



Changing patterns of motor vehicle collision risk during winter storms: A new look at a pervasive problem



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ABSTRACT

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.

1. 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

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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. Study area and data

2.1. 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 1369 km² (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 effects 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 Fig. 1, snowfall and temperatures below the freezing point are typically restricted to the months of November through April. Snowfalls that are measurable (≥ 0.2 cm) 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 (1981–2010) climate conditions (ECCC, 2018).

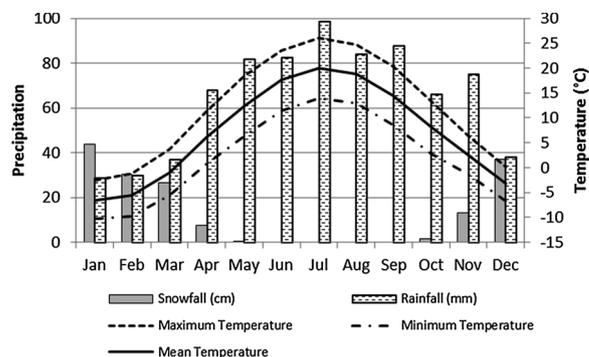


Fig. 1. Average climatic conditions (1981–2010) for Waterloo-Wellington (ECCC, 2018).

2.2. Data

2.2.1. Collision records

Collision records were obtained from the RMW Transportation Department covering all winter months (November–April) from 2002 to 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. Collision 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 3800 in 2002–03 to a low of almost 2900 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 (Fig. 2). On an annual basis, injury and non-injury per capita collision rates were about nine and 32

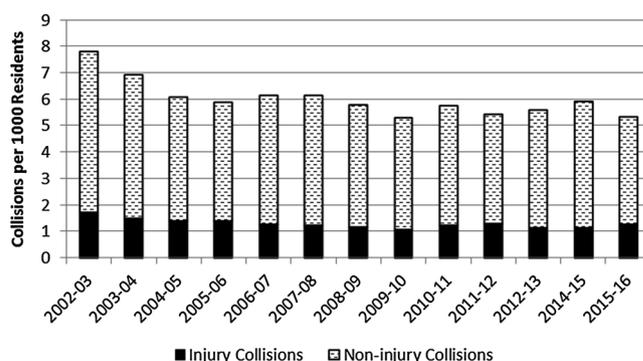


Fig. 2. Winter season (November–April) RMW collision counts per thousand residents.

percent lower than those for the Province of Ontario as a whole (MTO, 2014; RMW, 2014).

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.

2.2.2. 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 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 ECCC¹ 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 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 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 and warning 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.

3. 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 behavior 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; Hajar 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, 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

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

Table 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	<ul style="list-style-type: none"> ● Processed colour images of precipitation coverage and intensity derived from reflectivity signal (snowfall detection mode, approx.. 1 km 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	<ul style="list-style-type: none"> ● Processed colour images of precipitation coverage and intensity derived from reflectivity signal (snowfall detection mode, approx.. 1 km 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	<ul style="list-style-type: none"> ● 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
University of Waterloo Weather Station (City of Waterloo)	University of Waterloo	<ul style="list-style-type: none"> ● Maximum temperature (°C) ● Minimum temperature (°C) ● Rainfall (mm) ● Snowfall (cm) ● Total precipitation (mm) ● Air temperature (°C) ● Relative humidity (°C) ● 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)	<ul style="list-style-type: none"> ● 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)	<ul style="list-style-type: none"> ● Air temperature (°C) ● Rainfall (mm) (when warm temperatures permit use of tipping bucket gauge) 	Hourly	2002-2016

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

Event Criteria	Controls
Duration and Coverage <ul style="list-style-type: none"> • ≥ 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 <ul style="list-style-type: none"> • 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 <ul style="list-style-type: none"> • 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 <ul style="list-style-type: none"> • 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 <ul style="list-style-type: none"> • no radar-indicated precipitation coverage at any level (1,2,3) • no collision reports of precipitation (rain, snow, freezing rain, blowing/drifted snow) • no daily snowfall reported • no collision reports of wet or snowy/icy road surface conditions Exposure Criteria <ul style="list-style-type: none"> • 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

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. Winter storms in RMW are most often associated with developing, mature, or occluding mid-latitude cyclones. At their peak, as depicted in Fig. 3, these cyclones have three principal areas (or times, as these systems are transient) of precipitation that usually occur within an 8 to 24 h 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).

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 Fig. 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 h, 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

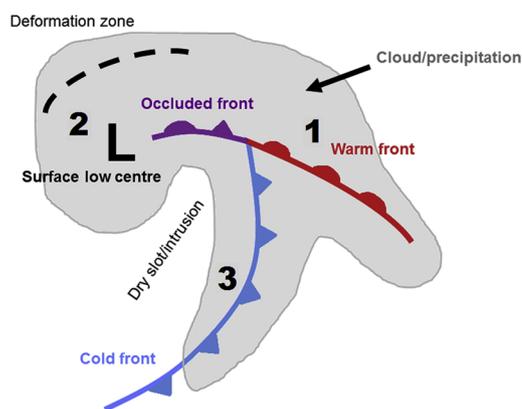


Fig. 3. Generic simplified model of an occluded mid-latitude cyclone (winter storm) and areas of potential precipitation (based on Barry and Chorley, 1987; Semple, 2003).

percent) was adopted yielding a total of 196 storm events for the analysis.

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:

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

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 Eqs. (2) and (3) based on a fixed-effects model for combining estimates of risk (as per Johansson et al., 2009:812).

Table 3
Description of criteria used to develop stratified analyses.

STRATIFICATION	CRITERIA	ADDITIONAL CONTEXT
Winter Storm Characteristics		
<i>Precipitation Type</i>		
All	<ul style="list-style-type: none"> • All events included 	
Snowfall	<ul style="list-style-type: none"> • Only events where precipitation consisted entirely of snowfall 	
Mixed	<ul style="list-style-type: none"> • Events with winter precipitation other than snow (freezing rain/drizzle, ice pellets), OR where both snowfall and liquid rainfall were observed 	<ul style="list-style-type: none"> • Mixed events were further stratified into those with and without reports of freezing rain/drizzle
<i>Precipitation (P) Amount</i>		
Very light	<ul style="list-style-type: none"> • $P < 2 \text{ cm/mm}$ 	<ul style="list-style-type: none"> • Units are expressed in cm for snowfall and mm of liquid-equivalent P for mixed events
Light	<ul style="list-style-type: none"> • $2 \leq P < 5 \text{ cm/mm}$ 	
Very light to Light	<ul style="list-style-type: none"> • $P < 5 \text{ cm/mm}$ 	<ul style="list-style-type: none"> • Event P estimated from maximum daily amounts recorded at area observation sites
Moderate	<ul style="list-style-type: none"> • $5 \leq P < 10 \text{ cm/mm}$ 	
Moderate to Heavy	<ul style="list-style-type: none"> • $P < 10 \text{ cm/mm}$ 	<ul style="list-style-type: none"> • Where storms covered partial days, hourly radar data were examined to determine the proportion of P that could be assigned to particular storms
Heavy	<ul style="list-style-type: none"> • $P \geq 10 \text{ cm/mm}$ 	
<i>Visibility</i>		
Good	<ul style="list-style-type: none"> • No hours with visibility $\leq 2 \text{ km}$ 	
Fair	<ul style="list-style-type: none"> • 1-14% of event hours with visibility $\leq 2 \text{ km}$ 	
Poor	<ul style="list-style-type: none"> • 15-29% of event hours with visibility $\leq 2 \text{ km}$ 	
Very Poor	<ul style="list-style-type: none"> • $\geq 30\%$ of event hours with visibility $\leq 2 \text{ km}$ 	
<i>Temperature (T) Profile</i>		
Rising	<ul style="list-style-type: none"> • T warms from $< -1 \text{ }^\circ\text{C}$ to $> 0 \text{ }^\circ\text{C}$ during event 	<ul style="list-style-type: none"> • Events were assigned in the following order: Rising, Falling, Very Cold, Cold, Warm
Falling	<ul style="list-style-type: none"> • T falls from $\geq 0\text{C}$ to $< -1\text{C}$ during event 	
Stable - Very cold	<ul style="list-style-type: none"> • $T \leq -8 \text{ }^\circ\text{C}$ throughout event 	<ul style="list-style-type: none"> • Events meeting both rising and falling criteria were assigned based on what occurred last in the event hour sequence
Stable - Cold	<ul style="list-style-type: none"> • $T < -1 \text{ }^\circ\text{C}$ throughout event 	
Stable - Warm	<ul style="list-style-type: none"> • $T \geq -1 \text{ }^\circ\text{C}$ throughout event 	
<i>Weather Warnings</i>		
Warned	<ul style="list-style-type: none"> • Event hours at least partially overlap an official winter weather watch or warning bulletin issued by Environment Canada 	<ul style="list-style-type: none"> • Includes watches and warnings for winter storms, snowfall, snowsqualls, blowing snow, freezing rain or drizzle, and flash freeze
Unwarned	<ul style="list-style-type: none"> • No watches or warnings overlap any event hours 	
<i>Temporal and Location Factors</i>		
<i>Temporal</i>		
Weekdays	<ul style="list-style-type: none"> • Events that occurred entirely on weekdays (Monday-Friday) 	
Weekends	<ul style="list-style-type: none"> • Events included weekend hours (Saturday-Sunday) 	
Month	<ul style="list-style-type: none"> • Events allocated to specific winter months (November, December, January, February, March, April) 	
Season	<ul style="list-style-type: none"> • Events allocated to particular winter seasons (e.g., 2002-03, 2003-04) 	<ul style="list-style-type: none"> • 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.)
<i>Location</i>		
Townships	<ul style="list-style-type: none"> • Collision counts spatially restricted to those occurring in RMW Townships, City of Cambridge, City of Kitchener, and City of Waterloo, for respective categories 	<ul style="list-style-type: none"> • Analysis also included a comparison of Townships with all cities, combined
City of Cambridge		
City of Kitchener		
City of Waterloo		

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

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 Eq. (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 (Eq. (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 3.

4. Results

4.1. Overall injury and non-injury collision risk

The 196 event-control pairs used in the analysis included 3936 paired hours during which 4650 event collisions (802 injury; 3848 non-injury) and 1904 (431 injury; 1473 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

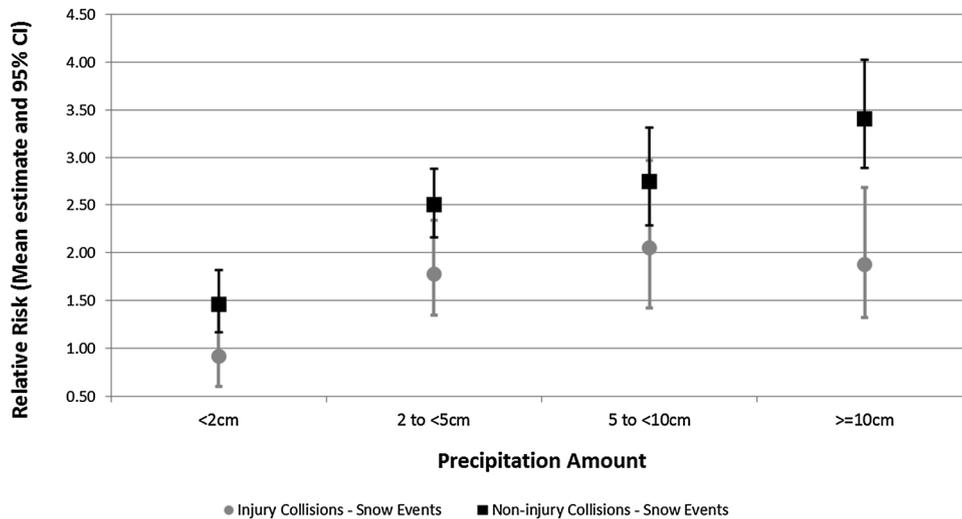


Fig. 6. Relative risk of injury and non-injury collision during snow events for varying accumulation amounts.

- Snowfall events with large accumulations (≥ 10 cm), a high proportion of (≥ 15 percent) of poor visibility (≥ 2 km) hours, or with very cold or falling temperatures, had the greatest effect on non-injury collisions, producing increases of between 200–250 percent.

4.2.2. 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. Fig. 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 Fig. 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 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.

4.3. 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

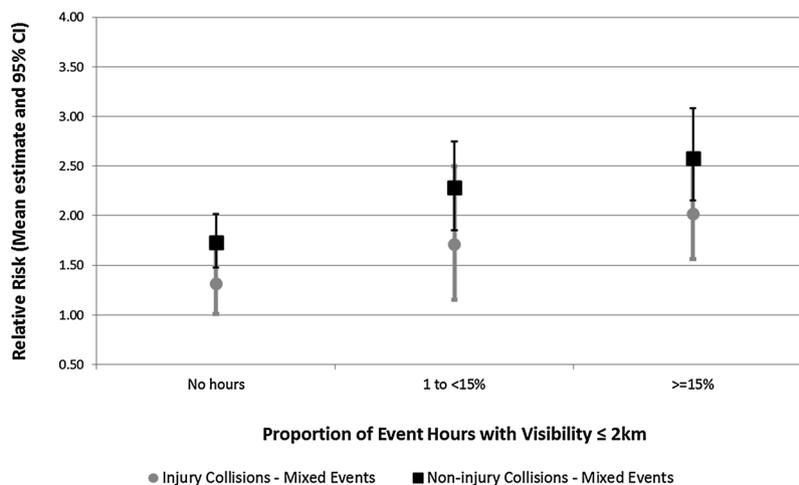


Fig. 7. Relative risk of injury and non-injury collision during mixed precipitation events for varying proportions of hours with reduced visibility (≤ 2 km).

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

WINTER STORM TYPE	Injury Collision Relative Risk (95% Confidence Interval)		Non-injury Collision Relative Risk (95% Confidence Interval)	
	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)

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 Fig. 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 ($p_{injury} = .028$, $p_{non-injury} = .001$) 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).

5. 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

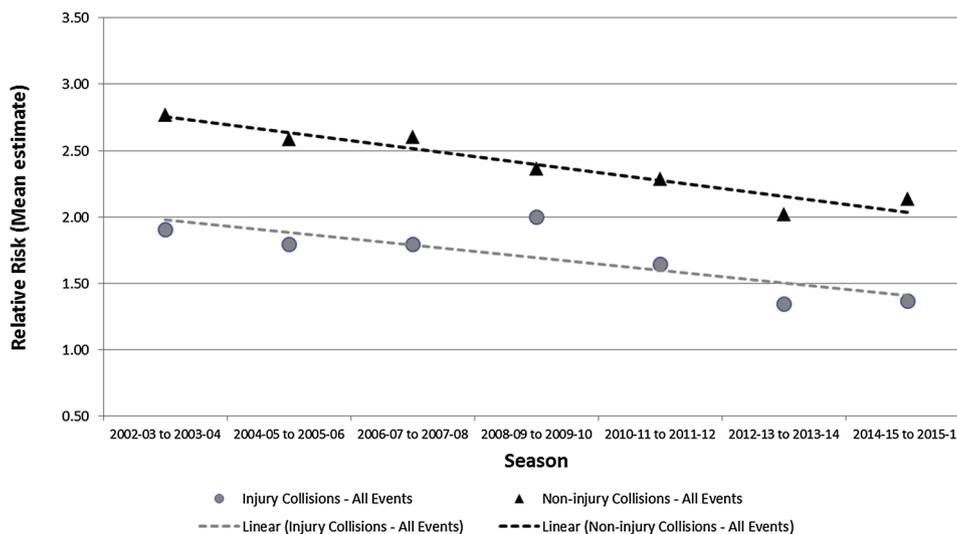


Fig. 8. Two-season mean estimates of relative risk of injury and non-injury collision during all winter storm events.

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 ($P_{\text{snow}} < 5 \text{ cm}$ or $P_{\text{mixed}} < 5 \text{ mm}$) to moderate ($5 \text{ cm} \leq P_{\text{snow}} < 10 \text{ cm}$ or $5 \text{ mm} \leq P_{\text{mixed}} < 10 \text{ mm}$) amounts, but then dropped slightly for events with higher accumulations ($P_{\text{snow}} \geq 10 \text{ cm}$ or $P_{\text{mixed}} \geq 10 \text{ mm}$). 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 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 'unwarned' 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 braking 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).

6. 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.

Declarations of interest

None

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References

- Andersson, A., Chapman, L., 2011. The use of a temporal analogue to predict future traffic accidents and winter road conditions in Sweden. *Meteorol. Appl.* 18, 125–136.
- Andrey, J., 1989. Relationships Between Weather and Traffic Safety. PhD dissertation. University of Waterloo, Waterloo, Canada.
- Andrey, J., 2010. Long-term trends in weather-related crash risks. *J. Transp. Geogr.* 18, 247–258.
- Andrey, J., Mills, B., Leahy, M., Suggett, J., 2003. Weather as a chronic hazard for road transportation in Canadian cities. *Nat. Hazards* 28, 319–343.
- Andrey, J., Hambly, D., Mills, B., Afrin, S., 2013. Insights into driver adaptation to inclement weather in Canada. *J. Transp. Geogr.* 28, 192–203.
- Barry, R.G., Chorley, R.J., 1987. *Atmosphere, Weather and Climate*. Methuen, New York, fifth ed. .
- Black, A.W., Mote, T.L., 2015. Effects of winter precipitation on automobile collisions, injuries, and fatalities in the United States. *J. Transp. Geogr.* 48, 165–175.
- Brenning, A., Andrey, J., Mills, B., 2011. Indirect modeling of hourly meteorological time series for winter road maintenance. *Environmetrics* 22, 398–408.
- Campbell, L.S., Steenburgh, W.J., Veals, P.G., Letcher, T.W., Minder, J.R., 2016. Lake-effect mode and precipitation enhancement over the Tug Hill Plateau during OWLeS IOP2b. *Mon. Weather Rev.* 144, 1729–1748.
- Changnon, S.A., 1996. Effects of summer precipitation on urban transportation. *Clim. Change* 32, 481–494.
- Cummings, P., Grossman, D.C., 2007. Antilock brakes and the risk of driver injury in a crash: a case-control study. *Accid. Anal. Prev.* 39, 995–1000.
- Cummings, P., Rivara, F.P., Thompson, D.C., Thompson, R.S., 2006. Misconceptions regarding case-control studies of bicycle helmets and head injury. *Accid. Anal. Prev.* 38, 636–643.
- Di Bartolomeo, S., Valent, F., Sbrojavacca, R., Marchetti, R., Barbone, F., 2009. A case-control study of alcohol consumption, meals and the risk of road traffic crashes. *BMC Public Health* 9, 316. <https://doi.org/10.1186/1471-2458-9-316>.
- ECCC, 2018. Canadian Climate Normals. Environment and Climate Change Canada. http://climate.weather.gc.ca/climate_normals/index_e.html.
- Eisenberg, D., 2004. The mixed effects of precipitation on traffic crashes. *Accid. Anal. Prev.* 36, 637–647.
- El-Basyouny, K., Barua, S., Islam, M.T., 2014. Investigation of time and weather effects on crash types using full Bayesian multivariate Poisson lognormal models. *Accid. Anal. Prev.* 73, 91–99.
- Elvik, R., 2016. Does the influence of risk factors on accident occurrence change over-time? *Accid. Anal. Prev.* 91, 91–102.
- Fleiss, J.L., 1973. *Statistical Methods for Rates and Proportions*. John Wiley & Sons, New York.
- Hijar, M., Carillo, C., Flores, M., Anaya, R., Lopez, V., 2000. Risk factors in highway traffic accidents: a case control study. *Accid. Anal. Prev.* 32, 703–709.
- Jaroszowski, D., McNamara, T., 2014. The influence of rainfall on road accidents in urban areas: a weather radar approach. *Travel Behav. Soc.* 1, 15–21.
- Johansson, O., Wanvik, P., Elvik, R., 2009. A new method for assessing the risk of accident associated with darkness. *Accid. Anal. Prev.* 41, 809–815.
- Keay, K., Simmonds, I., 2006. Road accidents and rainfall in a large Australian city. *Accid. Anal. Prev.* 38, 445–454.
- Khattak, A.J., Knapp, K.K., 2001. Snow event effects on interstate highway crashes. *Cold Regions Eng.* 15 (4), 219–229.
- Knapp, K.K., Smithson, L.D., 2000. Winter storm event volume impact analysis using multiple-source archived monitoring data. *Transp. Res. Rec.* 1700, 10–15.
- Knapp, K.K., Kroeger, D., Giese, K., 2000. Mobility and safety impacts of winter storm events in a freeway environment. Final Report Prepared for the Iowa Department of Transportation and Iowa Highway Research Program. Center for Transportation Research and Education. Iowa State University, Ames, Iowa Accessed September 2018. <https://ctre.iastate.edu/research/completed/mobility-and-safety-impacts-of-winter-storm-events-in-a-freeway-environment/>.
- Koetse, M.J., Rietveld, P., 2009. The impact of climate change and weather on transport: an overview of empirical findings. *Transp. Res. D Transp. Environ.* 14, 205–221.
- Leard, B., Roth, K., 2015. Weather, Traffic Accidents, and Climate Change. *Resources For*

- the Future discussion paper. RFF DP 15-19. www.rff.org. Accessed June 2015.
- Liu, A., Soneja, S.I., Jiang, C., Huang, C., Kerns, T., Beck, K., Mitchell, C., Sapkota, A., 2017. Frequency of extreme weather events and increased risk of motor vehicle collision in Maryland. *Sci. Total Environ.* 580, 550–555.
- Mills, B., Andrey, J., Hambly, D., 2011. Analysis of precipitation-related motor vehicle collision and injury risk using insurance and police record information for Winnipeg, Canada. *J. Saf. Res.* 42, 383–390.
- MTO, 2014. Ontario Road Safety Annual Report 2014. Ministry of Transportation of Ontario, Road Safety Policy & Education Branch, Safety Research Office, Toronto Accessed July 2017. <http://www.ontario.ca/orsar>.
- Qiu, L., Nixon, W.A., 2008. Effects of adverse weather on traffic crashes. *Transp. Res. Rec.* 2055, 139–146.
- RMW, 2011. Regional Transportation Master Plan: Moving Forward 2031. Regional Municipality of Waterloo.
- RMW, 2014. 2014 Collision Report. Regional Municipality of Waterloo, Transportation and Environmental Services Department, Transportation Division.
- RMW, 2017. Year-End 2016 Population and Household Estimates for Waterloo Region. Region of Waterloo Planning, Development and Legislative Services, Community Planning Report PDL-CPL-17-12.
- Ruin, I., Lutoff, C., Boudevillain, B., Creutin, J.-D., Anquetin, S., Rojo, M.B., Boissier, L., Bonnifait, L., Borga, M., Colbeau-Justin, L., Creton-Cazanave, L., Delrieu, G., Douvinet, J., Gaume, E., Grunfest, E., Naulin, J.-P., Payrastre, O., Vannier, O., 2014. Social and hydrological responses to extreme precipitations: an interdisciplinary strategy for postflood investigation. *Weather. Clim. Soc.* 6, 135–153.
- Semple, A.T., 2003. A review and unification of conceptual models of cyclogenesis. *Meteorol. Appl.* 10, 39–59.
- Smith, K., 1982. How seasonal and weather conditions influence road accidents in Glasgow. *Scott. Geogr. Mag.* 98, 103–114.
- Statistics Canada, 2017. Canadian Population Estimates (2002-2017). CANSIM Table 051-0005.
- Strong, C.K., Ye, Z., Shi, X., 2010. Safety effects of winter weather: the state of knowledge and remaining challenges. *Transp. Rev.* 30, 677–699.
- Tamerius, J.D., Zhou, X., Mantilla, R., Greenfield-Huitt, T., 2016. Precipitation effects on motor vehicle crashes vary by space, time, and environmental conditions. *Weather. Clim. Soc.* 8, 399–407.
- The SAM Group, Lenguerrand, E., Martin, J.L., Moskal, A., Gadegbeku, B., Laumon, B., 2008. Limits of the quasi-induced exposure method when compared with the standard case-control design. *Accid. Anal. Prev.* 40, 861–868.
- Theofilatos, A., Yannis, G., 2014. A review of the effect of traffic and weather characteristics on road safety. *Accid. Anal. Prev.* 72, 244–256.
- Villani, J.P., Jurewicz, M.L., Reinhold, K., 2017. Forecasting the inland extent of lake effect snow bands downwind of Lake Ontario. *J. Oper. Meteorol.* 5, 53–70. <https://doi.org/10.15191/nwajom.2017.0505>.
- Zheng, Z., Soyoun, A., Monsere, C.M., 2010. Impact of traffic oscillations on freeway crash occurrences. *Accid. Anal. Prev.* 42, 626–636.