amounts. Mixed precipitation events exhibited this same drop in relative risk as accumulation exceeded 10 mm—but for both injury and non-injury collisions.

Patterns similar to those observed for accumulation were noted in relative risks of injury and non-injury collisions during snow events with varying durations of limited visibility. As the proportion of storm event hours with visibility two km or less increased from zero to 15 percent, the relative risk of injury and non-injury collisions also grew; however, as the proportion of limited visibility hours exceeded 15 percent, injury collision risk decreased slightly while non-injury collision risk continued to increase. As indicated in Figure 2-7, the effects of visibility were different for mixed precipitation events. Relative risks of both injury and non-injury collisions increased during mixed events as the proportion of low visibility hours rose.

Official government-issued weather warnings, triggered during or in advance of winter precipitation events, provide another indicator of storm intensity. Weather watch and warning bulletins issued by ECCC for winter storms, snowfall, snowsqualls, blowing snow, freezing rain or drizzle, and flash freezes were obtained and assigned to respective winter storm events based on reported start and cancellation times. The resulting pool of 'warned' events was then compared with 'unwarned events' in the analysis. Results for injury collisions, as shown in Table 2-4, indicated slightly higher mean relative risks during warned snowfall events as compared to unwarned events. For mixed precipitation events, the opposite was observed, with mean relative risks lower for warned events as compared to unwarned events. Given the largely overlapping confidence intervals, none of these findings were statistically significant. For non-injury collisions, mean relative risks for warned and unwarned mixed precipitation events were almost identical. The 226 percent increase in relative risks for warned snowfall events, however, was much greater than the 132 percent increase observed for unwarned snowfall events; the difference was statistically significant.

Table 2-4. Comparison of relative risks of collision during warned and unwarned winter storm events.

	Injury Collision Relative Risk (95% Confidence Interval)		**Non-injury Collision Relative Risk (95% Confidence Interval)**	
WINTER STORM TYPE	Warned	Unwarned	Warned	Unwarned
Snowfall Events (n_{warned} =29, $n_{unwarned}$=88)	1.84 (1.29-2.61)	1.63 (1.34-1.99)	3.26 (2.77-3.83)	2.32 (2.10-2.57)
Mixed Precipitation Events (n_{warned} =42, $n_{unwarned}$=37)	1.56 (1.22-1.99)	1.75 (1.36-2.26)	2.16 (1.90-2.46)	2.19 (1.91-2.50)

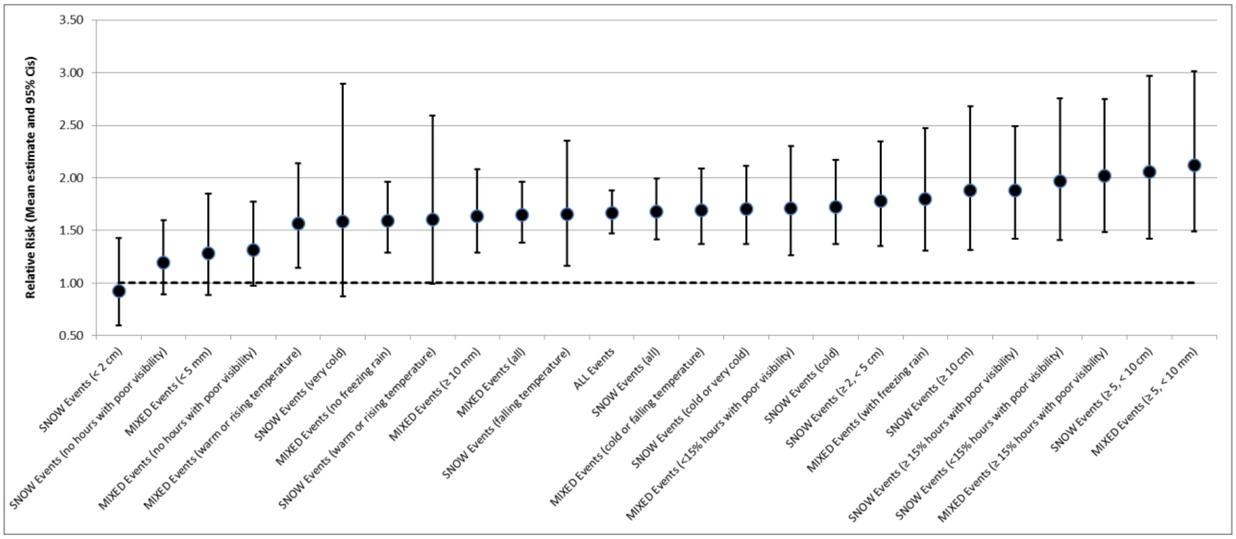


Figure 2-4. Relative risk of injury collision during winter storm events stratified by precipitation type and amount, visibility, and temperature profile.

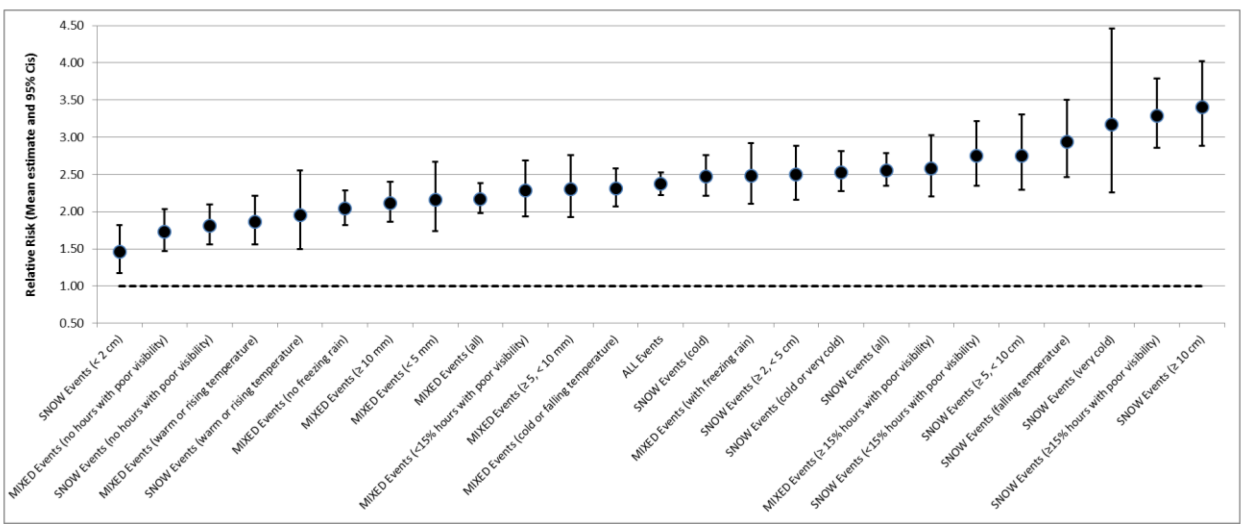


Figure 2-5. Relative risk of non-injury collision during winter storm events stratified by precipitation type and amount, visibility, and temperature profile.

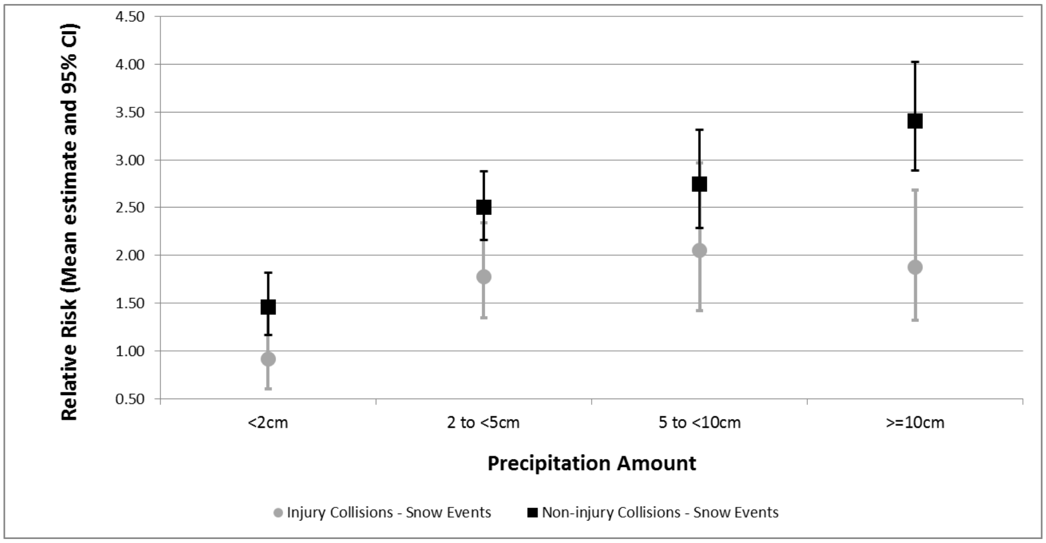


Figure 2-6. Relative risk of injury and non-injury collision during snow events for varying accumulation amounts.

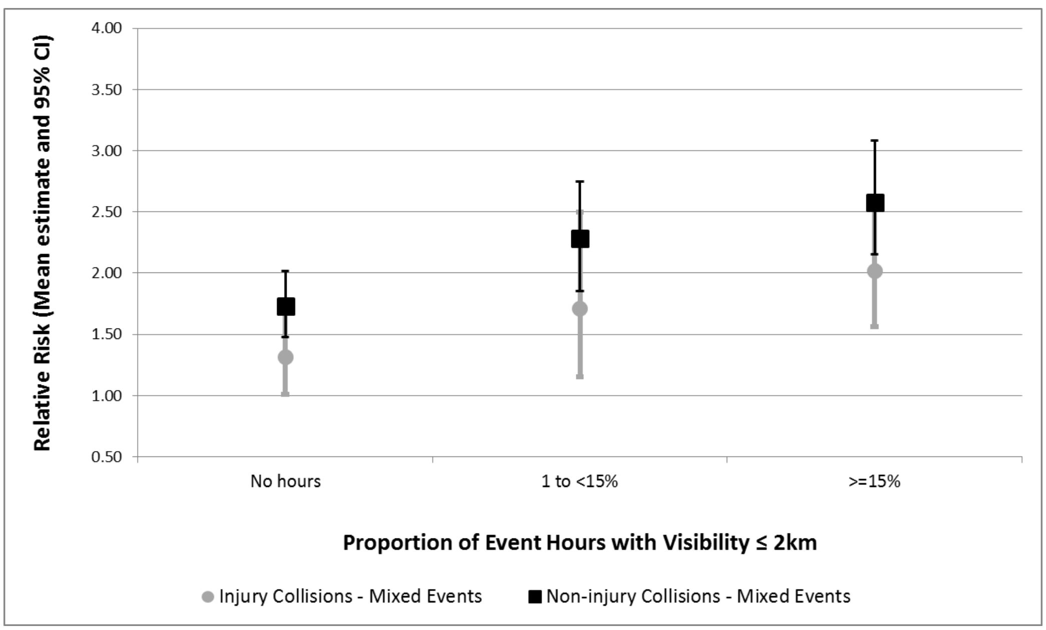


Figure 2-7. Relative risk of injury and non-injury collision during mixed precipitation events for varying proportions of hours with reduced visibility (≤ 2km).

2.5.3 Temporal and location factors

Several non-weather temporal and location factors were analyzed to detect effects of time and location that might not have been accounted for in the selection of control periods. Variation in relative risk by season, month, day-of-week, and location were examined. The most important finding, presented in Figure 2-8, was a decline in relative risk from the beginning to the end of the study timeframe. Mean increases in injury (non-injury) collisions during winter storm events relative to dry control conditions fell by 59 percent (36 percent), respectively, from 2002-04 to 2014-2016. When tested, the linear trends in two-season mean estimates were statistically significant (p_{injury}=.028, $p_{non\text{-}njury}$=.001) and similar patterns were observed for both snowfall and mixed events.

Additional results concerning other temporal and location factors included:

- Peak monthly relative risk during all winter storms occurred in January for injury (RR 2.30; 95% CI: 1.67, 3.17) and non-injury (RR 3.00; 95% CI: 2.57-3.51) collisions, while the lowest injury (RR 1.36; 95% CI: 0.94-1.98) and non-injury (RR 1.78; 95% CI: 1.43-2.21) collision risk estimates were observed in April, at the tail end of the winter storm season;
- Non-injury collision risks were slightly greater for storm events occurring on weekends (RR 2.61; 95% CI: 2.28, 2.99) rather than on weekdays (RR 2.31; 95% CI: 2.15, 2.48) but minimal day-of-week differences were observed for injury collision risks;
- Relative collision risks during winter storm events were slightly higher in the townships than cities, regardless of precipitation and collision type, with the greatest difference observed for non-injury collisions during mixed events ($RR_{Townships}$ 2.45; 95%CI:1.92, 3.13/RR_{Cities} 2.05;95% CI: 1.86, 2.27); and
- Among the three cities, relative collision risks were consistently greatest in Kitchener and lowest in Cambridge with the largest discrepancy observed for non-injury collisions during all types of events ($RR_{Kitchener}$ 2.31; 95%CI:2.09, 2.55/$RR_{Cambridge}$ 1.86;95% CI: 1.64, 2.12).

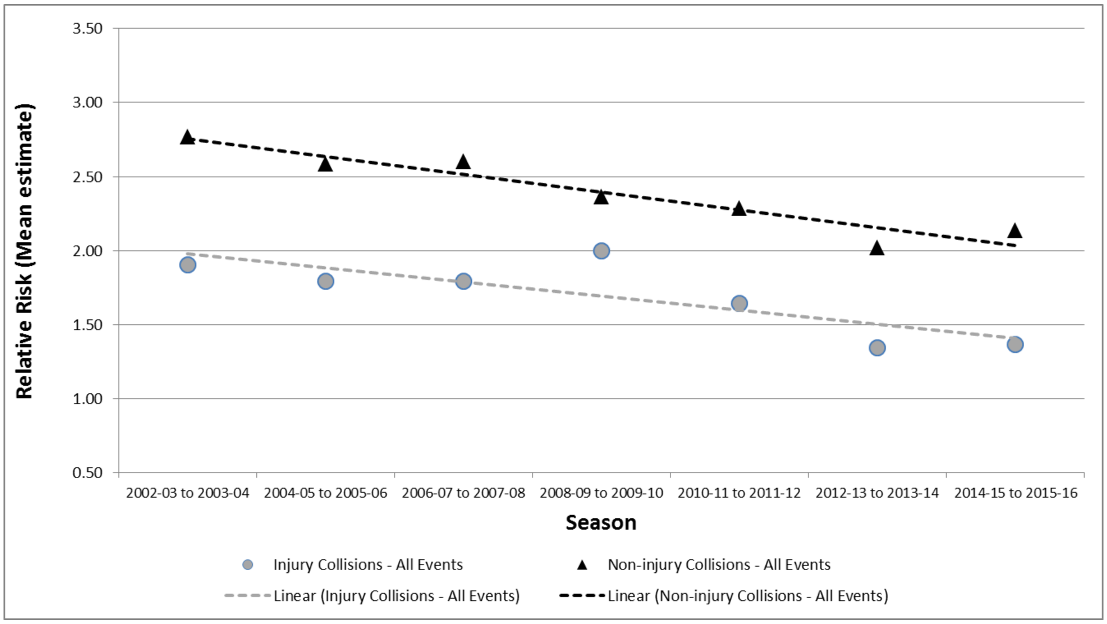


Figure 2-8. Two-season mean estimates of relative risk of injury and non-injury collision during all winter storm events.

2.6 Discussion

The primary objective of this research was to establish and apply an approach to accurately estimate MVC risk for entire winter storm events. Accordingly, the authors used a variable-length unit of analysis that conceptually better captured societal response over the complete life cycle and evolution of discrete winter storms than might be expected by focusing on fixed sub-daily or daily periods. This definition of event necessarily drew on multiple, complementary data sources and types. Key results are discussed and interpreted below in terms of their implications for trip decisions and behaviour—factors that influence both exposure and sensitivity to hazardous driving conditions.

The large relative risks for injury and non-injury collisions found in this investigation suggest that the responses by drivers, and organizations or institutions responsible for ensuring road safety and mobility, are insufficient and do not fully compensate for the effects of winter storms. The observed 66 and 137 percent increases in injury and non-injury collisions, respectively, were much higher than findings from similar studies of winter precipitation events conducted over the same timeframe (i.e., 2002-present) (Black and Mote 2015, Leard and Roth 2015, Liu et al. 2017, Tamerius et al. 2016). While some of the differences may be attributable to the unique qualities of each study area, it is suspected that results principally diverge because of the distinct approaches used by researchers to define the threshold and duration of winter storm events. This current research excluded short duration events that are unlikely, in most instances, to cause much impact, thus focusing attention on more intense, longer duration storms. The winter storm event criteria used in this study also captured at least some of the post-precipitation lag effects on collision frequency that other researchers have shown to be important (e.g., Tamerius et al. 2016).

Differences in relative risk observed between injury and non-injury collisions strengthens evidence in the literature that the effect of precipitation, snowfall in particular, lessens with increasing collision severity (Andrey et al. 2003, Eisenberg 2004, Koetse and Rietveld 2009, Qiu and Nixon 2008, Strong et al. 2010, Theofilatos and Yannis 2014). While insufficient to completely counter the hazardous conditions, this finding implies that drivers adjust their behaviour by making decisions and taking actions that alter their sensitivity (e.g., reduce speed, greater caution) and/or exposure (e.g., cancel or defer travel) during winter storms.

Behavioural effects appear to be influenced by both the type of precipitation and storm intensity, as indicated by precipitation accumulation and the presence or absence of government-issued severe weather warnings. Injury collision risk rose for both snowfall and mixed events as precipitation accumulation (P) increased from low (P_{snow}<5 cm or P_{mixed}<5 mm) to moderate (5 cm ≤ P_{snow} <10 cm or 5 mm ≤ P_{mixed} <10 mm) amounts, but then dropped slightly for events with higher accumulations (P_{snow} ≥10 cm or P_{mixed} ≥ 10 mm). A similar pattern was observed for non-injury collision risk, but only during mixed events. Non-injury collision risk during snowfall events continued to increase with accumulations in excess of 10 cm. These results are broadly consistent with several other studies (Andrey 2010, Eisenberg 2004, Leard and Roth 2017). It is plausible that most injuries tend to occur at the early onset stage of hazardous conditions before awareness of the seriousness of the situation encourages people to drive more carefully or, in response to weather or traffic warning information, has reduced the number of vehicles on the roadway through trip delays and cancellations. Significant attrition of traffic volume during long-duration winter storms with heavy accumulations has been observed in other studies (e.g., Knapp and Smithson 2000). Reductions in injury collision risk at higher accumulations could also partly reflect the lag between hazardous conditions and an effective winter maintenance response which, through snow-clearing and the application of de-icing chemicals and/or abrasives, temporarily improves road surface friction and vehicle traction. Subsequent deterioration of road surface conditions may explain the continued impact of snowfall, relative to mixed events, on non-injury collision risk beyond the 10 cm accumulation threshold. All but one of the mixed precipitation events analyzed had substantive periods of above-freezing temperatures which will melt ice and snow and substantially increase the effectiveness of de-icing applications thereby reducing the duration of hazardous conditions relative to snow events. Incorporating road surface condition information from winter maintenance authorities into future analyses, as recommended by other researchers (Tamerius et al. 2016), might provide additional insight.

Official weather watches and warnings issued by government authorities provide another indicator of winter storm intensity or severity—they are issued because hazardous conditions are prevalent or imminent. They are also integrative in that they may be issued due to multiple hazards (e.g., heavy snowfall, high winds and blowing snow, very cold temperatures) that simultaneously affect a region. Unlike traditional measures, such as precipitation accumulation, watches and warnings are forms of risk communication that may directly affect people's decisions to travel, exposure and sensitivity to hazardous conditions, and thus risk outcomes such as collisions. The results reported in Table 2-4 for snowfall events confirm that higher risks, both for injury and non-injury collisions, were observed during warned storms as compared with unwarned storms. This suggests that government agencies, in this case ECCC, are issuing warnings for high-impact snow events; however, a closer look at the sample indicates that up to 75 percent of impactful events went unwarned. It is unclear to what extent the warnings had any positive impact on collision risk by encouraging safer travel or reduced exposure. While it is possible that the collision risks could have been even greater had watches or warnings not been issued, the relatively high risk values suggest they had a modest effect at best.

Results for mixed precipitation storms were somewhat different than those for snowfall events. Injury collisions were about 20 percent more frequent during unwarned mixed precipitation storms than during warned events while non-injury collision risks were virtually identical for both. This suggests that the public took some actions to reduce their exposure and/or sensitivity to hazardous conditions, coincident with and possibly based in part on ECCC watches or warnings. It also implies that the public may take warnings for freezing rain and other mixed events more seriously than for snowfall events.

As with snowfall, a large portion of mixed event storms, about 47 percent, that contribute to elevated collision risks went unwarned. Since weather warning thresholds are typically based on meteorological rather than impact-based criteria, most winter storm events that significantly increase the frequency of collisions would likely go ‘under-warned’ in other regions as well. As specific thresholds and driving contexts vary between nations and even across sub-regions within individual countries, further analysis would be necessary to confirm the generalizability of this hypothesis.

The previous discussion identified several behavioural and other responses to winter storms that may help explain observed variations in relative MVC risk, aggregated for all winter seasons during the 2002-16 study timeframe. A key finding of this research was a substantive reduction in relative risks for both injury (59%) and non-injury (36%) collision types over the study period—significant downward trends that imply concomitant shifts in weather-related road hazards, sensitivity and exposure. Although Andrey (2010) did not observe this trend for snowfall events in a 1984-2002 longitudinal analysis of relative injury risk for 10 Canadian cities, meta-analyses of past empirical work have shown declines in collision risks during snowfall or slippery road conditions related to winter weather (Elvik 2016, Qiu and Nixon 2008). As the matched-pair technique used in the current study controls for shifts in factors that might affect safety similarly in all conditions (e.g., advances in emergency medicine, certain vehicle safety features such as airbags, DUI or age-related licensing regulations), the observed downward trend in relative risks suggest that something disproportionately affected exposure and/or sensitivity to hazardous winter storm conditions in the RMW. While the distribution of winter storm events and ratio of snowfall to mixed events showed little variation over the study period (i.e., no discernible trend in the hazard), there has been considerable investment and change in technology and human factors that intuitively seem to address winter storm related risks to a greater degree than for dry-weather collisions. Improvements to municipal winter road maintenance practices (e.g., switch from reactive to preventive maintenance, increased use of brine solutions); greater precision and skill in weather forecasting; expanded capability to communicate weather-related hazard information directly to the driving public (e.g., social media in general, weather or driving smartphone applications); certain aspects of vehicle design and associated owner behaviour (e.g., winter tire design and increased use, anti-lock or anti-slip breaking systems); and various social factors affecting trip demands (e.g., increased use of on-line shopping, telework) could all be contributing to the observed reduction in winter storm related collision risks.

Unpacking and explaining the absolute, relative, and interactive effects of these winter road safety interventions and other human behavioural factors will require researchers to move beyond traditional large-scale aggregate risk analyses of weather and collision variables. New or modified approaches are required which define and explain the impact of complete storm events, as described and applied in this paper, and account for weather-related variations in exposure (as discussed by Black and Mote 2015) during events. The latter might include direct measurement of traffic volume where such data are available, but could also be derived from activity participation levels, data documenting shifts to transit or other modes of travel, and inclusion of variables representing the presence, absence or extent of particular interventions (e.g., weather warnings, winter maintenance, winter tire use). Even with these additions, it will not be possible to fully disentangle the beneficial effects of past and potential interventions, whether related to infrastructure design, operation and maintenance, or modified behaviour. Taking a cue from health research, it may be fruitful to complement an epidemiological approach with a clinical focus on the individual—we could simply ask people what they do, and why they do what they do, when faced with winter storm hazards. In the analogous MVC case, this means examining intra-event features and space-time interactions that to date have received little attention in the road safety literature but are being applied and developed in other hazard contexts such as flash flooding (e.g., Ruin et al. 2014).

As with all studies, the findings of this analysis should be interpreted with consideration of the study design. A single North American city-region and subset of its road network were examined in the analysis, thus the reader is encouraged to consider issues of representativeness when extrapolating to other areas and driving contexts. While the matched-pair technique was used to control for variable traffic, it implicitly assumes that inclement weather does not reduce exposure during events and this likely leads to an underestimation of relative risk (*c.f.* Black and Mote 2015, Khattak and Knapp 2001).

2.7 Conclusions

Robust estimates of MVC risk associated with inclement weather are possible when two conditions are met: 1) The analysis uses a rigorous method for controlling non-weather factors, and 2) multiple data sources are used to characterize weather events. In this study, a matched-pair, retrospective cohort method was used to estimate injury and non-injury collision risk based on a new definition of winter storm events. This definition captured a greater portion of time during which drivers respond to hazardous weather and road surface conditions than in previous studies because of its detailed approach to characterizing conditions using multiple sources of weather information, including radar imagery and traditional surface station observations. These were combined in a unique manner to classify and characterize the variable-length storm events in terms of precipitation type and amount, visibility, temperature profile, location, and temporal factors.

Winter storms, whether involving snowfall or mixed precipitation, were found to significantly increase both injury and non-injury collision risk in RMW relative to dry, seasonal conditions. Storm definition criteria likely explain why collision risks were found to be greater in this analysis as compared to recent studies conducted over similar timeframes. Delayed awareness and response on the part of drivers, along with snow-clearing and de-icing practices of road maintenance authorities, were offered as plausible, but by no means certain, explanations for observed differences in relative collision risks across winter storm precipitation types and accumulation amounts.

An important contribution of the study is the insights it offers regarding the issuance of winter weather warnings. Official government weather watches and warnings were issued for just over one-half of the mixed precipitation events and about a quarter of the snowfall events examined in this study—up to 75 percent of impactful winter storm events, as defined in this analysis, go unwarned. This suggests authorities may wish to re-evaluate warning thresholds from an impact rather than purely meteorological perspective. Based on differences observed in relative injury collision risks, watches and warnings appear to influence driver behaviour in a positive manner during mixed precipitation events but not during snowfall events.

A second important contribution from this research is the insights offered on temporal trends in weather-related collisions. Results reveal a statistically significant decline in relative risk of injury and non-injury collisions during winter storms over the course of the study period—a disproportionately greater reduction than for collisions in general. Understanding why this is occurring, and then attributing improvements to specific winter road safety interventions and behavioural adjustments, is a key focus for future research and for informing future risk-mitigating investments. Advances in aggregate relative risk analyses, for example in better event definition classification and enhanced treatment of variable exposure as conducted in this study, will help fill this knowledge void. However, complementary research investigations at the intra-event level conducted to gain insight into small-scale interactions across space and time may hold even greater promise.

Chapter 3: Winter storms and fall-related injuries: Is it safer to walk than to drive?

Mills, B., J. Andrey, S. Doherty, B. Doberstein, and J. Yessis, 2020. Winter storms and fall-related injuries: Is it safer to walk than to drive? *Weather, Climate & Society*, 12(3):421-434. https://journals.ametsoc.org/doi/abs/10.1175/WCAS-D-19-0099.1.

3.1 Synthesis

Emergency department visitation data were analyzed using a matched-pair, retrospective cohort method to estimate the effects of winter storms on fall-related injury risks for a mid-sized urban community in Ontario, Canada. Using a unique definition and classification of winter storm events and dry-weather control periods, relative risks of injury were estimated for total falls and two subcategories (same-level falls involving ice and snow, all other falls) across two storm event types (snowfall-only, mixed precipitation). Winter storms were associated with 38 percent and 102 percent increases in the mean incidence of same-level falls involving ice and snow during snow events and freezing rain events, respectively. The incidence of other types of falls was slightly but significantly less during snow events relative to dry-weather control periods. Findings suggest that walking is not safer than driving during winter storms, as same-level falls involving ice and snow accounted for 64 percent more of the injury burden than motor vehicle collisions. Significant reductions in mean relative risk estimates for fall-related injuries were apparent over the 2009-2017 study period indicating possible long-term shifts in exposure, sensitivity, and/or risk-mitigating decisions, actions, and behaviour. Consistent and significant effects of government-issued weather warning communications on risk outcomes were not found. Practitioners engaged in developing injury prevention strategies and related public risk messaging, in particular winter weather warnings and advisories, should place additional emphasis on falls and multi-modal injury risks in communications related to winter storm hazards.

3.2 Introduction

Weather and climate affect many aspects of human health, whether directly, such as heat stress impacts induced by prolonged exposure to extreme temperature, or indirectly, for example by influencing the habitat and lifecycle of mosquitoes, ticks, and other infectious disease vectors

(Smith et al. 2014). Included among the more direct effects are fall-related injuries—slips and trips on wet and slippery surfaces that routinely occur to mobile people in pursuit of everyday activities.

Falls are the second-greatest source of unintentional death in the world with the highest fatality rates experienced in the wealthiest nations of Western Europe and North America (Peden et al. 2002). In Canada, unintentional falls accounted for over one million Emergency Department Visits (EDV) and 128,000 hospitalizations in 2010, placing tremendous demands on public health care systems, with direct annual costs reported to be in excess of CAD$6 billion (Parachute 2015). In 2014, there were about 13.7 fatalities attributed to falls per 100,000 Canadians, compared to 5.1 fatalities due to motor vehicle collisions (Parachute 2015, Transport Canada 2016). This difference suggests an answer to the question posed in the paper title and, more generally, supports calls to examine pedestrian falls that occur outdoors as an important complement to transportation safety and mobility studies focused on motor vehicle collisions (Elvik and Bjørnskau 2019, Methorst et al. 2017, Schepers et al. 2017).

Weather and climate are important environmental factors that affect the type and risk of injuries from falls. Researchers have examined the influence of particular storms or short periods of inclement weather, seasonal effects, and sub-seasonal scale impacts of weather or walking surface conditions. Studies have generally focused on one or more combinations of vulnerable populations (most often elderly cohorts), higher-risk occupations (e.g., mining, disaster response and recovery), and particular types of injuries (e.g., hip or wrist fractures). Most research has been completed in Europe and North America using a range of qualitative (e.g., focus groups, Nyman et al. 2013) and quantitative methods (see Schepers et al. (2017) for a thorough review). Quantitative studies have relied on self-reports and/or a variety of medical records (e.g., hospital admissions, emergency room visitations, other healthcare service use, insurance claim information) to develop descriptive statistical accounts, conduct retrospective analyses, or to establish prospective study samples.

Several researchers have documented the incidence of injury during or immediately following individual winter storm events, either in absolute terms (e.g., Smith and Nelson 1998) or in comparison to periods void of significant weather but consistent in other respects to the event (e.g., same duration, time of year, days of the week, etc.) (Avery 1982, Marshall et al. 2016, Ràliš 1981, Ràliš et al. 1988, Stansbury et al. 1995). The number of injuries during an ice or snow event is generally several times greater than a corresponding fine-weather period, although results vary by the type of injury (Stansbury et al. 1995). Many studies have observed that fall-related injuries, most commonly hip or wrist fractures, increase during the winter season or in colder relative to warmer regions of specific countries (Arnold et al. 2016, Bamzar and Ceccato 2015, Bulajic-Kopjar 2000, Chiu et al. 1996, Crawford and Parker 2003, Elvik and Bjørnskau 2019, Gyllencreutz et al. 2015, Hagino et al. 2004, Hemenway and Colditz 1990, Jacobsen et al. 1999, Lauritzen et al. 1993, Levy et al. 1995). While activities unique to winter, such as removing snow from roofs (Bylund et al. 2016, Pipas et al. 2002), have been shown to lead to falls, these account for only a small fraction of the seasonal burden. Greater incidence of injury in winter has also been found in occupational studies focused on construction (Lipscomb et al. 2006) and mail delivery (Bentley and Haslam 2001).

Most pertinent to the current study is literature that examined relationships between fall-related injuries and weather, or walking-surface conditions, at sub-seasonal scales over longer periods of time that include many weather events. Retrospective studies have compared the presence or absence of hazardous weather conditions during days with a high prevalence of falls relative to other days (e.g., Gevitz et al. 2017). Most investigations, however, relate daily to weekly fall or fracture incident counts or rates to one or more independent weather variables, such as temperature, snowfall, freezing rain, rainfall, wind speed, and day length (e.g., Bell et al. 2000, Bobb et al. 2017, Hajat et al. 2016, Hassi et al. 2000, Levy et al. 1998, Luukinen et al. 1996, Mondor et al. 2015, Morency et al. 2012, Murray et al. 2011). Exposure-related factors (e.g., location, day of week, month, year, self-reported walking distance) and socio-demographic variables (e.g., age, sex) have been controlled to varying extents in these studies. Analytical methods have ranged widely from descriptive statistics (e.g., Berggård and Johansson 2010) to non-linear time series modelling (e.g., Modarres et al. 2014) with each study adopting somewhat unique geographic boundaries, location, data sources, fall inclusion definitions, and sets of meteorological parameters. Despite these differences, common findings regarding precipitation effects are apparent:

- Most studies report increases in fall-related injuries associated with snowfall (generally less than 50 percent);

- Snowfall effects on injury counts are often lagged by one to several days following precipitation;
- Elderly (≥ 65yrs) and younger (school-age children) cohorts seem much less affected by precipitation events with researchers generally attributing this to exposure factors (e.g., ability to avoid travel in severe conditions, instituted school closures);
- Freezing rain or rain followed by dropping temperatures appear to have greater (up to 300 percent increase) and more immediate impacts on falls; and
- Risk of falls tends to rise as weather severity increases, except for snow events where risk levels taper off once accumulations become very large.

Weather warnings have the potential to affect related outcomes. While not normally considered in analyses of falls, two studies made novel use of government-issued weather warnings as a proxy indicator for injury-causing meteorological hazards to examine their association with fall-related injuries. Murray et al. (2011) found that severe weather warnings for icy roads issued by the UK Met Office for Edinburgh, Scotland were associated with a 40 percent increase in fractures (95% confidence limits, 20–52%). Mondor et al. (2015) conducted a study of a large elderly (≥ 65 yrs) cohort in Montreal, Canada over a nine-year period (1998-2006) to evaluate the association between fall-related injury incident rates and public warnings issued by the federal government (Environment Canada) for freezing rain and snowstorms. They observed a significant rise in injury Incident Rate Ratios (IRR) on days when freezing rain warnings were issued (IRR 1.20; 95% CI: 1.08, 1.33) and a significant decrease on days with snowstorm warnings (IRR 0.89; 95% CI: 0.80, 0.99) relative to days during the winter season without warnings. Except for the immediate day following freezing rain warnings, injury rates stayed significantly higher for up to five days after events had ended (Mondor et al. 2015).

Both of these investigations failed to acknowledge the potential role of weather warnings as an intervention of information that could directly or indirectly affect exposure, and other risk-mitigating behaviour. Risk was evaluated by comparing injuries or incidence rates during days with warnings against all days in the study period without warnings. The research did not appear to control for the occurrence of conditions that did not meet the threshold for the issuance of a weather warning but were still capable of influencing injury incidents; as a result, relative increases in injury incidence may actually be higher than reported. While potential effects of festive seasons were addressed by Murray et al. (2011), no other measures to control for variation in exposure caused by human factors were evident.

More generally, none of the studies identified in the literature review reported on long-term shifts in weather-related injury risk from falls that might be expected due to improvements in healthcare, outdoor walkway construction and maintenance technology, and safety measures. As well, no analyses examined or accounted for sub-daily scale effects of weather on injury occurrence. This may be particularly important as the same storm, measured by daily precipitation accumulation, will present a different risk depending on whether the timing of heavy snowfall, freezing rain, and associated hazardous conditions are coincident with activity patterns that lead to exposure (e.g., overnight storm with walkways cleared, salted and gritted before morning rush hour). As well, storms that occur over multiple days may not be properly discretized and accounted for as they may be recorded as separate events with smaller accumulations when in fact they are experienced by the public as a single, continuous and cumulative event.

This paper aims to address these shortcomings by applying a unique definition and classification of winter storm events and dry-weather control periods in a matched-pair design developed originally for an analysis of motor vehicle collision risk (Mills et al. 2019). In addition to providing a robust estimate of fall-related injury risk, the study facilitates comparisons of injury risks associated with winter storms across two primary modes of transportation—walking and automobile.

3.3 Study area, data and methods

3.3.1 Study area

The study area is a Canadian mid-sized community located about 100 km west of Toronto, Canada. It consists of the Cities of Cambridge, Kitchener, and Waterloo that together form the continuous urban core of the Regional Municipality of Waterloo (RMW). The approximately 525,000 people inhabiting the study area (RMW 2017) experience a continental climate modified in all seasons by the Great Lakes. Frequent synoptic weather systems producing snow and mixed precipitation events of varying intensities and durations affect the study area, thus making it an attractive place to study the effects of winter storms on injury risk. As shown in

Figure 3-1, below-freezing temperatures are typically observed from November through April with measurable snowfalls (≥ 0.2cm) recorded about 61 days each winter (ECCC 2018). Over the November 2009 to March 2017 study period, 74 warnings for severe winter weather in the forecast region were issued by Environment and Climate Change Canada (ECCC), including those for freezing rain (34), snowqualls (20), snowfall (12), winter storms (4), blowing snow (2), blizzards (1), and flash freezes (1).

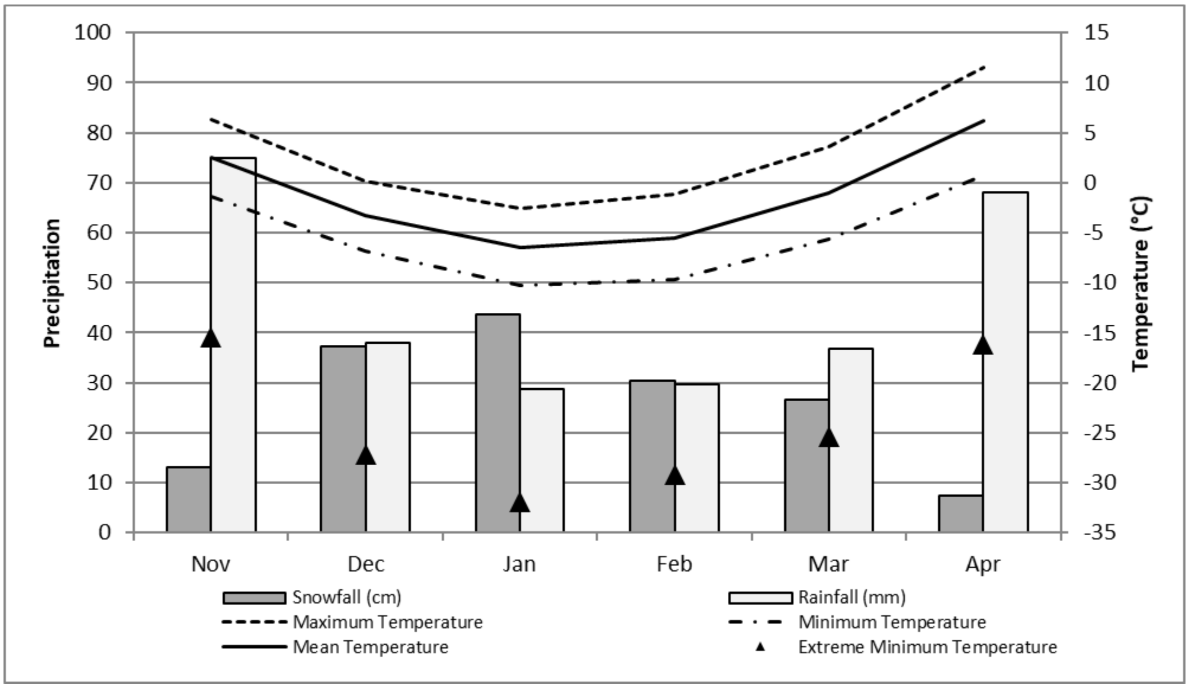


Figure 3-1. Average daily climatic conditions (1981–2000) during the winter season for the Region of Waterloo International Airport (ECCC 2018).

3.3.2 Data

Emergency Department Visitation (EDV) records

Disaggregated EDV data were obtained for the period April 2009 through March 2017 through the Canadian Institute for Health Information (CIHI). Records were drawn from the National Ambulatory Care Reporting System (NACRS) for all patients residing in Cambridge, Kitchener and Waterloo postal Forward Sortation Areas (FSAs) and presenting to a hospital emergency department with a fall-related injury problem, as defined in the International Classification of Diseases ICD-10-CA. EDV data were sorted into two subsets: 1) Falls on the same level involving ice and snow (ICD-10 code W00), and 2) All other types of falls (ICD-10 codes W01-W19). Lacking comprehensive information on the specific location where victims were injured, this distinction was made to isolate the subset of falls that were expected to be most sensitive to hazardous winter weather conditions (W00 Falls on the same level involving ice and snow). The second data subset is composed of all other falls, including those that would be expected to occur primarily indoors (e.g., W06 Fall involving bed), either indoors or outdoors (e.g., W11 Fall on and from ladder), outdoors but with little direct connection to hazardous winter weather (e.g., W02 Fall involving skates, skis, sport boards and in-line skates) and where the activity or situation was unspecified (W19).

As presented in Table 3-1, over 44,500 EDVs for fall-related injuries spread over eight winter seasons (November-April) were included in the final dataset. Falls involving ice and snow peaked in January, when they accounted for over 22 percent of all fall-related EDVs, and were most prevalent during the morning, whereas visits for other types of falls were greatest during the late afternoon and early evening hours.

Table 3-1. Fall-related Emergency Department Visitation (EDV) counts by season.

WINTER SEASON (NDJFMA)	Types of Fall-related EDV		
	Same-level involving ice and snow (W00*)	**All other falls(W01-W19*)**	**Total falls**
2009-2010	565	4684	5249
2010-2011	756	4732	5488
2011-2012	624	4856	5480
2012-2013	722	4663	5385
2013-2014	1078	4775	5853
2014-2015	797	4712	5509
2015-2016	613	5225	5838
2016-2017**	997	4757	5754
TOTAL	6152	38404	44556

* International Classification of Diseases and Related Health Problems Codes, 10th Revision, Canada (ICD-10-CA) for falls
**only includes period up to March 31, 2017

Weather condition data

Mills et al. (2019:189) provide a detailed description of the information sources used to define and characterize variable-length winter storm events and corresponding control periods. A combination of temperature, precipitation, and visibility data from two weather radar stations and four surface observation sites, supplemented with weather and road condition information from motor vehicle collision records, covering the period 2009-2017 were obtained from Environment and Climate Change Canada, Grand River Conservation Authority, and the RMW. These sources were used to characterize winter precipitation events by type (e.g., snow, mixed precipitation), amount of precipitation, thermal environment, and presence of government-issued weather watch and warning bulletins. Weather radar imagery was the primary source of information for determining the selection of winter storm events and controls. When precipitation was observed, the following criteria were used to assign each hour into one of three classes of coverage within the RMW:

- Class 1. Precipitation observed to be just entering RMW, restricted to a very small part of the Region, or consisting of widely scattered precipitation of low intensity (<0.5 cm/h)
- Class 2. Precipitation observed to affect two of the main cities (Cambridge, Kitchener, Waterloo)
- Class 3. Precipitation observed over most of RMW and all three main cities

3.4 Approach and method

A matched-pair, retrospective cohort method, as detailed in Mills et al. (2019), was applied to estimate fall-related injury risk during winter storm events for the study area. An event was defined as a period of time during which a winter storm occurs and was paired with a dry-weather control matched by duration, hour, and day-of-week, either one week prior to or one week following the event. Matching periods allowed for some control of non-weather influences on exposure that exhibit regular patterns (e.g., work and recreational activities, trip routines) and are often difficult to measure directly or representatively across a large area or population. Criteria used to determine events and assign controls are elaborated in Table 3-2 below. For the purpose of the analysis, winter storms were not restricted to the criteria used to issue official ECCC warnings[2], but rather included a broader set of events consisting of at least some winter precipitation.

[2] For criteria, see: https://www.canada.ca/en/environment-climate-change/services/types-weather-forecasts-use/public/criteria-alerts.html#winterStorm

Table 3-2. Criteria used to define winter precipitation (storm) events and corresponding control periods.

Event Criteria	Controls
Duration and Coverage • >= 8 consecutive hours of radar-indicated precipitation of any coverage level (1,2,or 3); up to 1 precipitation-free hour permitted in sequence, but total hours of precipitation must be 8 or more (i.e., 9 hour event consists of 8 hours of precipitation and a 1 hour break) • event must include at least 4 hours of radar-indicated precipitation of coverage level 2 or 3 • event must include at least 1 hour of radar-indicated precipitation of coverage level 3 Precipitation Type • event must include confirmed hours of observed winter precipitation (S-snow, ZR-freezing rain/ZL-drizzle, IP-ice pellets) from collision data (S, ZR), hourly ECCC station observations (S,ZR,ZL, IP), and/or daily snowfall totals Capture of storm and post-precipitation effects • the hour before the precipitation commences is added to the event (to ensure capture of event start) • 3 consecutive precipitation-free hours following the last precipitation hour are added to event (to account for sidewalk, drive or other walking surface condition lag)	Selection Process • Each hour within a defined event is matched to an hour exactly 1 week before and after the event hour • Only 1 control hour is selected for analysis. Preference is given to 'before' control period if both pass criteria test below (assumption is that the 'before' period is less influenced by the event being evaluated) Precipitation Criteria • no radar-indicated precipitation coverage at any level (1,2,3) • no collision reports of precipitation (rain, snow, freezing rain, blowing/drifting snow) • no daily snowfall reported • no collision reports of wet or snowy/icy road surface conditions Exposure Criteria • no hours that are allocated to a storm event • no hours on a statutory holiday • no Environment and Climate Change Canada weather watch or warning in effect

Estimates of risk were based on odds ratios—the ratio of the probability of a fall-related injury happening during the event condition (i.e., a winter storm) relative to the probability of a fall-related injury occurring during the control condition (i.e., dry weather). The method is congruous with underlying theory established by Fleiss (1973:110-111). Mills et al. (2011) note that each event-control pair produces four counts: A (injuries during the event period), B (injuries during the control period), C (an estimate of the number of safe outcomes during the event period), and D (an estimate of the number of safe outcomes during the control period). The odds ratio, *OR*, is calculated as below (Bland and Altman 2000):

$$OR = \left(\frac{A/C}{B/D} \right) \quad (1)$$

As thousands of safely negotiated walking motions or pedestrian trips occur every hour in large urban centres like the study region, C and D are very large and, for this investigation, were set at 50,000 minus recorded event or control injuries. This level of exposure was derived from a rounded-down survey-based estimate of average daily walking trips made by Regional Municipality of Waterloo residents in 2016 (Region of Waterloo 2019). Sensitivity analysis revealed minimal differences (less than 1 percent) in final relative risk estimates using exposure values ranging from 1,000 to 100,000. Lacking access to continuous trip count (or time or distance walked) data during specific winter storms, exposure was kept constant for both event and control periods. The implications of this decision are discussed later in the paper.

A log transformation of the sample odds ratio was conducted to ensure that the predictions were approximately normally distributed. A statistical weight for each event-control pair, w_i, based on a fixed-effects model for combining estimates of risk (verified as per Johansson et al. 2009:812), was calculated by taking the inverse of its variance, v_i , as shown in equations 2-3.

$$w_i = \frac{1}{v_i} \qquad (2)$$

where:

$$v_i = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D} \qquad (3)$$

The weighted mean effect on a set of g event-control pairs, $\bar{Y}$, was calculated as shown in equation (4) where y_i is the log of the OR. By taking the antilog of this value, an overall estimate of relative risk was obtained. The standard error (SE) of the risk estimate (equation 5) is used to calculate 95% confidence intervals for the weighted mean effect.

$$\bar{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i} \right) \qquad (4)$$

$$SE = \frac{1}{\sqrt{\sum_{i=1}^{g} w_i}} \qquad (5)$$

This procedure was followed to obtain estimates of injury risk for three general sets of winter storm events (all storm events, snowfall only, mixed precipitation) and three fall categories:

1. Emergency Department Visits for *any type of fall* ($EDVF_{TOTAL}$)
2. Emergency Department Visits for *falls occurring on the same level involving ice and snow* ($EDVF_{IS}$); and
3. Emergency Department Visits for *all other types of falls* ($EDVF_{OTHER}$).

Where samples were sufficiently large, relative risks were also tabulated separately for the subset of mixed events that involved freezing rain.

3.5 Results

Throughout the remainder of the paper, relative risks (RR) are reported in two primary ways: 1) as a mean estimate accompanied by 95 percent confidence intervals (e.g., RR 1.50; 95% CI:1.20,1.80), or 2) as a relative mean increase or decrease in fall-related injuries (e.g., 50 percent more). The analysis included 145 variable-length winter storm events that ranged from 12 to 80 hours in duration. Suitable controls for all hours were confirmed for 59 of these events with the remaining 86 having at least half of their event hours matched with acceptable controls. This lower 50 percent threshold was adopted to ensure a sufficiently large dataset of event-control pairs and injury incidents for disaggregated analysis. A sensitivity analysis confirmed that the effects of this decision on relative risk (RR) estimates were minimal.

3.5.1 Overall relative risk of injury

Modest increases in $EDVF_{TOTAL}$ were found during winter storms (RR 1.06; 95% CI:1.01, 1.10). In other words, one may expect between one and 10 percent more injuries to occur during winter storms as defined in this study than during comparable but dry weather conditions. The added risk was entirely attributable to more frequent same-level falls involving ice and snow ($EDVF_{IS}$) (RR 1.50; 95% CI:1.34, 1.68), where the increased incidence rate is much higher. Indeed a reduction in EDV was observed for other forms of falls ($EDVF_{OTHER}$), several of which occur indoors (RR 0.95; 95% CI:0.91, 1.00).

3.5.2 Precipitation type

Contrasting effects on fall-related injury risk were observed for events consisting entirely of snowfall (i.e., snow events) as compared to those involving mixed precipitation (i.e., snowfall and one or more of rainfall, freezing rain, or ice pellets; freezing rain alone or in combination with rainfall or ice pellets). For same-level falls involving ice and snow ($EDVF_{IS}$), snow events produced a smaller increase in risk (RR 1.38; 95% CI: 1.18, 1.61) than mixed precipitation events as a whole (RR 1.65; 95% CI:1.40, 1.96). This difference was statistically significant for the subset of mixed events that involved freezing rain (RR 2.02; 95% CI: 1.64, 2.53). No appreciable difference in relative risk for other types of fall-related injuries ($EDVF_{OTHER}$) was observed for mixed precipitation events, however, snow events were associated with significantly lower risks (RR 0.91; 95% CI:0.86, 0.98) than during comparable dry-weather control periods.

3.5.3 Precipitation amount

Four classes of storm event accumulation, estimated in millimetres (mm) of liquid-equivalent precipitation, were evaluated. Actual snow-to-liquid ratios can vary by storm type and temperature (3:1 to over 25:1) but are typically assumed to be 10:1 (1 cm or 10 mm of snow equals 1 mm liquid water) where the specific liquid water content of frozen precipitation is not directly measured (Baxter et al. 2005). As indicated in Table 3-3, $EDVF_{IS}$ mean risk estimates increased with precipitation amount, although there was notable overlap in confidence intervals across all categories. Very light events (≤ 2mm) exhibited minimal differences in $EDVF_{IS}$ as compared to dry-weather control conditions. No significant increase or decrease in relative risk was observed for $EDVF_{OTHER}$ for any accumulation class.

Table 3-3. Relative risk of falls on the same level involving ice and snow ($EDVF_{IS}$) during all winter storms.

Estimated Event Precipitation (P) Amount*	**Event-Control Pairs (n)**	**Mean Relative Risk Estimate (95% Confidence Intervals)**
P ≤ 2mm	23	1.26 (0.85-1.88)
2mm < P < 5mm	50	1.29 (1.02-1.65)
5mm ≤ P < 15mm)	44	1.57 (1.29-1.89)
P ≥ 15mm	28	1.66 (1.36-2.04)

*expressed as liquid-equivalent

In order to compare results by event precipitation type while maintaining sufficient sample size, accumulation thresholds were chosen to split each sample into roughly equal groups, 5 mm for snowfall events and 10 mm for mixed events. Modest (30-45 percent) mean increases in $EDVF_{IS}$ were observed during snowfall events whether above or below 5 mm liquid-equivalent accumulation. Significantly greater $EDVF_{IS}$ were found during mixed events with 10 mm or more precipitation (RR 2.17; 95% CI:1.77, 2.67) compared to those with less than 10 mm (RR 0.93; 95% CI:0.69, 1.26). For all other types of falls ($EDVF_{OTHER}$), only risks during snow events with less than 5 mm precipitation were significant, with a mean estimated reduction of 10 percent (RR 0.90; 95% CI:0.82, 0.98).

3.5.4 Temperature effects

Mean event temperatures (T_{avg}) were used to distinguish two groups each for snowfall events (warm, T_{avg} > -5.5°C; cold, T_{avg} ≤ -5.5°C) and mixed precipitation events (warm, T_{avg} > 0°C; cold, T_{avg} ≤ 0°C). Temperature thresholds were set to maintain similar event sample sizes in each grouping. Mean estimates for same-level falls involving ice and snow during cold snowfall events (RR 1.23; 95% CI:1.00, 1.52) were much lower than for warm snowfalls (RR 1. 60; 95% CI:1.26, 2.03) but again considerable overlap was observed in confidence intervals. Results for the two mixed precipitation groups were almost identical. For all other types of falls ($EDVF_{OTHER}$), modest reductions in risks were found during warm snowfall events (RR 0.90; 95% CI:0.82, 0.98). Otherwise fall risks did not vary significantly for other temperature classes and event types.

3.5.5 Temporal and spatial variation

Relative risks of injury during winter storms were calculated to assess long-term trends, subseasonal patterns, day-of-week variations, and differences across the three cities. Mean estimates of relative risk for $EDVF_{IS}$ fell over the course of the 2009-17 study period (Figure 3-2) while risks for $EDVF_{OTHER}$ showed no consistent pattern. Linear trends in mean relative risk estimates for $EDVF_{IS}$ (p =*.021*) and $EDVF_{TOTAL}$ (p =.018) were significant. No significant trends in $EDVF_{IS}$ were observed for snow or mixed events when analyzed separately.

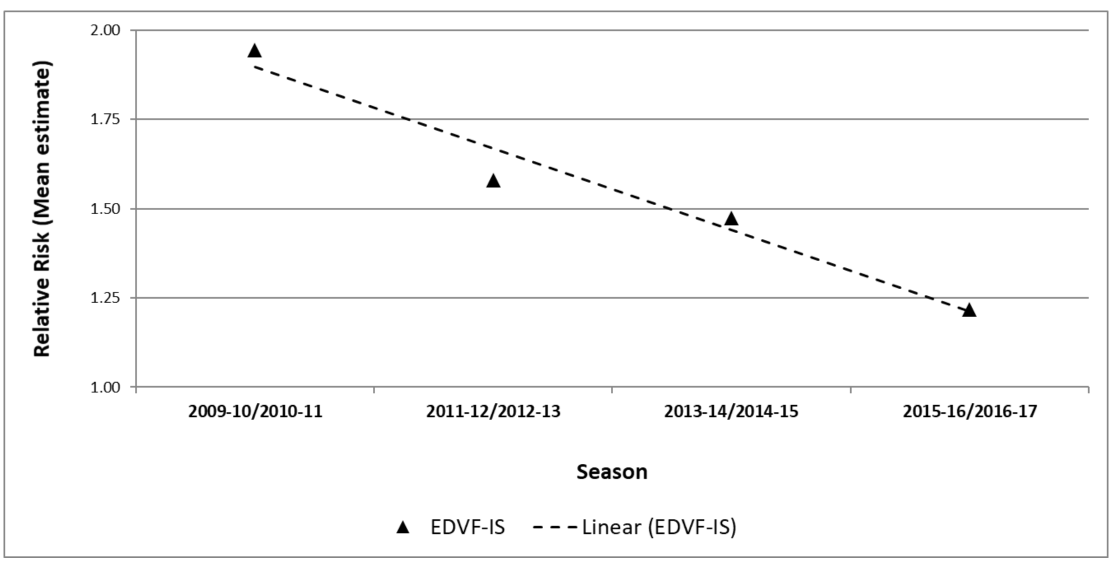


Figure 3-2. Two-season mean risk estimates for same-level falls involving ice and snow (EDVFIS).

Monthly fall risks were grouped into early winter (December-January), late winter (February-March) and shoulder (November, April) months to evaluate within-season variations. Mean risk estimates for same-level falls involving ice and snow ($EDVF_{IS}$) peaked during winter storms that occurred in the shoulder months (RR 2.83; 95% CI:1.77, 4.53). $EDVF_{IS}$ risks lowered steadily through the early winter months of December-January (RR 1.65; 95% CI:1.40, 1.94) and late winter months of February-March (RR 1.24; 95% CI:1.05, 1.48). The reduction in other types of falls ($EDVF_{OTHER}$) was most prominent in early winter (RR 0.93; 95% CI:0.87, 1.00).

Minor differences were apparent by day-of-week and city. $EDVF_{IS}$ risks increased by 40 percent during winter storm events that occurred during weekday hours and by 65 percent for events that involved any weekend hours. A comparison of the three cities showed that $EDVF_{IS}$ mean risk estimates for Kitchener (1.60) were higher than either Cambridge (1.34) or Waterloo (1.36), but the CIs showed considerable overlap. Reductions in $EDVF_{OTHER}$ during winter storms were significant in Cambridge (RR 0.89; 95% CI:0.82, 0.97) but not for the other cities.

3.5.6 Socio-demographic factors

The CIHI NACRS EDV data included information about the gender and age of patients, and analyses were undertaken to discern any implications for relative injury risks. Modest differences were observed across gender, with higher $EDVF_{IS}$ relative risks for females as compared to males during winter storms involving mixed precipitation. $EDVF_{OTHER}$ risks for females were consistently less than 1.0 during winter storms relative to dry weather controls. In terms of age, little variation in $EDVF_{IS}$ or $EDVF_{OTHER}$ risk was observed between the 18-54 and over 55 groups (Table 3-4). The youngest cohort (less than 18 years old) experienced lower risks than older cohorts in every injury category, with $EDVF_{OTHER}$ slightly but significantly less during winter storms than corresponding controls (RR 0.89; 95% CI:0.81, 0.97).

Table 3-4. Relative risk of Emergency Department Visits for Falls (EDVF) during winter storm events for different age cohorts.

Age Cohort	**Mean Relative Risk Estimate (95% Confidence Intervals)**	
	$EDVF_{IS}$	$EDVF_{OTHER}$
< 18 years	1.11 (0.87-1.42)	0.89 (0.81-0.97)
18-54 years	1.54 (1.31-1.81)	1.00 (0.93-1.09)
≥ 55 years	1.54 (1.27-1.86)	0.96 (0.89-1.04)

3.5.7 Lag impacts

As noted in previous research, fall-contributing snow and ice conditions on walking surfaces may endure for extended periods beyond a winter storm, even considering the three-hour lag built into the standard storm event definition criteria (Table 3-2). The analysis process described for winter storms was repeated for 6, 12, 24 and 48 hour lag periods immediately following the last event hour. Controls were obtained to match the lag-event periods by hour and day-of-week either one week prior to or following the event. Since the authors were less interested in extensive disaggregation of results and wanted the option of comparing individual event and event-lag risks, only events that had 90 percent or greater hours with matching controls were examined for lag effects. This provided 76 lag event-control pairs for analysis.

The net effect on risk for all falls ($EDVF_{TOTAL}$) was negligible for all four lag periods evaluated relative to dry control periods. Table 3-5 compares relative risks during winter storm events and the first and second 24-hour lag periods, Day 1 and Day 2, respectively, across each of the fall injury groups and storm types. Mean lag $EDVF_{IS}$ risk estimates for “all events” and the mixed precipitation subset remained elevated on Day 1 but were consistently lower than those observed during winter storms. While the mean $EDVF_{IS}$ risk estimate remained above 1.0, no significant lag effect was found for snowfall events. For all other types of falls ($EDVF_{OTHER}$) the opposite was observed, with significantly reduced risks estimated during Day 1 lag periods following snowfall events but no appreciable effect following mixed precipitation events. Day 2 results indicated no meaningful difference between 25-48 hour lag periods and corresponding dry weather controls.

Table 3-5. Relative risk of Emergency Department Visits for Falls (EDVF) during lag periods immediately following winter storm events.

Lag Period	**Mean Relative Risk Estimate (95% Confidence Intervals)***		
	$EDVF_{IS}$	$EDVF_{OTHER}$	$EDVF_{TOTAL}$
Winter Storm Events (0 lag) **(≥ 90 % valid E-C pairs)**			
All Event Types (n=76)	***1.73 (1.49-2.02)***	***0.92 (0.87-0.98)***	***1.05 (1.00-1.11)***
Snowfall Events (n=47)	***1.50 (1.22-1.84)***	***0.89 (0.82-0.97)***	0.98 (0.91-1.06)
Mixed Precipitation Events (n=29)	***2.07 (1.65-2.60)***	0.96 (0.88-1.04)	***1.14 (1.05-1.23)***
Day 1 Lag (Hours 1-24)			
All Event Types (n=76)	***1.38 (1.15-1.64)***	***0.93 (0.87-0.99)***	0.99 (0.93-1.05)
Snowfall Events (n=47)	1.20 (0.95-1.50)	***0.91 (0.84-0.99)***	0.96 (0.89-1.03)
Mixed Precipitation Events (n=29)	***1.72 (1.29-2.29)***	0.95 (0.85-1.06)	1.04 (0.94-1.15)
Day 2 Lag (Hours 25-48)			
All Event Types (n=76)	1.05 (0.85-1.29)	1.00 (0.93-1.08)	1.01 (0.94-1.08)
Snowfall Events (n=47)	0.95 (0.73-1.24)	1.00 (0.91-1.11)	1.01 (0.92-1.10)
Mixed Precipitation Events (n=29)	1.23 (0.88-1.71)	1.00 (0.89-1.12)	1.01 (0.91-1.13)

*results significantly greater or less than 1.0 are italicized and bolded

3.5.8 Impact of weather watches and warnings

As mentioned in the introduction, government-issued communications about expected (watch bulletins) and imminent or occurring (warning bulletins) severe winter weather have been used in previous research as proxy indicators of dangerous, impactful events. The effects of these communications were evaluated in this study by comparing relative risks in events for which a watch or warning was in place during any hour with those for events during which no bulletin was activated. Substantive differences were observed only for same-level falls involving ice and snow ($EDVF_{IS}$). As shown in Table 3-6, mean relative risk estimates were about 40 percent lower during snow events and about 20 percent higher during mixed events for which watches or warnings were issued as compared to events lacking such bulletins. It is noted that the sample of snow events with watches or warnings is rather small.

Table 3-6. Relative risk of falls on the same level involving ice and snow ($EDVF_{IS}$) during winter storms differentiated by precipitation type and presence of weather watch or warning.

Winter Storm (Precipitation Type/Presence of Watch or Warning)	**Event-Control Pairs (n)**	**Mean $EDVF_{IS}$ Relative Risk Estimate (95% Confidence Intervals)**
All Events	145	1.50 (1.34-1.68)
No Watch or Warning Issued	99	1.53 (1.32-1.77)
Watch or Warning Issued	46	1.46 (1.22-1.75)
Snowfall Events	84	1.38 (1.18-1.61)
No Watch or Warning Issued	65	1.51 (1.25-1.82)
Watch or Warning Issued	19	1.12 (0.84-1.49)
Mixed Precipitation Events	61	1.65 (1.40-1.96)
No Watch or Warning Issued	34	1.56 (1.22-1.99)
Watch or Warning Issued	27	1.75 (1.38-2.21)

3.5.9 Comparisons with motor vehicle collision injury risks

Mills et al. (2019) describe a parallel analysis of injury and property-damage-only motor vehicle collisions (MVCs) during winter storms. The collision data from that study were used to extract injury counts for an overlapping timeframe (2009-2016) and common set of 96 winter storm events and control periods. This facilitated a direct comparison and union of relative injury risks and absolute outcomes for two dominant modes of mobility in the Region. Results presented in Table 3-7 indicate that winter storms involving any type of precipitation present higher relative risks of injury for falls on the same level involving ice and snow ($EDVF_{IS}$) than for injuries associated with motor vehicle collisions. Differences were greatest for mixed precipitation storms involving either freezing rain or with accumulations of 10mm or more, with $EDVF_{IS}$ increasing by 108 and 139 percent, and MVC by 43 and 45 percent, respectively, during the same set of winter storms. In absolute terms, $EDVF_{IS}$ and MVC accounted for 62 and 38 percent of the total injury burden attributable to winter storms, respectively.

Combining the two sets of weather-sensitive injuries provides a multi-modal estimate of mobility-related winter storm injury risks (RR 1.59; 95%CI:1.43, 1.76). As expected, mixed precipitation storms (RR 1.79; 95%CI:1.54,2.09) were more problematic than storms involving only snowfall (RR 1.43;95% CI:1.24, 1.65).

Table 3-7. Relative risks of motor vehicle injuries and falls on the same level involving ice and snow ($EDVF_{IS}$) during winter storms differentiated by precipitation type (2009-2016).

Event Type	**Motor Vehicle Collision Injuries (MVC)***		**Same-level falls on ice and snow ($EDVF_{IS}$)**	
	Event/Control Injuries	**Relative Risk Estimate (95% CIs)**	**Event/Control Injuries**	**Relative Risk Estimate (95% CIs)**
All Event Types (n=96)	Event = 504 Control = 342	1.37 (1.18-1.58)	Event = 590 Control = 297	1.61 (1.38-1.87)
Snowfall (n=56)	Event = 242 Control = 178	1.27 (1.03-1.57)	Event = 283 Control = 178	1.44 (1.17-1.76)
Mixed Precipitation (n=40)	Event = 262 Control = 164	1.46 (1.19-1.80)	Event = 307 Control = 109	1.86 (1.47-2.37)

*Data obtained from Mills et al. (2019)

3.6 Discussion

The study provides the first comparable city-wide estimates of fall and motor vehicle injury collision risk associated with variable-length winter storms. Winter storms, as defined in this investigation, were found to significantly increase the incidence of EDV for same-level falls involving ice and snow. Common sense alone suggests that such falls should occur more frequently as snow and/or mixed precipitation coats surfaces, compacts or freezes, becomes very slippery, and therefore presents challenges to pedestrians. The greater risks estimated for mixed precipitation events than for storms consisting only of snowfall are consistent with previous research that associates slipperiness with surface temperatures near 0°C (Andersson and Chapman 2011). Snowfall at colder temperatures requires considerable mechanical packing (i.e., through foot or vehicular traffic) and/or warming to become slippery—conditions that may not always materialize before routine winter maintenance removes accumulated snow from walkways, streets, and parking areas and applies salt or sand to improve traction. This reasoning may also serve to explain in part why lag effects for same-level falls on ice and snow were weak to non-existent for snowfall events and observed to only last for the first 24 hours following mixed precipitation winter storms. Mixed precipitation, especially events with freezing rain or falling temperatures, leads to ice accumulations that are likely more difficult to physically or chemically remove than snowfall. In most cases, however, these are likely mitigated within a day in regions like the study area that have considerable resources dedicated to winter maintenance and municipal by-laws setting minimum standards for sidewalk clearance (e.g., City of Waterloo 2009).

The study results suggest that same-level falls involving ice and snow likely contribute more to the total winter storm related injury burden than motor vehicle collisions. Estimated risk of same-level falls involving ice and snow during winter storms was 24 percent higher than for injuries associated with motor vehicle collisions relative to dry-weather control periods. Because identical sets of event and control periods were used in both analyses, it was also possible to compare absolute effects and combine counts to develop an integrated injury risk estimate. Same-level falls on ice and snow accounted for 64 percent more of the injury burden attributable to winter storms than motor vehicle collision injuries over the 96 storms examined. Slight variations in minimum injury severity definitions (e.g., ED fall injury definition is more strict) and jurisdictional coverage (e.g., MVC data includes townships surrounding cities) result in a net underrepresentation of falls relative to MVC injuries, thus the importance of winter storms on falls noted in this paper is likely conservative. Therefore, returning to the title of this paper and within the confines of this particular study, driving appears to be a safer mode of travel than walking during winter storms. Although this finding demands additional research (e.g., injury severity and exposure aspects) and corroboration from studies in other locations, it supports greater consideration of pedestrian injuries when developing and evaluating policies to promote active transportation in winter cities. This includes greater investment in actions to reduce fall-related injuries during winter storms, such as improvements to winter maintenance servicing of sidewalks, paths, or walkways. More generally, it calls for an integrated look at transportation safety that extends beyond motorized vehicle-pedestrian interactions that comprise much of the literature. Towards this end, combining MVC and fall injury data into an aggregate analysis allowed the authors to provide a more complete picture of mobility-related injury risk during winter storms (59 percent increase in injuries) thereby addressing a need raised by the transportation safety research community (e.g., Methorst et al. 2017, Schepers et al. 2017).

While this study adds further evidence demonstrating that winter storms lead to increased risk of injury, both from falls and motor vehicle collisions, it also uncovered features that suggest these risks are variable and dynamic. Several stratified analyses were used to attempt to identify patterns or changes in risk that might be linked to societal factors including intentional interventions to influence exposure or sensitivity to winter weather hazards. A statistically significant linear downward trend of about 10 percent per season was observed in relative winter storm risk for same-level falls on ice and snow. No such trend was found for other types of falls. However, Mills et al. (2019) observed a similar trend over a longer timeframe (2002-16) for motor vehicle injury collisions, though at roughly one-fifth the rate estimated for $EDVF_{IS}$ in the current analysis. No obvious explanation for the trend in $EDVF_{IS}$ injuries was apparent to the authors, but some combination of shifts in activity patterns, decisions to seek treatment, emergency response and advances in medicine, awareness and protective actions on the part of the public, improvements in winter maintenance practices or transportation infrastructure might be interacting to produce a safer environment as indicated by better injury outcomes. The lack of significant trends in relative risk for either snowfall or mixed precipitation events, when analyzed separately, suggest a more complex interactive effect that requires a longer study timeframe in order to be resolved.

Variation in risk was evident at shorter timescales as well, with same-level falls involving ice and snow up to 183 percent greater during the shoulder season months of November and April as compared with 65 percent during early winter (December-January) and 24 percent in late winter (February-March) months. This finding lends support to the theory that pedestrians, much like drivers, take greater precautions to reduce their risks as they once again encounter and become familiar with winter conditions, with the reverse process taking place in April (i.e., surprise storms). The results might also be explained, however, by the greater chance of having ice and snow on walking surfaces—and therefore EDV for same-level falls involving ice or snow—during colder mid-winter control periods as compared to shoulder months when snow and ice typically completely melt away between precipitation events. This would have the effect of reducing relative risks outside of the shoulder months.

The analysis also revealed interesting relationships between winter storm events and the risk of other types of falls. In several cases, winter storm events were associated with a significant decrease in EDV for injuries other than those occurring on the same level involving ice and snow ($EDVF_{OTHER}$), many of which occur indoors. Estimated mean decreases ranged from eight to 15 percent during winter storms relative to dry control periods. Given that reductions were only prevalent for particular storm types, age cohorts and months, the results cannot be simply interpreted as a shift from $EDVF_{OTHER}$ to $EDVF_{IS}$ whereby it is assumed that people experiencing same-level falls involving ice and snow would have suffered another type of fall had there been no winter storm. It is not clear whether the findings result from reduced exposure (e.g., by encouraging people to stay indoors, walk less, take greater precautions) or deferred visits to an emergency department (i.e., falls still occur but treatment is not sought immediately).

From an intervention perspective, it would be important to ensure that any strategies or interventions designed to reduce the risks of same-level falls on ice and snow do not incidentally remove whatever protective effect winter storms seem to exert on risks for other types of falls. One such intervention involves the issuance of official warnings to alert the public about severe winter weather, possible impacts, and calls for risk-reducing actions, for example suggesting a higher likelihood of slippery walking surfaces and recommending restriction of non-essential travel. The intent is to provide information that could directly or indirectly affect exposure, other risk-mitigating behaviour, and weather-sensitive outcomes such as the incidence of same-level falls involving ice and snow. A simple stratification of winter storms with and without watches or warnings was analyzed to assess any effects. Risks were observed to be lower during snowfall events with watches or warnings than those without any alerts, though the opposite was found for mixed precipitation events. While these results were not statistically significant, they still imply that people may respond by adjusting their exposure or by taking other actions to reduce their sensitivity to snowfall events. They might also do this in response to mixed precipitation storms, but less effectively. Unfortunately, it was not possible to discern from the analysis the extent to which the responses were simply coincidental, habitual, due to intentional consideration and behaviour in reaction to weather warning information, or a function of seeing, experiencing, and reacting to the storm as it occurred. In the case of snowfall, a warned event could simply indicate a very heavy snowfall in which case one might interpret lower risks as a sign that people decided to remain inside, attempted to travel but altered plans because of deep snow, or experienced a fall but decided not to risk travel to an emergency department—the warning message may have had little impact on the behaviour and outcomes. For mixed precipitation events, in particular freezing rain, it is plausible that hazards initially appear less dangerous to people and decisions are thus made to venture out.

With respect to exposure, a few observational and stated adaptation survey studies have demonstrated that walking participation may decrease by a few to several percent during snowfall (e.g., Aultman-Hall et al. 2009, Böcker et al. 2013, Clarke et al. 2017) though the effect is likely not linear nor consistent across different types of winter storms, amounts of precipitation, or during the course of individual events. Lacking the data necessary to resolve trip counts at the scale of individual winter storms, exposure was held constant in the current investigation for both events and corresponding control periods. The primary effect of this decision was to generate more conservative RR estimates. For illustration, after reanalyzing the overall relative risk of $EDVF_{IS}$ assuming a five percent drop in exposure during all winter storm events, the mean estimate rose from 1.50 to 1.58. Reduction in event exposure would need to exceed 10 percent for these differences to be significant and ensure that the revised RR falls outside of the confidence intervals of the original estimate (RR 1.50; 95% CI:1.34, 1.68).

3.7 Conclusions

This study examined relationships between winter storms and the occurrence of fall-related injuries for a mid-sized urban community in Ontario, Canada. Main findings are as follows:

- Winter storms, in particular those involving mixed precipitation, were associated with significant increases in the incidence of same-level falls that involve ice and snow.
- Significant reductions in mean relative risk estimates were apparent over the 2009-2017 study period suggesting possible long-term shifts in exposure, sensitivity, and/or risk-mitigating decisions, actions, and behaviour.
- Lag effects for same-level falls involving ice and snow were weak to non-existent for snowfall events and observed to only last for the first 24 hours following mixed precipitation winter storms, most likely due to effective winter maintenance in the study region.
- Same-level falls on ice and snow likely contribute more to the total winter storm related injury burden than motor vehicle collisions.
- Clear, consistent and significant effects of government-issued watch and warning communications on risk outcomes were not found.

Additional sources of injury data (e.g., physician or clinic visitation) may have provided a more comprehensive estimate of fall-related risk, but would not likely have led to different associations with winter storms. Such data would be useful in conducting research on the severity of fall injuries and longer-term patient outcomes, something worthy of study but beyond the scope of the current investigation. In addition to estimating overall risks, retrospective population-based analyses of secondary data as conducted in this study seem best suited to raising or pointing to questions about why or how specific interventions such as weather warnings influence behaviour and risk outcomes, but less useful in explaining processes operating at finer social scales within winter storm events.

It is recommended that those engaged in developing injury prevention strategies and related public risk messaging, in particular winter weather warnings and advisories, should place additional emphasis on falls and multi-modal injury risks in future communications related to winter storm hazards. Strategies or interventions developed to reduce the risks of same-level falls on ice and snow should be designed not to incidentally remove the protective effect winter storms were found to have on risks for other types of falls. Additional research is required to assess the generalizability of the findings presented in this investigation, more precisely monitor pedestrian exposure, and to explore in greater detail the mechanisms through which weather, weather-related risk information, and associated interventions, influence behaviour and risk outcomes.

CHAPTER 4: Effects of methods and timing of data collection on insights into the influence of winter storm-related risk information on routine trip and activity behaviour

4.1 Synthesis

This study explores the effects of research design decisions regarding data collection and analysis methods on insights into the influence of winter storm-related risk information on trip and activity behaviour. A mixed-methods approach, consisting of content analysis of pre-winter season semi-structured interviews and experience sampling surveys during three winter storms in near real-time, was implemented to collect rich, detailed information about the perceptions, beliefs, actions, and behaviour of study participants. The analysis confirmed the general relevance of four factors in making routine mobility decisions during winter storms: response choice and efficacy, attributes of weather-related information sources and use, hazard perception, and perceived concern. It also demonstrated the distinct advantages of interviews relative to general surveys, and unique findings only made possible by employing experience sampling in near real-time, such as the inconsistencies observed between intentions and actual behaviour. Data and empirical findings were then reanalyzed through the lens of the Theory of Planned Behaviour (TPB) using a novel approach to assess construct consistency and demonstrate the theory's utility and limitations in providing guidance to improve the efficacy of warning information interventions.

4.2 Introduction

Attention to winter storms has focused primarily on extreme events despite the fact that, in some sectors, 'run-of-the-mill' events account for much of the total impact attributable to weather. This is particularly true for mobility-related risks, as supported by previous studies (Andrey 2010; Black and Mote 2015) and recent research by this author, which demonstrated that winter storms, even at modest levels of objectively measured severity (e.g., amount of precipitation), are associated with large and significant increases in the incidence of mobility-related injuries (Mills et al. 2019, 2020). Such chronic threats seem accepted by society, perhaps as a tradeoff for perceived benefits of a mobile life. This tolerance, however, hides the everyday behaviours and practices undertaken by citizens, business owners, government officials, and others that simultaneously produce and cope with storm risks (Hewitt 1983).

Notwithstanding the significant risk that remains in the system for winter weather-related mobility impacts, long-term reductions in relative risk for both motor vehicle collision (MVC) casualties and walking-related fall injuries have been observed. However, the reliance on aggregate analyses has led to only conjecture about possible reasons for the improvements. Among plausible explanations for reductions in mobility-related injuries during winter storms is an expanded quantity and improved quality of weather information and better accessibility and usability of this knowledge. While enhanced knowledge likely effects longer-term change through the decisions of authorities (e.g., winter maintenance providers, see Nurmi et al. 2013) to better mitigate aspects of the physical hazard (e.g., improve road surface friction), less certain is the influence of weather-related risk information on personal mobility—routine trips that serve or facilitate social interaction, employment, business, shopping, recreation and leisure activities. This uncertainty is the focus of the current investigation.

As noted by Bocker et al. (2013), the available literature concerning the role of weather information in activity and trip decisions is limited, with only a few studies (Barjenbruch et al. 2016, Brazil et al. 2017, Cools and Creemers 2013, Drobot 2008, Drobot et al. 2014, Elevant 2013, Kilpeläinen and Summala 2007, Matsuzawa et al. 2006, Strawderman et al. 2018) explicitly examining forecasts, warnings, or subjective perceptions of expected winter weather conditions. Yet this research and other studies in the broader weather risk literature (e.g., Gutteling et al. 2018, Kox and Thieken 2017, Morss et al. 2016, Sherman-Morris 2013, Taylor et al. 2019, Weyrich et al. 2020a) have identified, described or empirically tested factors associated with the potency of information at influencing protective decisions, intentions or behaviour. Variables noted in studies specific to winter travel hazards include: response choice and efficacy (Barjenbruch et al. 2016, Cools and Creemers 2013, Drobot et al. 2014, Strawderman et al. 2018); attributes of weather-related information sources and use (Barjenbruch et al. 2016, Brazil et al. 2017, Cools and Creemers 2013, Drobot 2008, Drobot et al. 2014, Elevant 2013, Kilpeläinen and Summala 2007); hazard perception (Drobot 2008, Kilpeläinen and Summala 2007, Matsuzawa et al. 2006); and perceived levels of concern (Drobot 2008).

Weather information studies are typically survey-based, cross-sectional, and reliant upon recall of singular events or reactions to hypothetical scenarios. Minimal attention is paid to dynamic factors (e.g., individual activity schedules that may affect exposure), variation in the social context or assumed determinants of behaviour, and linkages to outcomes such as safety. These tendencies and limitations may offer some explanation for observed gaps between intentions and actual protective behaviour (e.g., Potter et al. 2018, Taylor et al. 2019, Weyrich et al. 2020b) and more generally between improvements in hazard knowledge and corresponding action and societal benefits (White et al. 2001). Critically, research designs in weather information studies focused on winter travel hazards generally do not incorporate, examine, or evaluate the suitability of established theoretical models and constructs, especially those that are commonly applied in the broader behavioural and social change literature. One model, which has not been applied to weather-related information but is particularly prevalent in the literature, is the Theory of Planned Behaviour (TPB) (Ajzen 1991), rooted in social psychology and widely applied in health, consumer behaviour, and transportation fields.

Given the dearth of literature specific to chronic winter weather threats and the concerns and gaps referenced above, research was undertaken by the author to explore the following central question: *How and to what extent do the methods and timing of data collection affect insights into the influence of weather-related risk information on routine trip and activity decisions and behaviour?* Subsequent sections of the paper are used to describe the study design developed to tackle this question, report and summarize main findings, and discuss implications for future research and evaluation of winter weather-related information service interventions.

4.3 Study design

The study design adopted involved five components: literature review, pre-season interviews, winter storm surveys, inductive analysis, and conclusions/implications for future research and practice (Figure 4-1). The core novel feature of the design was the use of inductive analysis to define patterns emerging from the application of rich data collection methods (semi-structured interviews, experience sampling surveys) deployed over multiple measurement points during the course of a winter season, between several winter storms, and within individual storm events. This facilitated new insights into the effects of methods and measurement timing on information and behavioural efficacy, with implications for future research, theory and practice.

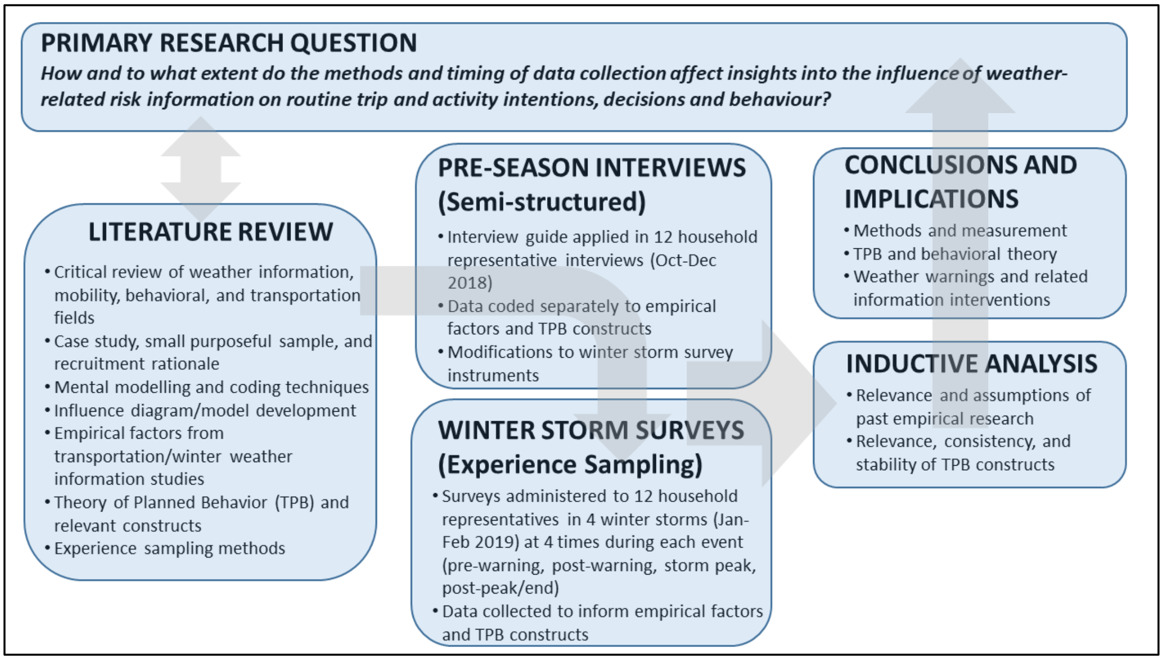


Figure 4-1. Main components of study design and chronological flow of research.

4.3.1 Case study recruitment and sampling

The study probed deeply into a small sample of households from the Canadian cities of Waterloo and Kitchener in the province of Ontario. These municipalities, with a combined population of about 400,000, lie within the larger Regional Municipality of Waterloo study area adopted in previous work by the author (Mills et al. 2019, 2020). A convenience sample was drawn from two sets of potential participants: 1) families holding membership at two local YMCAs, and 2) families with children registered in local youth soccer clubs. Recruitment was purposive in that it was designed to capture households that undertake substantive discretionary travel throughout the winter season (i.e., those with school-aged children, extensive involvement in recreational activities) which, relative to the general population, should afford more opportunities for weather information to affect activity and trip decisions. The following criteria were used to screen and accept participants:

- 18 years of age or older;
- primary residence located in either the City of Waterloo or City of Kitchener;
- parent of school-aged children who live at the primary residence;

- owns and operates at least one automobile and possesses a valid Ontario driver's license;
- conducts, organizes or schedules the majority of discretionary, non-work activities and trips for the children;
- familiar with the travel and activity schedules of family/household members;
- possesses and routinely uses a personal smartphone with access to the internet; and
- available and not taking an extended vacation outside of the study region during the activity and trip monitoring period.

Passive recruitment of members from the YMCA proceeded over four, two-hour in-person sessions over a three-week period (Oct-Nov 2018) inside the primary entrance of the Stork Family YMCA located in the City of Waterloo. An initial set of eight participants who showed interest and offered to contribute expanded to 12 after active solicitation and recruitment from members of the author's personal minor youth soccer-related contact list.

The relatively small size of the sample reflects the extensive time and resource commitment required to implement the exploratory mixed-methods approach of the study; and is justified by the probing orientation of the inquiry and relative uniformity of the subpopulation being examined (Collins and Evans 2017). This was verified over the course of the semi-structured interviews; i.e., by the tenth participant, little new information was revealed, a basic tenet in qualitative research (Guest et al. 2006). While TPB applications are normally conducted using surveys of large representative samples, the questionnaire development, testing, and validation process is typically undertaken using small groups (Fishbein and Ajzen 2010). Research employing experience sampling techniques, as adopted through the winter storm surveys and described in section 4.2.3, also often use small samples (e.g., Lawn et al. 2018, Smith et al. 2015). Readers are reminded that this small-sample element is one component of the larger thesis which includes complementary analyses of large risk outcome data sets (Chapters 2-3).

The study group included eight female and four male participants; four were between the ages of 30-39, seven between 40-49, and one between 50-59. Collectively, the participating households represented 59 people, an average of 4.9 per dwelling. All but one household exceeded the 2016 median annual income of the Kitchener Census Metropolitan Area (which includes both cities). An overview of select household, dwelling, and transportation characteristics is provided in Appendix A.

Remuneration in the form of gift cards was provided to each participant to encourage and maintain involvement (CA$25 for baseline interview and CA$100 for within-storm surveys). All aspects of participant recruitment were reviewed and approved by the University of Waterloo Office of Research Ethics.

4.3.2 Pre-season interviews

Baseline semi-structured interviews were scheduled from October-December 2018 and conducted in person by the author. They were held at a place and time of the participant's choice (e.g., residence, library study room, workplace office, author's residence), audio-recorded with permission, and transcribed for coding and further analysis by the author. Each interview lasted approximately one hour and consisted of three sections:

1. Documentation of pertinent individual and household demographic, socio-economic, and transportation characteristics;
2. Development of a household activity schedule for a typical mid-winter week including identification of the locations of activities, preferred mode(s) of travel, and routes typically taken to reach destinations; and
3. Completion of a mental modelling exercise to reveal participants' perceptions of winter storm-related travel risk; activity and trip practices, intentions, and behaviours; and use of weather-related information and knowledge in making decisions and taking actions.

Section three was based in part on the mental modelling approach pioneered by scholars at Carnegie Mellon University in the late 1980s and early 1990s (Bostrom et al. 1994, Morgan et al. 1992, Morgan et al. 2002). The technique has been utilized to examine a broad range of health and safety threats including those associated with natural hazards (e.g., flood, Wood et al. 2012, Lazrus et al. 2016; wildfire, Zaksek and Arvai 2004; heat waves, Chowdhury et al. 2008). In most of these studies, mental modelling was used to identify discrepancies between expert and lay-person understanding of risks and adjust public beliefs through improvements to formal risk communications; however, its primary relevance for the current investigation was as a technique to elicit rich input from participants. The key elements adopted from the Morgan et al. (2002) approach were the development of an influence diagram (i.e., expert-based model) and use of open-ended interview questions to establish the participant's mental model of mobility-related practices and activity and trip-taking decisions during winter storms. Presented in Figure 4-2, the influence diagram was developed through a review of relevant literature. It consists of four colour-coded categories of nodes representing: 1) winter storm hazards (red); 2) generation of mobility needs, decisions, and practices (dark blue); 3) actions, responses, and practices used to deal with winter mobility hazards (light blue); and 4) outcomes of trip decisions and practices (green). Arrows depict the direction of assumed relationships and flows among states of the system components.

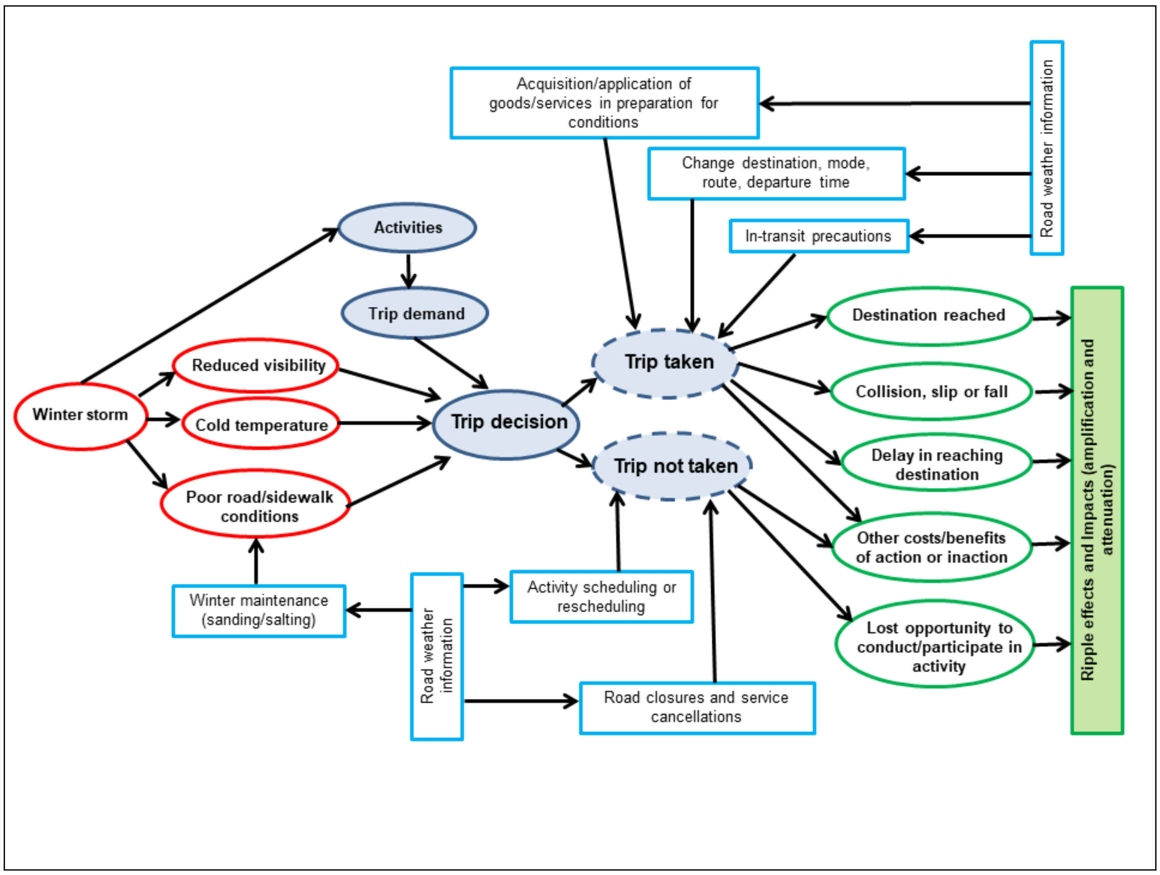


Figure 4-2. Influence diagram representing factors affecting decisions to take a trip during winter storms and potential outcomes.

After exhausting responses to the opening statement, "*Please tell me everything that you know about winter storms and how they affect the decisions that you and other members of your household make to participate in and travel to various activities*," a series of prompts (e.g., ‘anything else’, ‘can you tell me more’, ‘can you give a specific example’, ‘can you explain how or why’) were used to obtain further feedback. Additional semi-structured questions, derived from the components represented in the influence diagram, were used to prompt interviewees to expand upon their initial thoughts regarding activities, practices, routines and outcomes of importance; nature of winter storm hazards; perceptions of risk and concern; types, choices, feasibility, effectiveness and context of available decisions, actions, and behaviours; and sources and attributes of information considered in making decisions.

Deductive coding, consistent with the directed content analysis approach in Hsieh and Shannon (2005) and flexible coding advocated by Fletcher (2017), was applied to the transcribed comments. Two sets of relevant categories were established, based on:

1) Factors identified from the winter hazards empirical literature as being important in explaining behaviour (response choice and efficacy, weather-related information sources and use, hazard perceptions, perceived concern), and
2) Theoretical constructs identified in the TPB (instrumental and experiential attitude beliefs, injunctive and descriptive norm beliefs, autonomy and capacity related control beliefs, anticipated regret, habit, behavioural intention).

4.3.3 Experience sampling of winter storms

It seems obvious that measurement of variables understood to affect trip behaviour during winter storms should be conducted close in time to the actual weather events of interest. Yet much of the research referenced in the chapter introduction (Section 4.2) relied upon participant recall of thoughts, feelings, decisions, actions and responses that occurred either in the distant past or over a long series of disparate events. Social scientists have questioned the accuracy of such recalled information even if it is only several days removed from the event in question, noting availability and other cognitive biases that may distort interpretations of past events (e.g., Kahneman et al. 2004). Cross-sectional survey designs normally used in empirical and TPB research implicitly assume within-participant stability in the factors and constructs evaluated. This is inconsistent with recent meta-analyses of studies showing evidence of considerable within-participant variation across a wide range of psychological constructs (Podsakoff et al. 2019). Anecdotal accounts of individual actions revealed to the author through the course of the current investigation, together with evidence from empirical analyses of exposure, motor vehicle collision, and fall-related injury data (Mills et al. 2019, 2020), suggest that similar winter storm conditions may produce a variety responses and outcomes—again challenging assumptions of stability.

Experience Sampling Methods (ESM) (Hektner et al. 2007) offer an alternative to static retrospective evaluation and directly address the concerns noted previously. Although no studies making use of ESM were found that explicitly dealt with weather and travel, examinations of health and well-being associated with park visitation (Doherty et al. 2014) and relationships between weather and mood (Kööts et al. 2011) or risk perception (Hogarth et al. 2011) offered valuable insight for designing and tailoring an application for the current investigation.

Unlike many ESM studies, where the intent was to sample randomly or at regular intervals throughout an entire time period, the current study was interested in particular storms and critical phases within each event. The design aimed to capture and compare varying availability of official Environment and Climate Change Canada (ECCC) winter weather-related warning information; participant practices; and risk, activity and trip perceptions, intentions, decisions, and behaviour at four points within the lifecycle of four individual winter storms occurring between January 1, 2019 and March 15, 2019:

a) Prior to the storm and the release of any official winter storm weather watches or warnings by ECCC;
b) In advance or at the beginning of the storm once official government watches or warnings by ECCC had been issued;
c) During or immediately following the most intense precipitation and lowest visibilities expected during the storm once travel conditions became visibly deteriorated (i.e., snow or ice accumulation on walkways, roadways, etc.); and
d) After weather and road conditions had improved and official winter storm warnings issued by ECCC had expired.

Further references in the chapter to specific storm events and survey stages will use alphanumeric coding (e.g., where ‘WS2C’ refers to Winter Storm 2, third survey stage).

Text messages sent to each participant's smartphone at each stage in four separate storm events instructed them to complete an on-line survey accessible and formatted for use through mobile or web platforms. Questionnaires were tailored to each stage of the storm, with the first two instruments oriented to expected or anticipated conditions and actions, the third instrument to the immediate or on-going situation, and the final one to reflect and evaluate recent storm experience. Complete questionnaires are provided as Appendix B. The surveys were created, uploaded and made accessible through *Qualtrics Insight Platform*[3].

Profiles of the four storms are shown in Table 4-1. Timelines of meteorological conditions; weather bulletins issued by ECCC; and the time over which participants initiated and completed surveys at each stage in the storm are depicted graphically in Figures 4-3 to 4-6. Following a relatively mild start to the winter season, conditions became conducive to storm development in late January, yielding four candidate weather systems in quick succession from January 17 through February 14, 2019. The storm set included a couple of cold systems (WS1, WS2) and two warmer, mixed-precipitation events with a range of precipitation amounts (WS3, WS4). The first winter storm event materialized differently than predicted, peaking well southeast of the study area. Lacking the issuance of a weather watch or warning from ECCC as required by the study design protocol, only the first survey stage was completed for this event. All four stages were completed for the three subsequent winter storms.

[3] https://www.qualtrics.com/

Table 4-1. Profiles of four winter storm events examined.

Winter Storm Variable	Winter Storm 1	Winter Storm 2	Winter Storm 3	Winter Storm 4
Start[1]	Jan 17 (20:00)	Jan 26 (20:00)	Feb 5 (04:00)	Feb 10 (18:00)
End[1]	Jan 20 (09:00)	Jan 29 (21:00)	Feb 8 (03:00)	Feb 14 (04:00)
Duration (hrs)[1]	64	74	72	83
Precipitation Range (estimated from CaPA) (mm)[2]	7.0-10.4	17.9-21.2	11.4-13.7	24.7-30.5
Freezing rain/drizzle occurrence (hrs)[3]	0	0	4	2
Minimum hourly visibility (km) [3]	1.2	1.2	0.2	1.2
Visibility ≤ 8km (hrs) [3]	11	22	27	22
Visibility ≤ 2km (hrs) [3]	4	12	18	13
Minimum temperature (°C) [3]	-16.0	-23.3	-6.2	-6.6
Maximum temperature (°C) [3]	-1.8	-3.1	+5.2	+0.6
Mean temperature (°C) [3]	-9.7	-11.9	-1.6	-4.6

[1]based on lifecycle event criteria established in Mills et al. (2019); all entries are Eastern Standard Time based on a 24-hour clock
[2]liquid-equivalent estimates were derived from ECCC Canadian Precipitation Analysis (CaPA) data. Range represents spatial variation across the study region.
[3]based on data from ECCC Kitchener/Waterloo (Region of Waterloo International Airport) observation station (6144239)

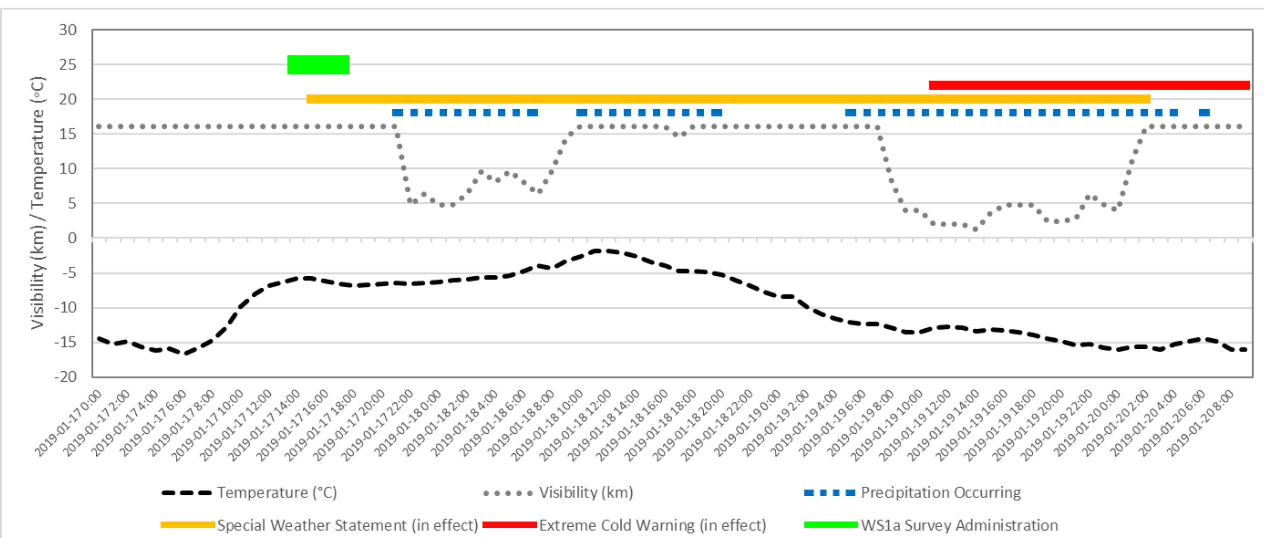


Figure 4-3. Timing (EST) of survey administration (between first and last respondents) for first winter storm (WS1) along with prevailing weather conditions and warnings.

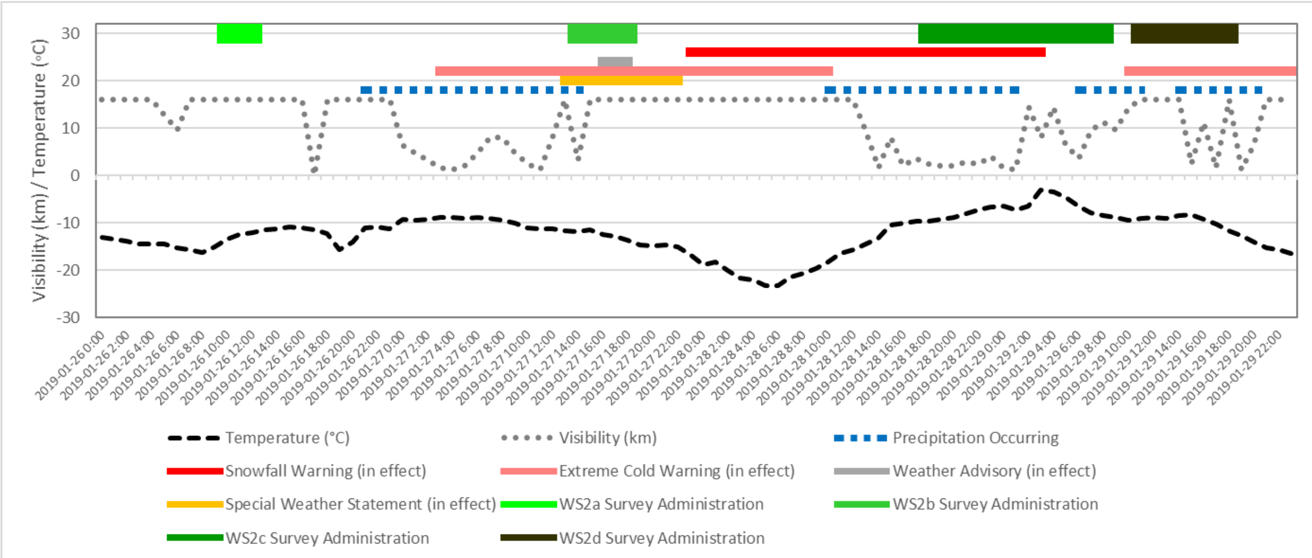


Figure 4-4. Timing (EST) of survey administration (between first and last respondents) for second winter storm (WS2) along with prevailing weather conditions and warnings.

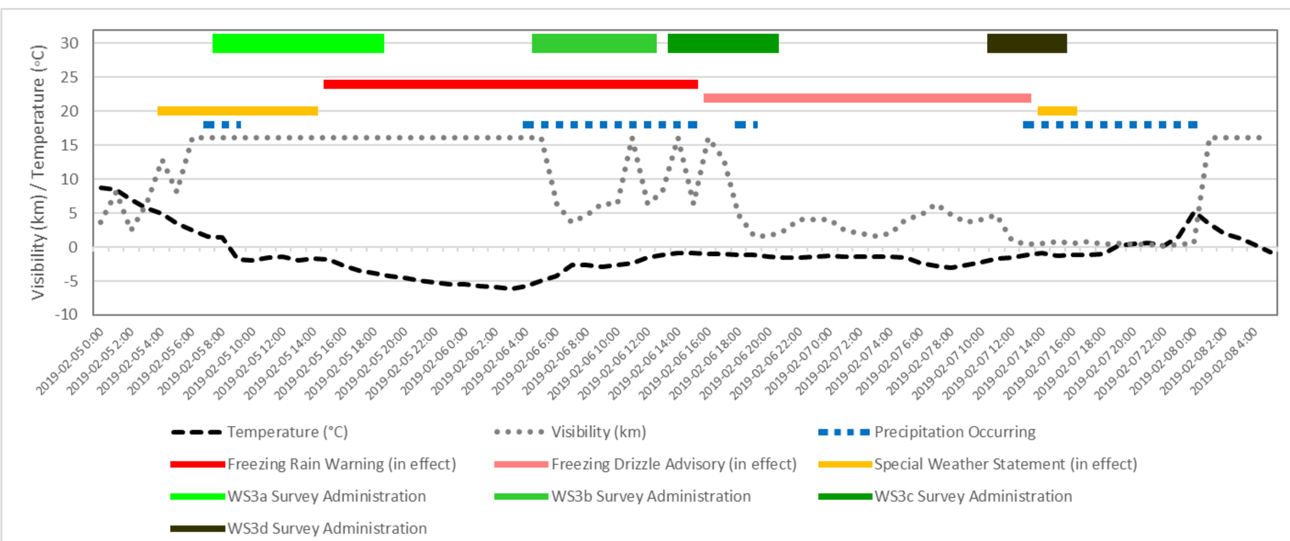


Figure 4-5. Timing (EST) of survey administration (between first and last respondents) for third winter storm (WS3) along with prevailing weather conditions and warnings.

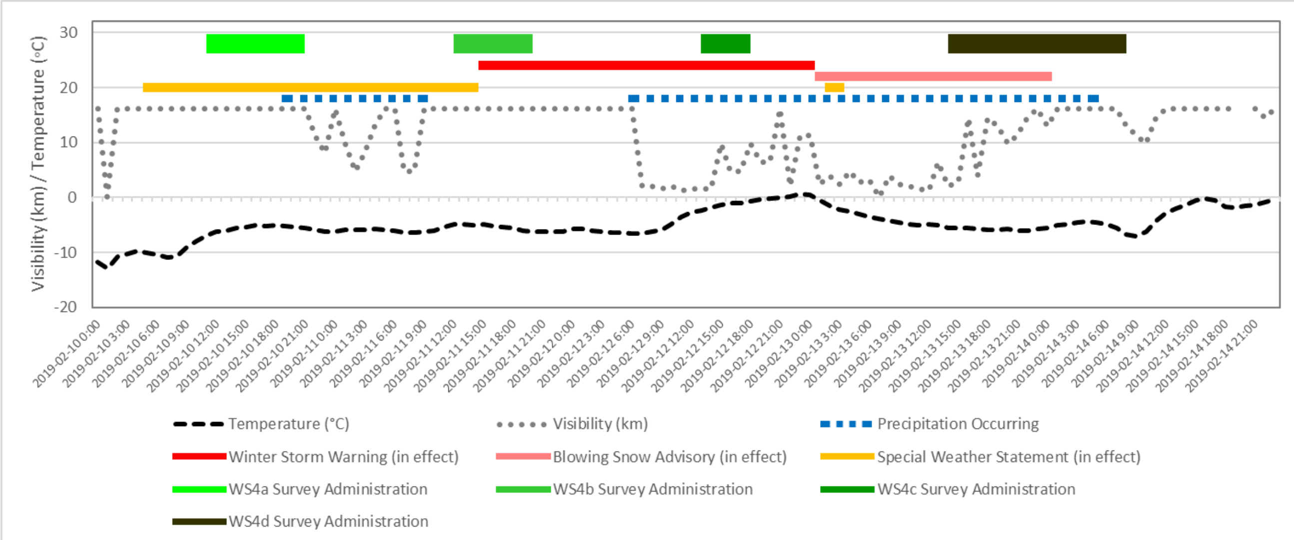


Figure 4-6. Timing (EST) of survey administration (between first and last respondents) for fourth winter storm (WS4) along with prevailing weather conditions and warnings.

4.4 Results

Results are organized around 1) factors identified in the empirical winter hazards literature, and 2) TPB constructs, that help to frame, characterize and understand the translation of weather-related risk information into trip decisions, behaviours and outcomes. Emphasis is placed on discussing the breadth of findings, qualitatively indicating any central tendency or majority participant view supplemented with median (M) or mean ($\bar{x}$) descriptive statistics, highlighting unique observations, and identifying changes in opinions, beliefs, perceptions and stated actions over time. Select quotes illustrate the richness found in participants' views. An inductive approach is taken to interpret the small sample results in each section through the lens of the primary research question.

4.4.1 Factors identified in the empirical winter hazards literature

As noted in the chapter introduction (Section 4.2), several variables are thought to affect the manner and extent to which weather-related risk information influences mobility decisions, actions and outcomes during winter storms. Descriptive and empirical findings from the pre-season interviews and storm surveys support the relevance of previously identified factors; in addition, they highlight the complexity and dynamic nature of the processes influencing decisions.

Response choice and efficacy

Winter storm warnings are effective only to the extent that they enable responses that reduce exposure or vulnerability (Lazo et al. 2020, WMO 2015a). It is therefore helpful to consider what behavioural options and other actions are available, preferred, and adopted by people, as well as their perceived efficacy, before attempting to understand the reasoning and feelings behind people's intentions and choices.

During the baseline interviews, participants were asked to talk about what (if anything) individuals and households can do to reduce the risks and address concerns associated with travelling during winter storms. Commonly cited actions and behaviours are listed in Table 4-2. These responses were not consistently adopted, however. Rather, actions and combinations or sequences of responses depended very much on activity and trip circumstances as well as the nature and severity of the storm.

Table 4-2. Number of study participants reporting specific responses to manage trips and activities during winter storms.

Response	**Interviewees Reporting (% in parentheses)**
Cancel or reschedule one or more activities and trips until after the storm ends and travel conditions improve	12 (100)
Search for and monitor weather forecasts and road information reports from media and government agencies	12 (100)
In-transit precautions (e.g., driving slower, walking more cautiously)	12 (100)
Seasonal preparations (winter tires, emergency kits, snow brushes/ice scrapers)	11 (92)
Winter maintenance (walkways, driveways, vehicles)	9 (75)
Adjust the schedule to leave early and allow more time to reach the destination	9 (75)
Change the route normally taken in order to avoid especially hazardous situations	9 (75)
Change the mode of travel (e.g., drove the kids to school instead of letting them walk, walked instead of biked, carpooled)	7 (58)
General planning/preparation for possible outcomes	6 (50)
Defer driving to another household member	5 (42)
Work from home or change the location of other activities to the home (e.g., fitness workout, on-line shopping, play-date)	4 (33)
Ensure boots, coats, gloves and extra winter clothing were ready to wear	4 (33)
Take the trip (no specific response taken)	3 (25)
Top-up vehicle fuel and/or windshield de-icing fluid	2 (17)
Discuss and share thoughts about the storm, possible implications, and potential actions with household members or other family, friends and neighbours through in-person, telephone, video or social media conversations	2 (17)

Several responses in Table 4-2 pertain to the acquisition and application of goods and services in preparation for anticipated conditions. Some of these actions were conducted during or just prior to a particular storm event in advance of travel, for example: topping up fuel and windshield de-icing fluid levels in vehicles; clearing snow and ice from walkways, driveways, and vehicles; and selecting the best-equipped vehicle to handle conditions (i.e., one with winter tires, all-wheel drive, or higher profile). Others were initiated on a seasonal basis (e.g., replace summer tires with winter tires, place an emergency kit into the vehicle, remove winter clothing and footwear from storage). Some responses within this category, but not included in Table 4-2, extended beyond the seasonal timeframe, specifically the purchase of all-wheel drive vehicles and the relocation of a residence to be closer to a recreational facility that was used daily by household members.

Another set of responses focused primarily on activities that generate demand for mobility, and were aimed at avoiding exposure to hazardous conditions. Activity scheduling and rescheduling, including outright cancellation, was mentioned by all participants as a way to reduce travel during winter storms. Interviewees suggested that they were likely to defer participating in an activity, and thus not travel, until it was clear that the worst of the storm had passed. Unless required by employers, schools or activity organizers, cancellation was deemed a last resort by many interviewees.

On other occasions, interviewees stated they did not significantly change the activity (or goal) but rather altered the temporal and spatial details of the trip, for example adjusting departure times to leave earlier and taking different routes that were deemed less hazardous. Changing the destination or location of the activity (e.g., working or schooling from home) was mentioned by one-third of participants while just over one-half indicated they would switch modes (e.g., walking to driving, driving instead of public transit, biking to walking) in response to winter storm conditions.

Several participants noted that they adjust their in-transit behaviour by driving more slowly, increasing following distance, switching on headlights, or by walking more cautiously to avoid slips and falls. Others stated that they would assign driving tasks to the assumed better-skilled or more willing driver during winter storms; notably, this was exclusively female household members deferring to their male partners. A few interviewees said they normally ‘tested’ conditions on their street (e.g., apply brakes to assess slipperiness) to gauge the extent of required driving adjustments.

Results from the pre-season interviews were used to develop a list of potential responses for inclusion in the storm surveys. Participants were asked to identify their intent to adopt each of the potential responses (Survey B) and indicate whether they had actually performed the behaviour or taken action (Surveys C, D). Tables 4-3 to 4-5 show results for trip rescheduling to an earlier time (i.e., before the storm), teleworking or otherwise relocating an activity to the home, and changing the route taken for a trip. Tables covering other response types are included in Appendix C. For each participant and storm, the degree of intent to perform the trip behaviour, measured after an official ECCC warning was issued but prior to the peak of the storm, was assigned numerically on a likelihood scale (1, *very unlikely*, through 7, *very likely*) with corresponding shades of gray. A check-marked box in the adjoining table cell indicates that the behaviour was actually performed while an x-marked box identifies that it was not performed. Bolding of the participant identifier confirms that the subject behaviour was also mentioned as a preferred response to winter storms during the pre-season interviews conducted several weeks prior to the storm surveys.

It is of particular note that actions taken during storms were routinely different from what was shared both during the baseline interview and during the early stages of the storm. Just because the response was (or was not) mentioned in the pre-season interviews did not ensure there would (or would not) be intent to conduct the behaviour once warnings for particular storms were issued. Similarly, strong (or weak) intent did not guarantee that a response would (or would not) be taken during a storm. As well, a degree of interaction, sequencing, or substitution seemed apparent. For example, despite roughly half the sample showing moderate to high levels of intent to adjust the route taken during WS4, no participants reported doing so. Extensive teleworking evident in WS4 (Table 4-4), partly a function of school and business closures, likely restricted the number of opportunities to take a different route (Table 4-5). In other cases, as demonstrated below in the descriptions of last recalled trips, when participants adopted a risk-mitigating action earlier in the storm, subsequent responses often introduced new or additional types of exposure.

Left work [early] at 4:15, ran home to pick up the kids, and drove to the other end of Cambridge for my daughter's birthday party. (P7 during WS3)

School, work, and all activities were cancelled. I drove two children to a friend's [home] for the day rather than letting them have a car. I went out quickly to get a few groceries to ensure we were set for the week. (P12 during WS4)

I had to take supplies to my office. Normally I would have driven but it was too icy so I carried the supplies on a walk instead. (P4 during WS4)

Table 4-3. Consistency between intent and actual reported behaviour during winter storms: Reschedule activity before storm occurs.

	Winter Storm 2		**Winter Storm 3**		**Winter Storm 4**	
Participant*	Intent	Actual	Intent	Actual	Intent	Actual
P1	4	×	6	×	4	
P2	1	✓	--NR--	×	1	×
P3	7	×	5	×	4	×
P4	--NR--	×	6	--NR--	6	✓
P5	3	--NR--	6	--NR--	7	×
P6	4	×	1	--NR--	--NR--	✓
P7	2	×	1	×	1	×
P8	4	×	7	✓	5	×
P9	--NR--	×	2	×	6	✓
P10	4	✓	4	×	6	×
P11	1	×	7	×	1	×
P12	1	×	2	×	4	×

**bold indicates participant mentioned performing behaviour during baseline interview*
--NR-- (not recorded)
Actual behaviour: Performed (✓)/Not (×)
Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	**2**	**3**	**4**	**5**	**6**	**7**

The aggregate efficacy of responses adopted by respondents during the winter storms was evaluated by asking participants to rate the extent to which they agreed that their trip and activity decisions during the storm were appropriate. Only one participant in one storm expressed disagreement (WS4). Median levels of agreement varied by storm event and were lower for WS4 (M=5.0) than WS2 (M=6.0) or WS3 (M=6.5). Despite relatively high levels of satisfaction with their own actions, virtually all respondents reported experiencing or personally witnessing some type of negative outcome during the sampled events (Figure 4-7), suggesting a degree of dissonance in their self-rated response efficacy.

Table 4-4. Consistency between intent and actual reported behaviour during winter storms: Substitute location/telework.

Participant*	Winter Storm 2 Intent	Winter Storm 2 Actual	Winter Storm 3 Intent	Winter Storm 3 Actual	Winter Storm 4 Intent	Winter Storm 4 Actual
P1	1	×	4	×	1	✓
P2	1	×	--NR--	×	1	×
P3	7	×	6	✓	7	✓
P4	--NR--	✓	3	--NR--	6	✓
P5	6	--NR--	6	--NR--	5	✓
P6	4	✓		--NR--	--NR--	✓
P7	1	×	1	×	1	×
P8	4	✓	7	×	6	✓
P9	--NR--	×	7	✓	5	✓
P10	3	✓	4	✓	4	✓
P11	1	×	7	✓	1	✓
P12	1	×	7	×	4	✓

**bold indicates participant mentioned performing behaviour during baseline interview*

--NR-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Table 4-5. Consistency between intent and actual reported behaviour during winter storms: Change route taken.

Participant*	Winter Storm 2 Intent	Winter Storm 2 Actual	Winter Storm 3 Intent	Winter Storm 3 Actual	Winter Storm 4 Intent	Winter Storm 4 Actual
P1	2	✓	1	×	1	×
P2	4	×	--NR--	✓	2	×
P3	6	×	5	×	1	×
P4	--NR--	×	5	--NR--	6	×
P5	7	--NR--	1	--NR--	6	×
P6	5	×	5	--NR--	--NR--	×
P7	5	✓	6	✓	5	×
P8	7	×	7	×	7	×
P9	--NR--	×	3	×	3	×
P10	3	✓	4	×	1	×
P11	6	×	7	✓	7	×
P12	3	×	2	✓	4	×

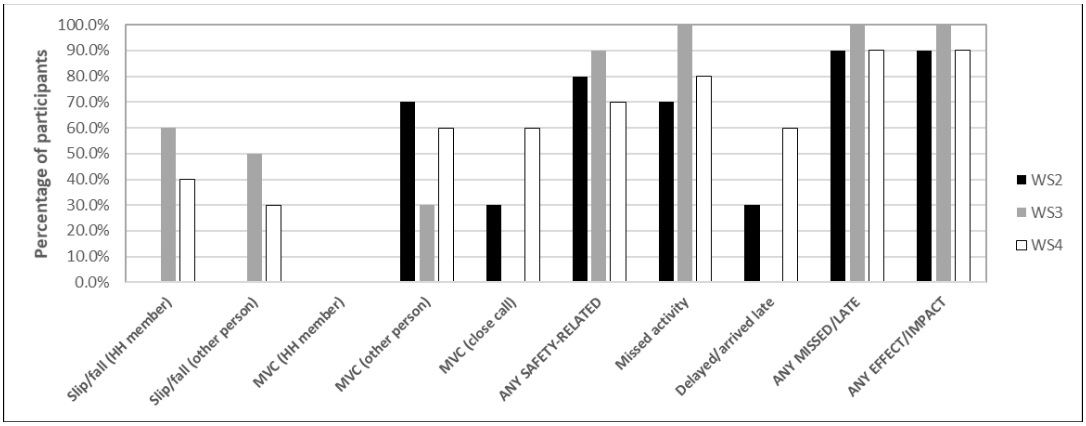
**bold indicates participant mentioned performing behaviour during baseline interview*

--NR-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7



HH = household; MVC = motor vehicle collision

Figure 4-7. Outcomes reported by participants during winter storms.

In summary, the investigation into response choice and efficacy reveal the following:

- A variety of responses were identified by—and potentially available to—participants, confirming what has been documented in studies of driver adjustments to weather (e.g., Andrey and Knapper 2003, Cools et al. 2010) and trip decisions more broadly (e.g., Stern and Richardson 2005).
- Levels of intent to perform specific actions, whether expressed several weeks, days or hours prior to a given event, are highly variable and often inconsistent with actual self-reported behaviour during winter storms, counter to assumptions or observations made in previous research (e.g., Barjenbrunch et al. 2016, Strawderman et al. 2018).
- Between-storm differences were observed in the intent, behaviour, and self-rated response efficacy of some participants. These variations appear to partly be a function of the potential for interaction, substitution and flexibility among the choice of possible actions, with combinations dependent on household activity and trip circumstances as well as the perceived hazards associated with individual storms. It is doubtful that cross-sectional stated adaptation survey methods that measure general 'protective action' (e.g., Drobot et al. 2014) or that restrict the choice of behavioural adjustments (e.g., Brazil et al. 2017) would be able to detect such interactive effects within or between storms. This may also be true of other studies that accommodate a broader selection of behaviours but rely on hypothetical weather condition scenarios (e.g., Cools and Creemers 2013) or ask respondents to recall and reflect upon multiple, intertwined decisions they have made over an extended (i.e., several days to months) period (e.g., Elevant 2013). In short, the mixed-methods adopted in this

dissertation, and ESM approach in particular, revealed a complexity and granularity of behavioural response that would be overlooked using traditional forms of inquiry.

Weather-related information sources and use

Weather-related information preferences, sources, and use attributes have been linked to the intended or stated adoption of risk-mitigating behaviour (Barjenbruch et al. 2016, Brazil et al. 2017, Drobot 2008, Drobot et al. 2014, Elevant 2013, Kilpeläinen and Summala 2007). As observed from the baseline interviews, the search, monitoring and use of media and government-sourced weather information was ubiquitous among participants (Table 4-2). Most participants stated that they accessed multiple channels of information in supporting their activity and trip decisions; however, it was apparent from the dialogue that they often did not distinguish between channel type and source of message content. Internet-based services (i.e., social media such as Facebook and Twitter, websites) delivered through personal mobile devices (e.g., smartphones, tablets to a lesser extent) and radio news/traffic broadcasts were the most commonly cited channels, followed by websites accessed through personal computers, television news broadcasts, conversations with others, and individual senses. The Weather Network (TWN)[4], a private sector multi-media weather information enterprise, was identified most often as the first or primary source of information, followed by local radio or television networks/station announcers; ECCC[5]; schools or local boards of education; municipal officials; family members, friends or co-workers; other weather media companies (The Weather Channel, Weathernet); and personal observations.

Compared with preferences expressed during the pre-season interviews, the use and utility of specific sources and channels of information for trip and activity decisions were varied within and over the course of storm events. During the first and second surveys, prior to and following issuance of a weather warning by ECCC, respectively, participants were asked to identify from a list of sources and channels, derived from the pre-season interviews, those that they relied upon to make a determination about the likelihood of a winter storm affecting the study area. A third survey, distributed at the peak of the winter storm, asked whether participants had searched

[4] See https://www.theweathernetwork.com/ca or its parent company, Pelmorex Corp. (Pelmorex.com)

[5] While the organization title became ECCC in 2015, *Environment Canada* remains the name referenced in weather forecast and warning products

for, consulted, or relied upon any of these sources in taking actions to deal with the storm and to rate their helpfulness in making trip decisions.

Participants' reported usage of information sources or channels is summarized across each storm in Table 4-6. Very low levels of use were observed across all three storm stages for television broadcasts, while about half or more of all participants across all stages of each storm made use of information from TWN. Websites, social media messages, and personal feelings, intuition or experience, were used by few participants through the first two stages of surveying. In most households, the number of sources consulted increased at each progressive survey stage within the storm with much greater usage typically observed during the peak of the storm. For at least two behaviours, trip cancellation/rescheduling and earlier departure, this increase was coincident with the expected timing of participant decisions/actions (Table 4-7). In more than 60 percent of situations over the course of three storms, participants indicated they would commit to stated intended actions no more than a few hours before the storm commenced. This suggests that more sources or channels were accessed to support specific trip or activity decisions than were used in establishing general expectations about the potential occurrence of a storm.

Table 4-6. Use of weather information sources/channels during different phases of winter storms (A-before warning, B-following warning, C-at storm peak).

Information source/channel	Participants reporting use during Winter Storm (WS) phase (%*)								
	WS2A	WS2B	WS2C	WS3A	WS3B	WS3C	WS4A	WS4B	WS4C
Personal feeling, intuition or experience	2 (18)	1 (10)	8 (73)	1 (10)	1 (9)	6 (67)	1 (9)	0 (0)	9 (75)
Personal observations of weather and environment around my home and neighbourhood	2 (18)	4 (40)	10 (91)	0 (0)	5 (45)	8 (89)	0 (0)	0 (0)	12 (100)
Discussion with member(s) of household	4 (36)	4 (40)	10 (91)	1 (10)	5 (45)	9 (100)	0 (0)	4 (36)	11 (92)
Discussion with friend, other relative, neighbour, or co-worker	1 (9)	6 (60)	8 (73)	3 (30)	2 (18)	8 (89)	2 (18)	5 (45)	11 (92)
Radio broadcast	2 (18)	2 (20)	8 (73)	3 (30)	4 (36)	6 (67)	4 (36)	5 (45)	7 (58)
Television broadcast	1 (9)	2 (20)	5 (46)	0 (0)	2 (18)	5 (56)	0 (0)	1 (9)	6 (50)
Information from *The Weather Network*	5 (46)	7 (70)	9 (82)	5 (50)	8 (73)	8 (89)	5 (45)	7 (64)	10 (83)
Information issued by *Environment Canada*	0 (0)	2 (2)	8 (73)	3 (30)	3 (27)	8 (89)	3 (27)	6 (55)	9 (75)
Information from a website	1 (9)	0 (0)	4 (36)	2 (20)	1 (9)	6 (67)	2 (18)	0 (0)	8 (67)
Twitter, Facebook, Snapchat or other social media message(s)	1 (9)	2 (20)	4 (36)	0 (0)	2 (18)	6 (67)	3 (27)	5 (45)	8 (67)
Smartphone weather application (weather app)	4 (36)	6 (60)	9 (82)	4 (0)	2 (18)	7 (78)	2 (18)	6 (55)	11 (92)
N	***11***	***10***	***11***	***10***	***11***	***9***	***11***	***11***	***12***

*percentages are rounded

Table 4-7. Stated expected timing of decision to perform or not perform particular behaviours during three winter storms (measured simultaneously with intent after initial ECCC warning bulletin issued).

Expected Timing of Decision	**Winter Storm 2**	**Winter Storm 3**	**Winter Storm 4**	**All Storms (%)[1]**
Cancellation or rescheduling behaviour				
Day before storm or earlier	1	1	0	2 (6.3)
Night before storm	1	1	1	3 (9.4)
Few hours or less before storm	0	3	5	8 (25.0)
After storm begins	8	6	5	19 (59.4)
N	10	11	11	32 (100.0)
Early departure behaviour				
Day before storm or earlier	1	0	0	1 (3.2)
Night before storm	4	3	2	9 (29.0)
Few hours or less before storm	3	4	6	13 (41.9)
After storm begins	2	4	2	8 (25.8)
N	10	11	10	31 (100.0)

[1]number rounded and may not add to 100

A series of tables were developed to explore usage patterns by individual participant across the three winter storms and to compare utility/helpfulness ratings expressed at the peak of the storm (Appendix D). Except for one participant in one storm, respondents universally made use of at least two sources or channels at every stage in each storm. Usage varied by storm and across survey stages for all sources/channels except for TWN, as shown in the examples for *discussion with household members* (Table 4-8) and *Environment and Climate Change Canada (ECCC)* (Table 4-9). In terms of utility, participants consistently rated information from TWN as very helpful; ratings for the remaining sources were more variable. Information from ECCC, smartphone apps, personal observation, discussion with household members, and discussion with other relatives, friends or co-workers were moderately to very helpful while the other sources were either rated much lower (e.g., personal feeling, intuition, or experience) or were used infrequently (e.g., television).

Table 4-8. Use of weather information sources/channels during winter storm stages: *Discussion with household members* before warning (A), following warning (B) and at storm peak (C).

	Winter Storm 2			Winter Storm 3			Winter Storm 4		
Participant	A*	B*	C*‡	A*	B*	C*‡	A*	B*	C*‡
P1	×	×	6	×	×	6	×	×	4
P2	✓	✓	5	×	--NR--	6	--NR--	✓	×
P3	×	×	×	×	×	1	×	×	6
P4	✓	--NR--	4	--NR--	✓	--NR--	×	×	5
P5	--NR--	×	--NR--	×	×	--NR--	×	×	5
P6	×	✓	6	--NR--	✓	--NR--	×	--NR--	6
P7	×	×	4	×	×	1	×	✓	3
P8	✓	×	7	✓	✓	7	×	×	7
P9	×	--NR--	3	×	✓	7	×	×	7
P10	×	✓	3	×	×	4	×	×	5
P11	×	×	7	×	×	7	×	✓	7
P12	✓	✓	5	×	✓	4	×	✓	5

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ --*NR*-- (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table 4-9. Use of weather information sources/channels during winter storm stages: *Information from Environment and Climate Change Canada (ECCC)* before warning (A), following warning (B) and at storm peak (C).

	Winter Storm 2			Winter Storm 3			Winter Storm 4		
Participant	A*	B*	C*‡	A*	B*	C*‡	A*	B*	C*‡
P1	×	✓	6	✓	✓	7	✓	×	7
P2	×	×	7	×	--NR--	7	--NR--	✓	×
P3	×	×	7	×	×	7	×	✓	6
P4	×	--NR--	1	--NR--	×	--NR--	×	✓	6
P5	--NR--	×	--NR--	✓	✓	--NR--	✓	✓	7
P6	×	×	×	--NR--	×	--NR--	×	--NR--	×
P7	×	×	6	×	×	3	×	×	×
P8	×	×	×	×	×	×	×	×	7
P9	×	--NR--	1	×	×	7	×	✓	7
P10	×	×	6	×	×	6	×	×	5
P11	×	✓	7	×	✓	7	×	×	7
P12	×	×	×	✓	×	6	✓	✓	5

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ --*NR*-- (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

The final winter storm survey included questions asking participants to identify the advisory, watch or warning bulletins they recalled ECCC issuing and to assess how well the predictions from ECCC compared to what they experienced during the storms. Although no respondent successfully identified all of the bulletin types issued in all three storms, between 70 and 90 percent selected at least one valid advisory or warning for each storm. At least half of all participants also selected a bulletin type that was not issued by ECCC during WS2 and WS4. These observations suggest that participants give greater attention to the general 'warning' condition rather than details about any specific hazard, impact or recommended actions in the message content.

While respondents were generally satisfied with the appropriateness of their responses to the winter storms analyzed, half of the participants indicated that they would, more likely than not, have made different decisions in one or more events if they had better knowledge about the storm or travel conditions. Most of these people offered specific situations and/or examples of how information might have better enabled their decisions, for example:

> *My daughter didn't bring home her homework the day before school was cancelled. I would have reminded her [if] I had known the storm would likely cancel school. I would have done an extra errand the night before. (P9 during WS3)*
>
> *Might not have traveled to [work location] on Wednesday. Wasn't expecting conditions to be that bad! (P6 during WS4)*
>
> *Less snow than expected - perhaps activity didn't need to be cancelled.(P12 during WS2)*

Such comments indicate discrepancies between what participants experienced and what they expected, in part based on ECCC warnings which are broadly communicated by the federal government, TWN, and other media outlets on a variety of platforms. Half or more of respondents felt that ECCC predictions underestimated snowfall amounts (WS3), accumulation or duration of freezing rain (WS3,WS4), and when storms ended (WS3,WS4). Over 50 percent also reported that WS2 ended earlier than forecast by ECCC. Prior to assessing ECCC predictions, participants were asked to compare their overall expectations with what they experienced for the same set of hazards in each storm. The proportion of participants stating that ECCC forecasts were 'as predicted' was greater than for participants' overall expectations related to precipitation and visibility. Conversely, the proportion of participants stating that ECCC forecasts were ‘as predicted’ was less than for participants’ overall expectations regarding when the storm event would begin. This implies that other sources of weather-related risk information may modify expectations derived from official warnings issued by ECCC.

In summary, study participants consulted an increasing number of formal and informal sources of weather-related information as winter storms progressed. Informal sources were mainly relied upon after the storm began and when specific activity and trip decisions were made. These variations across the lifecycle of winter storms have not been reported in other studies, though distinctions in information acquisition have been noted between pre-travel and enroute stages of trips (Brazil et al. 2017). In terms of sources, the relatively limited use of weather-related information from TV observed in the current study was in stark contrast to previous comparable research (post-storm surveys) in the United States where TV or local TV broadcasts were identified as the primary means of acquiring information (Barjenbrunch et al. 2016, Drobot 2008). That imperfect accounts of warnings were obtained while the weather event was just ending or weakening suggests potential for even greater recall error if measured days or months following a storm.

Hazard perceptions

Official weather warnings issued by ECCC and other national meteorological services have been designed to communicate information to the public about the potential occurrence and severity of hazardous weather events (WMO 2015b). Such knowledge can increase hazard perception (Burton et al. 1993) which may explain positive correlations between the use of weather forecast information and changes in intended or stated trip behaviour in most (e.g., Barjenbruch et al. 2016, Elevant 2013, Kilpeläinen and Summala 2007) but not all (e.g., Cools and Creemers 2013) studies focused on winter weather hazards.

In the current study, appreciating how people described and perceived ‘winter storms’ provided valuable context for interpreting their stated concerns, intentions, decisions and behaviour. During the pre-season interviews, participants defined a winter storm based upon expected impacts or consequences and then related these to meteorological hazard criteria commonly referenced in government-issued warnings. Several participants mentioned specific snowfall amounts (e.g., >5cm, 10cm, 10-15cm), presence of freezing rain, temperatures near freezing, and poor visibility. Discussions of these attributes, however, were universally preceded or contextualized with mobility or safety-specific terms, including: *icy roads*; *treacherous conditions*; *bad roads, not safe to drive*; *so much snow that we can't get out*; *when people stay home*; *can't see in terms of driving; when things might be shut down*; *risking safety*. In other words, interviewees understood and framed winter storm hazards principally by concern, impact or outcome rather than by meteorological quantities, though they easily and readily connected the two. Certain characteristics were emphasized or deemed less important based on individualized situations or experiences. For example, cold temperatures and windchill were particularly important to one household with asthmatic children (participant P5). Another participant (P12) suggested that only snowfall amount thresholds well above warning criteria were of significance to them given their household's investment in all-wheel drive vehicles and winter tires as well as close proximity to their workplaces.

During the storm surveys administered prior to (Survey A) and just after (Survey B) ECCC issued a warning, participants were asked whether they believed that a winter storm would affect the Region of Waterloo at some point in the next 72 hours and to rate their confidence in this expectation. Complementary questions, administered during surveys at the peak of the storm (Survey C) and again when conditions improved (Survey D), asked participants to state when they believed the storm began and ended. The final survey also requested participants to rate the severity of winter hazards experienced during the peak of the storm. Responses to all of these questions informed understanding of participant perceptions about the nature and severity of winter storm hazards.

About 86 percent of 74 valid responses over the first two survey stages (A,B) in all events stated that a winter storm would occur while the remaining 14 percent expressed beliefs that a storm would fail to materialize. With the exception of one participant during WS2, all statements that a storm would not occur were made during the first survey stage—each of these participants changed their expectation to believing a storm would occur following the issuance of official ECCC warnings.

Confidence in storm expectation beliefs, indicated on a scale of 1 (*not at all* confident) to 7 (*very* confident), varied by storm and survey stage. Confidence was lowest during WS1A (M=5.0) and highest in WS3B (M=7.0). Participants who expressed belief that a winter storm would not occur were consistently less confident in their opinion compared to those who expected a storm would affect the Region. Confidence increased between the first and second survey stages for 15 of 28 valid response pairs while only decreasing on two occasions, both where storm expectation beliefs changed. Confidence remained constant for the remaining response pairs. Overall this suggests that, for most participants, ECCC warnings contribute to enhanced or at least maintenance of confidence in winter storm expectations.

Input from responses to the third (C) and fourth (D) surveys provided additional information regarding participants' perceptions of winter storm hazards. As part of the third survey, administered during the height of the storm, respondents were asked to assess the severity of four hazards during the worst of the event: slipperiness of walking and driving surfaces, visibility, amount and duration of precipitation, and temperature or windchill. Based on median or average responses, participants experienced the worst visibility and coldest temperatures during WS2, the most problematic amounts of precipitation in WS4, and the most slippery conditions in WS3. Composite rankings, assuming equal weighting among the hazards, indicated that WS4 was the worst winter storm experienced by participants, followed by WS2 and then WS3. These measures of central tendency in the small sample, however, don't reveal the wide interpretation apparent in the distribution of ratings during any particular storm. As shown in Figure 4-8, individuals subjected to the same or similar meteorological conditions perceive the severity of specific travel-related hazards somewhat differently.

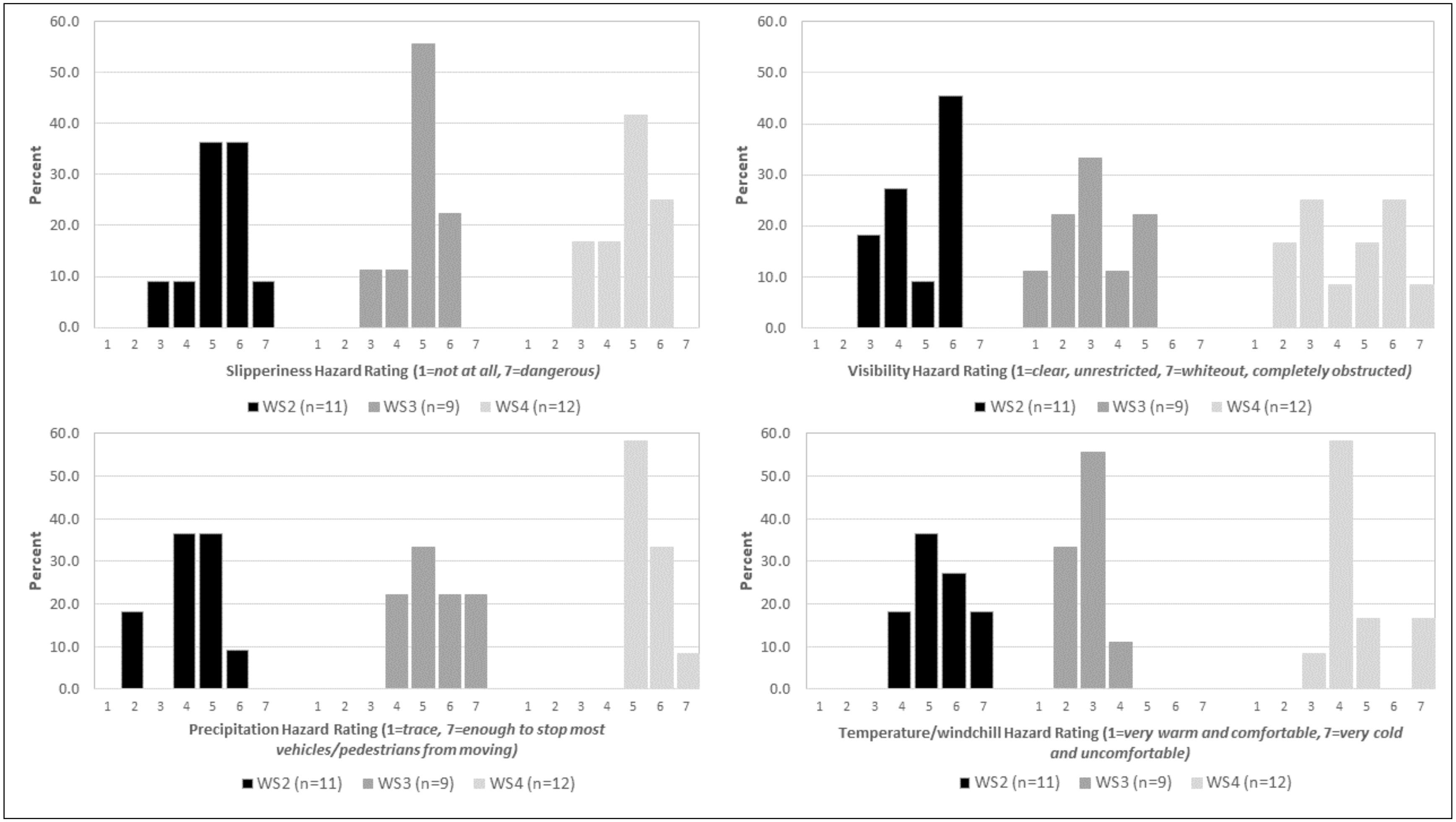


Figure 4-8. Perceptions of hazards during peak winter storm periods.

This generalization was further reinforced by participant estimates of the date and time that they believed the current winter storm began (Survey C) and ended (Survey D)[6]. Table 4-10 shows highly variable estimates of timing and duration inferring that participants perceive and recall similar conditions differently and, confirming what became apparent during the pre-season interviews, apply unique criteria and meanings in defining what constitutes a winter storm.

Table 4-10. Perceptions of winter storm timing and duration (all times local).

Timing Variable	Winter Storm 2	Winter Storm 3	Winter Storm 4
Start (date, time)			
Earliest	Jan 28 (10:00)	Feb 6 (00:00)	Feb 11 (23:00)
Latest	Jan 28 (16:00)	Feb 6 (05:00)	Feb 12 (12:00)
Median	Jan 28 (12:30)	Feb 6 (05:00)	Feb 12 (05:30)
Ended (date, time)			
Earliest	Jan 29 (01:00)	Feb 6 (10:00)	Feb 12 (21:00)
Latest	Jan 29 (12:00)	Feb 7 (17:00)	Feb 13 (23:00)
Median	Jan 29 (10:00)	Feb 6 (22:30)	Feb 13 (16:00)
Duration (hours)			
Minimum	9.0	12.0	12.0
Maximum	24.0	36.0	48.0
Median	22.0	29.0	33.0

Three main points emerge from this examination of hazard perceptions. First, winter storm expectation beliefs and confidence in those beliefs increased following the issuance of official weather warnings by ECCC. Second, individuals affected by the same winter storms and synoptic meteorological conditions perceived and experienced the severity, timing, and duration of travel-related hazards differently. Attempting to capture and represent such variability in a single public weather warning statement would be challenging, yet may not be necessary to raise threat awareness and understanding given the third point—that winter storms were defined first and foremost by their expected impact, consequence, or outcome to the participant and household. Most respondents were adept at relating these important attributes

[6] The free-text format of the question allowed respondents to indicate if they did not believe it had started or ended.

to the meteorological language and threshold criteria contained in traditional weather warnings. Unfortunately, as noted by Mills et al. (2019, 2020), this fusion has not sufficiently altered behaviour to completely offset elevated injury risk outcomes during winter storms.

Nevertheless, if this ability to translate or adapt official warning information into personal relevance and meaning is commonly held among the population, it may present issues for those attempting to measure the benefits of changes to improve the content or quality of warnings. Take for example public 'impact-based weather warning services' advocated by the World Meteorological Organization (WMO 2015b) and currently being piloted by many national weather service agencies (e.g., UK Met Office, Météo-France, US National Weather Service, ECCC) to design warning thresholds, communications, and services with greater emphasis on the impacts of weather events. Given the results of this study, the new service and language of the impact-based warning information may be merely replicating or acknowledging what people already think and do on their own for the most part. The lack of strong behavioural effects observed in the few empirical evaluations of impact-based warning information (Potter et al. 2018, Taylor et al. 2019, Weyrich et al. 2018) lend credence to this assertion.

Perceived concern

Higher levels of concern, and affect more generally, are also thought to lead to greater likelihood of adopting protective actions and behaviour (Drobot 2008, Weyrich et al. 2020b). Pre-season interviewees were prompted to rate their general level of concern (1-*not at all* to 7-*very*) after learning in a hypothetical scenario that a winter storm will affect the region. The median rating (3.5) divided a group of participants with minimal concern and another group with moderate to high levels of concern. Several people conditioned their initial estimates suggesting that concern would be greater in situations where long-distance trips were necessary, freezing rain was expected, travel occurred during nighttime, or where activities involved significant commitments (e.g., employment responsibilities, sports teams, school exams, etc.).

Further probing revealed more about the objects and outcomes of people's concern. All but two participants focused their discussion exclusively on personal vehicle travel. Fall-related risks were not top-of-mind even though, when prompted, four interviewees recalled a serious outdoor fall by a family member in previous winters. Safety outcomes from MVCs were routinely identified as the most important source of worry; property damage to vehicles seemed to matter little with the exception of one participant whose employment depended on access to a working vehicle. Like safety, reaching destinations on time was a universally significant contribution to overall concern, particularly when activities involved commitments to others (i.e., work, but also organized sports, hobbies, and social activities). This may explain why participants consistently expressed less worry about the timing of returning home after activities and errands and why several interviewees had significant reservations about cancelling and missing valued activities because of poor weather and road conditions. Other sources of concern, such as potentially becoming stranded, were of little consequence to the participants except for infrequent trips made outside of the region.

Interviewees offered or were prompted to compare their personal concerns with those of other household members. Five participants, almost half the sample, mentioned that their spouses/partners were either much more or much less concerned about travelling during winter storms. A few also mentioned that their children expressed some anxiety when driving in poor weather but, for the most part, emotions of anticipation and excitement were more prevalent among elementary school-aged kids given the potential for school closures and bus cancellations.

Most participants expressed concern beyond their own personal trip and activity plans. Whether or not the interviewee was traveling themselves, concern was frequently expressed for other household members reaching destinations and returning home safely during stormy conditions. A few interviewees also recalled worrying about neighbours, especially those who were elderly and less able to clear their driveways after heavy snowfalls. Several participants who were responsible for coordinating activities (e.g., sport practices, church or social functions, carpools) extended their field of concern to include others suggesting that they had a lower tolerance to travel during poor conditions and a preference “not to take chances”. Despite this, a couple of participants felt they had to attend in case others did not get the cancellation message and showed up at the activity location.

In addition to concern for others, half of the participants remarked that some of their anxiety during winter storms was attributable to the behaviour of other people. Specific mention was repeatedly made of other drivers who were unable or unwilling to take certain precautions (e.g., drive slower, leave greater distance between cars) or to properly equip or maintain their vehicles (e.g., winter tires, snow/ice cleared from windows). Also noted were city residents or business owners who failed to adequately clear snow and ice from sidewalks thus making walking more dangerous.

Perceived levels of concern were measured repeatedly during the study. General concern was established in the first two surveys (i.e., during pre- or early storm stages) while the third survey, administered at the peak of each storm, was used to assess the various aspects of concern discerned from the baseline interviews. The maximum rating from the third survey was compared with the first two stages. All ratings were acquired using a scale of 1 (*not at all* concerned) to 7 (*very* concerned).

Participant concern levels varied by storm, stages within each storm, and between storm and baseline responses. In terms of storm comparisons, WS3 (M=6.0) was the most troubling to participants followed closely by WS4 (M=5.0). Eight of 12 participants assigned their maximum concern (6 or 7) to one or more stages of WS3. Nine of 12 participants gave their minimum concern rating (1 or 2) to WS2.

Expressions of concern also differed over the course of individual storms. For the subset of participants that provided valid responses to all WS2, WS3, and WS4 surveys, levels of concern were higher in each storm after official weather warnings had been issued by ECCC. Considering first- and second-stage surveys, participants raised their level of concern in 17 out of 28 situations. No change was observed eight times (five of these were rated very high—6 or 7) while concern dropped in only three instances.

Concern was measured in a disaggregated manner in the third survey, administered at the peak of the winter storm. Ratings were requested for seven outcomes mentioned during the pre-season interviews (Table 4-11). The maximum level expressed across all categories was used to represent each respondent, necessarily assuming that concern is not ‘additive’ or ‘averaged’ across subcomponents. Observations from 28 valid paired responses between the second (just after warning issued) and third (peak of storm) surveys indicated that participants raised, maintained, or lowered their level of concern in 17, eight, and three times, respectively. In cases where ratings did not change, concern levels were very high (6 or 7).

Table 4-11. Levels of concern expressed during the peak stage of each winter storm.

CONCERN CATEGORY	MEDIAN (AVERAGE) WINTER STORM RATING		
	Winter Storm 2	Winter Storm 3	Winter Storm 4
Extra stress/anxiety	5.0 (4.9)	5.0 (4.9)	6.0 (5.8)
Arriving on-time	5.0 (5.1)	5.0 (4.8)	5.5 (5.4)
Cancel or defer trip/activity	5.0 (5.4)	6.0 (4.8)	6.0 (5.2)
Getting stranded	2.0 (2.8)	2.0 (2.3)	3.0 (3.2)
Damage to vehicle	4.0 (4.1)	4.0 (4.3)	5.0 (5.4)
Injury from collision or fall (safety)	5.0 (4.9)	4.0 (5.0)	5.0 (5.3)
Significant others (family, friends)	5.0 (4.8)	6.0 (5.7)	5.5 (5.7)
Maximum rating (any category)	6.0 (6.2)	6.0 (6.0)	6.0 (6.3)

To synthesize, levels of concern increased once ECCC warnings were issued, and either continued to rise or remain very high through the peak of the sampled winter storms. Once a high level was achieved, concern rarely lessened. These observations are consistent with those found in this study for hazard event expectations. While the storm survey results suggest a simple and positive relationship between ECCC information and concern, the pre-season interviews exposed a more complex mechanism underlying the ratings. Evidence of multiple dimensions of concern (i.e., plurality of objects, relevant outcomes/consequences, and sources) was found, with expressed levels often varying by household member, both within and between winter storms. The relative importance of safety concerns (i.e., vehicle collisions) to participants was higher during the pre-season interviews compared to levels observed during actual storms, while concern for activity cancellation or being late remained very important. It therefore might be more effective to emphasize in weather warning bulletins the disruptive implications of winter storms in addition to those associated with safety. Lastly, from a methodological perspective, results indicate a strong sensitivity to measurement timing, with reported levels of concern varying when assessed pre-season, between storms, and within different phases of a storm. Findings also raise questions about the adequacy of measuring concern based on a single dimension, such as self-reported anxiety (e.g., Drobot 2008).

An incomplete frame and fuzzy empirical picture

Returning to the larger research question, the above analysis confirmed the general relevance of four factors in making mobility decisions during winter storms: response choice and efficacy, attributes of weather-related information sources and use, hazard perception, and perceived concern. A wide range of potential responses was readily identified and used by participants to manage winter storm risks; however, individual intentions and behaviours varied considerably within and between storms, likely limited by and reflective of situational circumstances and interdependencies among behaviours. Official warning information appears to have been acquired and used by participants primarily to establish heightened awareness and more confident expectations of hazardous conditions, with attendant increasing levels of concern in advance of storms. Personal and other forms of weather-related information seemed to be more important in supporting specific trip and activity intentions during and immediately prior to the storm.

This descriptive narrative of relevance, however, fails to offer much explanation for the weak links observed between intentions and behaviour and the possible interactions among the factors identified. It also offers little reasoning for the considerable variability evident in the views, intentions and stated actions of individual participants at different stages of measurement (pre-season, between winter storms, within winter storms). Established theories of social change such as TPB may help to clarify the "how" and the "why" of the picture thus far framed by the empirical account and to further probe the influence of weather-related risk information on trip behaviour and mobility practices.

4.4.2 A Theory of Planned Behaviour (TPB) perspective

TPB overview

Likely the most widely tested and applied model in health and safety intervention evaluation, the TPB (Ajzen 1991, 2011; Fishbein and Ajzen 2010) is one of several social-cognitive models that attempt to understand what motivates the deliberate choices and actions of individuals. Other related models include Social Cognitive Theory (Bandura 1991), the Health Belief Model (Janz and Becker 1984), Protection Motivation Theory (Rogers 1975), the Protective Action Decision Model (Lindell and Perry 2012), and the Theory of Reasoned Action (Ajzen and Fishbein

1980), a precursor to the TPB. The TPB contends that individual action is explained largely by the strength of one's intentions modified by perceived and real constraints on their ability to perform and control behaviour. The predictive ability of the original model, as represented by the black-coloured constructs in Figure 4-9, is dependent on being able to measure intention, its attitudinal and social norm belief antecedents, and perceived control very precisely and in close temporal proximity (i.e., when the behaviour occurs) to a well-specified subject behaviour.

For illustration, understanding why someone would choose to cancel a trip because of poor weather would involve appreciating the individual's beliefs that form an outcome expectancy of performing the behaviour and a positive or negative attitude towards the cancellation; the expectations of significant others like family, friends, and peers (subjective norm); and their perceived ability to cancel the trip. Together, these factors would drive an individual's overall intention to cancel and, combined with any external constraints affecting their choice (e.g., options to re-book, resource limitations, physically impassable roads), guide their actual behaviour. The direct link between perceived control and the actual behaviour, unmediated by intention, is represented by the dashed line in Figure 4-9.

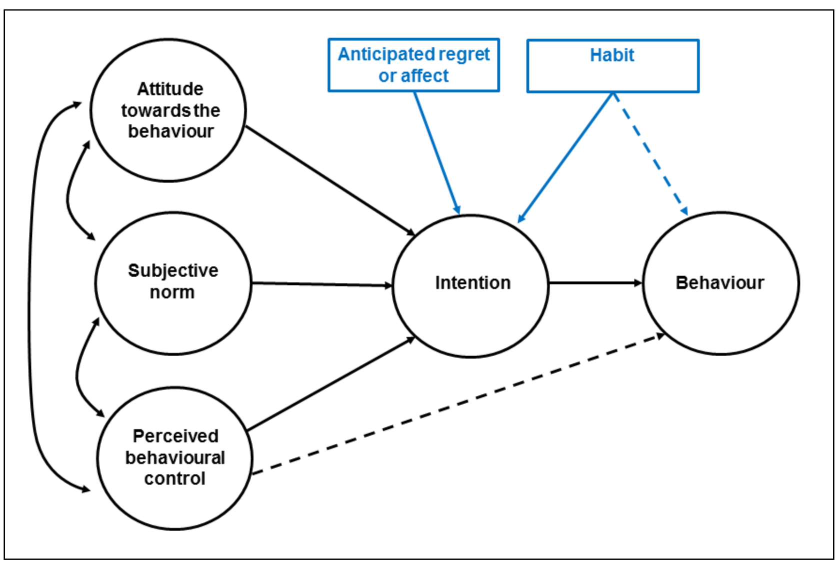


Figure 4-9. Main constructs represented in an extended Theory of Planned Behaviour (TPB) model (Ajzen 1991, 2011; Elliott and Thomson 2010; Richard et al. 1996).

The TPB has been used in several transportation-related applications, including studies on the effectiveness of safety interventions like seat belt use (Simsekogluw and Lajunen 2008), or the propensity to commit driving violations like speeding (automobiles, Forward 2009; motorcycles, Chorlton et al. 2012), drowsy driving (Lee et al. 2016), texting distractions (Prat et al. 2015), and driving while under the influence of alcohol (Parker et al. 1992). Pedestrians have also been the subject of study, with some researchers targeting risky behaviours such as distracted street crossing (e.g., Barton et al. 2016) and others examining motivations for adopting healthier modes of travel (Sun et al. 2015). Additional TPB applications include investigations of departure time choice (e.g., Thorhauge et al. 2016), effectiveness of incentives to encourage public transit (e.g., Bamberg et al. 2003), and modal choice more generally (e.g., Mann and Abraham 2012, Donald et al. 2014).

No TPB applications were found that dealt explicitly with weather-related information as it influences trip decisions. However, studies have considered the willingness of people to drive through flooded roadways (Pearson and Hamilton 2014), investigated avalanche-related information-seeking behaviour of snowmobilers (Baker and McGee 2016), and evaluated seasonality effects on walking behaviour (Williams and French 2014). Hoss and Fischbeck (2018) used TPB to examine emergency managers' use of short-term weather forecasts and observations, and a few researchers have applied TPB in studying intentions to use climate information in farming decisions (Artikov et al. 2006, Hu et al. 2006, Sharifzadeh et al. 2012).

A significant amount of empirical research has accumulated in the applications noted above and in dozens of other studies that validate the TPB and its ability to explain variance in intention and behaviour, whether self-reported or observed. Statistical analyses and tests are conducted to determine the strength and significance of variables in explaining intentions and self-reported or independently analyzed behaviour. Meta-analyses that synthesize results from dozens of empirical tests for a wide range of behaviours report mean correlation (R) values between intentions and behaviour from 0.40 to 0.53 (Armitage and Conner 2001, McEachan et al. 2011). Mean multiple correlations between intentions and a combination of its three antecedents (attitude, subjective norm, perceived behavioural control) for an even larger number of studies range from 0.40 to 0.67 (Ajzen 2011, Armitage and Conner 2001, McEachan et al. 2011, Rivis and Sheeran 2003).

While empirical research generally validates the TPB and its constructs, much variation in both intention and behaviour remains unexplained. Such belief-intention and intention-behaviour "gaps" are chief reasons why many researchers have sought to identify and graft additional independent variables onto the TPB, a scenario that the original model developers have readily encouraged where empirically justified (Ajzen 2011, Fishbein and Ajzen 2010). New predictive variables have been introduced to the TPB to account for behaviours that are not fully volitional and thus driven more by intuitive or heuristic information processing of cues and emotions rather than cognitive-intensive reasoning (i.e., System 1 of dual processing models, Evans 2008). As shown in Figure 4-9, these extra factors include anticipated affect or regret (Richard et al. 1996) and the concept of habit (Triandis 1977, Verplanken and Orbell 2003) both of which can be invoked in explanations as to why behaviour deviates from what would be anticipated from a strictly rational or expected-value perspective.

Other researchers have refined the existing TPB constructs by distinguishing dimensions that uniquely contribute to explaining intentions and behaviours. Attitudes have been broken into instrumental (associated with cognitive assessment) and experiential or affective (feelings toward behaviour) components; subjective norms have been split into injunctive (beliefs about significant others' opinions about what a person ought to do) and descriptive (what significant others actually do) elements; and perceived behavioural control has been parsed into self-efficacy (capacity to control internal factors) and perceived control or autonomy over external factors (Ajzen 2011, Elliott and Thomson 2010, Richard et al 1996, Rivis and Sheeran 2003).

Of fundamental importance to the current study, however, is the nature of the evidence used to validate and extend the TPB. Surveys are typically used to measure each contributing independent TPB belief variable and the dependent variables of intention and behaviour. Single- or multi-item statements are offered to respondents who indicate their level of agreement, preference, or emotive state (i.e., binary or a scale, typically strongly agree—strongly disagree). The insights from the current study raise questions about the fundamental validity of this approach for rapidly changing circumstances, such as weather-related travel risks.

TPB application and findings

Information from both the pre-season interviews and winter storm surveys was used to examine the TPB and interrogate its ability to explain aspects of trip and activity behaviour during winter storms. Interview transcripts were coded to identify references to salient beliefs associated with the core attitude (instrumental, experiential), subjective norm (injunctive, descriptive), and perceived behavioural control (autonomy, capacity) constructs within TPB. Anticipated regret and habit variables, added to the TPB through previous research, were also coded as were references to actual external controls on behaviour. Examples for each construct, with reference to the intended behaviour, are provided in Table 4-12.

All forms of trip-related behavioural response to deal with winter storm conditions were considered during the coding, most having been identified earlier in Table 4-2. Salient beliefs were offered by at least 10 participants for seven of the nine TPB constructs. Beliefs corresponding to descriptive subjective norm and actual control constructs were provided less frequently, only by seven and four respondents, respectively.

In several cases, references to multiple constructs were coded from single statements. For example, the excerpt below reveals salient beliefs that contribute to both instrumental (rational evaluation of safety because vehicle is bigger and you're higher up) and experiential (affective aspect of feeling 'safer' relative to their other vehicle) attitude.

> *I prefer to drive in the van when it's bad, when there's a storm, because I just feel safer in it. I just feel, I feel it doesn't slide as much as the car. I just feel safer in it too, because you're up higher and it's bigger. (P1)*

Responses were specific not only to the behaviour, but also to the particular activity and situation. The comment below is indicative of a salient normative belief wherein the participant's trip decision is based in part on values towards important referents, in this case other soccer player teammates and families, who would be affected if the participant's child did not participate. This normative belief did not appear to extend to situations involving other activities for this household.

> *I think if it's not too bad, if I think it's safe to drive, then I will probably still drive my son to the soccer because he is on a team and that's a commitment. If he doesn't come, then the rest of the team members have to work harder…the rest of the activities, I will probably just skip, if we have winter storm notice. (P2)*

Table 4-12. Examples of references to salient beliefs underlying extended Theory of Planned Behaviour (TPB) constructs obtained through pre-season interviews.

TPB Construct	**Intended behaviour**	**Participant belief/comment***
Attitude (Instrumental)	Trip/activity cancellation or deferral	*…we did seriously think about that night if we were going to go to swim lessons or not and, um, and I just thought it wasn't that far so it wasn't a big deal even if there was a lot of snow. (P3)*
Attitude (Experiential)	Change the mode of travel	*[My spouse] would be worried about trying to bike in that, ice. [My spouse] has walked, for sure…[my spouse] but doesn't like to do that, cause it's going to take, like, three times as long, probably. [My spouse] would never drive there. (P5)*
Subjective Norm (Injunctive)	Trip/activity cancellation or deferral	*I mean honestly my spouse's opinion, I would want to take that into account, not just my own. (P10)*
Subjective Norm (Descriptive)	Trip/activity cancellation or deferral	*…if everyone is not going, it must mean conditions are really bad. (P2)*
Perceived Behavioural Control (Autonomy)	Trip/activity cancellation or deferral	*Well, we get, like I get stressed because we always have something to do. So, it's not that I prefer like driving in it, but I just kind of have to so that's why I do it, otherwise I would stay home.(P8)*
Perceived Behavioural Control (Capacity)	Change the route taken	*I will always favour the route less taken if it's bad outside. So I prefer less people around me because I'm confident in myself but I'm not comfortable with the idiots around me. So I'll take a country road even though it's not very well plowed and everything because I know I can drive on it but I know that there's not going to be hardly anyone around me so I consider it safer for me. (P7)*
Actual Behavioural Control	Trip/activity cancellation or deferral	*In our street [winter maintenance by City] doesn't get done in time and the problem is our house is almost at the end of the block so when the truck cleans, there is always a huge [windrow; you get everyone else's snow]. Oh my god, it's terrible. Us and our neighbour, we're the worst, and we got stuck a few times. (P6)*
Anticipated Regret	Trip/activity cancellation or deferral	*…if I've been with the kids all day and I really wanted to get a little break, and let's say I was going to the gym, and that was my break, then I'd feel like "ah, should I risk going out in this weather?" Sometimes I will and sometimes I won't. But if I don't then I feel frustrated that I didn't get to go. (P9)*
Habit	Departing earlier to reach destination	*Every time that there is any weather event that could extend the driving time, I will add time…There's always extra time being padded in because I'd rather just get there early. Now, in reality, I tend to be a more "on-timer" so I have to add that padded time or even if it's 5 minutes of scraping the car puts me late so I have to add that time on top. (P12)*

*participant reference in parentheses at end of comment; coding and benign gender references used to protect anonymity

Satisfied that the TPB constructs emerged and were sufficiently discernible from the semi-structured interviews, the winter storm surveys were finalized to permit measurement of two types of behaviour taken in response to winter storms: 1) cancellation or rescheduling of trips and activities, and 2) departing earlier to reach a destination. These particular behaviours were chosen since they were frequently mentioned by participants during the interviews (Table 4-2) and could directly affect the extent of exposure to winter storm conditions. Importantly, relative to other commonly adopted responses (e.g., seasonal preparations such as winter tire installation; in-transit precautions; winter maintenance), the chosen behaviours and antecedent beliefs were expected to be more sensitive to the influence of short-term, storm-specific weather warnings and related information issued by ECCC and media outlets.

To investigate the validity of TPB, participants were asked during the second survey, following issuance of official weather warnings by ECCC, to rate the strength of their intent to perform the behaviours. They were also asked to answer a series of questions designed to evaluate experiential and instrumental aspects of attitude, injunctive and descriptive components of subjective norm, autonomy and capacity elements of perceived behavioural control, and anticipated regret. Reported actual behaviour was measured in the subsequent surveys taken at the peak of the storm and again after conditions improved. Consistent with Fishbein and Ajzen (2010), questions were structured as in standard TPB studies and ratings were assigned using a series of seven-point semantic differential scales, each with bipolar adjectives (e.g., very bad to very good) (Appendix B).

The consistency of each independent TPB construct with measures of intent and actual behaviour was assessed. Figure 4-10 illustrates the specific responses from one participant over the course of two sampled winter storms to questions probing trip/activity cancellation or deferral behaviour. For WS2, the top panel in Figure 4-10, all but one measure was consistent with the anticipated influence on behavioural intent. The behaviour was expected to lead to a bad outcome and unpleasant experience, unlikely to be supported by the opinions of significant others, difficult to perform, out of the participant's control and, if executed, result in a feeling of regret. These responses were consistent with the 'very unlikely' intention to cancel or defer trips reported by the participant as well as their actual reported behaviour (i.e., did not cancel/defer). The 'descriptive subjective norm' measure was neutral. In contrast, during WS3, only the 'injunctive subjective norm' and 'autonomy' measure of perceived behavioural control were consistent with the 'very likely' intent to cancel or defer trips and actual reported behaviour. Both aspects of attitude were inconsistent with stated behavioural intent while the remaining measures (descriptive subjective norm, capacity to perform, anticipated regret) were neutral.

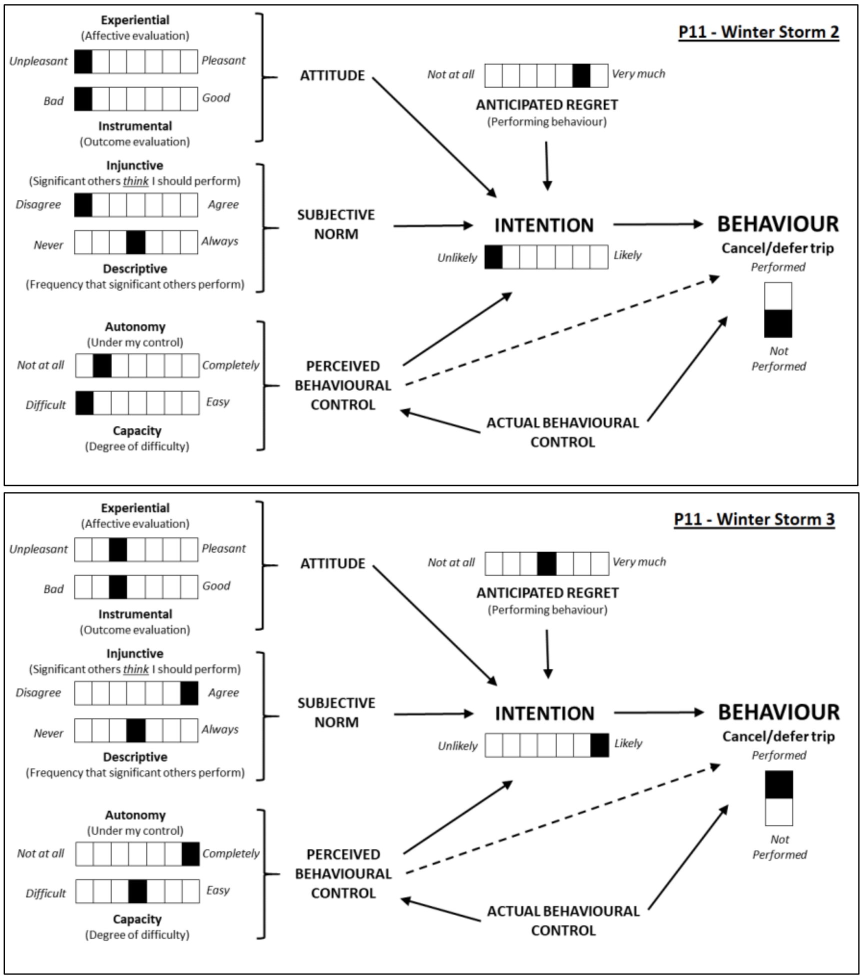


Figure 4-10. Example of TPB results for trip/activity cancellation or deferral behaviour (participant P11 during WS2 and WS3).

Analyzed similarly and compiled for all participant responses across all storms for each behaviour, one begins to decipher patterns (Table 4-13). Composite variables noted in the table represent the average ratings of the underlying subconstructs specific to attitude, subjective norm, and perceived behavioural control. The strength of consistency for each construct was assessed by determining whether the percentage of *consistent responses* met the following incremental thresholds: 1) exceeded that for inconsistent responses (low level of consistency); 2) accounted for one-half to two-thirds of all responses (moderate level of consistency); or 3) represented two-thirds or more of all responses (high level of consistency). Failing the first criterion inferred the presence of an *inconsistent* relationship.

TPB constructs in general were moderately consistent with intention to cancel or defer a trip/activity. The first criterion held for all but the subjective norm variables. The second threshold was satisfied for overall attitude, composite PBC, autonomy, and anticipated regret, while the third criterion was never met. Intention to cancel or defer a trip/activity was moderately consistent with actual reported behaviour. Belief associations with actual behaviour were weaker for attitude (low consistency) and subjective norm (inconsistent) measures, but similar for perceived behavioural control and anticipated regret (moderate consistency). Although assessed differently given the small sample, findings about the relative consistency of TPB constructs generally agreed with TPB studies employing regression analyses of large samples; such studies often observe lower significance for subjective norm constructs relative to attitude and perceived behavioural control, and overall weaker relationships with behaviour, whether direct or mediated through intention (Fishbein and Ajzen 2010).

Table 4-13. Consistency between TPB constructs, intention and behaviour (all storms combined).

	Percentage of responses indicating Consistent (C), Neutral (N), or Inconsistent (I) relationships between TPB construct and intention or behaviour*											
	Trip/activity cancellation or deferral						**Earlier departure**					
TPB Construct	**INTENTION**			**BEHAVIOUR**			**INTENTION**			**BEHAVIOUR**		
	C	**N**	**I**	**C**	**N**	**I**	**C**	**N**	**I**	**C**	**N**	**I**
Attitude	**53.1**	6.3	40.6	46.4	14.3	39.3	***71.0***	12.9	16.1	37.0	22.2	40.7
Experiential	43.8	18.8	37.5	35.7	25.0	39.3	**61.3**	19.4	19.4	37.0	25.9	37.0
Instrumental	43.8	18.8	37.5	42.9	25.0	32.1	***74.2***	6.5	19.4	40.7	14.8	44.4
Subjective Norm	40.6	9.4	**50.0**	25.0	10.7	**64.3**	***80.6***	6.5	12.9	48.1	11.	40.7
Injunctive Norm	43.8	21.9	34.4	25.0	25.0	**50.0**	***87.1***	0.0	12.9	44.4	7.4	48.1
Descriptive Norm	31.3	18.8	**50.0**	21.4	17.9	**60.7**	***77.4***	6.5	16.1	**51.9**	14.8	33.3
Perceived Behavioural Control	**50.0**	12.5	37.5	**53.6**	10.7	35.7	***80.6***	6.5	12.9	44.4	14.8	40.7
Autonomy	**53.1**	12.5	34.4	**50.0**	14.3	35.7	***83.9***	3.2	12.9	40.7	11.1	48.1
Capacity	46.9	15.6	37.5	42.9	17.9	39.3	***71.0***	9.7	19.4	40.7	18.5	40.7
Anticipated Regret	**55.6**	14.8	29.6	**55.6**	14.8	29.6	***74.2***	6.5	19.4	44.4	14.8	40.7
Intention	-	-	-	**53.6**	14.3	32.1	-	-	-	42.9	14.3	42.9
N	32[a]	32[a]	32[a]	28[b]	28[b]	28[b]	31	31	31	27[c]	27[c]	27[c]

bold percentages** indicate half or more valid responses; ***italicized bold percentages indicate two-thirds or more valid responses

[a] n=31 for Anticipated Regret measure

[b] n=27 for Anticipated Regret measure

[c] n=28 for Anticipated Regret measure

A different pattern emerged for the other behaviour that was examined. All but one TPB construct achieved high levels of consistency with intention to depart earlier; the experiential component of attitude fell just short of the threshold but was still moderately consistent. Intention was inconsistent with actual reported behaviour and, in general, associations between belief variables and behaviour were weak with only descriptive norm being moderately consistent. Composite subjective norm, overall perceived behavioural control, and anticipated regret measures were found to have low consistency with actual behaviour. The observed intention-behaviour gap could result from poorly perceived real constraints on actual behaviour (e.g., extra time required to clean a vehicle, path or driveway prior to commencing trip) or possibly engrained habits (i.e., default to automatic regular routine/timing).

Modest differences were observed in overall consistency between belief constructs and intent or behaviour across individual storms, the most significant for actual early departure behaviour where intent and belief variables exhibited consistency during WS2 but inconsistency for WS3. Overall consistency results seemed to mask within-participant variation though. While belief strengths expressed by individual participants across the three storms were similar for early departure behaviour, they varied markedly by storm for cancellation/deferral behaviour as illustrated in Figure 4-10. This suggests that, for certain behaviours, individual attitude, subjective norm, and control beliefs may be unstable and thus subject to other storm-specific and contextual factors.

TPB and the influence of weather information as an intervention

Based on the above assessment of consistency, the TPB constructs reasonably accounted for overall intentions to perform two specific behaviours in response to winter storms: cancellation or deferral of trips/activities and departing earlier to reach destinations. Intention was modestly consistent with self-reported performance of the former behaviour and inconsistent with the latter. Given these mixed results, how might the TPB be used to better understand the influence of weather and related risk information, improve warning communications and adoption of recommended actions, and positively affect outcomes associated with trip/activity decisions?

An excerpt from an ECCC winter storm warning communicated during WS4, typical of the content and structure of most bulletins, provides a sense of what this type of information includes. Italicized bolding has been added to highlight behaviours recommended for adoption by the public to reduce risk.

> Winter Storm Warning…Hazardous winter conditions are expected.
> A winter storm with total snow and ice pellet amounts near 15 cm, freezing rain, and strong winds continues tonight.
> A wintry mix of snow, ice pellets, and freezing rain continues across the area late this afternoon. This mix of precipitation is expected to transition back to snow this evening. An additional 5 cm of snow is expected tonight.
> Wind has eased somewhat across the region, however strong easterly winds gusting near 70 km/h continue closer to the Lake Ontario shore. Visibilities have improved late this afternoon however local blowing snow is likely tonight as the precipitation changes back to snow.
> Total snowfall and ice pellet amounts near 15 cm are possible by the time snow tapers to flurries Wednesday.
> This weather is associated with a Colorado low that will cross Southern Ontario tonight into Wednesday.
> Consider ***postponing non-essential travel*** until conditions improve. There may be a ***significant impact on rush hour traffic*** in urban areas. If visibility is reduced while driving, ***turn on your lights*** and ***maintain a safe following distance***.
> Please ***continue to monitor alerts and forecasts*** issued by Environment Canada. To report severe weather, send an email to ONstorm@canada.ca or tweet reports using #ONStorm…(ECCC bulletin WWCN11 CWTO 122125, issued 4:25 P.M. EST Tuesday 12 February 2019)

Warning bulletins at earlier stages in this event also had noted that surfaces may become icy and slippery and recommended that people take extra care when walking or driving in affected areas. Postponing non-essential travel is equivalent to the trip/activity rescheduling or cancellation behaviour evaluated in Table 4-13 while reference to the potential impact on rush hour traffic is suggestive of the need to depart earlier, the second behaviour analyzed.

TPB posits that such warning information is influential to the extent that it generates or reinforces salient beliefs towards the behaviour, those that are associated with positive attitudes, supportive subjective norms, greater levels of perceived behavioural control, and reduced anticipated regret. Influence is arguably limited to the time until a firm decision or commitment is made. Empirically, results showed that while this varied across behaviours, the vast majority of decisions were made during or just prior to the storm commencing (Table 4-7).

Instrumental attitude seems to be the most significant and direct construct through which weather information affects individual salient beliefs. Positive instrumental evaluations of the effectiveness of the two behaviours examined depend in part on the ability of warning information to change or reinforce beliefs that conditions will be problematic enough to warrant taking such actions and that doing so will lead to beneficial outcomes. The warning bulletin excerpt above aligns with this thinking. Based on the increase in the variety of sources of weather information consulted by participants as the storms unfolded (Table 4-6), it seems that people seek confirmation of warning messages and/or clarity on additional situational details that might support their behavioural choices.

It is important to note that the bulletins do not target the affective element of attitude in relation to the subject behaviour (e.g., expected feelings or emotions associated with *postponing non-essential travel* as highlighted in the example warning bulletin). To be clear, this is different than altering warning messaging to utilize affect or emotion as a means of amplifying risk perception (e.g., through fear appeals). Evidence presented in the descriptive account (Section 4.4.1) already showed that concern for, and confidence in, the prospects of a winter storm occurring increase after warnings are issued. Instead, the cited affective void relates to the experience of engaging in the recommended behaviour—postponing or cancelling a trip and, more importantly, the attendant activity. While Table 4-13 showed little difference between either instrumental or experiential belief consistency with intention, a related and possibly overlapping variable that is also rooted in emotion—anticipated regret—was very consistent with both intention and reported behaviour. In other words, even when warning information evokes or reinforces a strong belief that avoiding travel is a rational choice, this logic may be overwhelmed by strong emotions of desire to participate in the activity, and expectations of regret if they cannot.

The potential influence of formal weather warning information through the subjective norm construct in TPB is less clear. No explicit or implicit reference to subjective norm beliefs is apparent in the language of the winter storm bulletin example or others reviewed for this study. The strength of the connection depends on each individual's social sphere and definition of who they value and consider to be important. Based on the interviews, which shaped the subsequent storm survey questions, this included spouses, other household members, friends, co-workers, and co-participants of social and recreational activities. Preferences for information sources could be assumed to be indicators of value and trust, such that the injunctive norm sphere might be expanded to include organizations such as TWN or ECCC—the former because it was most frequently cited (Table 4-6) and rated very useful, the latter because it is the 'official' government source of weather warnings, including those communicated via TWN. Conceivably then, efforts to raise the level of trust with such organizations or their public-facing representatives (e.g., weather presenters, expert meteorologists) might further encourage adoption of recommended behaviours.

Descriptive norm beliefs (i.e., taking cues from the behaviour of others) might be enhanced by facilitating greater access to evidence (e.g., text/numerical data, but also video or pictures) showing the extent that others are adopting recommended behaviours (e.g., live traffic[7] or transit participation levels, road closures; facility, organization, or activity closures and cancellations).To some extent social media already provides access to this type of information but it might be amplified further to increase normative belief strength (e.g., through a common platform alongside or integrated with weather warnings).

Control beliefs are unlikely to be strongly or directly influenced by information currently contained in short-term weather warnings. This includes beliefs about a person's perceived freedom or autonomy to make volitional decisions about—or the difficulty they anticipate experiencing in trying to perform—the rescheduling or early departure behaviours that were evaluated. General storm preparedness behaviours (e.g., winter tire installation, vehicle maintenance), as identified by many participants during the pre-season interviews, may be encouraged through seasonal information campaigns. In turn, adopting such preparedness measures may provide some people with a greater sense of control. Similarly, simply informing people of storm potential through longer-term weather forecasts/outlooks might afford them additional flexibility, and thus sense of control, to rearrange activities and trip demands. However, given the timing when most decisions seem to be made (Table 4-7), it appears doubtful that more advanced warning would have a large effect on public response.

Outside of the attitudinal variables in TPB, the greatest impact of weather information on trip decisions may be through the actions of other organizations that operate, regulate, or manage transportation infrastructure, education institutions, businesses, and various social and recreational activities. By closing offices or schools, implementing telework or remote learning policies, and cancelling activities, these organizations effectively reduce trip demands and exposure to winter storms or, in the case of winter maintenance by public and private sector

[7] For example, see Google Maps (https://www.google.ca/maps) or TomTom (https://www.tomtom.com/en_gb/traffic-index/)

agencies, ameliorate storm-related hazards and increase safety. All of these decisions that serve as controls on actual behaviour (e.g., school closures reducing trip demands) are influenced by weather information that formally or informally triggers action.

Issues and challenges with interpreting TPB theory

A few issues became apparent in working through and applying TPB to explain trip behaviour and guide weather information services. The first highlights a general difficulty in translating results of this or a more traditional TPB application to a focused direction for interventions such as improvements to weather warnings. Given the presence of a 'highly consistent' relationship between instrumental belief variables and intent, how realistic is it to expect further strengthening of this relationship through the provision of better information? The potential for diminishing returns might suggest focusing on normative or personal control beliefs for enhancement in order to leverage influence on intent and subsequent behaviour. Alternatively, one might use TPB to explicitly identify and target subpopulations that express weaker instrumental or experiential beliefs with appropriate tailored warning communications.

The other two issues relate to the specification and characteristics of the subject behaviour. Travel enables involvement in heterogeneous activities. This heterogeneity introduces variation in the measurement of TPB instrumental and affective attitudinal beliefs toward specific mobility behaviours (e.g., to drive or not drive, to change mode or not). One cannot separate the trip decision from the activity and the various psychological, social, and economic goals satisfied through participation. The pre-season interviews and storm surveys showed that variation is large between and even within generic categories of activity. For example, pre-season interviews showed that certain organized recreational and social activities were as or more 'essential' and 'inflexible' than work, which runs counter to general assumptions. Even within the broad 'work' category, participants remarked how demands to be present were not constant and this had a demonstrable influence on the type and degree of intended behavioural adjustment required to deal with winter storm conditions. In a post-Covid world, one would expect even more assessment of what constitutes high-priority, in-person activity, with implications for travel and exposure to weather-related mobility risks.

> *I've done that [telework] where you know what, it's not worth it to go all the way down to [work location] because: a) the traffic will be awful and, b) safety might be*

> *questionable…and if it's nothing I need to be in person to do something, I'll schedule a work from home day. There are other times where, and I've done this in the past, where I've got, you know, a formal meeting, maybe an executive meeting; there's like 10 or 12 of us and so I need to be there in person and I've got to be there for like 8:00 or 8:30 in the morning in [work location] and it's like a big storm overnight and I know it's going to be horrible in the morning, I'll make a decision to just drive down at night when there's not as many people on the road and stay in a hotel. (P6)*

This heterogeneity in activity importance, coupled with the uniquely perceived timing, duration, and severity of hazardous conditions, are an important consideration for other TPB applications where the subject behaviour, like mobility, is enabling in nature (e.g., water or electricity use) but intrinsically tied to a range of activities, needs and goals of variable importance.

The final issue, also reflected in the interview excerpt above, relates to the focus of TPB on singular behaviours and the resulting inability to deal directly with substitution or interaction among related or alternative actions. On the one hand, the predictive strength of the TPB is reliant upon detailed and narrow specification of the subject behaviour in terms of action, target, context and timing (Fishbein and Ajzen 2010). Yet, as discovered through the interviews and storm surveys, various behaviours may be available to and adopted by the participant, all of which ameliorate perceived risks and satisfy the same goals. For instance, one can cancel a trip/activity, eliminate exposure, and stay 'safe'; however, this could also be achieved by deciding to travel but leave earlier; take a safer vehicle, mode, or route; or have another household member drive or make the trip. As shown in Section 4.4.1, the availability of such alternative courses of action, several of which could be adopted simultaneously or sequentially, varies considerably among participants and households, and over time, even between winter storms. It is unclear how such alternatives might affect, directly or indirectly, beliefs and intentions represented in the TPB. Fishbein and Ajzen (2010) suggest this issue may be resolved by defining a more generalized form of behaviour. However, given the different levels of consistency between TPB belief constructs and intention or actual behaviour for just two of these potentially interchangeable actions, as reported in Table 4-14, it is doubtful that an aggregate definition of action would be very helpful in guiding and refining weather-related information and other interventions.

4.5 Discussion and conclusions

Evidence provided in this study demonstrated the significant effects that different data collection methods have on insights into the influence of winter weather-related information on routine trip and activity decisions and behaviour. Pre-season semi-structured interviews, based partly on a mental modelling approach, were used to identify a wide range of weather information sources and potential behavioural adjustments intended to manage mobility risks during winter storms. Findings from the small 12-person cohort were comparable in breadth to those attained in survey or focus group studies involving much larger samples (e.g., Andrey and Knapper 2003, Harris/Decima 2012). Relative to survey-based research, the in-depth interviews exposed more nuanced and detailed interpretations of factors thought to affect behaviour, including variable definitions and perceptions of winter storm hazards and a complex arrangement of elements that comprise concern. Despite revealing interesting information, the pre-season interviews, like many survey designs, were reliant upon single measurements of stated beliefs, preferences, and actions derived from general recall, recollection of distant events, and/or hypothetical situation prompts.

Experience sampling was applied to the same participant cohort to explore the effects of an alternative survey method involving repeated measurement of beliefs, intentions, and behaviour as actual winter storm events unfolded. This facilitated comparisons between methods, winter storms, and periods within storms. Results reinforced certain findings from the interviews but deviated in other instances, as observed in the relatively lower importance of safety concerns during actual storms compared to pre-season interview beliefs.

The most distinct and noteworthy contribution of the ESM approach was adding insights into the dynamic aspects of factors and TPB constructs thought to affect the influence of winter weather-related risk information on trip and activity behaviour. While the pre-season interviews yielded a large inventory of weather information sources and channels that people access during storms, the ESM approach facilitated understanding of how the number, selection, use and perceived value of different sources evolved between and over the lifecycle of storm events. The value of in-depth study relative to single-measurement surveys was revealed in four distinct findings: 1) the role of ECCC warnings in raising participant awareness and increasing confidence in general storm expectations and concern, 2) greater number of informal sources being accessed to inform specific mobility intentions and behaviours as the storm progressed, 3) participant tendency to commit to protective behavioural actions no more than a few hours before, and often only after, storm initiation, and 4) inconsistencies between intentions and actions, with the size of gap varying by storm, type of protective behaviour, circumstances of specific households, and interdependencies among behaviours at particular points in time.

The latter finding was explored further through the lens of TPB, a social change theory commonly applied in transportation but not previously used to probe the influence of weather-related risk information on mobility decisions during winter storms. A consistency analysis of ESM results illustrated the temporal instability of TPB constructs—beliefs, attitudes, and intentions—as they affected adoption of two risk-reducing behaviours during and between winter storms. An interpretive analysis, using an example ECCC warning bulletin, raised doubts about the adequacy of TPB to guide and improve warning information services, in particular how one might strengthen already strong attitudinal beliefs and how to account for situational variability introduced through the heterogeneity and differential importance of activities that generate mobility demands.

Also problematic was an apparent inability of TPB to accommodate interaction, sequencing, or substitution among certain behaviours between and over the course of individual winter storms. Such effects may be captured in the perceived behavioural control construct of TPB, for example through external constraints (e.g., winter maintenance practices), but it was not evident how they could be discretized within TPB to orient and inform adjustments to weather warnings and related actionable information. Part of the difficulty associated with applying TPB may lie in the framing of winter mobility risk largely as an individual knowledge-deficit issue. Other conceptual models, such as Social Practice Theory (Shove 2010, Shove et al. 2012) which takes routine 'practices' rather than individual behaviour as the central unit of analysis, or frameworks that integrate individual, social, material and institutional factors (e.g., ISM framework, Darnton and Evans 2013), may be worth investigating further as alternative theoretical approaches.

Results from this investigation should be considered within the scope, limitations, and resources available to the study, in particular its small sample size. Such limitations do not detract from the relevance of the study for future research and especially for winter weather warning practice. For those evaluating the efficacy of winter weather information and explaining how it influences behaviour, there is value in using small samples targeted on the basis of exposure, vulnerability and general capacity to respond. As adopted in this study, research designs that incorporate an open or semi-structured interview component and carry the same cohort sample into an ESM application offer rich insights that can be used to complement, inform, and corroborate those obtained using a traditional cross-sectional large sample survey. Participant recall bias and limitations associated with reliance on hypothetical scenarios can be minimized by sampling multiple winter storm events and periods within events. This design strategy enables researchers to capture dynamic interactions and processes over an entire event lifecycle which appears key to explaining variability in the perception of winter storm hazards, use of weather warnings and adoption of protective behaviour.

For practitioners designing and implementing new types of warnings, including those within national weather service organizations, this study supports the need to carefully and thoroughly test potential products and services before rolling them out to the general public. This applies equally to those developed using theory-based design (i.e., whether based on TPB or other concepts like nudging, prospect theory, etc.) or best practices canvassed from experiences of other agencies (e.g., WMO 2015b).

The considerable variability in empirical factors and theoretical constructs affecting the influence of weather-related risk information on trip and activity behaviour uncovered by this study raises questions about the efficacy of static impact statements and behavioural recommendations or calls to action contained in current official winter storm warnings issued by ECCC and propagated by media outlets. Building on mobility-as-a-service applications (e.g., Alyavina et al. 2021), future collaborative research could examine the potential benefits of discretizing and dynamically targeting such information in warning messages across temporal (i.e., specific storms and times within events), spatial (i.e., communities, neighbourhoods) and social (i.e., individual/household exposure, vulnerability, response capacity, risk tolerance) scales. This level of tailoring is already possible for aspects of winter storm hazards (i.e., high-resolution numerical weather prediction); the results of this study point to the need and possible ways (e.g., using TPB, ESM) of developing a social science based complement to better incorporate changing situational exposure, vulnerability, response capacity, and beliefs and preferences of individuals.

Chapter 5: Dissertation synthesis

This dissertation aimed to critically explored the variable influence of weather and weather-related risk information (i.e., public warnings) on mobility decisions, behaviour, and risk outcomes during winter storms. A variety of methods were applied to analyze secondary data obtained from several government agencies and to examine original data acquired using interview and experience sample survey techniques. The main research contributions toward the goal are synthesized below in themes aligned with the dissertation objectives described in Section 1.3.

5.1 Making mobility risk estimation more compatible with behavioural response

Weather-related travel risk has been a focus of inquiry for half a century. To date, even in those studies rigorously applying retrospective cohort analysis to estimate risk levels, weather events have been defined in static ways detached from the mobility experiences and situational context of people dealing with disruptive and potentially dangerous travel conditions. While often justified because of data availability or quality constraints, such approaches have limited potential insights into connections among weather phenomena, physical hazards, safety interventions, and behavioural responses. Three methodological innovations in study design were incorporated in this dissertation to better capture these important linkages and the dynamic nature of weather events more generally: 1) characterization framed from a synoptic meteorology perspective, 2) adoption of variable-length event periods, and 3) incorporation of pre- and post-storm buffers. Informed by synoptic meteorology and multiple sources of weather data, event criteria were developed and successfully applied to capture the entire life cycle and evolution of discrete winter storms as might be perceived and experienced by the travelling public and winter maintenance authorities, and monitored and warned by ECCC (Section 2.4, Table 2-2). This resulted in variable-length but generally much longer event observation periods than those considered in previous research. Events included time in advance of a storm, when pre-storm preparations might be expected; they also incorporated short periods during and immediately after the storm when precipitation was absent, situations that could encourage people to resume travel, but when hazardous road and walkway surface conditions continue to prevail. This treatment resolved concerns from reviews of previous research, including the need to accommodate lag effects in risk outcomes and issues of independence, whereby shorter-duration criteria end up splitting individual storms into multiple, separate events.

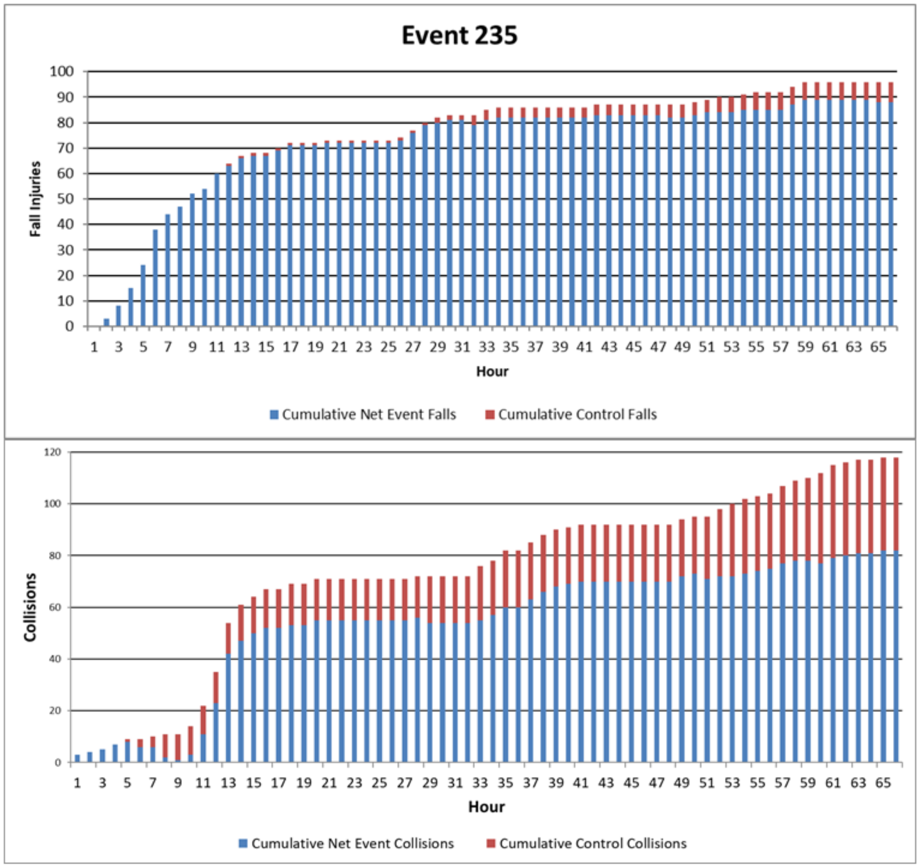
In addition to developing a more complete and socially relevant characterization of winter storm events, the dissertation estimated, compared, and combined estimates of relative and absolute injury risk for two dominant modes of travel—driving and walking—in the study region (Section 3.5.9). Traditionally treated separately, this more comprehensive picture of mobility-related injury risk during winter storms addressed a large knowledge gap raised by the transportation safety research community—and also apparent in public fall-related injury risk perceptions as revealed during the participant interviews discussed in Chapter 4. Although significant increases in injury risk were estimated for both modes relative to dry, seasonal conditions, same-level falls on ice and snow accounted for over 60 percent more of the injury burden attributable to winter storms than motor vehicle collision injuries. This is an important empirical contribution to the weather hazard literature.

5.2 Inferred understanding of behavioural response through risk analysis

The dissertation also provides novel insights into the role of weather warnings in ameliorating travel risk because of unique data and analytical approach taken. Almost two-thirds of all winter storm events and three-quarters of snow-only events analyzed in the study went unwarned, an indication that ECCC warning thresholds were established primarily using meteorological parameters rather than consideration of safety risk. No statistically significant differences were observed between warned and unwarned events in relative risks, even when stratified by dominant precipitation type (snow, mixed) and risk outcome (MVC injury, fall-related injury). Relative to unwarned events, slight reductions in mean risks were found for fall-related injuries during warned snowfall events and for MVC injuries during warned mixed events; slight increases in mean risks were observed for fall-related and MVC injuries during warned mixed and warned snowfall events, respectively. While plausible behavioural explanations for these mixed results are presented in Chapters 2 and 3, it was not possible to discern the independent and possibly interactive effects among storm hazard characteristics, winter maintenance actions, and individual behaviour—let alone whether or not the latter was due to intentional consideration of weather warning information.

Temporal changes in risk were also examined as possible indicators of behavioural response. An important finding from this dissertation is the observation of substantive (several percent per year) and statistically significant reductions in long-term relative MVC and fall-related injury risks during winter storms (Figs. 2-8, 3-2). While a few researchers have examined such trends in weather-related collision injury risk (Andrey 2010, Elvik 2016, Qiu and Nixon 2008), the current investigation is the first to report trends for both driving and walking modes. As noted in Chapter 2-3, the reductions point to structural, technological, or behavioural factors affecting exposure and sensitivity to winter storm hazards to a much greater extent or rate than for normal, dry weather conditions. Shifts in risk were also noted at finer temporal scales often with different implications for MVC and fall-related injury outcomes. For example, the highest risks for fall-related injuries were during the shoulder months (November, April) while peak risks for MVC injuries occurred in January. Modestly higher fall-related risks were estimated for winter storms occurring on weekends compared to weekdays while minimal differences in mean risk by day-of-week were observed for MVC injuries. Although not formally analyzed and presented in Chapters 2-3, Figure 5-1 illustrates the variability in risk outcomes at an hourly level within winter storms.

Lacking additional detailed information about exposure, winter maintenance practices, and individual response during past winter storms, these analyses of secondary data raised important questions about how specific interventions such as weather warnings might influence behaviour and risk outcomes. The temporal analyses in particular suggested that important structural, technological, and social factors interact at multiple scales to uniquely affect different risk outcomes. Clearly, additional and complementary approaches to formal risk analysis of secondary data are necessary to better understand the influence of winter storms and warnings on trip decisions and behaviour.



*sum of red and blue bars indicates observed hourly total collision/injury count

Figure 5-1. Cumulative MVC and fall-related injury counts during winter storm event-235 (Jan 2012).

5.3 Effects of method and data collection timing on insights into behaviour

Chapter 4 elaborated a mixed-methods approach complementary to the quantitative risk analysis of earlier chapters, based on a convenience sample of households that undertake considerable discretionary travel throughout the winter season (Section 4.3). The research design, summarized in Figure 4-1, addressed several methodological issues discerned from a review of the limited extant literature, including overreliance on cross-sectional survey designs that measure just one instance of a recalled event, event/hazard type, or hypothetical scenario. Inductive analysis was used to identify, describe, and compare patterns emerging from coded semi-structured interviews and experience sampling surveys deployed over multiple measurement points during the course of a winter season, between several winter storms, and within individual storm events, i.e., the intra-season scales highlighted in Section 5.2.

The analysis confirmed the general relevance of four factors in making mobility decisions during winter storms: response choice and efficacy, attributes of weather-related information sources and use, hazard perception, and perceived concern. It also demonstrated the advantages of different methods. For example, compared to survey-based research, the in-depth interviews exposed more nuanced and detailed interpretations of factors thought to affect behaviour, including variable definitions and perceptions of winter storm hazards and a complex arrangement of elements that comprise concern. Importantly, it did not appear that this added depth was attained by sacrificing breadth—the range of behavioural adjustments derived from the small 12-person cohort were comparable to those obtained through studies involving much larger samples (e.g., Andrey and Knapper 2003, Harris/Decima 2012).

Experience sampling conducted in near real-time over four stages of three separate winter storm events added different unique insights to those attained from pre-season interviews, including:

- Role of ECCC warnings in raising participant awareness and increasing confidence in general storm expectations and concern;
- Greater number of informal sources being accessed to inform specific mobility intentions and behaviours as the storm progressed;
- Tendency for people to commit to protective behavioural actions no more than a few hours before, and often only after, storm initiation; and
- Inconsistencies between intentions and actions, with the size of gap varying by storm, type of protective behaviour, circumstances of specific households, and interdependencies among behaviours at particular points in time.

Standard, single measurement surveys or interviews would not have been able to capture these observations which are vital to understanding the dynamic aspects of variables and processes influencing individual trip and activity behaviour.

5.4 Use of existing social theory to interpret warning influence on behaviour

The dissertation also advanced the application of theory in this field. The literature review failed to reveal any studies that applied social theory to evaluate the role of warning or other weather information in influencing trip and activity decisions and behaviour. Given numerous examples in public health, transportation and natural hazard fields, the dissertation filled this research void with an application of TPB, a well-established and empirically test social cognitive model (Ajzen 1991, Fishbein and Ajzen 2010). The evaluation of TPB involved two procedures: 1) a consistency analysis set within the interview and ESM components of the dissertation, and 2) an interpretation of an example winter storm warning intervention through the lens of TPB.

Pre-season interview transcripts described in the previous section were successfully recoded against the main attitudinal and belief constructs of TPB to confirm their availability and relevance to the discussion with study participants. The ESM survey instruments were amended to include questions to measure the constructs and both intent and actual mobility risk-reducing behaviours for two commonly adopted responses: 1) cancelling or rescheduling of trips and activity, and 2) departing earlier to reach a destination.

A consistency analysis developed by the author to accommodate the small sample nature of the study revealed considerable differences between the two behaviours examined. Consolidated results across all three storms (Table 4-13) showed that TPB constructs, in general, were moderately consistent with intention to cancel or reschedule a trip/activity and intention was moderately consistent with actual reported behaviour. While all but one TPB construct was shown to be highly consistent with intention to depart earlier, intention was very inconsistent with actual reported behaviour. The aggregate results, however, disguised important within-participant variation in consistency between belief constructs and intent or behaviour across individual storms, especially for trip/activity cancellation or rescheduling. This supports the view that, for at least some behaviours, individual attitude, subjective norm, and control beliefs may be unstable and thus subject to other storm-specific and contextual factors.

A second procedure was undertaken to evaluate the utility of TPB in providing supportive guidance to improve weather warnings. Using a typical but actual ECCC winter storm warning bulletin issued during the sampled storms, the relevance of each TPB construct was examined in relation to the content of the warning. The interpretive analysis raised serious questions about the effectiveness of guidance offered through TPB, specifically:

- Difficulties attempting to strengthen already strong attitudinal beliefs,
- Reconciliation of the heterogeneity and differential importance of activities that generate mobility demands, and

- Inability to accommodate and discretize potential interaction, sequencing, or substitution among certain protective behaviours.

The issues raised by the analysis warrant further investigation of TPB and other applicable theories, including those like Social Practice Theory (Shove et al. 2012) that challenge framing winter mobility risk largely as an individual knowledge-deficit issue.

5.5 Practical implications

The findings of this dissertation present several relevant implications for ECCC, other agencies that issue weather warnings, and transportation authorities that are responsible for winter maintenance. Mobility-related injury risks during winter storms are significant—in Canada, almost certainly greater than those associated with tornadoes, severe thunderstorms, lightning, and flooding, combined—and thus worthy of greater attention in future efforts to redesign and improve weather warnings. Fall-related injuries in particular seem underappreciated by weather service providers, transportation authorities and citizens alike, though this study demonstrated this type of injury burden may be as or more significant than those associated with MVCs.

On the positive side, all ECCC warnings examined in the risk analyses conducted as part of this dissertation captured impactful, excess injury-causing winter storm events. The meteorological threshold criteria used to make warning decisions, however, meant that almost two-thirds of winter storm events analyzed in the study went unwarned while posing elevated threats to life and property. This finding strongly supported on-going efforts by ECCC and other NMHS agencies to move toward a risk- or impact-based warning system (IBWS).

As public weather services advance the impact-based approach, they must be aware of issues that may affect internal or external evaluations of warning efficacy as measured through stated or observed changes in behaviour. One example raised in this dissertation was a concern that IBWS benefits may be masked by established public impact- or risk-based interpretations of current winter storm warnings and forecasts. Members of the public may already be adapting warnings into impact-oriented forms of knowledge that are salient and relevant to their decisions and protective behaviour. Efforts to change or introduce IBWS may not yield significant shifts in decisions or behaviour as they are merely reinforcing connections between weather and impact that already exist.

An alternative explanation for limited empirical evidence of warning efficacy at influencing actual behaviour rather than just intentions (Potter et al. 2018, Taylor et al. 2019, Weyrich et al. 2018) may lie in how members of the public access and use different sources of information to support their decisions. While this dissertation presented evidence that ECCC warnings are associated with increasing confidence that a winter storm will affect them and rising concerns about its implications, other sources of information and additional factors seem to exert greater influence on specific decisions and behaviours, most of which are taken during rather than before the storm. This suggests that behavioural recommendations or ‘calls to action’ in warning messages are not sufficiently tailored to specific individuals and situations, something that should be explored further.

The significance of mobility-related injury risk is also pertinent to the winter maintenance operations and policies of transportation authorities, especially those in the RMW but probably in other winter climate jurisdictions as well. While it is likely that the long-term downward trend in relative injury risk can be attributed in part to improved winter maintenance technologies and procedures, the risk of both MVC and fall-related injuries remains very high. As demonstrated in the analysis, most fall-related injuries occur during and on the day following a winter storm suggesting that municipal policies and by-laws requiring residents to clear sidewalks within 24 hours after the conclusion of a winter storm are insufficient. Clearly more could be done during and immediately after a storm event, including investing additional public resources in sidewalk and pathway winter maintenance. Even a small reduction in fall-related injuries and attendant healthcare resource demands might justify the added expenditure associated with a municipal sidewalk clearing program. The observation that fall-related injury risks are similarly high for both working age (18-54) and older (55+) RMW residents suggests that such actions would be beneficial to much of the population.

5.6 Recommendations for future research

Three avenues for future research are immediately evident from the dissertation. The first builds on and extends the current study empirically. Retaining the existing set of mixed-methods (i.e., objective risk analysis of secondary data; interviews, and ESM surveys of a sample cohort), it would be helpful to expand the study to other city-regions, larger more representative public samples, and others targeted to more vulnerable populations who may lack flexibility and resources necessary to respond and reduce their risks. It would also be worthwhile examining other mobility modes, especially transit and cycling, and warm-season weather hazards with the aim of comparing acute and chronic threats to health and safety.

A separate research track is recommended to pursue further evaluation and interpretation of TPB, using a more traditional large sample frame, but in combination with parallel assessments of other social change theories, for example Social Practice Theory. Contemporary reviews, syntheses, and interpretations of the history and underpinnings of social practice as theory are provided by Schatzki (1996), Reckwitz (2002), Shove (2010), and Shove et al. (2012). These authors situate SPT as a compelling alternative to TPB and other dominant social psychology (attitude, behaviour, choice models) and economic (expected utility models) perspectives which assume a primacy of the individual and its rationality or self-interest, while ignoring the social context in which beliefs, attitudes, and intentions are formed, decisions made, and behaviour or practices are performed.

A third research thrust is envisioned that will design, test, and evaluate a real-time, app-based, dynamic decision support tool bespoke to particular citizens and households. Such an effort would involve merging 'street-level' hazard prediction, a capability that already exists for certain atmospheric phenomena but needs extension to mobility-specific hazards, with attributes of risk, behaviour, and social practice as monitored and understood through personal mobile devices and social scientific analysis. The resulting 'tool' might be something analogous to a financial planning survey instrument, but one that is more frequently updated to produce salient, custom guidance for the user.

5.7 Summary of unique contributions and final remarks

The research presented in the dissertation resulted in several unique empirical findings, theoretical considerations, and methodological contributions that have not been published or reported elsewhere to the author's knowledge.

Empirical results provided evidence for the following assertions:

- Falls account for a greater proportion of the excess injury burden during winter storms than motor vehicle collisions;

- Official government warnings are issued for less than half of winter storm events that produced excess injuries; and
- Official government warnings raise awareness and increase confidence in general winter storm expectations and concern, but people tend to rely on informal sources to inform specific mobility intentions and behaviours during a storm.

This dissertation is among the first to incorporate and evaluate a general behavioural theory—the Theory of Planned Behaviour (TPB)—to help explain the influence of weather information on trip and activity practices during winter storms. An interpretive analysis raised questions about the effectiveness of guidance offered through TPB, diagnosing a particular inability of the model to accommodate and discretize potential interaction, sequencing, or substitution among certain protective behaviours.

Other unique contributions of the dissertation were methodological, including:

- Development and successful application of new event definition criteria for risk analysis that captures the entire life cycle and evolution of discrete winter storms as might be perceived and experienced by the public;
- Design and implementation of a consistency analysis method to evaluate TPB constructs using data obtained from small samples; and
- Integration of a pre-season interview component with a novel experience sampling procedure that enabled exploration of inter- and intra-storm effects.

These and other contributions from the dissertation, as summarized in Chapter 5, revealed multiple dimensions of temporal and within-participant variation in beliefs, perceptions, preferences, exposure and risk outcomes during winter storms. The findings of the thesis strongly point to a future of winter storm warning services that necessarily must be tailored to individual situations and circumstances at discrete points in time in order to increase efficacy and societal value. The mixed-methods adopted in the thesis can be further developed and applied to help shape and implement the research necessary to achieve this goal.

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Appendix A: Supplementary characteristics of participants and households

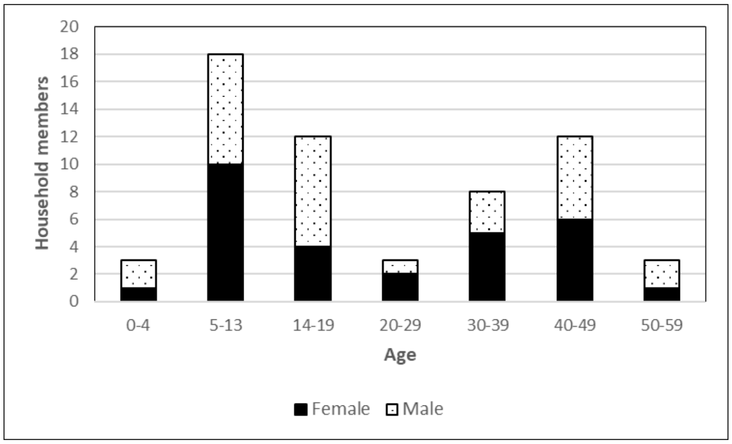

Figure A-1. Composite age and gender distribution of members from participating households

Table A-1. Respondent marital status/living arrangement

MARTIAL STATUS/LIVING ARRANGEMENT	COUNT	PERCENTAGE
Single, including widowed/widower	0	0.00
Married and living with partner in household	11	91.7
Married, divorced or separated and living apart	1	8.3
Total	12	100.0

Table A-2. Respondent household gross income level ($C 77,000 is the 2018 median income for Kitchener CMA)

HOUSEHOLD INCOME (GROSS)	COUNT	PERCENTAGE
Less than $C 77,000	1	91.7
$C 77,000 or greater	11	8.3
Total	12	100.0

Table A-3. Respondent dwelling type

DWELLING TYPE	COUNT	PERCENTAGE
Single family home	12	100.0
Other	0	0.0
Total	12	100.0

Table A-4. Respondent dwelling ownership type

DWELLING OWNERSHIP	COUNT	PERCENTAGE
Owned	12	100.0
Rented	0	0.0
Total	12	100.0

Table A-5. Respondent length of time living in current home and region

HABITATION (COMMUNITY FAMILIARITY)	MIN (YEARS)	MAX (YEARS)	MEDIAN (YEARS)
Current home	1	18	10.5
Any home in Kitchener or Waterloo	3	44	17.5

Table A-6. Items/services used by respondents on a daily basis

ITEMS/SERVICES USED ON DAILY BASIS	COUNT	PERCENTAGE (n=12)
Television	9	75.0
Radio	10	85.3
Landline telephone	3	25.0
Smartphone/cell phone	12	100.0
Personal laptop, tablet or desktop computer	12	100.0
Internet	12	100.0

Table A-7. Items/services used by respondents to clear snow and ice

ITEMS/SERVICES USED CLEAR SNOW/ICE	COUNT	PERCENTAGE (n=12)
Electric, battery or gas-powered snowblower	3	25.0
Shovel/broom or own truck-tractor/blade	12	100.0
Salt or other de-icing chemical applied to surfaces	10	83.3
Sand or other 'grit' applied to surfaces	0	0.00
Private snow-clearing contractor	0	0.00
Taken care of by building or condominium staff/contractor	0	0.00
Neighbour or friend not living in my household helps me	5	41.7
City staff or contractors clear my sidewalks	0	0.00

Table A-8. Passenger vehicle characteristics for all household members

PASSENGER VEHICLES (ALL HOUSEHOLDS)	COUNT	AVG PER HOUSEHOLD
Passenger vehicles owned	23	1.9
Passenger vehicles with winter tires	19	1.6
Passenger vehicles sheltered in garage/carport	7	0.6

Table A-9. Household member vehicle, transit pass, and cell phone possession characteristics

HOUSEHOLD MEMBER CHARATERISTIC	COUNT	PERCENTAGE (n=59)
Owns or drives a motorized vehicle	29	49.2
Holds a valid transit pass	2	3.4
Uses a smartphone or cell phone	42	71.2

Appendix B: Winter storm survey instruments

[Survey A – Pre-storm/pre-warning]

Q1 Welcome and thank you for participating in this University of Waterloo study examining activity and trip decisions during winter storms. This is the first of up to four surveys that are to be completed for this particular storm situation. Please respond to the following questions as completely and accurately as possible—this is not a test and there aren't any correct or incorrect answers. It's important that we know what you really think. Your identity will remain confidential. This project and survey has been reviewed and approved by the University of Waterloo Office of Research Ethics.

Q2 Do you believe that a winter storm (snow, ice pellets, and/or freezing rain) will affect the Region of Waterloo sometime during the next 3 days?

- ○ Yes (1)
- ○ No (2)

Q3 What did you rely upon to form this opinion? *(check all that apply)*

- ▢ Discussion with friend, other relative, neighbour, or co-worker
- ▢ Discussion with member(s) of my household
- ▢ Information from a website
- ▢ Information from *The Weather Network*
- ▢ Information issued by *Environment Canada*
- ▢ Personal feeling, intuition or experience
- ▢ Personal observations of weather and environment around my home and neighbourhood
- ▢ Radio broadcast
- ▢ Smartphone weather application (weather app)
- ▢ Television broadcast
- ▢ Twitter, Facebook, Snapchat or other social media message(s)
- ▢ Other *(please specify)* ____________________

Display This Question:

If Do you believe that a winter storm (snow, ice pellets, and/or freezing rain) will affect the Regi... = Yes

Q4 How confident are you in your opinion that a winter storm will affect the Region of Waterloo sometime during the next 3 days? Please select the most appropriate value on the scale where 1 indicates *not confident at all* and 7 indicates *very confident*.

- ○ 1 - Not confident at all (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Very Confident (7)

Display This Question:

If Do you believe that a winter storm (snow, ice pellets, and/or freezing rain) will affect the Regi... = No

Q5 How confident are you in your opinion that a winter storm will not affect the Region of Waterloo sometime during the next 3 days? Please select the most appropriate value on the scale where 1 indicates *not confident at all* and 7 indicates *very confident*.

○ 1 - Not confident at all (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Very Confident (7)

Skip To: End of Survey If How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 5

Skip To: End of Survey If How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 6

Skip To: End of Survey If How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 7 - Very Confident

Q6 How concerned are you that a winter storm will affect your or other household members' activity and trip plans sometime during the next 3 days? Please select the most appropriate value on the scale where 1 indicates *not concerned at all* and 7 indicates *very concerned*.

○ 1 - Not concerned at all (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Very Concerned (7)

[Survey B – Following watch/warning issued by Environment Canada]

Q1 Welcome and thank you for participating in this University of Waterloo study examining activity and trip decisions during winter storms. This is the **second of up to four surveys** that are to be completed for this particular storm situation. This survey may take a little longer to complete--about 10-15 minutes. Please respond to the following questions as completely and accurately as possible—this is not a test and there aren't any correct or incorrect answers. It's important that we know what you really think. Your identity will remain confidential. This project and survey have been reviewed and approved by the University of Waterloo Office of Research Ethics.

Q2 Do you believe that a winter storm (snow, ice pellets and/or freezing rain) will affect the Region of Waterloo sometime during the next 24 hours?

- ○ Yes (1)
- ○ No (2)

Q3 What did you rely upon to form this opinion? *(check all that apply)*

- ☐ Personal feeling, intuition or experience (1)
- ☐ Personal observations of weather and environment around my home and neighbourhood (2)
- ☐ Discussion with member(s) of my household (3)
- ☐ Discussion with friend, other relative, neighbour, or co-worker (4)
- ☐ Radio broadcast (5)
- ☐ Television broadcast (6)
- ☐ Information from The Weather Network (7)
- ☐ Information from a website (8)
- ☐ Information issued by Environment Canada (9)
- ☐ Twitter, Facebook, Snapchat or other social media message(s) (10)
- ☐ Smartphone weather application (weather app) (11)
- ☐ Other *(please specify)* (12) ____________________

Display This Question:

If Do you believe that a winter storm (snow, ice pellets and/or freezing rain) will affect the Regio... = Yes

Q4 How confident are you in your opinion that a winter storm will affect the Region of Waterloo sometime during the next 24 hours? Please select the most appropriate value on the scale where 1 indicates *not confident at all* and 7 indicates *very confident*.

- ○ 1 - Not confident at all (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Very Confident (7)

Display This Question:

If Do you believe that a winter storm (snow, ice pellets and/or freezing rain) will affect the Regio... = No

Q5 How confident are you in your opinion that a winter storm will not affect the Region of Waterloo sometime during the next 24 hours? Please select the most appropriate value on the scale where 1 indicates *not confident at all* and 7 indicates *very confident*.

- ○ 1 - Not confident at all (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Very Confident (7)

Skip To: End of Survey If How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 6

Skip To: End of Survey If How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 7 - Very Confident

Q6 How concerned are you that a winter storm will affect your or other household members' activity and trip plans sometime during the next 24 hours? Please select the most appropriate value on the scale where 1 indicates *not concerned at all* and 7 indicates *very concerned*.

- ○ 1 - Not concerned at all (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Very Concerned (7)

Display This Question:

If Do you believe that a winter storm (snow, ice pellets and/or freezing rain) will affect the Regio... = Yes

Or How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 1 - Not confident at all

Or How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 2

Or How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 3

Or How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 4

Or How confident are you in your opinion that a winter storm will not affect the Region of Waterloo... = 5

Q7 How *likely or unlikely* are you or other members of your household to take the following actions to prepare for this storm? Please select the most appropriate value on the scale where 1 indicates *very unlikely* and 7 indicates *very likely*.

	1 - Very unlikely (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 - Very likely (7)
Top-up vehicle fuel and/or windshield de-icing fluid (1)	○	○	○	○	○	○	○
Make sure boots, coats, gloves and extra winter clothing are ready to wear (2)	○	○	○	○	○	○	○
Search for and monitor weather forecasts and road condition reports from media and government agencies (3)	○	○	○	○	○	○	○
Discuss and share thoughts about the storm, possible implications, and potential actions with household members or other family, friends, and neighbours through in-person, telephone, video or social media conversation (4)	○	○	○	○	○	○	○
Reschedule one or more activities and trips to a time before travel conditions become poor (5)	○	○	○	○	○	○	○
Cancel or reschedule one or more activities and trips until after the storm ends and travel conditions improve (6)	○	○	○	○	○	○	○
Adjust your schedule to leave early and allow more time to reach your destination (7)	○	○	○	○	○	○	○
Work from home or change the location of other activities to your home (e.g., fitness workout, on-line shopping) to avoid travel during the storm (8)	○	○	○	○	○	○	○

Change the mode of travel for you or another member of your household (e.g., take public transit instead of driving, drive kids to school instead of letting them walk, carpool) (9)	○	○	○	○	○	○	○
Change the route that you would normally take to avoid especially hazardous situations (11)	○	○	○	○	○	○	○
Do nothing (10)	○	○	○	○	○	○	○

Display This Question:

If How likely or unlikely are you or other members of your household to take the following actions t... = Do nothing [5]

Or How likely or unlikely are you or other members of your household to take the following actions t... = Do nothing [6]

Or How likely or unlikely are you or other members of your household to take the following actions t... = Do nothing [7 - Very likely]

Q8 Please identify any reasons you have for not taking any actions or decisions to prepare for this storm (check all that apply)

▢ The storm or its effects won't be that bad (1)

▢ It is too early to know what will happen or what we will do (2)

▢ We always stick to our routine no matter what the conditions might be (3)

▢ Other (please specify) (4) ____

Skip To: End of Survey If Please identify any reasons you have for not taking any actions or decisions to prepare for this... = We always stick to our routine no matter what the conditions might be

Q9 When would you likely *make the decision* to cancel or reschedule one or more activities and trips until after the storm ends and travel conditions improve?

○ Day or more before storm (1)

○ Night before storm (2)

○ Few hours or less before storm (3)

○ After storm begins (4)

Q10 How *good* or *bad* would it be for you personally to cancel or reschedule one or more activities and trips until after the storm ends and travel conditions improve? Please select the most appropriate value on the scale where 1 indicates *very bad* and 7 indicates *very good*.

- 1 - Very bad (1)
- 2 (2)
- 3 (3)
- 4 (4)
- 5 (5)
- 6 (6)
- 7 - Very good (7)

Q11 How *pleasant* or *unpleasant* would it be for you personally to cancel or reschedule one or more activities and trips until after the storm ends and travel conditions improve? Please select the most appropriate value on the scale where 1 indicates *very unpleasant* and 7 indicates *very pleasant*.

- 1 - Very unpleasant (1)
- 2 (2)
- 3 (3)
- 4 (4)
- 5 (5)
- 6 (6)
- 7 - Very pleasant (7)

Q12 How strongly do you *agree* or *disagree* that people who are important to you believe that you should cancel or reschedule one or more activities and trips until after the storm ends and travel conditions improve? Please select the most appropriate value on the scale where 1 indicates *strongly disagree* and 7 indicates *strongly agree*.

- 1 - Strongly disagree (1)
- 2 (2)
- 3 (3)
- 4 (4)
- 5 (5)
- 6 (6)
- 7 - Strongly agree (7)

Q13 How *often* would people who are important to you cancel or reschedule one or more of their activities and trips until after a storm ends and travel conditions improve? Please select the most appropriate value on the scale where 1 indicates *never, during any winter storm*, and 7 indicates *always, during every winter storm*.

- 1 - Never, during any winter storm (1)
- 2 (2)
- 3 (3)
- 4 (4)
- 5 (5)
- 6 (6)
- 7 - Always, during every winter storm (7)

Q14 How *easy* or *difficult* is it for you to cancel or reschedule one or more activities and trips until after the storm ends and travel conditions improve? Please select the most appropriate value on the scale where 1 indicates *very difficult* and 7 indicates *very easy*.

- ○ 1 - Very difficult (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Very easy (7)

Q15 To what extent is canceling or rescheduling one or more activities and trips until after the storm ends and travel conditions improve *under your control*? Please select the most appropriate value on the scale where 1 indicates *not at all under my control* and 7 indicates *completely under my control*.

- ○ 1 - Not at all under my control (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Completely under my control (7)

Q16 How much do you think you would *regret* canceling or rescheduling one or more activities and trips until after the storm ends and travel conditions improve? Please select the most appropriate value on the scale where 1 indicates *not at all* and 7 indicates *very much*.

- ○ 1 - Not at all (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Very much (7)

Q17 When would you likely *make the decision* to adjust your schedule to leave early and allow more time to reach your destination?

- ○ Day or more before storm (1)
- ○ Night before storm (2)
- ○ Few hours or less before storm (3)
- ○ After storm begins (4)

Q18 How *good* or *bad* would it be for you personally to adjust your schedule to leave early and allow more time to reach your destination? Please select the most appropriate value on the scale where 1 indicates *very bad* and 7 indicates *very good*.

○ 1 - Very bad (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Very good (7)

Q19 How *pleasant* or *unpleasant* would it be for you personally to adjust your schedule to leave early and allow more time to reach your destination? Please select the most appropriate value on the scale where 1 indicates *very unpleasant* and 7 indicates *very pleasant*.

○ 1 - Very unpleasant (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Very pleasant (7)

Q20 How strongly do you *agree* or *disagree* that people who are important to you believe that you should adjust your schedule to leave early and allow more time to reach your destination? Please select the most appropriate value on the scale where 1 indicates *strongly disagree* and 7 indicates *strongly agree*.

○ 1 - Strongly disagree (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Strongly agree (7)

Q21 How *often* would people who are important to you adjust their schedule to leave early and allow more time to reach your destination? Please select the most appropriate value on the scale where 1 indicates *never, during any winter storm*, and 7 indicates *always, during every winter storm*.

○ 1 - Never, during any winter storm (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Always, during every winter storm (7)

Q22 How *easy* or *difficult* is it for you to adjust your schedule to leave early and allow more time to reach your destination? Please select the most appropriate value on the scale where 1 indicates *very difficult* and 7 indicates *very easy*.

○ 1 - Very difficult (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Very easy (7)

Q23 To what extent is adjusting your schedule to leave early *under your control*? Please select the most appropriate value on the scale where 1 indicates *not at all under my control* and 7 indicates *completely under my control*.

○ 1 - Not at all under my control (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Completely under my control (7)

Q24 How much do you think you would *regret* adjusting your schedule to leave early and allowing more time to reach your destination? Please select the most appropriate value on the scale where 1 indicates *not at all* and 7 indicates *very much*.

○ 1 - Not at all (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Very much (7)

[Survey C – During peak of winter storm]

Q1 Welcome and thank you for participating in this University of Waterloo study examining activity and trip decisions during winter storms. This is the **third of up to four surveys** that are to be completed for this particular storm situation. The survey should take about 10-15 minutes to complete. Please respond to the following questions as completely and accurately as possible—this is not a test and there aren't any correct or incorrect answers. It's important that we know what you really think. Your identity will remain confidential. This project and survey has been reviewed and approved by the University of Waterloo Office of Research Ethics.

Q2 Approximately when did the current winter storm (snow, ice pellets, and/or freezing rain) begin affecting your location? Please indicate by selecting the text box and **typing in** the day of the week (e.g., Monday, Tuesday...) and time of day (e.g., 8am or early morning).

Q3 How severe have the following weather and travel hazards been *during the worst* of the storm? Note the different scale definitions for each category.

	1 - see scale definition (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 - see scale definition (7)
Slipperiness of roads, walkways and sidewalks (1=Not slippery at all, 7=Dangerously slippery) (1)	○	○	○	○	○	○	○
Visibility (1=Clear, unrestricted; 7=Whiteout, completely obstructed) (2)	○	○	○	○	○	○	○
Temperature/windchill (1=Very warm and comfortable, 7=Very cold and uncomfortable) (3)	○	○	○	○	○	○	○
Amount of snow or freezing rain (1=Just a trace, 7=Enough snow or ice to stop most vehicles/pedestrians from moving (4)	○	○	○	○	○	○	○

Q4 How concerned have you been during the storm about the following trip outcomes? Please select the most appropriate value on the scale where 1 indicates *not concerned at all* and 7 indicates *very concerned*.

	1 - Not concerned at all (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 - Very concerned (7)
Reaching destination without significant stress or anxiety (1)	○	○	○	○	○	○	○
Arriving at a destination on time (2)	○	○	○	○	○	○	○
Having to cancel or defer a trip and not being able to participate in the activity (3)	○	○	○	○	○	○	○
Being stranded in a vehicle or bus or at the activity location location (4)	○	○	○	○	○	○	○
Getting to your destination without damaging your vehicle (5)	○	○	○	○	○	○	○
Getting to your destination safely without being injured in a collision, slip or fall (6)	○	○	○	○	○	○	○
Safe arrival of significant others (household members, friends, relatives) travelling during the storm (7)	○	○	○	○	○	○	○

Q5 Has there been a need for *you* to make a trip and leave your home since the storm began?

○ Yes (1)

○ No (2)

▢ *Display This Question:*

▢ *If Has there been a need for you to make a trip and leave your home since the storm began? = Yes*

Q6 Please provide a detailed description of the last trip or trip decision that *you* made since the storm began, noting the general purpose of the trip (activities), how you travelled (car, bus, taxi, walked, etc.), when and where you went, who joined you on the trip, how easy or difficult it was to travel, and whether you experienced any delays or had to cancel, reschedule or relocate any activities (select the box to add text). Here are two examples: 1) I left work at 5:15pm and gave a colleague a ride to their house (near Erb St/Fischer-Hallman) residence before stopping at Sobeys to pick up a few things for dinner. The roads were terrible by then and it took me an extra 20 minutes to get home (6:30pm). 2) My daughter's soccer practice at 8pm was canceled because of the weather so we stayed home from that point on.

____

____

____

Q7 Please indicate if *you or another* household member have taken any of the following actions since learning about the current winter storm (check all that apply).

▢ Cancelled or rescheduled one or more activities and trips until after the storm ends and travel conditions improve (1)

▢ Rescheduled one or more activities and trips to a time before travel conditions became poor (2)

▢ Worked from home or changed the location of other activities to our home (e.g., fitness workout, on-line shopping, play-date) to avoid travel during the storm (3)

▢ Changed the mode of travel (e.g., took public transit instead of driving, drove kids to school instead of letting them walk, walked instead of biked, carpooled) (4)

▢ Adjusted schedule to leave early and allow more time to reach the destination (5)

▢ Changed the route normally taken in order to avoid especially hazardous situations (6)

▢ Topped-up vehicle fuel and/or windshield de-icing fluid (7)

▢ Made sure boots, coats, gloves and extra winter clothing are ready to wear (8)

▢ Searched for and monitored weather forecasts and road condition reports from media and government agencies (9)

▢ Discussed and shared thoughts about the storm, possible implications, and potential actions with household members or other family, friends, and neighbours through in-person, telephone, video or social media conversation (10)

▢ Taken other action(s) (please specify) (11) ____

Q8 Please indicate whether you or another member of your household *used (searched for, consulted, or relied upon)* any of the following sources of weather and travel information when deciding to take or not to take any actions to deal with the storm. For the sources that were used, please *rate how helpful they were in making your trip decisions* for this particular storm on a scale where 1 indicates *not helpful at all* and 7 indicates *very helpful*.

	1 - Not helpful at all (1)	2 (2)	3 (3)	4 (4)	5 (5)	6 (6)	7 - Very helpful (7)	**Did not use** (8)
Personal feeling, intuition or experience (1)	○	○	○	○	○	○	○	○
Personal observations of weather and environment around my home and neighbourhood (2)	○	○	○	○	○	○	○	○
Discussion with member(s) of my household (3)	○	○	○	○	○	○	○	○
Discussion with friend, other relative, neighbour, or co-worker (4)	○	○	○	○	○	○	○	○
Radio broadcast (5)	○	○	○	○	○	○	○	○
Television broadcast (6)	○	○	○	○	○	○	○	○
Information from The Weather Network (7)	○	○	○	○	○	○	○	○
Information from a website (8)	○	○	○	○	○	○	○	○
Information issued by Environment Canada (9)	○	○	○	○	○	○	○	○
Twitter, Facebook, Snapchat or other social media message(s) (10)	○	○	○	○	○	○	○	○
Smartphone weather application (weather app) (11)	○	○	○	○	○	○	○	○

[Survey D – Following winter storm after conditions have improved]

Q1 Welcome and thank you for participating in this University of Waterloo study examining activity and trip decisions during winter storms. This is the **final survey** that needs to be completed for this particular storm situation. It will take about 5-10 minutes to finish. Please respond to the following questions as completely and accurately as possible—this is not a test and there aren't any correct or incorrect answers. It's important that we know what you really think. Your identity will remain confidential. This project and survey has been reviewed and approved by the University of Waterloo Office of Research Ethics.

Q2 Approximately when did winter storm conditions (snow, ice pellets and/or freezing rain) affecting your location end? Please indicate the day of the week (e.g., Monday, Tuesday...) and time of day (e.g., 8am or early morning).

____

Q3 To what extent did the timing of the winter storm and travel conditions unfold as you expected for each of the listed characteristics? Please select the most appropriate value on the scale where 1 indicates *much earlier than expected*, 4 indicates *as expected*, and 7 indicates *much later than expected*.

	1 - Much earlier than expected (1)	2 (2)	3 (3)	4 - As expected (4)	5 (5)	6 (6)	7 - Much later than expected (7)
Time when the winter storm began (1)	○	○	○	○	○	○	○
Time when the winter storm ended (2)	○	○	○	○	○	○	○

Q4 To what extent did the slipperiness of roads, walkways and sidewalks and visibility unfold as you expected during the winter storm? Please select the most appropriate value on the scale where 1 indicates *much better than expected*, 4 indicates *as expected*, and 7 indicates *much worse than expected*.

	1 - Much better than expected (1)	2 (2)	3 (3)	4 - As expected (4)	5 (5)	6 (6)	7 - Much worse than expected (7)
Slipperiness of roads, walkways and sidewalks (1)	○	○	○	○	○	○	○
Visibility (2)	○	○	○	○	○	○	○

Q5 To what extent did the amount/duration of precipitation unfold as you expected during the winter storm? Please select the most appropriate value on the scale where 1 indicates *much less than expected*, 4 indicates *as expected*, and 7 indicates *much more than expected*.

	1 - Much less than expected (1)	2 (2)	3 (3)	4 - As expected (4)	5 (5)	6 (6)	7 - Much more than expected (7)	**Not applicable for this storm** (8)
Amount of snowfall/ice pellets (1)	○	○	○	○	○	○	○	○
Amount/duration of freezing rain (2)	○	○	○	○	○	○	○	○

Q6 Which of the following weather advisories, watches and warnings do you recall being issued by Environment Canada for the storm? (check all that apply)

- ▢ I do not recall **any** weather advisories, watches and warnings being issued by Environment Canada for the storm (1)
- ▢ Blizzard warning (2)
- ▢ Blowing snow advisory (3)
- ▢ Extreme cold warning (4)
- ▢ Flash freeze warning (5)
- ▢ Fog advisory (6)
- ▢ Freezing drizzle advisory (7)
- ▢ Freezing rain warning (8)
- ▢ Rainfall warning (9)
- ▢ Snowfall warning (10)
- ▢ Snowsquall watch (11)
- ▢ Snowsquall warning (12)
- ▢ Weather advisory (13)
- ▢ Weather warning (14)
- ▢ Wind warning (15)
- ▢ Winter storm watch (16)
- ▢ Winter storm warning (17)
- ▢ Other (please specify) (18) ____

Skip To: Q9 If Which of the following weather advisories, watches and warnings do you recall being issued by Env... = I do not recall any weather advisories, watches and warnings being issued by Environment Canada for the storm

Q7 To what extent did the timing of the winter storm and travel conditions unfold as **Environment Canada predicted**? Please select the most appropriate value on the scale where 1 indicates *much earlier than predicted*, 4 indicates *as predicted*, and 7 indicates *much later than predicted*.

	1 - Much earlier than predicted (1)	2 (2)	3 (3)	4 - As predicted (4)	5 (5)	6 (6)	7 - Much later than predicted (7)	**Unsure/don't recall** (8)
Time when the winter storm began (1)	○	○	○	○	○	○	○	○
Time when the winter storm ended (2)	○	○	○	○	○	○	○	○

Q8 To what extent did the <u>amount/duration of precipitation</u> and <u>visibility</u> unfold as **Environment Canada predicted** during the winter storm? Please select the most appropriate value on the scale where 1 indicates *much less/better than expected*, 4 indicates *as expected*, and 7 indicates *much more/worse than expected*.

	1 - Much less/better than predicted (1)	2 (2)	3 (3)	4 - As predicted (4)	5 (5)	6 (6)	7 - Much more/worse than predicted (7)	**Unsure/don't recall** (8)
Amount of snowfall/ice pellets (1)	○	○	○	○	○	○	○	○
Amount/duration of freezing rain (2)	○	○	○	○	○	○	○	○
Visibility (3)	○	○	○	○	○	○	○	○

Q9 Please indicate if *you or other members of your household* experienced any of the following effects during the winter storm (check all that apply).

▢ Slipped or fell on ice or snow (1)

▢ Saw another person slip or fall on ice or snow (2)

▢ Involved in a collision with another motor vehicle or slid off the roadway (3)

▢ Saw other vehicles that were involved in a collision or slid off the roadway (4)

▢ Had at least one 'close call' where control of my vehicle was temporarily lost or almost hit by another vehicle (5)

▢ Became stuck or unable to drive, walk or bike in deep snow or on icy surfaces (6)

▢ Stress and anxiety beyond that felt while travelling in good weather and road conditions (7)

▢ Missed work, school, or another scheduled activity or appointment (8)

▢ Arrived late for work, school, or another activity or appointment (9)

▢ Did not experience any effects (10)

▢ Experienced other effects (please specify) (11) ____

Q10 To what extent do you agree that the trip and activity <u>decisions you made during this winter storm were appropriate</u> given the information you had about the storm and the travel conditions that you experienced? Please select the most appropriate value on the scale where 1 indicates *very strongly disagree* and 7 indicates *very strongly agree*.

○ 1 - Very strongly **disagree** (1)

○ 2 (2)

○ 3 (3)

○ 4 (4)

○ 5 (5)

○ 6 (6)

○ 7 - Very strongly **agree** (7)

Q11 How *likely* would you have responded differently if you had received better or additional information about the winter storm or travel conditions? Please select the most appropriate value on the scale where 1 indicates *very unlikely* and 7 indicates *very likely*.

- ○ 1 - Very **unlikely** (1)
- ○ 2 (2)
- ○ 3 (3)
- ○ 4 (4)
- ○ 5 (5)
- ○ 6 (6)
- ○ 7 - Very **likely** (7)

▢ *Display This Question:*

▢ *If How likely would you have responded differently if you had received better or additional informat... = 4*

▢ *Or How likely would you have responded differently if you had received better or additional informat... = 5*

▢ *Or How likely would you have responded differently if you had received better or additional informat... = 6*

▢ *Or How likely would you have responded differently if you had received better or additional informat... = 7 - Very likely*

Q12 Please provide an example of what you might have done differently if you had received better or additional information about the winter storm or travel conditions.

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▢ *Display This Question:*

▢ *If How likely would you have responded differently if you had received better or additional informat... = 4*

▢ *Or How likely would you have responded differently if you had received better or additional informat... = 5*

▢ *Or How likely would you have responded differently if you had received better or additional informat... = 6*

▢ *Or How likely would you have responded differently if you had received better or additional informat... = 7 - Very likely*

Q13 Please describe what would have made the weather and travel condition information more relevant and useful in support of this different decision.

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Appendix C: Consistency between intent and actual behaviour during winter storms

Table C-1. Consistency between intent and actual behaviour during winter storms (WS): Search/monitor for weather and road condition information

	WS2		WS3		WS4	
Participant*	Intent	Actual	Intent	Actual	Intent	Actual
P1	7	✓	7	×	7	✓
P2	7	✓	--NR--	×	7	×
P3	7	✓	7	✓	7	×
P4	--NR--	×	7	--NR--	5	×
P5	6	--NR--	7	--NR--	7	×
P6	5	✓	7	--NR--	--NR--	✓
P7	5	✓	3	×	5	✓
P8	6	✓	4	✓	7	×
P9	--NR--	×	7	✓	3	✓
P10	4	✓	4	×	1	×
P11	7	✓	7	✓	7	✓
P12	3	✓	4	✓	6	✓

**bold indicates participant mentioned performing behaviour during baseline interview*

--NR-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Table C-2. Consistency between intent and actual behaviour during winter storms (WS): Cancel or reschedule activity until after storm ends

	WS2		WS3		WS4	
Participant	Intent	Actual	Intent	Actual	Intent	Actual
P1	6	×	4	×	5	×
P2	7	✓	--NR--	✓	1	×
P3	7	×	4	×	7	×
P4	--NR--	×	6	--NR--	6	✓
P5	6	--NR--	6	--NR--	6	✓
P6	3	×	4	--NR--	--NR--	✓
P7	2	×	1	×	1	×
P8	4	×	7	×	5	✓
P9	--NR--	✓	7	✓	5	✓
P10	3	×	4	✓	6	×
P11	1	×	7	✓	1	✓
P12	1	×	4	×	4	✓

**bold indicates participant mentioned performing behaviour during baseline interview*

--NR-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Table C-3. Consistency between intent and actual behaviour during winter storms (WS): Reschedule activity before storm occurs

Participant*	WS2 Intent	WS2 Actual	WS3 Intent	WS3 Actual	WS4 Intent	WS4 Actual
P1	4	×	6	×	4	✓
P2	1	✓	--NR--	×	1	×
P3	7	×	5	×	4	×
P4	--NR--	×	6	--NR--	6	✓
P5	3	--NR--	6	--NR--	7	×
P6	4	×	1	--NR--	--NR--	✓
P7	2	×	1	×	1	×
P8	4	×	7	✓	5	×
P9	--NR--	×	2	×	6	✓
P10	4	✓	4	×	6	×
P11	1	×	7	×	1	×
P12	1	×	2	×	4	×

**bold indicates participant mentioned performing behaviour during baseline interview*

--NR-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Table C-4. Consistency between intent and actual behaviour during winter storms (WS): Substitute location/telework

Participant*	WS2 Intent	WS2 Actual	WS3 Intent	WS3 Actual	WS4 Intent	WS4 Actual
P1	1	×	4	×	1	✓
P2	1	×	--NR--	×	1	×
P3	7	×	6	✓	7	✓
P4	--NR--	✓	3	--NR--	6	✓
P5	6	--NR--	6	--NR--	5	✓
P6	4	✓		--NR--	--NR--	✓
P7	1	×		×	1	×
P8	4	✓	7	×	6	✓
P9	--NR--	×	7	✓	5	✓
P10	3	✓	4	✓	4	✓
P11	1	×	7	✓	1	✓
P12	1	×	7	×	4	✓

**bold indicates participant mentioned performing behaviour during baseline interview*

--NR-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Table C-5. Consistency between intent and actual behaviour during winter storms (WS): Change mode of travel

	WS2		WS3		WS4	
Participant	Intent	Actual	Intent	Actual	Intent	Actual
P1	1	×	1	×	1	×
P2	4	✓	--NR--	✓	6	×
P3	1	×	1	×	1	×
P4	--NR--	✓	2	--NR--	6	✓
P5	6	--NR--	6	--NR--	1	×
P6	1	×	1	--NR--	--NR--	×
P7	1	×	1	×	1	×
P8	2	×	5	×	6	×
P9	--NR--	✓	3	×	3	×
P10	5	×	4	×	4	×
P11	1	×	1	×	1	✓
P12	1	×	2	×	2	×

**bold indicates participant mentioned performing behaviour during baseline interview*

--*NR*-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Table C-6. Consistency between intent and actual behaviour during winter storms (WS): Change route taken

	WS2		WS3		WS4	
Participant	Intent	Actual	Intent	Actual	Intent	Actual
P1	2	✓	1	×	1	×
P2	4	×	--NR--	✓	2	×
P3	6	×	5	×	1	×
P4	--NR--	×	5	--NR--	6	×
P5	7	--NR--	1	--NR--	6	×
P6	5	×	5	--NR--	--NR--	×
P7	5	✓	6	✓	5	×
P8	7	×	7	×	7	×
P9	--NR--	×	3	×	3	×
P10	3	✓	4	×	1	×
P11	6	×	7	✓	7	×
P12	3	×	2	✓	4	×

**bold indicates participant mentioned performing behaviour during baseline interview*

--*NR*-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Table C-7. Consistency between intent and actual behaviour during winter storms (WS): Leave at an earlier time

Participant	WS2 Intent	WS2 Actual	WS3 Intent	WS3 Actual	WS4 Intent	WS4 Actual
P1	7	✓	7	×	7	✓
P2	7	×	--NR--	✓	7	✓
P3	7	×	5	×	7	×
P4	--NR--	×	7	--NR--	6	×
P5	7	--NR--	7	--NR--	6	×
P6	5	✓	7	--NR--	--NR--	×
P7	7	✓	7	✓	7	✓
P8	7	×	7	✓	6	✓
P9	--NR--	×	5	×	4	×
P10	3	×	4	×	4	×
P11	1	×	7	✓	7	×
P12	4	×	5	✓	6	✓

**bold* indicates participant mentioned performing behaviour during baseline interview*

--NR-- (not recorded)

Actual behaviour: Performed (✓)/Not (×)

Intent scale: 1 – *Very Unlikely* to 7-*Very Likely*

1	2	3	4	5	6	7

Appendix D: Participant-level use and rating of weather information sources/channels during winter storms

Table D-1. Use of weather information sources/channels during winter storms: *Personal feeling, intuition or experience* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	×	×	3	×	×	×	×	×	4
P2	×	×	×	×	--NR--	×	--NR--	×	×
P3	×	×	×	×	×	1	×	×	3
P4	×	--NR--	3	--NR--	×	--NR--	×	×	3
P5	--NR--	✓	--NR--	×	✓	--NR--	×	×	6
P6	✓	×	5	--NR--	×	--NR--	✓	--NR--	5
P7	×	×	×	×	×	1	×	×	×
P8	×	×	3	×	×	×	×	×	×
P9	×	--NR--	7	✓	×	4	×	×	5
P10	✓	×	3	×	×	7	×	×	5
P11	×	×	6	×	×	7	×	×	7
P12	×	×	2	×	×	3	×	×	5

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-2. Use of weather information sources/channels during winter storms: *Personal observations of weather and environment around home or neighbourhood* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	×	×	6	×	×	6	×	×	5
P2	×	×	7	×	--NR--	×	--NR--	×	7
P3	×	×	×	×	×	1	×	×	4
P4	✓	--NR--	5	--NR--	×	--NR--	×	×	5
P5	--NR--	✓	--NR--	×	×	--NR--	×	×	4
P6	×	✓	7	--NR--	✓	--NR--	×	--NR--	6
P7	×	×	7	×	✓	2	×	×	7
P8	×	✓	5	×	✓	7	×	×	7
P9	✓	--NR--	7	×	✓	7	×	×	7
P10	×	✓	3	×	×	4	×	×	6
P11	×	×	7	×	✓	7	×	×	7
P12	×	×	5	×	×	6	×	×	5

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-3. Use of weather information sources/channels during winter storms: *Discussion with household members* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	×	×	6	×	×	6	×	×	4
P2	✓	✓	5	×	--NR--	6	--NR--	✓	×
P3	×	×	×	×	×	1	×	×	6
P4	✓	--NR--	4	--NR--	✓	--NR--	×	×	5
P5	--NR--	×	--NR--	×	×	--NR--	×	×	5
P6	×	✓	6	--NR--	✓	--NR--	×	--NR--	6
P7	×	×	4	×	×	1	×	✓	3
P8	✓	×	7	✓	✓	7	×	×	7
P9	×	--NR--	3	×	✓	7	×	×	7
P10	×	✓	3	×	×	4	×	×	5
P11	×	×	7	×	×	7	×	✓	7
P12	✓	✓	5	×	✓	4	×	✓	5

Surveys: A-*pre-warning*, B-*post-warning*, C-*peak storm*

* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)

‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-4. Use of weather information sources/channels during winter storms: *Discussion with friends, other relatives, neighbors, or co-workers* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	×	✓	6	×	×	5	×	×	5
P2	×		×	×	--NR--	×	--NR--	✓	×
P3	×	✓	4	✓	✓	7	×	✓	6
P4	✓	--NR--	2	--NR--	×	--NR--	✓	✓	3
P5	--NR--	×	--NR--	×	×	--NR--	×	×	1
P6	×	✓	6	--NR--	×	--NR--	×	--NR--	6
P7	×	✓	×	✓	×	1	✓	×	7
P8	×	×	7	×	×	7	×	×	7
P9	×	--NR--	7	×	×	1	×	✓	7
P10	×	✓	4	×	×	4	×		5
P11	×	✓	×	✓	✓	7	×	✓	7
P12	×	×	2	×	×	2	×	×	1

Surveys: A-*pre-warning*, B-*post-warning*, C-*peak storm*

* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)

‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-5. Use of weather information sources/channels during winter storms: *Radio broadcast* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	✓	✓	7	✓	✓	7	✓	✓	7
P2	×	×	7	✓	--NR--	6	--NR--	✓	×
P3	×	×	4	×	×	1	×	×	1
P4	✓	--NR--	4	--NR--	×	--NR--	✓	✓	5
P5	--NR--	✓	--NR--	✓	✓	--NR--	✓	✓	7
P6	×	×	×	--NR--	✓	--NR--	×	--NR--	×
P7	×	×	5	×	×	2	×	×	6
P8	×	×	7	×	×	×	×	×	×
P9	×	--NR--	1	×	×	×	×	×	×
P10	×	×	5	×	✓	7	✓	✓	5
P11	×	×	×	×	×	×	×	×	×
P12	×	×	×	×	×	1	×	×	1

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-6. Use of weather information sources/channels during winter storms: *Television broadcast* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	✓	✓	6	×	✓	7	×	✓	7
P2	×	×	×	×	--NR--	×	--NR--	×	×
P3	×	×	4	×	×	1	×	×	1
P4	×	--NR--	1	--NR--	×	--NR--	×	×	1
P5	--NR--	×	--NR--	×	×	--NR--	×	×	7
P6	×	×	×	--NR--	✓	--NR--	×	--NR--	×
P7	×	×	×	×	×	2	×	×	×
P8	×	×	×	×	×	×	×	×	×
P9	×	--NR--	1	×	×	×	×	×	×
P10	×	✓	4	×	×	4	×	×	5
P11	×	×	×	×	×	×	×	×	×
P12	×	×	×	×	×	1	×	×	1

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-7. Use of weather information sources/channels during winter storms: *Information from The Weather Network (private sector media company)* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	✓	✓	7	✓	✓	7	✓	✓	7
P2	✓	✓	7	✓	--NR--	7	--NR--	✓	×
P3	×	✓	7	✓	✓	7	×	✓	7
P4	×	--NR--	1	--NR--	×	--NR--	×	×	1
P5	--NR--	✓	--NR--	✓	✓	--NR--	✓	✓	7
P6	✓	✓	7	--NR--	✓	--NR--	✓	--NR--	6
P7	×	×	×	×	✓	7	×	✓	7
P8	×	×	7	×	✓	7	✓	✓	7
P9	×	--NR--	4	×	×	×	×	×	×
P10	✓	✓	6	×	×	6	×	×	5
P11	✓	×	7	×	✓	7	×	×	7
P12	✓	✓	6	✓	✓	6	✓	✓	5

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Table D-8. Use of weather information sources/channels during winter storms: *Information from Environment and Climate Change Canada (ECCC)* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	×	✓	6	✓	✓	7	✓	×	7
P2	×	×	7	×	--NR--	7	--NR--	✓	×
P3	×	×	7	×	×	7	×	✓	6
P4	×	--NR--	1	--NR--	×	--NR--	×	✓	6
P5	--NR--	×	--NR--	✓	✓	--NR--	✓	✓	7
P6	×	×	×	--NR--	×	--NR--	×	--NR--	×
P7	×	×	6	×	×	3	×	×	×
P8	×	×	×	×	×	×	×	×	7
P9	×	--NR--	1	×	×	7	×	✓	7
P10	×	×	6	×	×	6	×	×	5
P11	×	✓	7	×	✓	7	×	×	7
P12	×	×	×	✓	×	6	✓	✓	5

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful | 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Table D-9. Use of weather information sources/channels during winter storms: *Information from a website* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	×	×	×	×	×	5	×	×	7
P2	×	×	×	×	--NR--	×	--NR--	×	×
P3	×	×	4	×	×	7	×	×	1
P4	×	--NR--	2	--NR--	✓	--NR--	✓	×	2
P5	--NR--	×	--NR--	×	×	--NR--	×	×	7
P6	✓	×	×	--NR--	×	--NR--	✓	--NR--	×
P7	×	×	×	×	×	7	×	×	7
P8	×	×	×	✓	×	×	×	×	×
P9	×	--NR--	1	×	×	7	×	×	7
P10	×	×	6	✓	×	6	×	×	5
P11	×	×	×	×	×	×	×	×	×
P12	×	×	×	×	×	5	×	×	4

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-10. Use of weather information sources/channels during winter storms: *Twitter, Facebook, Snapchat or other social media message(s)* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	×	×	×	×	×	5	×	×	6
P2	×	×	×	×	--NR--	×	--NR--	×	×
P3	×	✓	4	×	×	7	✓	×	7
P4	×	--NR--	1	--NR--	×	--NR--	×	×	1
P5	--NR--	×	--NR--	×	×	--NR--	×	×	7
P6	×	×	×	--NR--	×	--NR--	×	--NR--	×
P7	✓	✓	×	×	×	2	✓	×	4
P8	×	×	×	×	×	×	×	×	×
P9	×	--NR--	1	×	×	×	×	×	×
P10	×	×	2	×	✓	7	✓	×	5
P11	×	×	×	×	✓	7	×	×	7
P12	×	×	×	×	×	2	×	×	1

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*
* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)
‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7

Table D-11. Use of weather information sources/channels during winter storms: *Smartphone weather application* before warning (A), following warning (B) and at storm peak (C)

	WS2			WS3			WS4		
Participant	A*	B*	C‡	A*	B*	C‡	A*	B*	C‡
P1	✓	×	×	×	×	6	×	×	6
P2	×	×	×	×	--NR--	×	--NR--	×	×
P3	✓	✓	7	✓	✓	7	✓	✓	7
P4	×	--NR--	3	--NR--	×	--NR--	×	×	1
P5	--NR--	✓	--NR--	×	×	--NR--	×	✓	7
P6	×	✓	7	--NR--	×	--NR--	×	--NR--	6
P7	×	×	7	×	×	2	×	×	6
P8	✓	✓	7	×	×	7	✓	✓	7
P9	×	--NR--	1	✓	✓	×	×	✓	7
P10	×	×	6	×	×	4	×	×	5
P11	✓	✓	7	✓	×	7	×	✓	7
P12	×	✓	6	✓	×	5	×	✓	5

Surveys: A-*pre-warning,* B-*post-warning,* C-*peak storm*

* *Source used* (✓)/*Not used* (×)/ *--NR--* (not recorded)

‡ *Utility* scale: 1 – Not helpful at all 7-Very helpful

1	2	3	4	5	6	7