The Influence of Weather and Climate Change on Pedestrian Safety

by

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Author's Declaration

I hereby declare that I am the sole author of this 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.

Abstract

Although walking is one of the most sustainable means of transportation with a number of related health benefits to human life, in a number of regions, walking on roads can lead to increased chances of injury and death from a collision. Due to the dramatic growth in motor vehicle usage, pedestrians are easily susceptible to collisions with these vehicles. This problem is even more enhanced when inclement weather occurs. Pedestrian vulnerability is more heightened during weather hazards, since such hazards tend to increase the risk of collisions. The influence of weather hazards on motor vehicle safety and collision risk is established in the road safety literature, but fewer research exists on the safety and risk of pedestrian-vehicle collisions during inclement weather. Therefore, the first objective of the thesis is to estimate the relative risk of collisions during rainfall in two urban Canadian Regions: the Greater Toronto Area and Greater Vancouver. The second objective is predictive in nature using a combination of the relative risk estimates and available climate models to understand the possible influence of climate change on pedestrian safety in both regions by the mid-century.

The results indicated that present-day relative risk of collisions during rainfall relative to dry weather is higher for pedestrians in Vancouver than Toronto, however, at a finer temporal scale the relative risk is almost the same for both regions. By mid-century, the results of the climate modeling exercise estimate an increase in mean annual rain days for both regions, where much of the increase is for light rainfall days. This additional increase in mean annual rain days will increase pedestrian collisions each year by a small amount in Toronto and by a slightly higher amount in Vancouver. In both regions, collisions occurring at public intersections and casualties have significant increase in risk during rainfall. Moreover, with climate change, the additional collisions are belonging to public intersection collisions and casualties in Toronto and Vancouver, respectively.

Evidently, most of the increase in risk and additional collisions by mid-century is attributable to moderate and heavy rainfall periods. Therefore, safety interventions should consider the impact of intense rainfall on pedestrian safety in the present and future possible climate.

Acknowledgements

Foremost, I would like to thank my professor and teacher Jean Andrey. There is a very special saying in Arabic that goes, *"Rise to the teacher and honor them, for the teacher is almost a prophet",* you exemplify that and more. Your dedicated support, teaching ability, and knowledge have made me a better student. Thank you for the unforgettable inspiration and encouragement.

I wouldn't have been able to complete this thesis without the data, and for that I would like to thank Derrick Hambly for the assistance. I really admire your work and your ability to tell a story from large complicated sets of data. I would also like to thank my thesis committee member Brent Doberstien for reviewing and reading the thesis. Your comments and suggestions have been very helpful during the last crazy bit of this process. In addition, I would like to thank my committee members Linda Mortsch and Jeff Casello.

On a more personal note, to my best friends and sisters Asil and Leena. Thank you for the laughter. I can't image my life without you two. To Ali, looking back at my academic years it would have been a challenge to reach this stage without your powerful presence. Thank you for helping me through the lows and the highs. Finally, to my amazing mother Khadija, thank you for the never ending motivation, patience, and guidance throughout this process.

Dedication

I dedicate this thesis to my father, Abdelmoniem Badri. I'm unable to put in words how grateful I am for the support and unconditional love you provided. I'm so lucky to have you as a role model and my only wish is that you are always proud of your daughter.

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List of Abbreviations

AR4	Fourth IPCC Assessment Report
CCDS	Canadian Climate Data and Scenarios
GCM	Global Climate Models
IPCC	Intergovernmental Panel on Climate Change
LARS-WG	Long Ashton Research Station Weather Generator
NCDB	National Collision Database
RCM	Regional Climate Models
SRES	Special Report on Emission Scenarios
VRU	Vulnerable Road Users
WMO	World Meteorological Station

Chapter 1: Introduction

1.1 Research Context

Walking is the most sustainable mode of human locomotion, but also can be the least safe depending on the spatial - temporal context. Pedestrians who rely on walking as a form of travel and exercise operate in a complex and challenging transport system. Pedestrians are susceptible to the risk of motor-vehicle collisions, which have high implications on society and road safety.

This thesis contributes to pedestrian-vehicle collision research by examining weather and climate as risk factors. Weather and climate already have been investigated in studies of vehicle-vehicle collisions, with the conclusion that active weather has negative implications for safety. Associated risks vary depending on temporal patterns, societal policies for traffic safety, and the local micro-climatic conditions (Andrey, 2009).

There is an established understanding that pedestrians are susceptible to injury in collisions with motor vehicles. Due to the lack of any structural protection, pedestrians can easily be killed or sustain severe injuries that can produce long-term medical and social costs. Therefore, the pedestrian safety literature tends to be dominated by research in fields such as pediatrics, trauma, and epidemiology. This has led to studies that investigate the effectiveness of different interventions that can reduce or prevent the extent of pedestrian injuries.

Studies that explore risk factors that contribute to pedestrian-vehicle collisions have focused on different characteristics (time of day, day of week, location, and weather) and accompanying factors, such as the behaviour/condition of the motorists, behaviour/condition of the pedestrian, road configuration, and environment. Many factors and characteristics of pedestrian-vehicle collisions are well emphasized in the literature, but the role of inclement weather is overlooked which is problematic due to increasing urbanization, changing climate and the shift to sustainable forms of transportation. By contrast, numerous studies provide an in-depth investigation of inclement weather's influence on the risk of vehicle collisions. Weather conditions such as rain, snow, hail, and fog are problematic conditions that occur worldwide. Such weather affects the ability of drivers to respond to road challenges, thereby elevating the risk of collisions (Andrey et al., 2012). During rainfall, studies have clearly shown that hazards such as slippery roads and reduced road-tire friction elevate the risk of driver error and the risk of vehicle collisions with other drivers, property, or pedestrians (Andrey & Hambly, 2012; Andrey & Olley, 1990; Eisenberg, 2004; Mills et al., 2011).

The first part of this thesis investigates the influence of weather, specifically liquid precipitation or rainfall on pedestrian safety. It is important to study the influence of weather on pedestrian safety for four reasons. First, pedestrians continue making trips during inclement weather (Miranda-Moreno et al., 2013; Aultman-hall et al., 2010). Second, there is evidence in a diversity of places like New York, Israel, and England that there is the added risk of collisions for pedestrians who venture out during weather events (Brodsky & Hakkert, 1988; Dimaggio et al.,1997; Smeed, 1968). Third, it is difficult for pedestrians to cope with hazards such as slippery roads/sidewalks and lack of visibility (Li et al.,2013, Sullivan et al.,2007; Mueller et al, 1987). And finally, pedestrians often neglect traffic rules during precipitation due to the urgency to find shelter or reach the desired destination (Li et al., 2010).

The second part of this thesis is an examination of the influence of anthropogenic climate change on pedestrian safety. Climate change is expected to introduce significant societal and ecological challenges in the future. Transportation systems will be challenged due to more frequent storms, intense precipitation, and higher temperatures that may compromise the current system's integrity (Chapman, 2007). One notable study by Hambly et al. (2013) introduces the use of climate change risk assessments in transportation to identify the expected change in collision risk due to change climate. This thesis applies a similar approach to investigate the impacts of climate change on pedestrian collisions, a question that is briefly explored in only one other study by Böcker (2012), to the best of the author's knowledge.

The focus of this thesis is on predictive risk assessment of rain-related pedestrian-vehicle collisions in Toronto, and Vancouver, Canada under a climate change scenario. The thesis provides risk estimates under present-day rainfall as well as future mid-century rainfall as projected in several climate change models.

“Pedestrian collision”, in this study, exclusively refers to a collision between a pedestrian and one or more vehicles since road authorities do not provide reports of pedestrian collisions with cyclists or other road objects. The terms “crashes” and “collisions” are used interchangeably in the thesis.

1.2 Thesis Objectives

The purpose of this study is to advance the understanding of pedestrian collision risk during inclement weather in association with climate change in Toronto and Vancouver – two study areas with different climatological conditions. The thesis will provide risk estimates of pedestrian collisions under rainfall relative to “normal” weather conditions for the present system using six-hourly and daily data as the temporal units of analysis. The changes in risk will be estimated for the future mid-century period under the expected climate change.

The study has the following research objectives:

- To produce present risk estimates of pedestrian collisions under rainfall relative to normal weather.
- To understand the implications of climate change for pedestrian collision risk estimates for the future mid-century.

The novel focus of this thesis is its investigation of pedestrian safety during adverse weather events. The investigation of rainfall influence on pedestrian safety is important due to the increasing number of pedestrians in continuously urbanizing areas that receive more rainfall events than any other weather condition. An important contribution of this thesis is the exploration of pedestrian collisions through a climate change impact assessment. There are climate change implications for pedestrian safety as global temperatures and precipitation are expected to increase, and research is needed to initiate discussions on coherent safety responses or modifications of the current road system to alleviate anticipated future negative impacts on pedestrians’ safety.

Chapter 2: Literature Review

2.1 Pedestrians as Vulnerable Road Users

The term "vulnerable road users" or VRUs applies to pedestrians, cyclists, motor-cyclists, and three-wheeler motorists, who naturally lack the protection of safety structures against collisions with motor vehicles. As the use of motor-vehicles increases worldwide, vulnerable road users are increasingly exposed to risks, especially in countries with poor planning or traffic laws (Zegeer et al., 2001). The increasing number of VRUs means higher exposure to risk of injury in both developing and developed countries, especially in densely populated urban areas (Shinar, 2012). Worldwide, 45 percent of vehicle collisions involve VRUs (Shinar, 2012). In developing countries, VRUs in low and middle income groups are consistently at risk. In India and China, 60 to 80 percent of road fatalities involving VRUs are from low-income groups (Gandhi & Trivedi, 2007). In developed countries, the improved roadways and greater dependency on vehicles generally reduces the exposure of VRUs to risk. Still, in Canada, almost a quarter of traffic-related fatalities are VRUs with the largest subset of these being pedestrians (Lauwers, 2010). From 2003 to 2006, 400 pedestrians were killed per year, in Canada, comprising 13 percent of total road fatalities, and approximately 6,000 were in serious injuries per year (Miranda-Moreno et al., 2011). It is estimated that all transport-related injuries in Canada cost approximately $4 billion annually, which is 20 percent of the total economic cost of all injuries (Brown et al., 2012). A conservative estimate of the cost of pedestrian injuries is half a billion dollars per year.

Since the thesis combines the pedestrian safety problem with climate change, it's important to define terms to avoid confusion. Table 2-1 provides an overview of the terminology used in climate change studies, and an adjacent explanation of how each term applies to pedestrian traffic safety issues. The term vulnerability has a different interpretation in pedestrian related literature as compared to climate change or natural hazards literature. The term exists outside the context of hazard and adaptive capacity, as it is used to emphasize the natural defenseless nature of the pedestrian around motor vehicles. To avoid confusion, this term is used in the thesis exclusively in the same manner as the pedestrian safety literature interpretation.

Table 2-1: Key Terms

Key Term	**In the Context of Climate Change and Natural Hazards**	**Application to the Pedestrian Safety Context**
Exposure	The presence of people or systems that could be adversely affected by a hazard or climate change	Number of pedestrians on road systems.
Hazard	The agent of harm that could cause a loss of life, injury, damage to health or personal property.	The agent of harm is vehicles. The hazard is rainfall.
Risk	The probability of an impact occurring from the interaction of vulnerability, exposure and hazard.	Expressed as relative risk, the change on the involvement of pedestrians in collisions during specific conditions.
Vulnerability	The characteristics of the human, natural, and physical system, its possible stressors, and ability to cope that makes likely to be adversely affected.	Pedestrians natural lack of protection by any structure, and the interactions in road environments with motor vehicles.
Impact	The effects on natural and human system from a disruptive event	Pedestrian collisions and injuries sustained.
Safety	Addressing factors and problems that contribute to accident outcomes (injuries or fatalities) that are responsive to modification.	The reduction of collisions, fatalities and injuries or accident outcomes.
Sources: IPCC, 2014 pp.4-5 and Elvik (2004)		

Two concepts from Table 2-1 that warrant elaboration are exposure and risk. Exposure quantifies the number of pedestrians in the road environment and thus represents the frequency with which people have the chance of being in a collision. From exposure, risk is a rate expressed as:

$$\text{Risk} = \text{Number of Collisions} / \text{Exposure}$$

Exposure is important because there is evidence that pedestrian trips vary by time of day, location, environmental setting and other circumstances. Table (2-2) briefly summarizes themes or factors that may influence pedestrian exposure. Exposure is difficult to estimate for pedestrians due to a lack of readily available data. Ideally, exposure reflects the time or distance travelled by pedestrians. Sometimes surrogate measures are used such as population, employment and bus transit statistics to estimate the number of possible pedestrians. But the number of kilometers walked, roads crossed, and hours of walking are more accurate reflections of exposure. Exposure data has been collected in some previous studies using extensive surveys and personal interviews, usually for small communities or a town, known as micro-scale analysis. In these studies, surveys are used to provide needed pedestrian exposure data, but authors argue that surveys are time consuming to collect and highly complex, especially for children. The built environment, such as intersections and sidewalks, provide an opportunity for site-specific pedestrian counts through mounted sensors (Miranda-Moreno et al., 2011). This has been used as source of exposure data in some studies, but these studies also are usually confined to a small location from which results cannot be easily generalized.

Table 2-2: Selected themes and factors that influence pedestrian exposure

Study	Theme	Findings
Pucher & Dijkstra (2003)	Built environment	Pedestrian facilities, convenience and safety encourages walking especially among the adolescent and elderly pedestrians
Busch et al. (2015)	Depression and anxiety	Walking is one of the most preferred exercises that reduces anxiety and depression symptoms
Kytta et al. (2015)	Children independent mobility (CIM)	CIM has decreased significantly from 1990 to 2011 especially in rural areas
Davies & Westen (2015)	Organized walking groups	Engrained dependency on vehicles to reach group walks meeting point
Cauwenberg et al. (2015)	Park proximity and retirement	Parks simulate walking among non-retired and those who already walk.

In part due to data limitation, risk estimation, as a whole, is less frequent in pedestrian-vehicle collision literature in comparison to vehicle-vehicle collision literature. Only a handful of studies were found specifically on risk estimation of pedestrian collisions (Brodsky & Hakkert, 1988; Mueller et al., 1987; Smeed, 1968). Related studies agree that the relationship between collisions with vehicles and pedestrian volume is non-linear: as the number of pedestrians increases the risk to each individual decreases, an effect known as “safety in numbers” (Miranda-Moreno et al., 2011). In the following subsections, the concepts of exposure and risk estimation will be revisited.

Studies have attempted to understand the characteristics and contributing factors of pedestrian collisions. Elements such as the demographics, behaviours of road users, and the built environment are found to be associated with pedestrian crash risk (Senserrick et al., 2014). An understanding of these factors is vital to transport safety planners since they provide insights into societal-environmental pre-determinants of crashes. Zegeer and Bushell (2012) provided an overview of the factors that influence the likelihood of pedestrian collisions and injury, which is reproduced in Figure (2-1). The figure illustrates that there is simply no single cause of these collisions, but certainly some factors are more important than others. Recently, interest has been increasing on the influence of environmental factors such as visibility and road design on pedestrian safety.

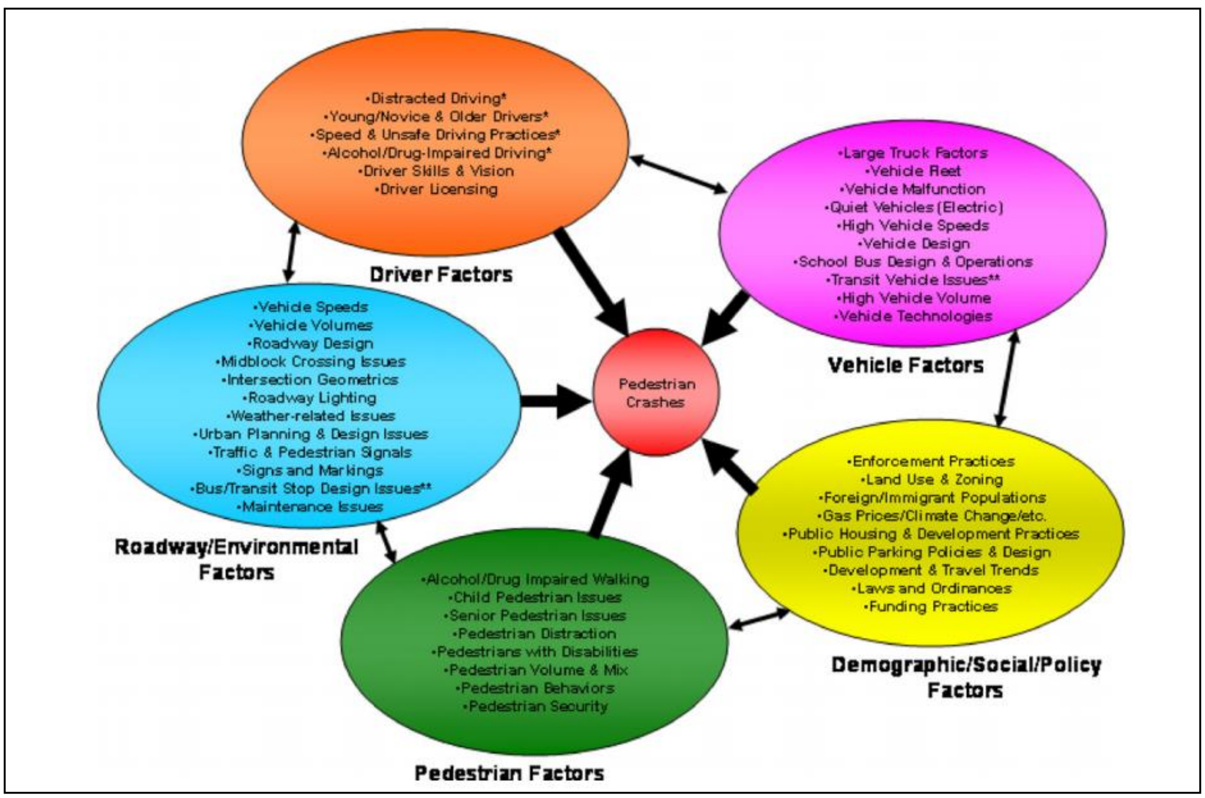

Figure 2-1: Factors that contribute to pedestrian crashes (reprinted from Zegeer & Bushell, 2012 p.6)

One way to summarize the literature on risk factors for the pedestrian collision problem is to organize insights into two themes: the factors that increase chance of collision and the factors that influence injury severity after impact. For example, there are direct factors that increase risk of pedestrian collisions (pedestrian type and behaviour, and built environment), from that, there are factors attributed to the severity level of injury a pedestrian sustains (vehicle size and speed). Nonetheless, the factors in each theme are not exclusive. The built environment, such as urban or rural forms for example, not only affects collision frequency but also injury severity, which tends to influence vehicle speed. This concept is illustrated in Figure (2-2), which draws on Zegeer and Bushell (2012) and Stocker et al. (2015).

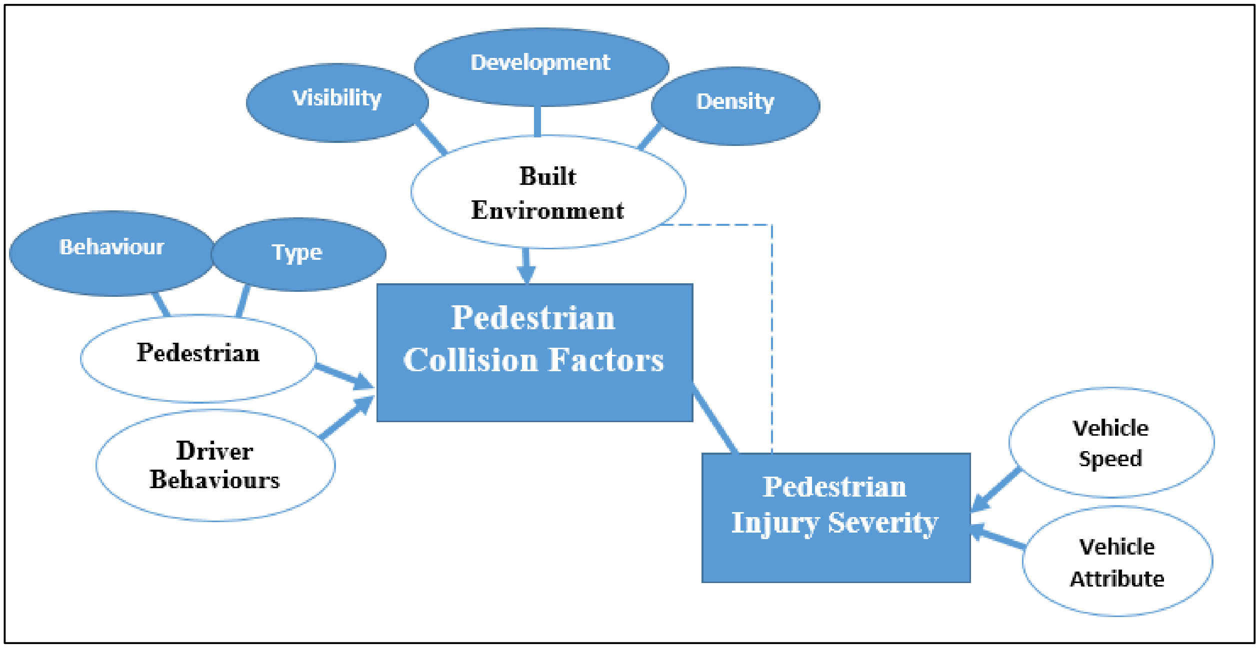

Figure 2-2: Factors that influence pedestrian crashes and injury severity

Section 2.1 of this chapter is organized by the three themes based on Figure (2-2): built environment, driver and pedestrian (types and behaviours), and injury severity factors (vehicle speed and attributes). The subsections investigate these three themes in that order as it pertains to pedestrian safety. Moreover, insights are provided into related interventions. Safety interventions consist of adjustments to the built environment, understanding of problematic pedestrian or driver behaviours, and the use of smart traffic safety technologies.

2.1.1 Built Environment

The built environment and its characteristics play significant roles in pedestrian safety. The patterns of the built environment at the local scale (density and regional development) all shape the characteristics of the environment in which travellers operate.

With respect to density, there is inconsistency in the literature in regards to the effects of density on pedestrian collisions. Some authors argue that, as local areas become denser, the number of pedestrians and vehicles (i.e., exposure) increases, thereby elevating pedestrian collisions (Agran et al., 1996, LaScala et al., 2001). Earlier studies were in agreement. For example, in one U.S. study, children living in high-density residential areas were three times more likely to be in a collision than those living in single-family residential areas (Agran et al., 1996). There is little doubt that the number of pedestrian crashes increase with density. However, some authors argued that the relationship between density and pedestrian crashes may not be completely linear due to the "safety in numbers" effect (Bhatia & Wier, 2011; Thompson et al., 1985). This theory states that a driver is less likely to hit a pedestrian if there are more vulnerable users (mainly walkers and cyclers) , a pattern that has been found from small to large cities and across different time periods (Jacobsen, 2003). Still, this theory is one-dimensional since it does not explicitly take into account the built environment such as roadway design, traffic policies and pedestrian infrastructure (Stocker et al, 2015). It is suggested that pedestrian casualty rates are reduced when areas become extremely dense, due to the effect of traffic congestion, restricted vehicle movement or speed, and abundant pedestrian facilities (Graham & Glaister, 2003).

Due to the influence of density, pedestrian crashes tend to be higher in urban areas because of traffic and higher supply of pedestrians. If a region's population is mostly urban, pedestrian crashes will likely be concentrated there. Urban areas are important regions, since approximately 50 percent of the world's population is concentrated in urban centers (Jaroszweski et al.,2014).

At the micro-local level, other environmental factors that are influenced by development is roadway design. Generally wider roads with a large number of lanes experience higher rates of pedestrian crashes (Gårder, 2004). Wide lanes has been found to influence "run-off roadway" crashes, where a vehicle in transit leaves the roadway and collides with a pedestrian or other nearby objects (Sayed, 2012,Stocker et al,2015). Wider lanes helped reduce run-off-roadway crashes in rural areas, but had the opposite effect in urban areas where run-off road crashes were elevated (Stocker et al., 2015).

An important environmental condition in pedestrian safety is poor visibility which can arise due to road design, pedestrian clothing, or meteorological conditions (Mueller et al., 1987). As expected, pedestrian crashes elevate significantly at twilight or dawn/dusk hours (Wanvik, 2009). Roadways that are poorly lit have a high frequency of pedestrian crashes especially during nighttime hours (Stocker et al., 2015). Visibility is not only a problem for drivers, but it also influences the pedestrian's ability to adequately judge the vehicle speed and distance (Siddiqui et al., 2006). Conversely, pedestrians tend to overestimate the driver's ability to see at low visibility conditions.

To identify the influence of environmental factors on pedestrian crashes, risk estimation in different environmental settings is necessary. Several studies have considered this issue using multiple regression analysis and odds ratios. Table (2-3) summarizes the findings of these studies which have been successful in raising a discussion on the importance of the physical environment in pedestrian safety. Busier streets, unlit roads, high traffic volumes, lack of marked crosswalks, and driveways or garages that are exposed to open roads have been found to impact pedestrian crashes (Mueller et al., 1990).

Table 2-3: Risk estimation studies of pedestrian crashes

Author	Study	Findings
Sullivan & Flannagan (2007)	The influence of natural day light vs. darkness on pedestrian crash scenarios	Risk of crashes is 2.5x higher during dark conditions relative to light conditions
Mueller et al. (1988)	Risk of dying in urban vs. rural areas	Relative risk is 2.3 of fatal collisions (not general collisions) in rural compared to urban
Siddiqui (2006)	Risk estimate of pedestrian collision midblock vs. intersections	Odds of sustaining a fatal injury is 42 % lower at intersections than at midblock locations.

Wanvik (2009)	Effects of road lighting on rural roads	The risk of pedestrian injury was found to increase in darkness. Average increase in risk is 17% on lit rural roads and 140% on unlit rural roads.

2.1.1.1 Interventions to Pedestrian Road and Environment

Interventions into the pedestrian crash problem through the built environment are a challenge. Studies remind transportation authorities and planners about the importance of designing a built environment that reduces the risk of crashes for all road users. However, it is challenging to provide a safe environment that takes into consideration the needs of both pedestrians and vehicles, and sometimes a trade-off is involved. For example, in some the residential areas of Netherlands, one of the policies implemented in the 1970s, the “woonerf”, which allowed vehicles on roads under strict conditions of low speed, limited parking and traffic (Stocker et al., 2015). The policy was successful in making pedestrians and cyclists a priority at the expense of motorists. To promote similarly safe outcomes, several initiatives have been implemented around the world, such as, reduced vehicle speeds in residential and school zones, raised medians, and marked crosswalks (Zegeer et al., 2001). One key finding of the literature is that an effective way to reduce pedestrian crash rates is roadway design and treatments. This includes building well-lit roads, narrowing roads or reducing the number of lanes, and installing frequent stop signs and pedestrian warning signals. Lastly, it’s important to provide attractive and safe walking facilities to reduce the dependence on vehicle use, especially in areas of urban sprawl and low-density development.

It is documented that some collisions can be mitigated through the use of visibility aids by pedestrians (Kwan & Mapstone, 2004). Visibility aids consist of handheld lamps, flashing lights, and reflective materials. These adjustments highlight the movement and shape of the pedestrian, thereby increasing the ability of the driver to detect and recognize pedestrians using such aids (Sayer & Mefford, 2004). The public acceptability of these aids will depend on ease of application and cost. Also, visibility aids should be coupled with built environment adjustments discussed above as the optimal intervention strategy.

Moving forward, there will be a continued need for proactive planning when it comes to building communities that are safe for pedestrians and other vulnerable road users. As the world population and urban centers' populations increase, local regions will need to modify their transportation and mobility patterns to reduce auto-related risk to pedestrians.

2.1.2 Pedestrian Collision Factors

Pedestrians form a diverse, mixed group of people with different ages, genders and socioeconomic status. There is a large body of literature that focuses specifically on characterising pedestrians. Table (2-4) demonstrates and describes the broad types of pedestrians included in risk studies. Collision characteristic reports provided by road authorities help illuminate the dominant types of pedestrians involved in collisions. Several studies have identified the risk for some of the pedestrian types. The elderly over the age of 65 and children under the age of 10, had a very high risk of being in fatal collisions (Lauwers, 2010; Leden & Johansson, 2006; Keall, 1995; Ward, 1994) . The risk is also significant for intoxicated and distracted pedestrians (Beck et al, 2007;Lauweres, 2010; Jensen,1998), and male pedestrians were always over-represented in collisions compared to their counterparts (Brown et al., 2012; Zegeer et al.,2001) .

Table 2-4: Pedestrian Type

Pedestrian Type	Description	Source
Young Children	Worldwide almost 21 percent of fatalities involve young children	Stocker et al. (2015) (Posner et al., 2002)
Young Adults	For 15 to 21 year olds, pedestrian fatalities are leading cause of death	Stocker et al. (2015)
Gender	61 percent of pedestrian fatalities were male, and 39 percent females (Canada)	Zegeer et al., (2001) Lauwers (2010)
Elderly	36 percent of pedestrian collision involve elderly (Canada)	Stoker et al. (2015) Lauwers (2010)
Socioeconomic status	Pedestrian crashes are four times more likely in low-income neighbourhoods	Beck, et al (2007), Chen et al. (2012) Agran et al. (1996)
Intoxicated or impaired pedestrians	Involved in 48 percent of pedestrian collisions (Canada)	Campbell et al. (2004), Lauwers, (2010), Hatfield et al.(2007)

Disabled pedestrians	10 percent of fatalities were pedestrian using mobility aids (Canada)	Lauwers (2010)

Although some of the research on pedestrian types is conducted in certain regional locations, the results are easily generalized. Nevertheless, Stocker et al. (2015) argues that some types of pedestrians are sometimes specific to a certain locale. For example, in low-income countries, females have a higher risk of being in pedestrian collisions than males due to different gender roles than North America. Walking as a form of transport is more common among females than males in Africa (Stocker et al., 2015). Similarly, there is an unequal distribution of older populations around the world, two-thirds of which live in developing countries (Stocker et al., 2015). Therefore, developing countries will likely be challenged to provide the elderly with safe, easily accessible walking facilities.

Pedestrian behaviours while on the road are important because correcting unsafe behaviours is an effective way to reduce collisions. Walking on roads does not have age, skill, or impairment restrictions as long as the pedestrian adheres to a small number of traffic rules which are rarely enforced by road authorities. Not surprisingly, through observation of pedestrian behaviours, it was noted that there is generally widespread non-compliance with traffic rules (Bennett et al, 2001; Carsten et al.,1998; Li & Fernie, 2010). This consists of pedestrians making last minute decision errors, poor judgments to cross mid-road, and failure to perceive approaching vehicles (Bungum et al., 2005; Carsten et al.,1998; Hatfield et al., 2007). Pedestrians were found to be more likely to be at fault than drivers in pedestrian crashes in the U.S, while, in Saudi Arabia both groups had equal responsibility (Cinnamon, et al., 2011) . Again this demonstrates that local characteristics and attributes of the region or city influence pedestrian and driver behaviours and safety outcomes.

The literature is abundant with studies that observed problematic pedestrian behaviours such as the non-compliance to traffic rules. Bungum et al. (2005) argued that a large portion of pedestrians failed to obey traffic signals and safety guidelines when crossing busy streets. Usually, the largest number of collisions occur when a pedestrian is crossing (Carsten et al., 1998; Hatfield et al., 2007; Luoma & Peltola, 2013). In the U.S., 63 percent of crashes between

1995 and 1998 occurred while a pedestrian was trying to cross the road (Hatfield et al., 2007). The most documented causes of collision for a pedestrian is “ran into road” or “crossing a road”, and for drivers, the “fail to yield right of way” to a pedestrian (Campbell et al.,2004). Lastly, research in Toronto, Canada, for a two-stage crossing (a signalized intersection with a refugee island in the middle) revealed that pedestrians have a compliance rate of only 13 percent for both stages, 10 percent complied with only the first stage of crossing, and 77 percent of pedestrians decided to cross the two-stage crossing in one walk and were facing a red light upon finishing the crossing (Li & Fernie, 2010). Unsurprisingly, it appears that pedestrians, while on the road, strive to complete trips with minimal delay and inconvenience.

2.1.2.1 Driver Collision Factors

The behaviours and movements of vehicle users while on the road certainly contributes to pedestrian collisions. A limited number of studies comprehensively examined driver and vehicle movement factors in relation to pedestrians. The following summarizes some of the findings in the literature:

- ❖ Drivers can become distracted by eating, listening to headphones, speaking on cell phones, chatting with other passengers, and manipulating vehicle technologies (Bungum et al., 2005; Hatfield & Murphy, 2007).
- ❖ Drivers usually decrease vehicle speeds when large clusters of pedestrians are present, but are consistently inadequately prepared for child pedestrians (Thompson et al,, 1985).
- ❖ Older drivers are involved in pedestrian crashes with less severe injuries. Elderly drivers have a tendency to hit pedestrians in low-speed zones, perhaps reflecting differences in driving patterns by age (Kim, 2014).
- ❖ Young male drivers are typically involved in fatal pedestrian collision which tends to be linked to more high-speed driving (Kim, 2014; Siddiqui et al., 2006).
- ❖ Vehicles turning left or right produced lower injury severity rates among pedestrians than vehicles impacting pedestrians while travelling straight on the roadway (Moudon et al., 2011).

- ❖ Vehicles turning left on a red signal resulted in conflicts with pedestrians, which usually consisted of drivers violating a "no turn on red" traffic rule (Campbell et al., 2004; Leden, 2002).

Although the literature captures reasonably well the influence of driver actions on pedestrian crashes, there is little research that relates attentiveness, concentration and overall behaviour of the driver to injury severity (Moudon et al.,2011).

2.1.2.2 Pedestrian & Driver Interventions

There is a concern regarding effective interventions for non-compliant pedestrians at traffic signals. There are several issues with intersections and traffic signals that reduce the compliance of pedestrians. A pedestrian is sometimes required to activate the walking stage by the push-button, where the walking stage is often very short in duration. In England, a small-scale analysis on pedestrians revealed those who complied with traffic signals (e.g., don't walk) had the highest number of delays (Carsten et al., 1998). Pedestrians that usually arrive during the last seconds of the walking stage, due to urgency, conflict with vehicles approaching a green light. For increased safety, pedestrian delays seem inevitable. Therefore, it is suggested to increase the frequency of pedestrian walking, or provide pedestrian exclusive walking stages where pedestrians are allowed to cross in any direction (Carsten et al., 1998). Human error is inevitable, and these interventions may not correct or change the unsafe behaviours of eager late-arriving pedestrians, but it can help promote the importance of safe crossings for pedestrians in public intersections.

Regarding other pedestrian movements, moving pedestrians were detected from greater distances by drivers than stationary pedestrians (Langham & Moberly, 2003). Using data from driver behaviour (e.g. braking, speed, stopping) and probabilistic modelling, a study tested the response of drivers to pedestrians at varying distances. The results indicate that the probability of a driver being aware of a pedestrian decreases as distance increases (Fukagawa & Yamada, 2013). A common action noticed during the study is the driver lowering the speed of the vehicle.

Other types of interventions include the use of Intelligent Transportation System (ITS), a rapidly developing field in pedestrian safety literature and a field that is dominated by engineers and transportation technology researchers. Within ITS research, there is a significant focus on pedestrian or vehicle detection systems. The main objectives of ITSs are crash prevention and mitigation of crash severity (Oh et al., 2008). Some technologies detect pedestrians, thus warning the driver and releasing automatic braking or aversion of impact through evasive steering (Gandhi & Trivedi, 2007), while others have been tested in regards to preventing crashes with alcohol-impaired pedestrians in high-risk locations and high-risk periods (Lenné et al., 2007). Evasive safety systems employ vehicle detection systems and computer vision algorithms to detect nearby pedestrians. Several of these systems were tested to estimate accuracy in detecting nearby pedestrians obstructed by objects (Broggi et al., 2009) . Some vehicular technological safety adjustments were found to be successful in automatically braking or evasively steering away from pedestrians, which could be beneficial for drivers who are distracted and inattentive. Lastly, some studies analyzed the suitability and effectiveness of pedestrian-to-vehicle communication systems for collision risk reduction. These were found to be less effective than other options (Sugimoto et al., 2008). Overall, it is apparent that challenges still remain in producing reliable and cost-effective ITSs that could be easily integrated for road users.

2.1.3 Pedestrian Injury Severity

Pedestrian collisions risk assessments often consider both relative frequency and consequence, for example when expressed as the probability of pedestrians sustaining severe injuries in a collision. Vehicle speed strongly influences the degree of injury, especially when the pedestrian is struck from certain body angles. Traffic speed is affected by roadway design where traffic conditions are influenced by the type of development and overall built environment. Speed is also influenced by the characteristics of the driver. Younger drivers tend to be more involved in pedestrian collision resulting in fatalities (Lauwers, 2010; Rosén et al.,2009).

Within the safety community, there is an established consensus that injury severity is a function of vehicle speed at the time of impact. The effect on crash injury risk is a relationship between speed and the time needed to reach a full stop. Usually, the higher the speed of the vehicle, the shorter time a driver has to avoid a collision (Rosén et al.,2009). Findings in Canada and U.S., indicate that most fatalities occurred in rural areas, where vehicles are usually travelling between 70-90 km/hr (Campbell et al., 2004; Lauwers, 2010; Senserrick et al., 2014). Rural areas influence injury severity significantly due to four reasons: 1) The speed limit is higher on rural roads 2)the vehicle miles travelled (VMT) per capita is also higher 3) rural roads are located further away from emergency responses 4) rural roads are less likely to have a pedestrian-friendly built environment (Stocker et al.,2015). This is not to say that fatal injuries are only restricted to rural areas. Some research suggested sprawling urban areas are also problematic. Urban sprawling areas tend to be widely dispersed, low-density development with poorly defined road connectivity. A comprehensive study by Ewing et al. (2003) found that each percent decrease in urban sprawl resulted in a 1.5 to 3.6 percent decrease in pedestrian fatality rates. It was estimated that speed increases the probability of fatality in a collision from 5 to 45 percent when the speed of the vehicle increases from 30 km/hr to 50 km/hr (Moudon et al., 2011). Research in vehicle speed and pedestrian injury severity seems to overlook some variables such as the role of pedestrian's characteristics (i.e., age) and the influence of emergency medical treatment in fatality risk (Rosen et al., 2009).

All vehicles on the road are a hazard to pedestrian safety and level of injury severity, but larger vehicles have created a concern among researchers due to the severe types of injuries sustained in collisions with larger vehicles. In comparison to conventional vehicles, pedestrians hit by larger vehicles in the U.S, were more likely to have a higher risk of severe injuries and deaths (Ballesteros et al., 2003). Larger vehicles types (SUVs, vans, and trucks) are more dangerous for several reasons: heavier moving mass, faster vehicle speed, longer stopping distance, and hazardous frontal design. Larger vehicles have more kinetic energy, which when dispersed upon impact causes a greater potential for injury than conventional vehicles (Gårder, 2004). At lower speeds, larger vehicles still resulted in specific types of injuries (spinal and above the knee injuries) due to the vehicle design (Ballesteros et al., 2003). A one percent increase in large vehicles on the road leads to a 34 percent increase in annual traffic fatalities for all road user groups. This is particularly an important issue in regions with high sales of trucks, vans, and SUV's. In the U.S., just over the course of two decades (1985-2005), truck and van sales have increased from approximately 20 to 50 percent (Anderson, 2008).

2.1.3.1 Pedestrian injury severity Interventions

Safety interventions for injury severity are mainly reactive in nature. They are intended to reduce current injury severity through “soft safety measures” such as lowering speed limits on roads (Moudon et al., 2011). Lowering speed of vehicles and traffic calming measures require drivers to adjust speed and potentially be more attentive (Dai, 2012b; Leden et al., 2006; Moudon et al., 2011). One successful policy in the Netherlands set speed limits based on road function resulting in one-third fewer injuries per million vehicle kilometres (Stocker et al., 2015).

Since pedestrian-vehicle collisions are more likely to result in fatalities in comparison to other collision types, the safety community have become interested in safety measures through advanced vehicular technologies (Oh et al., 2008). These include systems such as collision-absorbing components or pop-up bonnets “active hood lift system” and windscreen airbags (Gandhi & Trivedi, 2007). These systems specifically target reduced pedestrian fatalities caused by head injury, identified as the most critical region of the body resulting in fatalities (Oh et al., 2008). Although this field is increasingly advancing, challenges remain in accurately estimating the effectiveness of such technologies. In fact, most authors emphasize the need for standardized methodologies to quantify and estimate effectiveness of advanced vehicular safety technologies. Moreover, a societal barrier to these technologies is the expense and technological efforts needed to integrate these safety measures in road environments.

From the preceding discussion, it is clear that the pedestrian collision problem is caused by a combination of many factors, characteristics and variables. A blend of interventions is thus likely needed to address the various risk factors to respond to the undesirable social implications such as pedestrian injuries. An important topic requiring attention is the influence and role of weather. The next section will discuss this influence on road safety.

2.2 Travel Risks and Inclement Weather

The field of weather-related travel risks is well established, with many studies exploring driving risk during rainfall, snowfall, fog, heat, and wind. The public, professional communities, and safety researchers all recognize the importance of weather as it relates to road safety. Although a vehicle collision depends on many technological and societal factors, vehicle drivers are more prone to errors that increase the risk of collision during inclement weather. It has been acknowledged by several authors that weather influences road safety in various ways; weather causes travel reductions (a decrease in number of trips) and increases the risk of a collision per unit of exposure (Andrey & Olley, 1990; Satterthwaite, 1976). This section will discuss the influence of inclement weather on pedestrians and drivers.

2.2.1 Motorist Weather Hazards

Weather events such as fog, hail, wind, blowing snow, and rainfall cause visibility challenges, reduce road-tire friction, and result in more difficult vehicle handling conditions. Even "minor" weather phenomena have been found to cause delays and travel reductions. Each type of weather event influences road safety in different ways:

- During extreme heat, the risk of single-vehicle collisions in Australia was found to increase significantly due to an increase in aggressiveness and impatience among drivers (Koetse & Rietveld, 2009).
- Strong winds generally increase the risk of collisions whether acting alone or in combination with another weather condition (Andrey et al. 2001).
- Fog, especially if sudden or localized, increases collisions involving a large number of vehicles (Ahmed et al., 2014).
- Winter storm events are known to influence traffic mobility and delays including travel on vital highway routes (Stethem et al., 2003).

The magnitude of damage from weather hazards largely depends on the resiliency of a region. The geography associated with of traffic safety demonstrates that incident rates and trends vary spatially due to different built environments, traffic policies, population, and demographics (Andrey, 2010). The variable nature of risk during inclement weather has been explored in the literature at three general levels. Table (2-5) summarizes the type of studies that have quantified the risk of weather in vehicle collisions.

Table 2-5: Spatial and Temporal Types of Vehicle Collision Risk Studies

Study Type	Spatial and Temporal Scale
Macroscopic	State or regional level Aggregated weather variables
Meso-scales	City-level Detailed hourly and daily weather data
Micro-scale	Road segments/ individual collisions Detailed weather and road condition
Adapted from Andrey & Hambly (2013)	

Macroscopic studies often rely on estimation of the percent of time inclement weather is present and the percent of collisions occurring during that weather. Macroscopic-scale studies provide a large regional sense of the problem but the associated data reduces our ability to understand the relationship between certain outcomes and weather (Andrey & Hambly, 2012). Micro-scale studies, for example on an individual intersection, provide very specific situational details on weather hazards and collisions, often using multivariate statistical approaches. Although an exposure component (a measure that accounts for travel reductions that occur in inclement weather) can be included at this level, the results are less predictive and difficult to generalize (Andrey & Olley, 1990). As such, meso-scale studies were found to be the most accurate for comparative studies and in estimating the average effect of weather on collision rates. At this scale, an estimate of relative risk can be conducted which includes the measure of exposure to weather hazards (Andrey & Olley, 1990). A common approach used by several authors to address this issue is to conduct a comparison of collision frequency on wet days versus dry days. This approach is adopted for the analysis of risk estimation of pedestrian collisions in this thesis.

2.2.2 Rainfall as a Driving Hazard

In terms of weather-related driving hazards, the most frequently studied condition is precipitation. Rainfall occurs frequently, except in the Polar Regions and arid climates, it is present all over the world. Most of the time, Canada’s largest cities receive more rainfall than snowfall (Andrey et al., 2005). With climate change, higher temperatures and more precipitation is expected to make the presence of rainfall more pronounced (Meyer & Weigel, 2011).

Rain is formed when the atmospheric water vapour condenses and falls under the force of gravity (Andrey & Hambly, 2012). Rainfall creates hazards such as slippery roads or low visibility, and has hazardous consequences such as flooded streets and submerged infrastructure. Over the past years, numerous studies have examined rainfall as a compound driving hazard.

A number of authors have reviewed the risk of vehicle collisions during rainfall (Andrey et al., 2003; Eisenberg, 2004; Qiu & Nixon, 2008; Sherretz & Farhar, 1978). Collision rates usually increased during precipitation by 50-100 percent in comparison to dry conditions with a larger increase during snowfall than rainfall (Andrey, 2010; Qiu & Nixon, 2008), while injuries increased by lesser amounts. The results vary from study to study because of different research methods, weather characteristics, and driving practices – however, a common consensus in the literature is that there is elevated risk during rainfall. The collision rates were found to return quickly to normal levels after the cessation of the rainfall. Fortunately, from a temporal perspective, collision risk in Canada during rainfall has declined over the past two decades in absolute and relative terms (Andrey, 2010).

An important research question related to rainfall crashes is how many crashes are due to low visibility and how many crashes are due to wet pavement. The effect of wet pavement on tire friction is extensively examined in the literature (Andrey, 2010). In addition to an increase in stopping distance, the water film that forms on roads can cause hydroplaning, or the complete loss of control of the vehicle from loss of tire friction. Hydroplaning can occur at high travel speeds (more than 50km/h) and water depth within 0.76 millimetres (Bernardin et al., 2014). Rainfall amounts of just 0.2 millimetres are enough to wet roads. Wet conditions can last up to an hour or more depending on the adequacy of the drainage and land-use planning efforts (Andrey & Hambly, 2012; Andrey & Yagar, 1993). In Canada, more than one-third of accidents that occurred in the first hour post rain events, took place on wet roads because of lingering effects. Eisenberg (2004) discussed how rainfall events occurring after a prolonged dry-spell are especially problematic. This is mostly due to engine oil and gasoline that accumulates on the road, which can increase the slipperiness of roads when the oil mixes with water. This phenomena increases the number of collisions after long dry periods. However, if rainfall occurs two days in a row, the second day tends to be less hazardous since most of the oil is washed off the road, and possibly because drivers have adjusted.

Regarding the visibility hazard during rain, Authors Andrey and Yagar (1993) discuss the effects of visibility and wet roads on accident causation; the findings reveal that collision rates return to "near-normal" levels after the cessation of rainfall suggesting that much of the risk is associated with reduced visibility. The reduction in visibility is enhanced at night time, under low luminance levels, low speed wipers, and when small raindrops are on the windshield (Bernardin et al., 2014). Rainfall also lowers the contrast between objects and their background, lowering the motorist's ability to detect pedestrians. The motorist's visibility is also reduced during rainfall due to splashing of rain-water from nearby vehicles, increased interior humidity levels which can cloud the vehicle windshield, and night-time blinding from oncoming vehicle headlights reflecting off of the wet road (Andrey & Hambly, 2012) .

Rainfall events have the tendency to influence motorist behaviour, especially travel speed and traffic volume. Evidence suggests that motorist employ some adaptation methods when driving in wet conditions. Some drivers cancel scheduled trips in response to inclement weather, which is reflected in a decrease in traffic volume. Other travellers shift to other travel modes by taking public transit or by delaying trips. Traffic volume is usually decreased by a small amount during wet conditions (Qiu & Nixon, 2008), and there are other common adjustment behaviours while driving, such as increased attention and reduced vehicle speeds. In fact, speed reduction is the primary response. Estimates suggest speed reductions of up to 50 percent during heavy precipitation (Andrey et al., 2001). As drivers adjust vehicle speed during inclement weather, there is evidence of a reduction in severe casualty collisions (Hambly, 2011). However, not all motorists apply adequate adjustment, and there are ample data records that indicate that many motorists drive well above the speed limit during precipitation and fog conditions (Andrey et al., 2012). Roads with higher speed limits are especially problematic with drivers maintaining higher speed levels during wet conditions and low visibility. Thus, driver's current adaptive responses are insufficient to completely offset the risk of a collision during precipitation, mostly because of the variables mentioned (Andrey et al., 2001).

2.2.3 Weather and Pedestrian Safety

The research regarding the influence of rainfall on pedestrian collisions is very limited. To the author's knowledge, only a couple of studies briefly explored the influence of rainfall and other weather conditions on pedestrian crashes. However, a handful of studies explored how inclement weather affects pedestrian trips, and some inferences can be drawn on pedestrian behaviours during inclement weather, including rainfall.

The role of weather is researched in the context of its influence on pedestrian activity and daily trips. Regarding this question, studies usually use automated measuring techniques such as sensory counters in micro-scale intersections and crosswalks. This method requires various field observations at different locations for obtaining proper statistical data (Böcker et al., 2013). Miranda-Moreno & Lahti (2013) determined that pedestrian flows in Montreal, Canada are more sensitive to weather on weekends than on weekdays, and more affected during winter than in temperate season. In comparison to cyclists, pedestrians are less sensitive to weather conditions and specifically to rainfall. Temperature, on the other hand, encouraged walking, cycling and a slightly reduced reliance on vehicle usage or public transport. However, in Toronto, temperatures above 28 degrees Celsius are found to be uncomfortable, thereby reducing the number of pedestrian trips (Böcker et al., 2013). De Montigny et al. (2012) observed the amount of walking in relation to air temperature, sunlight, and precipitation. Web-based cameras in nine European cities collected observations over a seven month period. Through regression analysis, the research demonstrated pedestrians' flows increased for a 5 degree Celsius increase in temperature, a shift from snow to dry conditions, and an increase in sunlight. Moreover, temperature has different effects on pedestrians depending on the purpose of the trip; leisure trips are less affected than commuting and errand related trips. During heavy winds, cyclists share of trips were found to decrease by 30 percent, mostly increasing the proportion of pedestrians (Böcker et al., 2013).

The influence of weather on pedestrian facilities such as sidewalks and compliance with traffic controlled intersections has been briefly investigated by two studies (Li & Fernie, 2010; Li et al., 2013). Key elements that decrease walking activity and act as pedestrian hazards are icy or slushy sidewalks, intersections, and curb ramps (Li et al., 2013). The cold temperatures were found to have little impact on walking. However, unmaintained pedestrian facilities were found to keep some at home, specifically elderly pedestrians. Only one study examined pedestrian signalized intersection compliance during precipitation (Li & Fernie, 2010). The micro-scale analysis was completed in a two-stage intersection (a signalized intersection with a refugee island in the middle) crossing in Toronto. Using a month-long video recording in dry, windy and snow conditions for comparisons, the authors came to several conclusions. The compliance at the two-stage crossing was significantly lower, only 10 percent for temperatures under 10 degrees Celsius compared to 23 percent in normal weather. Only three percent crossed with the right of way during snowy conditions. The compliers and non-compliers were also crossing the intersection at higher speeds than in normal conditions. The study calls the effectiveness of such traffic safety measures to question. The results indicate that inclement weather has the ability to compromise pedestrian safety, and proper judgement, and possibly elevate crash risk.

Only a handful of earlier studies examined the risk of pedestrian crashes during rainfall. Overall results do indicate an added risk of pedestrian crashes in rainy conditions, but each study had limitations. In England, Smeed (1968) investigated the effect of rainfall on adult pedestrian casualties. The risk of pedestrian crashes when it's raining relative to dry conditions was found to be 2.9 to 3.3 times higher. The first shortfall of that the weather data was exclusively acquired from collision reports provided by road authorities who included observations of the weather condition at time of a collision. Second, variables used in the calculation of risk when it's raining were based on assumptions, such as the fraction of time during which rain fell. Broadsky and Hakkert (1986) examined the risk of pedestrian-vehicle collisions in Israel. Using the wet pavement method (proportion of wet pavement accidents to proportion of wet pavement time) the risk ratio was calculated as 5.7 times higher during the rainy winter season. This method may have grossly overestimated the results, because the drying time of wet pavements was assumed to be 30 minutes after a rainfall event. This drying time was applied for the entire day regardless of the seasonal temperatures. Finally, Dimaggio et al. (1997) using the collision characteristics database of the City of New York, demonstrated that out of all pedestrian collisions 11% (aged 6-9) and 16% (age 15 -19) of pedestrians were injured on wet roads between 1991-1997. This study did not demonstrate any risk estimates for the influence of wet roads on pedestrian collisions, and it only focused on the reported characteristics of pedestrian collisions of certain population groups.

In conclusion, the vehicle safety literature is much more advanced as compared to pedestrian safety literature when it comes to inclement weather. Further research is required to understand the behaviours and risk of pedestrian crashes during adverse weather – this should be further studied alongside the vehicle safety research.

2.3 Human and Physical Dimensions of Climate Change

The earliest realization of human activity and climate interaction were observed by physicist Williamson in 1771, and then scientist Svante Arrhenius in 1890, both of whom argued that human activities such as fossil fuel combustion and deforestation, could influence the earth's climate system (Von Storch & Stehr, 2006). More than a century later, the Intergovernmental Panel on Climate Change (IPCC) declared "The balance of evidence, from changes in global mean surface air temperature …. suggests that there is discernible human influence on the global climate" (IPCC, 1995 pp22). The statement has been reconfirmed various times over the past decade. Climate change is defined as "the change of the statistical property of the atmosphere, not just the mean or average, but the year-to-year variation, seasonal variations, and weather anomalies" (Aguado & Burt, 2013 p466).

While some changes have already been observed, additional physical changes are expected to occur because of climate change. Over the past 150 years, atmospheric concentration of carbon dioxide has risen by an unprecedented value of 31 percent, and methane concentrations more than doubled during the same period (McBean, 2004). The ocean and land surface temperatures have demonstrated an increase of 0.65 to 1.06 degrees Celsius over the period 1880 to 2012 (IPCC, 2013). The IPCC predicts an additional increase of global mean surface temperature of 1 to 3 degrees Celsius by 2100 (Dessai & Hulme, 2001). Frequency of heat waves, warm days and nights is expected to increase in areas such as Europe. There is some evidence of an increased frequency of heavy precipitation in mid-and high latitudes, especially in regions such as Canada (McBean, 2004). Northern regions in Canada will encounter challenges such as permafrost degradation which results in more methane emissions (IPCC, 2013). The expected higher temperatures will also cause sea level rise through thermal expansion of ocean water. There has been a significant increase the number and costs of atmospheric related extreme events (Easterling et al., 2000; McBean, 2004). These physical changes have consequences for natural and human systems.

By the time the contribution of human activities to the climate is grasped by the scientific community, one response strategy that emerged is mitigation, meaning the curtailing of greenhouse gas emissions (Kane & Shogren, 2000). Mitigation became a priority of international organizations such as the United Nations Convention of Climate Change (UNFCC) – which paved the way for initiatives such as the Kyoto Protocol (IPCC, 2014). This global international cooperation is a necessity, because mitigation requires collective action since greenhouse gases mix globally across different scales.

A second response strategy is adaptation, or the process of adjustment to expected climate change and its effects on societal or environmental systems (IPCC, 2014). The need for adaptation arose due to the irreversible accumulation of greenhouse gases and the non-immediate benefits of mitigation (IPCC, 2014; Klein et al., 2005; Pittock & Jones, 2000). Events such as the European heat wave of 2003, Hurricane Katrina of 2005, and the Australian drought of 2007, demanded a focus on adaptation for natural and human systems. Concerns grew over how to adapt, what to adapt to, when to adapt , and how to estimate costs (Pittock & Jones, 2000; Vogel et al. 2007). Adaptation plans and policies started to emerge from different levels of government to integrate adaptation into the broader developmental plans. However, implementation is not an easy goal. Various constraints were quickly realized such as, uncertainty, lack of funds, lack of support from governments, lack of monitoring tools, and differing perceptions of risk (IPCC, 2014, Dow et al., 2013).

There has been interest in simultaneous implementation of mitigation and adaptation, but the strategies sometimes substitute one for the other. For example, many developing countries are still economically growing and so mitigation is more challenging (Kane & Shogren, 2000). On the other hand, small islands perceive mitigation as a priority because adaptation strategies such as “abandon” and “retreat” are seen as being inevitable unless carbon emission rates are seriously reduced. Thus the emphasis on each would depend on a number of local and context-specific factors that would make such a balance difficult to achieve. There are also concerns over social systems that depend on adaptation, ignore mitigation and create cases of "maladaptation" which result in further harm (Klein et al., 2005; Smithers & Smit, 1997).

Limits to adaptation are tied in part to vulnerability. Vulnerability is defined as an intrinsic characteristic of a system or element including its responses to a stress. Vulnerability is dependent on the potential hazard; it simply ceases to exist without the hazard context (Birkmann, 2006; O'Brien et al. , 2004; Füssel, 2007). In the early 70s and 80s, the term vulnerability strictly meant the physical sensitivity of an infrastructure (Birkmann, 2007). In recent literature, there has been a proliferation of vulnerability assessments which are different from the traditional impact assessments that focus on a single environmental stressor. Current vulnerability assessments tend to "evaluate groups or social entities in relation to multiple interacting social and environmental stresses"(McLaughlin & Dietz, 2008; p99). The motive behind the expanded interpretation of vulnerability in the literature is to understand the underlying causes of whom and what is vulnerable to help shape effective responses (Ford et al., 2006). Vulnerability, most importantly, has helped scientists, policy-makers and researchers understand that climate change responses are largely context-specific and require a disaggregated focused analysis.

2.3.1 Climate Change Impact Assessments

Societal responses such as mitigation or adaptation require detailed assessments on the potential effects of climate change on systems such as transport. The IPCC advocates standardized procedures for impact assessments to improve consistency of future projections. The future projections are derived from Atmospheric-Ocean Global Circulation Models (GCMs) which are "mathematical representations of the Earth land-ocean- atmosphere that calculate three-dimensional motion of the earth and atmosphere" (Aguado & Burt, 2013 p495). GCM output is used to define the change in climate between the present day and a future condition for risk and impact assessment. These observed and modeled changes relate directly to the understanding of the impacts on social-ecological systems. GCMs physically consider how the atmosphere will respond to different levels of greenhouse gases. Therefore, the IPCC tests high, medium, and low greenhouse gas emission scenarios using a number of GCMs (Krinner et al., 2013). Although significant improvements have been made to GCMs, these mathematical models use input factors such as economic development that is difficult to predict for a 100 year period (Klein et al., 2005). The uncertainty regarding the magnitude, frequency, timing and intensity of climate change has become a central issue. However, all projections strongly indicate imminent consequences, such as a rise in average global temperature, increase in precipitation, sea-level rise, melting of glaciers, and permafrost thaw (IPCC 2014).

Greenhouse gas emission scenarios are known as Special Reports on Emission Scenarios or (SRES). SRES were developed to provide a standardized method of assessing the influence of atmospheric changes. A SRES scenario is a plausible storyline of the state of the world in the future. SRES have been used in climate change impact assessments since 1992 when they were first developed by the IPCC (Nakicenovic et al., 2000). Because of the number of possible states of the world in 2100, four different "family" scenarios (A1, A2, B1, B2) were developed, each illustrating a different relationship between the forces driving greenhouse gas emissions for global and regional areas (IPCC-TGICA, 2007). The scenarios encompass future change in driving global forces such as population, demographics, economic development, and technology; when they are used in impact assessment studies "they extrapolate the current economic, technological and social trends" (Nakicenovic et al., 2000 p.4).

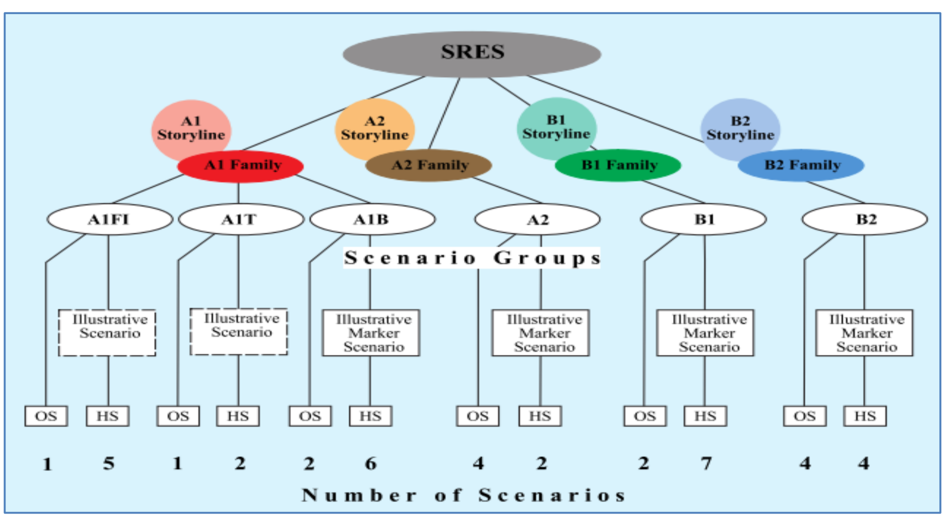

Figure 2-3: A schematic illustration of SRES Scenarios (reprinted from Nakicenovic et al., 2000 p.4)

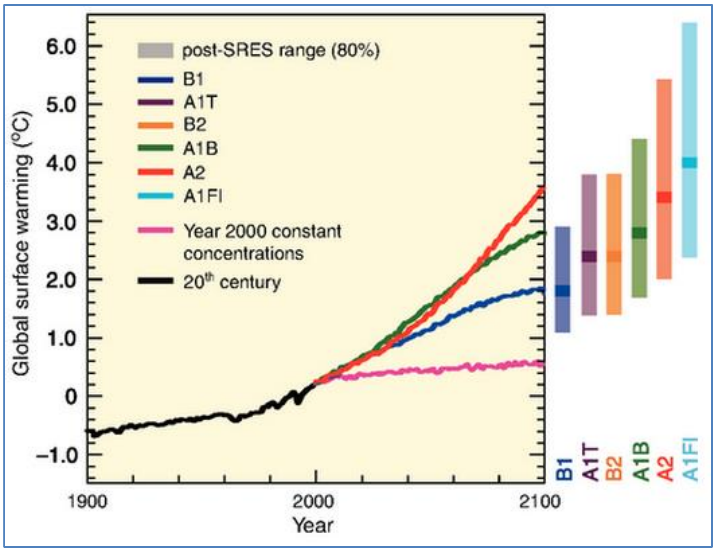

Figure 2-4: The range of projected temperatures for GCM simulations using different SRES scenarios (reprinted from IPCC, 2007, p.7)

The storyline of the four family scenarios were quantified by integrated assessment models resulting in a six scenario grouping (A1FI, AIT, AIB, A2, B1, B2), for a total of 40 scenarios, Figure (2-3) (IPCC-TGICA, 2007). The IPCC recommends using a variety of SRES scenarios and more than one family in mitigation, vulnerability or risk assessments since they do not include the influence of mitigation and adaptation practices. Figure (2-4) illustrates the projected global temperature rise of each group's storyline.

In addition to physical GCMS, there are other ways scenarios can be derived, including synthetic scenarios (arbitrary) and analogue scenarios. Synthetic scenarios are developed by changing incrementally temperature (+2 degrees Celsius) and precipitation (-10 percent) values after examining the simulation of climate models (Kattsov et al., 2005). The most problematic shortfall of this method is its arbitrary nature and inconsideration of greenhouse gas emissions. Analogues base possible future climates according to current and past climatic conditions of which there are two main types. Temporal analogues are based on historical climate conditions, and spatial analogues are based on current climate conditions (IPCC-TGICA, 2007). Analogues do not account for the atmospheric changes that climate models include as there are problems regarding the availability and resolution of historic and geological climate data (Kattsov et al., 2005). However, these scenarios are usually adequate for some assessment studies.

A key limitation of GCMs is the resolution. As mentioned, GCMs utilize complex and intensive computing operations to produce results. They tend to run at a coarse spatial scale usually 500 x 500 kilometres. Therefore, GCMs fail to consider small-scale environmental weather parameters such as elevation, which limits their ability in predicting outcomes for small regions. For this reason, impact studies need GCM models to be downscaled. Two types of downscaling have been developed, dynamic and statistical.

Dynamic downscaling involves the use of Regional Climate Models (RCM) which are models that use certain outputs from GCMs such as boundary conditions (Cressie & Kang, 2015). RCM output is at a finer temporal and spatial resolution (Cressie & Kang, 2015). However, RCMs are computationally demanding and expensive to build which limits their processing flexibility and availability. There are also consistent precipitation biases and errors from RCM outputs, which is especially problematic at finer temporal and spatial scales and in regions of complex topography (Cozzetto et al., 2011; Moriondo et al., 2011; Wilby & Dawson, 2007).

A second method is statistical downscaling using numerical models rather than physical models such as weather generators. Weather generators use complex statistical distribution models to perturb meteorological parameters based on outputs of GCMs to generate future climate scenarios (Semenov & Barrow, 2002). Weather generators have shown a reasonable ability to predict precipitation, temperature and solar radiation, and have the ability to efficiently downscale monthly GCM data to a daily-level (Wilby & Dawson, 2007). Moreover, weather generators are widely available, and less technical. They also apply to a range of GCM models and several different emission scenarios (Kattsov et al., 2005). The recent enhancement of weather generators enhanced their forecasting ability. In fact, recent studies comparing RCM and weather generator outputs have concluded that both models produce fairly consistent results across a range of scenarios, specifically for daily extreme temperatures (Aghabayke et al., 2014; Mearns et al., 2013; Qian et al., 2015). The only limitation of weather generators is that simulated precipitation amounts sometimes do not closely match observed data especially for seasonal-heavy precipitation. However, this can be adjusted through statistical calculations (Green et al., 2011).

There is no right answer as to which GCM, emission scenario, or downscaling method should be used in climate change impact studies. Authors emphasize that the decision is largely dependent on the objectives of a study, as each method has its advantages and disadvantages. However, the common issue of uncertainty in climate projections remains difficult to avoid due to changing human behaviours and systems. To minimize uncertainties and biases it is recommended to use different models and climate scenarios. The thesis will use projections from GCMs and downscale these projections using a stochastic weather generator.

2.3.2 Climate Change, Transportation, and Pedestrian Safety

There is a growing literature on the impacts of climate change on transportation. A number of national transportation climate change assessments exist for certain regions and vulnerable populations. The effects of climate change such as permafrost degradation, sea level rise, freeze-thaw cycles, and excess heat on transport infrastructure have been enumerated (Hambly et al., 2013). Various authors have comprehensively summarized such impacts in many studies (Chapman, 2007; Koetse & Rietveld, 2009; Vajda et al., 2014).

In traffic safety literature, there are only three notable studies on the influence of mid-century climate change on vehicle-collisions by Hambly et al. (2013) and, Andersson and Chapman (2011a; 2011b). Using climate change scenarios and temporal analogues, Andersson (2011a) estimated a reduction of traffic accidents related to frost conditions by 43 percent in 2080 in West Midlands, United Kingdom. They acknowledge that implications of higher temperatures by 2080 include lower maintenance efforts during frost days which may offset the projected reduction in traffic accidents. Andersson (2011b) compared crashes throughout Sweden in January 2005 with those in January 2006, as temporal analogues for future climate change. They concluded that, as warmer climate ensues the number of severe collisions attributed to slipperiness will be reduced. The Andersson and Chapman (2011a:2011b) studies had a couple of limitations. Weather data relied on output from Roadside Weather Information Systems (RWIS) stations that were often located several kilometers away from the collision scene. And, the studies depended upon the use of temporal analogues which tend to be an unreliable estimate of climate change.

A more reproducible empirical study is Hambly et al.'s (2013) climate change impact assessment of traffic collisions for Vancouver. The approach of this study is to estimate present elevated risk estimates during wet precipitation relative to dry conditions, and to combine the risk estimates with projected changes in the frequency of days in 2050 (Hambly et al., 2013). The matched-pair design was used to estimate differences in collision risk during precipitation relative to dry conditions, a common method in traffic accident risk estimation. This study shows that the projected number of collisions attributable to rainfall in Vancouver, is expected to increase by 17 to 28 percent. Vancouver is expected to face more intense and frequent rainfall events that translate into this higher collision frequency, assuming all other mobility conditions remain the same such as vehicle technology, street design, population and many other transport factors that influence traffic and pedestrians.

The Hambly et al. (2013) and Andersson and Chapman (2011a:2011b) studies demonstrate the potentially problematic implications of climate change on vehicle collisions. Indeed, climate change and other weather stresses are largely region-specific and will depend on local travel practices/policies, societal norms, and the frequency of adverse weather events. The authors argue that future polices and mobility patterns will change the current transportation system which may influence this exposure to risk. The existing climate projections and assessments, however, do not take into account such future changes in societal traffic practices.

Pedestrians and other forms of sustainable transport are less frequently discussed in such assessments, despite global trends towards larger and denser cities and numerous initiatives to shift towards a non-motorized mode of transport. The sensitivity of pedestrians to vehicle collisions requires research and analysis within the climate change literature to identify the risk in the future. Only one study explored the effects of mid-century climate change on travel choice behaviour (Böcker et al., 2012). The study was based in Holland. Two types of data were used; Dutch meteorological data for 2050 climate projections, and travel survey data from 2004 to 2009. Using multivariate statistics and climate projections, the results demonstrated positive effects of climate change on walking, cycling and public transport. However, the projected intensification of summer precipitation by 2050 was expected to negatively affect walking trips and total distance travelled.

In summary, the relationship between inclement weather, climate change and traffic safety is established. However, the question regarding pedestrian safety and weather is yet to be explored. This thesis is attempting to replicate the approach taken by Hambly et al. (2013) to understand the implications of climate change on pedestrian safety in two Canadian cities, Toronto and Vancouver.

Chapter 3: Data and Methods

This chapter explains the methods used to calculate present-day risk estimates and future climate projections for 2050s. The present-day risk estimates are combined with climate projections to estimate the implications of future climate on pedestrian safety. The thesis analysis examines the influence of liquid precipitation or rainfall on risk and future pedestrian safety. The three sections in this chapter address the following:

- ❖ *Section 3.1* describes the study areas' characteristics and traffic safety patterns. This includes an explanation of the data sources, collision characteristics and meteorological conditions.
- ❖ *Section 3.2* explains the analytical method undertaken to calculate the present-day risk analysis.
- ❖ *Section 3.3* details the climate change analysis, including the rationale behind a series of decisions relating to climate scenarios, time period and model outputs.

Study Area	**Relative Risk Analysis**	**Future Climate**
• Explanation of study areas characteristics • An exploration of pedestrian and traffic safety patterns in study areas • Identification of current and historic weather and climate activities	• Selection and explanation of analystical approach • Identification of control and event criteria • Calculation of present-day relative risk	• Selection of climate and emission scenario • Choose a climatological baseline and future climate period • Explanation of statistical downscaling method • Calculation of future change in climate

Figure 3-1: General description of the thesis analysis steps

3.1 Study Area

This section explores the study areas of the thesis, the Greater Vancouver and the Greater Toronto areas. The period for which present-day risk estimates for pedestrian collisions under rainfall are calculated is from 2003 to 2009, the period with latest available pedestrian collision data provided by Transport Canada National Collision Database (NCDB). These estimates are also used for climate change risk assessment for mid-century, which are discussed and presented in Chapter 4. The following subsections attempt to explain the characteristics of each city, the traffic and pedestrian collision characteristics, and the historical – study period climate activity.

3.1.1 Characteristics of the Study Areas

The Greater Toronto Area is Canada's most populous metropolitan area. In 2011, the total number of inhabitants in the metropolitan region was 5.5 million, in an area comprising 23 municipalities and 5,000 square kilometers (Statistics Canada, 2015). Toronto is bordered by Lake Ontario on the south, and Lake Simcoe to the North. Most of the urban and metropolitan areas are surrounded by protected "green spaces". The downtown core of the city contains the largest clusters of skyscrapers in Canada, and is very densely populated (around 1100 per square kilometer). Toronto is currently working to create a safe environment for pedestrians. The City's Transportation Services Division implements a number of campaigns each year to promote and educate the public on pedestrian safety.

The Greater Vancouver area, also known as Metro Vancouver, is a coastal city on Canada's Pacific West Coast. This is the third largest city in Canada, according to Statistics Canada, There are approximately 2.3 million inhabitants in the area living in 21 municipalities covering 2,000 square kilometers (Statistics Canada, 2015). Metro Vancouver has a population density of 1150 people per square kilometre. It is bounded to the north by the English Bay and to the south by the Burrard Inlet. The largest urban park in North America, Stanley Park, is also located in Vancouver. The City of Vancouver is aiming to become one of Canada's most walk-friendly cities through the creation of vibrant walking spaces and safer pedestrian crosswalks. This is an important priority especially for the City of Vancouver because it has the highest walking share compared to municipalities in the lower mainland.

A **B**

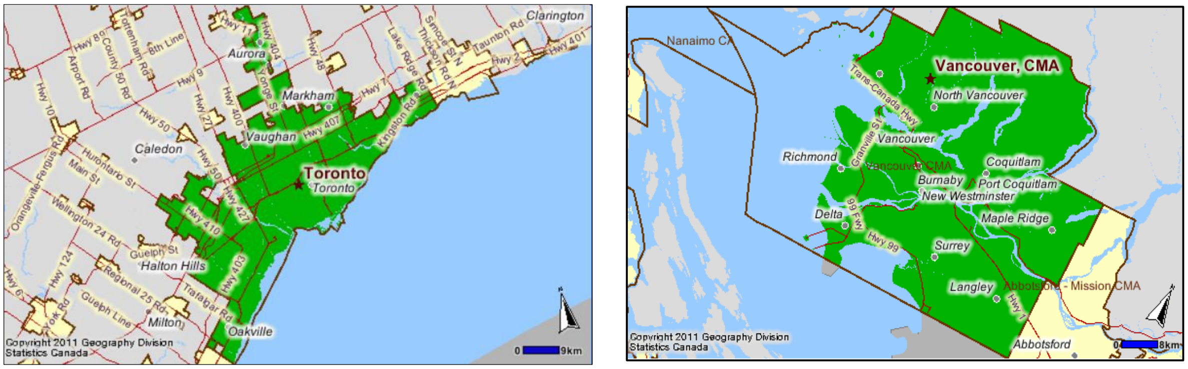

Figure 3-2: Map of the study Areas, Toronto (A), Vancouver (B)

Table 3-1: The proportion of commuters using each mode of Transport

City	**Car, truck or van (total)**	**Public transit**	**Walking**	**Bicycle**
Greater Toronto	69.9	23.3	4.6	1.2
Metro Vancouver	70.8	19.7	6.3	1.8
Data Source: Statistics Canada (2011)				

Both regions have slightly different travel behaviours as seen in Table (3-1). The inhabitants of the Greater Toronto Area are slightly less dependent on travel by a vehicle in comparison to metro Vancouver, but the city has a lower share overall for walking. Table (3-1) also demonstrates that a large portion of Vancouver's population is dependent on vehicles for travel or commuting. However, it has one of the nation's highest percentage of people using walking as a mode of travel, which is supported by its inclusion of active transportation features, such as wider pavements and bike lanes. This is specifically the case in the downtown core of Vancouver, where on average, walking is about six percent of the total modal share for the area. In Toronto, many users depend on the widely accessible transit and commuter rail network throughout the city and urban sprawl areas.

3.1.2 Pedestrians and Traffic Patterns

Over the 2003-2009 period, the number of pedestrian collisions increased each year in Toronto. In Vancouver pedestrian collisions increased after 2004 and remained elevated until a slight decrease in 2009. The data shows that on average, each year, 2,400 pedestrian collisions occur in Toronto, and 1,108 in Vancouver. Toronto has the highest number of collisions, victims, and injuries, which may be due to the large amount of commuter travel especially in the downtown core where vehicles and pedestrians are in close proximity. However, the number of collisions are proportionate to the regional population. Vancouver has 41 percent of Toronto's population, and 46 percent of Toronto's collisions. Toronto's population is greater than Vancouver by 139 percent, and its collisions are greater than Vancouver by 116 percent.

Table (3-2) introduces the characteristics of pedestrian collisions. About 97 percent and 95 percent of reported pedestrian collisions in Toronto and Vancouver, respectively, are injury or fatal collisions. This demonstrates that pedestrians are highly sensitive to injury or fatality from a collision.

Table 3-2: Characteristics of pedestrian collisions in study areas, 2003-2009

Study Area	Toronto	Vancouver
# of Collisions	16,634	7,759
Victims	17,779	8,216
Fatal Collisions	321	220
Injury Collisions	16,098	7,351
Non-injured pedestrians	709	285
Average # of Collisions per day	6.5	3.3
Average collisions per year per 10,000	4.4	4.8

The collision records were derived from NCDB. The records contain data recorded by police at the time of a collision. The driver behaviour, pedestrian behaviour, and characteristics of these collisions are examined in order to illuminate factors that may contribute to collision risk in the study areas. Table (3-3) presents the characteristics of pedestrian collisions recorded by road authorities.

In both cities, the lowest number of collisions is in the summer season when daylight hours are the highest (Table 3-3). The distribution of crashes are consistent through the week, while weekend days have lower collision percentages, most likely due to the decrease in the number of commuting pedestrians and vehicles. For both cities, mid-day and afternoon rush collision occurrence are similarly distributed. This is likely from the concentration of pedestrians and vehicles during lunch and commuting hours. A higher proportionate of pedestrian collisions occur in the morning in Toronto than Vancouver. Again, this may be due to higher amount of commuter travel.

Most collisions occurred on roads with a posted speed between 40 km/hr and 60 km/hr. It is safe to argue that most collisions are concentrated in urban areas or urban sprawling areas where the majority of the population is concentrated.

Overall both regions have similar characteristics but when it comes to rainfall, there is a difference. Vancouver has 10 percent more collisions during rain than Toronto. Rain is reported in the majority of collisions that occurred during a weather event, suggesting that many pedestrians continue their trips during rainfall. A higher proportion of pedestrian collisions occur in wet roads in Vancouver, but Toronto has more snowfall events, so naturally some collisions would occur during these conditions.

Table 3-3: Characteristics of pedestrian collisions as defined by reports, 2003-2009

Season Pattern	**Toronto %**	**Vancouver %**
Winter (Dec _Feb)	26%	30%
Spring (Mar_May)	22%	21%
Summer (Jun_Aug)	21%	18%
Autumn (Sep_Nov)	31%	29%
Day of the Week		
Monday	15%	14%
Tuesday	16%	15%
Wednesday	17%	15%
Thursday	16%	15%
Friday	17%	17%
Saturday	11%	12%
Sunday	8%	10%

Time of Day		
Morning Rush Hour (6:00 - 9:59)	19%	14%
Mid-day (10:00 - 14:59)	25%	24%
Afternoon Rush Hour (15:00 - 18:59)	31%	32%
Evening (19:00 -23:59)	20%	21%
Late Night (0:00 - 5:59)	5%	7%
Weather condition		
Rain	15%	26%
Snow	3%	1%
Frozen precipitation	0%	0%
Visibility limitation	1%	1%
Road surface conditions		
Wet	23%	35%
Snow, slush, or ice	4%	2%
Posted Speed Limit		
40 km/h	17%	7%
60 km/h	80%	73%
80 km/h	3%	1%
100 km/h	1%	0%
110 km/h	0%	0%

In Toronto, almost half of pedestrian collisions occurred at a signalized intersection, while in Vancouver, signalized and non-signalized intersections are problematic. Signalized intersections are complex for pedestrians to navigate with right and left turns, and frequently, heavy traffic. At non-signalized intersections, proper judgement by the pedestrian and driver is needed to avoid a collision. According to Table (3-4), Vancouver has 27 percent more collisions occurring at non-signalized intersections than Toronto, which may reflect differences in traffic control norms, differences in driver behaviour or pedestrian behaviour at intersections, or a combination of the above.

Road authorities also record the actions of drivers that contribute to collisions, which in comparison to environmental factors, are important. Most cities have laws regarding pedestrian actions while on the road. Toronto and Vancouver pedestrians are obligated to abide by traffic control devices in signalized intersections and mid-road crossings. Pedestrians must practice sound judgment when crossing to avoid vehicles that are unable to yield right of way. Table (3-

4) and (3-5) represent pedestrian behaviours associated with the occurrence of collision. There are common behaviours from drivers and vehicles that contribute to collision.

In both cities, most pedestrians are hit when a vehicle is moving straight ahead, turning left, or turning right. Collisions at right turns are expected because pedestrians and turning vehicles are both utilizing the intersection since both crossing phases tend to run simultaneously. In Toronto, failing to yield the right of way is the main cause of more than half of pedestrian collisions. This could occur at a stop sign, right or left turn, and crosswalks. In Vancouver, distracted or inattentive drivers are the cause of more than half of pedestrian collisions which may explain the higher percentage of collisions at non-signalized intersections. But other factors such as visibility, weather, and environmental settings may also contribute to driver inattentiveness.

Table 3-4: Pedestrian contributing factors as defined by collision reports, 2003-2009

Pedestrian contributing factors	**Toronto**	**Vancouver**
Crossing Action		
Crossing Intersection with Traffic Control, right of way	46%	32%
Crossing Intersection with Traffic Control, not right of way	17%	11%
Crossing Intersection with no traffic control	8%	35%
Crossing Roadway at a Cross Walk	6%	0%
Crossing Roadway non-intersection	0%	0%
Walking & Other Actions		
Walk Along Roadway Against Traffic	1%	1%
Walk Along Roadway with Traffic	2%	2%
On sidewalk, median, or safety Zone	7%	8%
coming from behind parked vehicle or object on road	2%	7%
running into roadway	7%	0%
Getting off/on other vehicle	2%	1%
working on roadway	1%	2%

Table 3-5: Driver and vehicular contributing factors as defined by collision reports, 2003-2009

Driver & vehicle contributing factors	Toronto	Vancouver
Vehicle movement		
Going straight ahead	45%	49%
Turning left	28%	27%
Turning right	17%	14%
Reversing	5%	6%
Slowing or stopping in traffic	4%	2%
Leaving roadside	1%	1%
Driver behaviour or action		
Under the influence or alcohol	2%	5%
Distracted, inattentive	24%	57%
Driving too fast for conditions	2%	2%
Improper turning or passing/ improper land changes	9%	3%
Failing to yield right-of-way	58%	24%
Disobeying traffic control device or traffic officer	5%	4%
Backing unsafely	0%	5%

3.1.3 Historical Climate and Weather

In the thesis, for comparison, the two study areas have different climates. These differences in climate will provide interesting insights into how pedestrian safety is influenced by weather and climate. This section discusses the weather pattern during the study period and historical baseline period. Toronto and Vancouver are ideal locations for weather and climate examination due to complete historical weather records that are compatible with the World Meteorological Organization (WMO).

3.1.3.1 Climate Normals (1971-2000)

The Greater Toronto Area is located within the Great Lakes lowland and along the northern-west shore of Lake Ontario (Theobald et al., 2011). This location affects Toronto's climate because water bodies regulate the occurrence of extreme temperatures in summer and winter months. Toronto has mild winters due to the release of heat contained by the lake. During early summer the lakes are usually cooler than the air temperature which in turn cools the region. As Table (3-6) illustrates, there is a difference of roughly 25 degrees Celsius from January to July in average temperatures. Toronto is dominated by Maritime Polar and Maritime Arctic air masses that bring warm or cool dry air. It is also influenced by tropical air rising the Gulf of Mexico that brings hot and humid days during the summer producing frequent thunderstorms (Theobald et al., 2011). In the winter, cold and dry continental Arctic air covering the region brings snow, freezing rain, and ice pellets (Theobald et al., 2011). In terms of precipitation, approximately 43 percent of the year involved days with precipitation, 30 percent of precipitation days is in liquid form or rain. Rainfall can occur through the year but is mostly common from early spring to late fall. The peak number of rainfall days is in May and October. However, during the humid and hot summer months (June to August), days with extreme rainfall (at least 25 millilitres) are common due to thunderstorm activities. Each year, rainfall accumulation is around 710 millimetres. As winter starts in the region, snow, ice pellets, and freezing rain are more common. Snow falls occur on roughly 13 percent of days and are concentrated in the period from late November to late March. On average 125.6 centimeters of snowfall is accumulated each year.

Table 3-6: Climate Normals for Toronto and Vancouver, 1981-2010

Variables	**Toronto**	**Vancouver**
Climate ID	6158733	1108447
Latitude, longitude	43° 40' N, 79° 36' W	49° 11' N, 123° 10' W
Elevation (m)	173.4 m	4.3 m
Annual # of rain days	111.8	161.3
Annual # of snow days	46.5	10.9
Annual Rainfall (mm)	684.6	1154.7
Annual Snowfall (cm)	115.4	48.2
Daily Average temp Jan	-6.3	3.3
Daily Average temp July	20.8	17.6
Annual days with min temp , 0	57.2	4.5
Annual day with max temp >30	12.6	0.2
Data source: Environment Canada, 2015a		

The climate in Vancouver is wetter and less cold than Toronto. Vancouver is located on the Pacific West Coast, which affects both winter and summer temperatures. The winters are milder than Toronto since the warm temperatures of the ocean are retained during the season, causing the colder air from the Alaskan Current to warm (Rattray, 1945). In the summer, the temperature of the ocean is cooler than the surrounding land, which prevents summers from becoming extremely hot (Rattray, 1945). Unlike Toronto, the proximity of Vancouver to the ocean moderates its temperature throughout the year resulting in less extreme hold and cold temperatures. A few days fall below zero degrees Celsius and there are almost no hot days or days above 30 degrees Celsius. Vancouver has more moderate temperature differences throughout the year, with a difference of roughly 13 degrees Celsius from January to July average temperature (Table 3-6). Precipitation occurs throughout the year in Vancouver, most heavily in the fall (October to November) and early winter months (December to January). There are less frequent episodes of rainfall in the summer. Precipitation is measured on approximately 50 percent of days, where 44 percent (88 percent of precipitation days) is rainfall. Snow is uncommon during winter as the temperature rarely falls below zero degrees Celsius (Rattray, 1945). On average each year has approximately 1,127 millilitres of rainfall. The heaviest rainfall days (at least 25 millilitres) occur in the late fall / early winter.

3.1.3.2 Weather Activities of 2003-2009

For the present-day risk analysis, the data period of 2003 to 2009 was selected based on the availability of complete pedestrian collision data. This section discusses the weather characteristics throughout this period. Overall, the temperature during the study period was higher than the 1971-2000 climate normals for Toronto and Vancouver of Table (3-6). With regards to precipitation, both regions had more precipitation days than climate normals. More simply, the 2003-2009 study period was "warmer and wetter" than usual for both study areas. Table 3-7 demonstrates the observed rainfall, snowfall, temperatures and other weather characteristics. Appendix D contains monthly comparisons of temperature and precipitation between the 2003 to 2009 period and climate normals (1971-2000).

Table 3-7: Weather characteristics summary, 2003-2009

Weather Variable	2003-2009 Average	2003	2004	2005	2006	2007	2008	2009
Toronto Pearson International Airport Station								
Annual # of rain days	116.7	111.0	124.0	98.0	140.0	106.0	128.0	110.0
Annual # of snow days	47.0	51.0	53.0	57.0	24.0	54.0	59.0	31.0
Average Temp in Jan	-1.6	-4.2	-5.2	-2.8	3.8	0.6	1.3	-4.5
Average Temp in July	26.9	27.1	25.2	29.9	28.6	27.0	26.6	24.2
Total precipitation (mm)	832.8	895.6	755.0	766.7	865.7	592.7	1049.6	904.0
Total rain (mm)	710.2	752.0	643.3	612.2	833.9	478.2	840.9	810.8
Total snow (mm)	125.6	129.6	134.9	162.6	32.4	114.1	216.5	89.0
Vancouver International Airport Station								
Annual # of rain days	168.1	159.0	178.0	158.0	176.0	197.0	162.0	147.0
Annual # of snow days	9.0	7.0	3.0	9.0	6.0	11.0	17.0	10.0
Average Temp in Jan	6.6	9.1	6.6	6.7	8.6	5.6	5.5	4.1
Average Temp in July	23.2	23.7	24.1	22.3	23.1	22.8	24.1	22.3
Total precipitation (mm)	1170.7	1106.1	1210.6	1215.2	1224.2	1322.4	1025.8	1090.6
Total rain (mm)	1,127.1	1086.2	1200.8	1183.8	1175	1274.4	913.8	1055.6
Total snow (mm)	39.1	18.5	8.1	29	44.8	37.7	109	26.4
Data sources: Environment Canada, 2015b								

In 2003, Toronto experienced a very cold and dry winter and higher than average rainfall amount. The year also produced a mid-spring ice-storm that was troublesome for the region (Theobald et al., 2011). The year 2004 had less rainfall than normal but had much more snowfall indicating a cooler season than the year prior. The year 2005 had a record snowfall and was drier than the previous year with much less rainfall. The year was warmer than normal particularly during the summer and fall months. Interestingly, 2006 was the hottest on record and one of the wettest years. This year had a high amount of rainfall recorded. The higher winter temperatures returned in 2007, where also rainfall was lower than average for the entire year. Record amounts of rainfall and snowfall were present in 2008. It is known as Toronto's most snowy winter and was characterized by a rainy-wet summer. The trend continued into 2009, where record rainfall was observed, and winter and summer were both cooler than usual. In general, Toronto had more rainfall than usual and snowfall that varied year to year. The average annual temperatures for January and July were much higher than the 30-year normal period.

The study period conveys a different story for Vancouver. The year 2003 had mild winter temperatures than usual and a warm summer. It had more rainfall than average, with a record amount falling in a two-day period during October. In the following year, Vancouver experienced a hotter than usual summer and a cooler winter than the year prior. Rain was much less consistent throughout the year but the amount deposited was more than the average. The years 2005 and 2006 had above average rainfall amounts. The average temperatures in 2005 introduced very wet January and February months with record rainfall amounts. The year 2006 had a milder winter and warmer summer. Snowfall in 2006 was also above normal levels. The next year had more precipitation events and specifically much more rainfall accumulation during the month of December. Above average snowfall amounts and snowfall days occurred in 2008, the month of December had a higher than usual snowfall precipitation. Rainfall amounts dropped below the average for the year and summer temperatures were slightly higher than usual. Finally, in 2009 rainfall and snowfall amounts returned to normal levels. The temperatures were slightly below the average. Vancouver's study period is warmer with higher temperatures in January and July, the average precipitation amounts was slightly lower than the 30-year average.

In conclusion, the study years for Toronto had marginally above average temperatures and precipitation relative to the normal period. Vancouver had a slightly drier period than average, but had temperatures in July and January that were higher than normal.

3.2 Analytical Approach

The empirical study was designed to evaluate the influence of rainfall on pedestrian collisions. It is based on the integration of two national databases for the years 2003 to 2009. The NCDB provides details on collisions reported by police in their respective jurisdictions. The data includes information of on the time, cause, number of victims, weather, and location of a collision. The data includes characteristics on contributing behaviours of a pedestrian or driver as discussed in Section (3.1.2). The second dataset is provided through Environment Canada which maintains principal weather stations in each study area. Weather data are available in hourly, six-hourly and daily levels and provide detailed information on precipitation, visibility, and wind**.**

The first type of information in this analysis is the reported pedestrian collisions in the study areas. The most recent readily available collision data is from 2003 to 2009. This defines the study period of the analysis. This data is managed by the NCDB and organized by province. It contains information from forms completed by road officers at the site of collisions. For each pedestrian involved in a collision, province, time, weekday, injury severity, weather, road condition among other characteristics are reported. Missing is the geo-referenced information which was unavailable over the 2003 to 2009 period, however, road officers provided sufficient information on the location of the collision and roadway characteristics.

The second type of information includes the daily and six-hourly weather data derived from Environment Canada for the 2003 to 2009 period. The study areas have reliable climate data recorded by Environment Canada according to the standards and the practices advised by the World Metrological Organization (WMO). The climate data for Toronto and Vancouver has complete records dating back to 1937 (Environment Canada, 2015b). This weather data is of high importance to the analysis because it provides detailed meteorological observations from quality-controlled weather stations (Toronto Pearson International Airport and Vancouver International Airport) at different temporal scales (hourly, six-hourly, and daily). This data is used against road officers' basic reports on the weather condition at the time of collision to provide more information on the weather, such as, temperature in Celsius, precipitation accumulation, visibility, and wind speed. Another type of data that could supplement the research is road weather information systems (RWIS), i.e., roadside weather identification stations that provide real-time and location specific weather readings for a road segment. However, this type of data is intended for individual site analysis (micro-scale), does not report precipitation amount, and it is not readily available for city-wide or regional studies (Suggett et al., 2006). So, it is not used in this study.

The Environment Canada weather data has been used in various relative risk estimation studies along with the reports of weather for a collision by road officers. Authors Hambly (2011), Andrey and Olley (1990) found an agreement between precipitation recorded by airport stations and collisions reporting weather in Edmonton, Alberta. According to Hambly (2011), if there are no precipitation recordings by airport stations, almost, 100 percent of collision reports had no precipitation recorded either. Similarly, if precipitation is recorded by weather stations, more than half of collision reports reported the presence of precipitation.

3.2.1 Matched Pair Approach

A matched pair design is adopted for the study to calculate the present-day relative risk (Andrey & Olley, 1990). A temporal period (hour, six-hours, or day) with a hazardous weather condition, defined as an "event" is paired with a day or a six-hour period with normal weather, defined as a "control". In this thesis, an event is a day or six-hour period where rainfall was present, a control is a day or six-hour period with dry weather. The Environment Canada weather data are used to identify the event and control day or six-hour period. Due to the matching exercise and the averaging of observations, this approach reasonably controls for the influence of time-dependent variables such as season, time of day, and day of the week. A rainy Monday in May (event) is matched with a dry normal Monday (Control) a week before or after. Thus the travel activity in each day of the week is reasonably controlled. Similarly, a rainy six-hour period on a Monday (event) is matched to the dry corresponding six-hour period (control) one week before or after. If an event is not paired with a control it is omitted from the analysis. The only limitation of this approach is its inability to account for exposure or the travel reductions that occur due to precipitation.

The first criteria to identify an event is the selection of periods and days that had liquid precipitation or rainfall. Several meteorological factors determine whether precipitation falls as rain or snow, such as temperature of the atmospheric layer, air mass movement, humidity and type of clouds (Kienzle, 2008). However, authors agree that near-surface air temperature is generally used to identify whether precipitation is in liquid, mixed, or snow form. If the near-surface temperature is below 0 degrees Celsius, most precipitation falls as snow. Temperatures just above zero degrees Celsius in the lower part of the atmosphere produces mixed precipitation (snow-rain (sleet), and freezing rain) (Dai, 2008). As temperatures increase above zero, rainfall becomes the dominant form of precipitation. In some instances snow and freezing rain occur but not with nearly as much frequency as the rainfall. To identify if precipitation is in a liquid form for the matching exercise, the average hourly dry temperature for six-hourly and the minimum daily temperature for daily periods must be greater than or equal to 2 degrees Celsius. This threshold was chosen to avoid matching control periods with possible mixed precipitation periods. Even with this threshold, three days in Toronto freezing rain and snow was observed, but no days in Vancouver appeared to have precipitation other than rainfall. In the six-hourly level of analysis, Toronto appeared to have 65 six-hour periods were snow and freezing rain were observed. For Vancouver, there were 19 six-hour periods. It should be noted that the average-hourly dry temperatures for these periods are mostly around the threshold of 2° Celsius (Table 3-9).

Table 3-8: Event and control criteria for present-day relative risk analysis

Event Criteria	• A minimum precipitation measurement of 0.4 mm • Average hourly dry and minimal daily temperature must be ≥ 2° C • Statutory holiday days are removed from the analysis
Control Criteria	• All corresponding 6-hours or day periods one week before or after must have zero mm of precipitation • Dry roads mentioned in least 85% of collision reports in both units of analysis • Average hourly winds less than 40 km • Statutory holiday days are removed from the matching exercise (see Appendix A for excluded holidays)

The second criterion for a day or six-hour period to be classified as an event is the amount of rainfall in millimetres to ensure sufficient moisture and wetness in roads. Environment Canada classifies a precipitation hour or day if more than 0.2 millimetres of precipitation is measured. Below this amount it is called a “trace” (Environment Canada, 2015b). In order to ensure moisture to wet road pavements, and for a day or six-hourly period to be classified as an event, a minimum of 0.4 millimetres of rainfall must be measured.

Table 3-9: Number of rainfall events at daily and six-hourly periods, 2003-2009

Study Area	**# of Rain Days**	**# of 6-hourly Rain Periods**	**Total mm (Daily)**	**Total mm (6 hourly)**
Vancouver	920	2232	6,907.1**	7,572*
Toronto	533	1184	3,907.2**	4,728*

Only precipitation of greater than or equal to 0.4 millimetres was counted for both time periods
Daily minimum temperatures must be ≥ 2° C
Six-hourly average temperatures must be ≥ 2° C
*Precipitation measured per 6-hour includes winter/mixed precipitation
**Daily level strictly measures liquid precipitation (i.e. rainfall)

Due to the large amount of collision and weather data involved, the matching of event-control pairs was completed using Microsoft-*Excel*. The statutory holidays and associated weekends were removed from the matching exercise because of the distortion in traffic and pedestrian trips on those days (Mills & Andrey, 2003). This reduced the number of events by 9 percent for both study areas and time periods. Control days must have zero accumulated precipitation, zero hours of reported fog conditions and less than 40 kilometres of wind speed. An identified event day or 6-hour period was matched with a control day or 6-hour period in order starting from January 1st, 2003 to December 30^{th,} 2009. Days and 6-hour events or control periods that were matched were removed from the data pool. Controls and events that did not have a week before or after the corresponding match were also removed from the analysis.

Table 3-10: Results of the matching analysis daily and six-hourly, 2003-2009

Number of	**Toronto**		**Vancouver**	
	6-Hourly	Daily	6-hourly	Daily
Events	1,184	533	2,231	920
Matched E-C pairs	1,057	462	1,852	603
Unmatched events	127	71	379	317
Events in holidays	102	40	211	81

The matching exercise captured most of the events for Toronto: 89 percent of events in the six-hour analysis and 87 percent in the daily analysis were captured. In Vancouver, 83 percent of the six-hourly events were successfully matched, but about 65 percent in the daily analysis were matched. Overall, Toronto's climate provided more control days for the matching process because there were fewer rainfall hours during the day. In comparison, Vancouver experiences more rainfall hours and days and is known to have the highest accumulation of moderate rainfall than any other Canadian city (Andrey & Hambly, 2012). This is evident by the high number of unmatched events in Table (3-10) relative to Toronto. In both locations, higher number of events and matched pairs is obtained in the six-hourly level of analysis than daily. This is normal because each of the 24 pairs is divided into four, providing more periods with rainfall and control conditions.

Table (3-11) demonstrates the distribution of the matched pairs by month. Vancouver has a more even distribution throughout the year. Rainy season has the lowest percent of pairs due to unavailability of controls. In the spring and summer months more controls are available. In Toronto, there are fewer periods with rain. As a result, 93 percent of the matched pairs fall between April and November.

Table 3-11: The distribution of matched pairs and rainy days, 2003-2009

Month	**Toronto**		**Vancouver**	
	% of matched pairs*	% of rain days*	% of matched pairs	% of rain days
Jan	1%	2%	6%	10%
Feb	0%	0%	7%	7%
mar	3%	3%	12%	12%
Apr	9%	9%	11%	9%
May	14%	15%	11%	9%

Jun	12%	11%	9%	7%
Jul	13%	13%	5%	4%
Aug	13%	13%	6%	5%
Sep	10%	11%	8%	6%
Oct	14%	14%	11%	12%
Nov	8%	8%	9%	12%
Dec	1%	1%	4%	8%
*only includes days with ≥ 0.4 mm and ≥ 2°C *percent of matched pairs from daily level of analysis				

3.2.2 Relative Risk Calculation

Johansson et al. (2009) presented a method for assessing relative risk of accidents associated with darkness using odds ratios. In order to estimate the contribution of rainfall to collision risk, Johansson et al.'s (2009) method has been implemented in this study to empirically calculate the odds ratio. The odds ratio represents the probability of a collision occurring during one condition (normal days or six-hour periods) relative to the odds of a collision during a different condition (rainy day or six-hour period). The method controls for periods with low count of collisions which may influence relative risk estimates. The first step is to calculate the odds ratio for each matched pair as follows:

1.

$$Odds\ Ratio = \frac{(Collisions\ during\ an\ event/\ safe\ outcomes\ during\ an\ event)}{(Collisions\ during\ a\ control/safe\ outcomes\ during\ a\ control)} = \frac{(B/D)}{(A/C)}$$

The safe outcomes represent the number of trips where a collision did not occur. It is an arbitrary number since it is unknown, but should be appropriately large such as 1,000,000. Table (3-12) illustrates the process of calculating the relative risk as per Johansson et al. (2009).

Table 3-12: Relative risk calculation

2.The logarithm of the odds ratio (yi) is first computed	$yi = \text{In}\ \frac{(B/D)}{(A/C)}$
3.The variance (vi) is calculated	$vi = \frac{1}{A} + \frac{1}{B} + \frac{1}{c} + \frac{1}{d}$

4.According to Johansson et al. (2009) there are two methods to combine the estimates of risk; first is the fixed effect model which has a statistical weight (*wi*) that is inversely proportional to the variance is calculated	$wi = \frac{1}{vi}$
5.The weighted mean effect based on a set of *g* matched pairs is then calculated, which provided an overall relative risk estimate by taking the antilog of this value – the weighted mean effect ȳ is calculated	$\bar{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right)$
6. A fixed-effect model assumes that the difference in estimate of risk from one pair to the other is purely due to random chance, or sampling error. To test the validity of the fixed-effect variation assumption, a *Q* test is performed	$Q = \sum_{i=1}^{g} w_i y_i^2 - \frac{\left(\sum_{i=1}^{g} w_i y_i\right)^2}{\sum_{i=1}^{g} w_i}$
7. The Q tests were statistically significant for rainfall matched pairs in Toronto's daily level of analysis only. A random effect model is used - which indicate that the difference in risk from one pair to the other is due to heterogeneity or that each event-control pair impacts the risk estimate results differently – a common effect size should not be assumed. A variance component is calculated to reflect this variation of estimates of risk.	$\sigma_\theta^2 = \frac{[Q - (g-1)]}{c}$
8.*g* is the number of event-control pairs and *C* is the following calculated estimator	$c = \sum_{i=1}^{g} w_i - \left[\frac{\sum_{i=1}^{g} w_i^2}{\sum_{i=1}^{g} w_i}\right]$
9.In the random-effect model, the variance is calculated for event-control pair	$v_i^* = \sigma_\theta^2 + v_i$
10.Then, a corresponding statistical weight is calculated for each pair	$w_i^* = \frac{1}{v_i^*}$
11.Once again, an overall relative risk estimate is calculated	$\bar{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right)$

12.For which, the standard error is calculated	$SE = \frac{1}{\sqrt{\sum_{i=1}^{g} w_i^*}}$
13. A new weighted mean for the set of matched pairs is calculated, then an overall estimate of risk is obtained by taking the antilog of this new weighted mean. A 95% confidence intervals are calculated using the standard error for the weighted mean estimate of effect	95% confidence interval = relative risk estimate ± 1.96 x SE
Reproduced from Johansson et al. 2009	

3.3 Future Climate Change Projections

In order to estimate the implications of climate change on pedestrian safety in Toronto and Vancouver by 2050, the study is undertaking a climate change assessment and developing climate change scenarios to identify changes in weather variables. The first stage of the climate change analysis is the selection of appropriate climate scenarios and baseline data. The decisions on the selection of appropriate climate scenarios and data will greatly influence the outcome of the impact assessment. Therefore, it is important to have a thoughtful methodology that is consistent with IPCC 2007 guidelines on climate scenario selection and data for impact assessments (IPCC-TGICA, 2007). In this section and remainder of the thesis, “Obs” refers to 1971-2000 historical baseline period obtained from airport stations, “20C” is simulated baseline (1971-2000) by GCMs, and “21C” is projected future period by GCMs. The delta change represented as “ΔC” is the difference between 21C future projections and simulated baseline 20C. These abbreviations are provided to prevent confusion due to the various datasets used in the climate analysis.

3.3.1 Climate Scenario and Baseline

As discussed in Section (2.3.1) there are three main approaches for obtaining future climate data: 1) model-based such as GCM or RCM, 2) synthetic or analogue, and 3) statistically downscaled. The approach chosen for the study is model-based GCM data. GCM models are most suitable to the study because they describe changes in a sufficient number of climate variables (temperature, precipitation, humidity, wind speed, and radiation) at different spatial (global and continental) and temporal scales (daily or monthly). GCMs aim to estimate changes in climate though different emission scenarios or future storylines. During the deliberations of the IPCC Fourth Assessment Report (AR4), results and simulations from 24 GCMs were used. After this, modelling centers such as the Canadian Climate Data and Scenarios (CCDS) provided the outputs of these GCM simulations using the three emission scenarios (A1B, A2, and B2) which provides 72 different future outcomes. GCMs are common and suitable for impact assessments due to these advantages.

The future period 2050s has been selected for this analysis, also known as 2041-2070. The future period sufficiently considers the influence of higher carbon dioxide concentration on the climate. Further future time periods such as 2070-2100 have greater uncertainty regarding projections. The 2050s period is near enough to expedite required adaptation strategies to address pedestrian safety. 2050s is valuable in informing and guiding safety interventions in pedestrian traffic infrastructure such as intersections and mid-road crossing which would require some time to be modified.

The assessment uses the A2 SRES emission scenario from the AR4 report to compare results with the Hambly (2011) study. The A2 scenario describes a future with medium-high rates of greenhouse gas emissions, population growth, and economic development. Most comprehensive climate change assessments use the A2 scenario, as it is unlikely that there will be substantial change in energy sources or a decline in population growth by 2050 (Andrey & Hambly, 2012; Goodarzi et al.,2015; Moriondo et al., 2011; Picketts et al., 2012). Thus, the A2 scenario closely conveys the future prevailing conditions best.

3.3.1.1 Baseline Climatological Data

The baseline climatological period (Obs) is used to demonstrate historical long-term trends in climate against which future climate simulated by GCMs can be compared. This baseline data is also used to validate the performance of GCMs in simulating historical data. The baseline data are usually 30 years long daily or hourly data. According to the WMO, the 30 year period is identified as a sufficiently long period of time for “characterizing” normal or representative climate of a region. The chosen baseline climatological period for this analysis is the1971-2000 period, since it is the official baseline period used by Environment Canada and the CCDS. The criteria for the baseline data according to the IPCC is proximity to the region of analysis, data completeness, and sufficient length to include weather phenomena such as droughts (IPCC-TGICA, 2007). The most common source of baseline data are the national meteorological agencies. The baseline data for this climate change analysis were obtained from Environment Canada Meteorological records for Toronto and Vancouver. Each variable in the baseline data (Obs) was checked for completeness. Temperature units is recorded in degrees Celsius and precipitation is measured in millimetres. Finally, the period has been checked for the "3 and 5 rule" that stipulates that baseline data must not be incomplete for more than 3 consecutive days and no more than 5 consecutive days for temperature and precipitation, respectively.

3.3.2 Weather Generator Models

The selection of the appropriate model is an important and challenging step in climate change impact assessment studies. There are 24 different GCMs presented and validated through the IPCC. The models simulate many small scale physical processes that are averaged over larger scales to estimate change. If many models are used for a region and time period, they may simulate very different responses to the same forcing. Each model contains an inherent bias; some models consistently project warmer temperatures than average or higher precipitation amounts than expected. Therefore, impact assessment studies and IPCC guidelines recommend using a minimum of two models for projections. The use of one model is unrealistic since it is difficult to define and select the "best" model. Nonetheless, the models selected should simulate the baseline and the climate sensitivity skillfully relative to other models.

To assess local climate change impacts on pedestrian safety, the projections from GCMs will need to be downscaled through numerical based modeling. The coarse spatial grid-output from GCMs (>100 kilometers squared) represents a limitation for evaluating climate change impacts on the local scale. Local processes such as precipitation are not adequately represented by GCMs. For this reason, weather generators have become a useful, less computationally intensive tool for quickly downscaling GCM outputs for impact assessments and adaptation planning

(Glenis et al., 2015). The downscaling methods have utilized the Long Ashton Research Station Weather Generator (LARS-WG) developed in the late 1990s. LARS-WG combines outputs from GCMs to produce site-specific climate change scenarios that includes changes in climate means and climate variability (Semenov, 1997). The advantages of this method is the generation of long weather time-series and the extension of weather simulation to nearby locations (Mikhail a. Semenov & Barrow, 1997). The basis of modeling is the duration of dry and wet periods, daily precipitation, and radiation distribution series. The output includes a number of climate variables such as precipitation, maximum and minimum temperature.

LARS-WG latest model incorporates built-in GCMs models from the fourth IPCC report, readily available for statistical downscaling. The generator runs 15 out of the 24 models, and using the A2 scenario as a criteria, nine models were available for this study.

3.3.2.1 Validation of Selected Models

The validity method stipulates that the adopted models for the study should have the best or the closest simulations of the baseline period when compared to the historical observation (IPCC-TGICA, 2007). Several large-scale impact assessments have used this approach (Smith & Pitts, 1997) . Table (3-13) illustrates the ability of the models selected in accurately simulating observed annual climate variables for Toronto and Vancouver relative to the documented conditions from the airport weather stations. Naturally, some models had substantial cool and wet biases for both study areas. Many models weren't able to accurately simulate Vancouver's weather. This is possibly due to local factors such as Pacific Ocean proximity, elevation, and the location of Vancouver's international airport located on an island. Furthermore, GCM data produces the simulations based on grid by grid point, while the baseline data is from airport stations is from one particular location. Refer to Appendix B for complete list of models and differences in absolute value.

Table 3-13: Difference between simulated and observed baseline by model

	Toronto		**Vancouver**	
Model	*Temperature (^oC)*	*Precipitation (mm/day)*	*Temperature (^oC)*	*Precipitation (mm/day)*
CNRMCM3	-1.899	0.513	-2.002	0.551

ECHAM5OM	-0.300	1.214	-6.276	3.001
GFDLCM	-2.777	0.782	-5.514	1.244
HADCM3	-1.206	0.921	-8.454	2.043
HADGEM1	-1.613	0.701	-4.541	3.182
INMCM3	-1.017	0.459	-1.297	-0.231
IPSLCM4	-2.326	0.969	-3.170	1.220
NCARCCSM3	-1.046	0.031	-5.596	1.459
NCARPCM	-2.999	0.416	-5.205	0.677
The values represent the difference between Obs and 20C by models. The simulations are based on the average year-month data. Data source: CCDS (2015a)				

Next, the representation of climate sensitivity by the models is analyzed. The selected models for the impact assessment should be consistent and representative, with global projections for climate sensitivity (IPCC-TGICA, 2007). Climate sensitivity is the response of the global climate system to a given forcing (e.g. CO_2, aerosols or ozone). There are two indicators of climate sensitivity. The first is the Equilibrium Climate Sensitivity (ECS), which is the eventual annual mean surface air temperature when the concentration of CO_2 has doubled and a new equilibrium state is achieved or when global temperatures stop changing (Randall et al., 2007). The second is the Transient Climate Response (TCR) which is the "annual mean surface air temperature change at the time this doubling of CO_2 occurs before any equilibrium is attained" (Randall et al., 2007, p629). The range for the transient climate response is 1.4 to 2.6 ^{O}C, and for the equilibrium climate sensitivity it is between 2 and 4.5 ^{O}C (Randall et al. 2007, IPCC-TGIGA, 2007). Both ECS and TCR are equally important measures of climate sensitivity. However, it is important to focus on climate sensitivity based on TCR, because it will take a number of decades for the climate to reach an equilibrium state after CO_2 doubling – perhaps well after the 2050s. According to Sokolov et al., 2009, the doubling of CO_2 is expected to occur in mid to late 21 century Figure 3-2.

Table 3-14: Climate sensitivity of selected models

Selected Model	Equilibrium climate sensitivity (°C)	Transient climate response (°C)
CNRMCM3	n.a	1.6
ECHAM5OM	3.4	2.2

GFDLCM	3.4	1.5
HADCM3	3.3	2.0
HADGEM1	4.4	1.9
INMCM3	2.1	1.6
IPSLCM4	4.4	2.1
NCARCCSM3	2.7	1.5
NCARPCM	2.1	1.3
Reproduced from Randall et al. 2007		

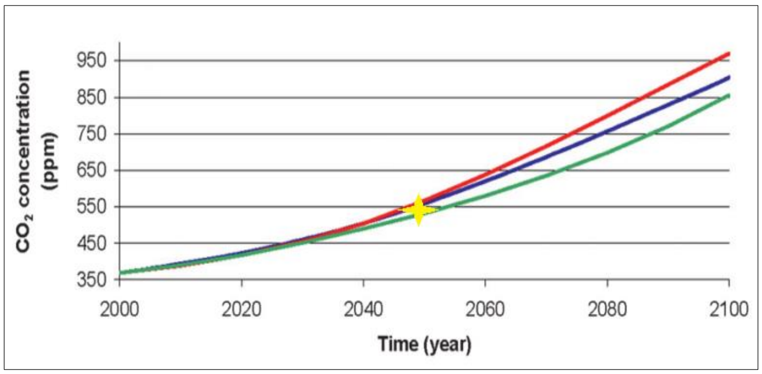

Figure 3-3: Atmospheric CO2 Concentration Projections- Red symbolizes A2 Scenario (reprinted from Sokolov et al. 2009)

Finally, the selected models were plotted to visualize the models projections of the change in climate (ΔC). The models were plotted in a scatterplot to demonstrate their presentation of the projected changes in annual mean climate by 2050 relative to other models. Figure (3-4) illustrate the models estimation of delta change (future projection difference from the simulated baseline) at the local level for Toronto and Vancouver. In Toronto, models are projecting an increase in annual precipitation from 5 to 11 percent, with one model projecting a decrease in annual precipitation by 5 percent. In Vancouver, there is more variability in the change of future precipitation. Five models are projection an increase in annual precipitation between 5 to 17 percent, and three models are projecting decrease in annual precipitation. It seems that local geographical and atmospheric processes influence model output. Models that project an increase in precipitation in Toronto are projecting a decrease in precipitation in Vancouver and vice versa. However, in both locations, there is a consensus on the overall change of mean surface temperature. All models are projecting an increase in annual surface temperatures between 1.5 to

3.9 degrees Celsius in Toronto, and 1.5 to 3.4 degrees Celsius in Vancouver. This demonstrates that uncertainty exists within projections relating to precipitation. It is important to use a number of models to understand patterns that may emerge that could provide insight into possible biases.

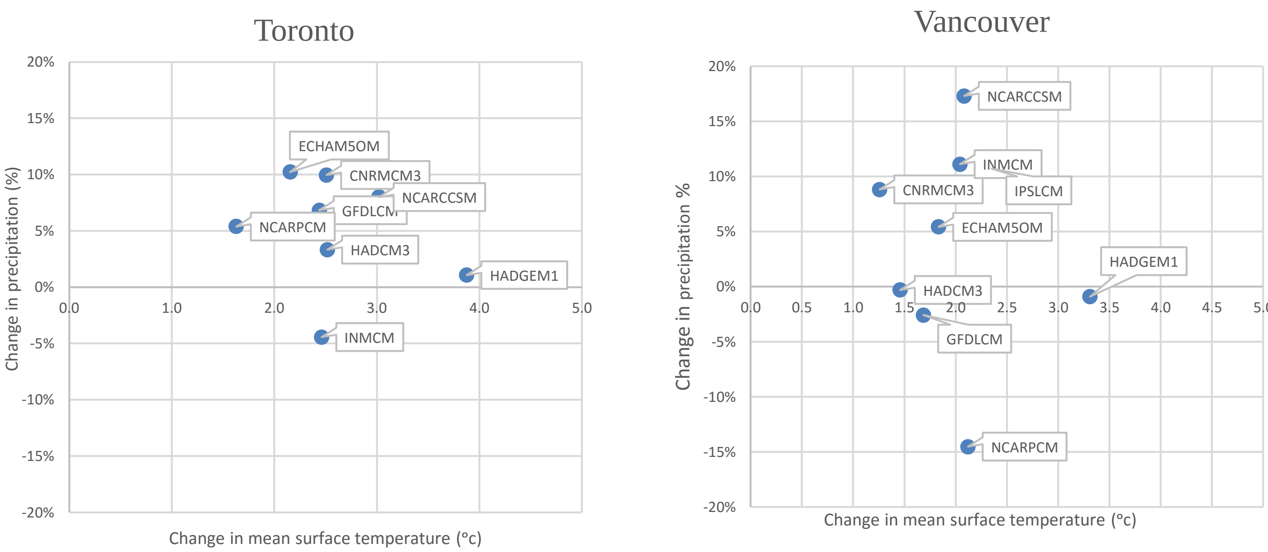

Figure 3-4: Delta Change (ΔC) in Temperature and Precipitation, 2050s

3.3.2.2 Technical Steps: LARS-WG

There are two main processes in the LARS-WG model: calibration of the model and production of simulated climate change data for the 2050s. Before the process of downscaling started, two files was created for the model, the baseline period of 1971-2000 and a second file describing the physical properties of each study area.

The LARS-WG is first calibrated using the two files. The first file describes the latitude, longitude and elevation of the region. The second contains the baseline data from 1971 to 2000 (Obs). The model uses both files to determine the statistical characteristics of the region, also known as the “site analysis” stage. After the model calibration is completed, the data is stored in two separate files. The first file (*sta) contained the statistical characteristics of the observed data such as the length of wet and dry series of days, distribution of precipitation, precipitation statistics by month, and extreme minimum and maximum temperatures for each month (Semenov & Barrow, 2002). The second file (*wg) contained statistical parameters which are used to simulate synthetic weather data. The file contain means, standard deviations of maximum and minimum temperatures on dry and wet days, and autocorrelation values. Using the statistical characteristics of the two files, the generator produced a baseline simulated data (20C). This simulated baseline is usually used to test and validate the performance of the weather generator against the historical baseline.

Finally, the generator is used to produce future climate change projections for 2041 to 2070 (2050s) derived from GCM output of a specific emissions scenario, in this case A2. The generator uses the GCM outputs to determine how weather parameter values should be perturbed. During this stage, the generator runs nine times for the models selected using the A2 scenario for Toronto and Vancouver.

Overall, the weather generators provides two files for each study area. A simulated baseline (1971-2000) and a climate change projection file using the A2 scenario and selected models for the 2041 to 2070 period.

3.3.2.2 Climate change risk estimates

The last step of the impact assessment is to estimate the future influence of climatic changes to pedestrian safety. To obtain this estimate, the difference between the modeled future period (21C) and the simulated baseline period (20C) is calculated for each model (INMCM3, CGCM3T47, and CISROMK3.5) and study area. The projected change in climate (ΔC) estimate is applied to the present relative risk estimates to evaluate the change in pedestrian risk of crashes by 2050.

Chapter 4: Results

4.1 Risk estimates of pedestrian collisions, 2003-2009

This thesis focuses on rainfall-related risks experienced between pedestrians and motor-vehicles in two of Canada's largest cities. The initial analysis is based on "current" climate. As such, it provides baseline estimates of the mobility risks currently faced by pedestrians. These estimates are derived using secondary data sets from both Transport Canada and Environment Canada in a matched-pair research design. More specifically, the analysis estimates the relative risk of pedestrian collisions during rainfall in Toronto and Vancouver from 2003 to 2009.

The relative risk estimates provided in this section are based on two temporal units of analysis, six-hourly and daily. As will be elaborated later, the choice of a temporal unit of analysis affects the risk calculations—and it affects these estimates differently in the two comparison cities because of local climates.

The risk outcomes of interest include total collisions, non-casualty collisions, casualty collisions (count of casualty collisions with fatal and non-fatal injuries), casualties (count of persons with fatal and non-fatal injuries), and collisions at different road locations during different rainfall intensities. Table (4-1) illustrates the sample size for the risk outcomes of interest in both regions. The reader is reminded that the reference to "rainfall", "rain days", or "events" specifically refers to a subset of liquid rain where the minimum temperature (for the day), and average temperature (for six-hours) was above 2 degrees Celsius, and more than or equal to 0.4 millimetres of precipitation was measured. These criteria ensure the removal of snowfall and winter precipitation periods from the analysis.

Table 4-1: Pedestrian collisions sample size summary, 2003-2009

Sample	Toronto	Vancouver
Matched Pairs (six-hourly)	1,057	1,852
Matched Pairs (daily)	462	603
Collisions	16,634	7,759
Non-casualties	709	285

Casualty Collisions	16,419	7,574
Casualty	17,070	7,925
Non-intersection collisions	3,914	2,071
Public intersection collisions	11,261	4,280
The values represent the total number of collisions by type.		

For the six-hourly analysis, the matching process (i.e., rain events are matched with non-rain events) produced 1,057 matched pairs for Toronto and, 1,852 for Vancouver. In the daily analysis, the counts are lower because of the occurrence of multiple six-hour events on some rain days; the result was 462 matched pairs for Toronto and 603 for Vancouver. As Table (4-2) demonstrates, the event-control pairs represent more than one-fourth of all pedestrian collisions that occurred in the in the study areas during the seven-year study period.

Table 4-2: Summary of collision counts 2003-2009, and matched pair results

Six-Hourly								
Study Area	**Total # of pedestrian collisions**	**Rain Events**		**Matched Events collisions**		**Matched Control collisions**		**E-C pairs**
		Sum	**% of Total**	**Sum**	**% of Total**	**Sum**	**% of Total**	**% of Total**
Toronto	16,634	2,944	18%	2,637	16%	1,571	9%	25%
Vancouver	7,759	2,531	33%	2,089	27%	1,133	15%	42%
Daily								
Toronto	16,634	3,767	23%	3,298	20%	2,903	17%	37%
Vancouver	7,759	3,338	43%	2,090	27%	1,606	21%	48%

When comparing the six-hourly and daily analyses, many more pedestrian collisions are captured in the daily analysis, because as the unit of time increases, the number of trips also increases. Interestingly, in the daily level of analysis, Vancouver only had 30 percent more matched pairs than Toronto, but at the six-hourly level the percentage increased to 70. It is apparent that matches are more challenging to obtain in Vancouver at the daily level. An explanation for this is the fact that Vancouver had 72 percent more rainfall days than Toronto, which substantially reduces the available control days. Also, when aggregated to the daily level, relative to Toronto, a higher proportion of pedestrian collisions in Vancouver occur during rainfall. This results in a lower number of daily matched pairs for Vancouver. That said, the sample size remains large; and thus estimates of relative risk are possible at both temporal units of analysis for both cities.

4.1.1 The temporal influence on Risk Estimates

Relative risk ratios indicate the extent to which pedestrian collision rates are higher (or lower) during rainfall relative to normal dry conditions. A risk ratio that is equal to 1.0 would indicate that the rate of pedestrian collisions in rainfall is the same as during dry conditions. A risk ratio under 1.0 would indicate that pedestrian collisions are lower during rainfall, and a ratio above 1.0 would indicate that pedestrian collisions are higher during rainfall. At the 95 percent confidence level, the relative risk in both cities is well above 1.0 indicating a significant increase in risk as rainfall occurs (Table 4-3). At the daily level, the 95% confidence interval for relative risk of pedestrian collisions in Toronto is 1.04 to 1.17, and for Vancouver it is 1.17 to 1.35. This can be interpreted as a 4 to 17 percent increase on rain days in Toronto and a 17 to 35 percent increase on rain days in Vancouver relative to dry days. At the six-hourly level, the relative risk is estimated to be 1.37 to 1.57 (37 to 57 percent higher) for Toronto, and 1.34 to 1.53 (34 to 53 percent higher) for Vancouver. These differences in relative risk estimates calculated for the two units of analysis (daily and six-hourly) are as expected, as explained below.

Table 4-3: Pedestrian collision relative risk, 2003-2009 (95% confidence Intervals)

Study Area	**Toronto**		**Vancouver**	
Risk Estimate	**Six-hourly**	**Daily**	**Six-hourly**	**Daily**
Total Collisions	1.37-1.57	1.04-1.17	1.34-1.53	1.17-1.34

These results compare reasonably well with vehicle collision studies regarding risk estimates during rainfall. For daily level analysis, the relative risk of pedestrian collisions in Toronto is slightly lower than what was reported for vehicle collisions during rainfall by Hambly (2011). His study indicated a 9 to 15 percent increase in vehicle collision risk. For Vancouver, the risk estimated by Hambly is 19 to 24 percent, quite close to the pedestrian collision estimate presented here. At the six-hourly level, pedestrian collision risk estimates are slightly lower than the risk of vehicle collisions, which is estimated to be 75 percent higher during rainfall (Andrey et al., 2003; Andrey, 2010). However, a similar six-hourly analysis on property damage vehicle collisions for Vancouver and Toronto, indicated an increase in risk during rainfall by 43 to 51 percent and 36 to 39 percent respectively (Hambly, Andrey, Mills, & Fletcher, 2013) . This demonstrates that, at the six-hourly level, pedestrian collisions appear to have the same, if not a higher risk, during rainfall than vehicle collisions in both cities.

The reason the daily analysis provided a lower risk estimate of pedestrian collisions than the six-hourly period, is due to the influence of dry hours at the daily level. The risk is especially lower during light rainfall periods captured in the analysis. It can be argued that the six-hourly analysis provides a clearer interpretation of risk, since there is a lower number of dry hours during the six hours, and thus a lesser dilution of risk. Vancouver and Toronto had the same relative risk at the six-hourly analysis level because rainfall occurs on average four out of six hours, and three out of six hours, respectively. Also the walking and driving culture is similar enough in order to make a comparison. However, at the daily analysis level, the relative risk is not the same and in fact, the relative risk is much lower for Toronto than Vancouver. This can be explained by Toronto's drier climate, where there is a higher number of dry hours during a typically rainy day than Vancouver, which dilutes the daily relative risk. For example, during a rainy day, rain occurs for an average of 8.8 hours (or 36.7 percent of the day) in Vancouver, and in Toronto an average of 5.9 hours (or 24.9 percent of the day). Furthermore, to demonstrate the influence of dry hours on risk estimates, the six-hourly risk estimates can be translated to daily using the average number of rainfall hours during the day. For example, Toronto's translated risk estimate would be 1.14 (i.e., [(1.57-1) *.249] +1), and Vancouver's translated daily risk estimate would be 1.19. Both translated values compare reasonably with daily risk estimate results in Table (4-3). Both units of analyses contribute valuable pieces of information on pedestrian collision risk. The six-hourly relative risk establishes that both cities have similar risk during rainfall since the comparison is based on a higher temporal resolution. The daily analysis suggests that the presence of dry hours during a rainy day influences daily risk levels because the duration of elevated risk is determined by storm characteristics, which in turn are tied to local and regional climate.

4.1.2 Breakdown of Risk Estimates by Rainfall Intensity and Time

Environment Canada weather data provides information on the total rainfall accumulation during the six-hour and daily periods. The accumulation of rainfall does not specifically characterize the intensity of rainfall during an event (i.e. heavy rain for two hours vs. light rain over several hours). However, it is useful to understand how average rainfall intensity contributes to risk. The current analysis used rainfall intensity categories based on previous vehicle collision studies. These categories reasonably capture a range of rainfall events and provide a sufficient sample size. The six-hourly rainfall categories selected for the current analysis are light rain (0.4-1.9 mm), moderate rain (2.9-9.9 mm), and heavy rain (≥10 mm), based on a study by Andrey (2010). In the daily analysis, the categories selected are very light rain (2 to 4.9 mm), light rain (5 to 9.9 mm), moderate rain (10 to 19.9 mm), and heavy rain (≥ 20 mm) based on a study by Hambly (2011). Certain rainfall intensities occur at a much higher frequency at the daily analysis level. For example, rainfall intensities of more than 20 millimetres are much less frequent at the six-hourly level. If the same daily categories were to be used in the six-hourly analysis, this would result in an insufficient sample size.

As might be expected, there is a positive association between rainfall intensity and collision risk in both study areas as seen in Figure (4-1 to 4-4). This is consistent with the findings of vehicle collision relative risk studies, in which several authors concluded a strong elevation of risk as rainfall intensifies (Andrey et al., 2005; Eisenberg & Warner, 2005; Eisenberg, 2004). In effect, the risk doubles during moderate and heavy rainfall. In Toronto, there is little or no increase in risk for days with rainfall less than five millimeters, but at six-hourly analysis level, there is an evident increase of risk due to less dilution of risk by dry hours. This also applies to Vancouver where the six-hourly periods tend to be wetter than Toronto, which explains the relatively higher risk for light rainfall (5 to 9.9 mm). Vancouver has a higher risk for moderate and heavy rainfall at the daily level, but both areas has overlapping relative risk at these intensities at the six-hourly level. The increase in risk as rainfall intensifies, maybe be linked to the decrease in visibility for both drivers and pedestrians, lower tire-pavement friction, and the influence of “low ambient illuminance” (Andrey & Olley, 1990).

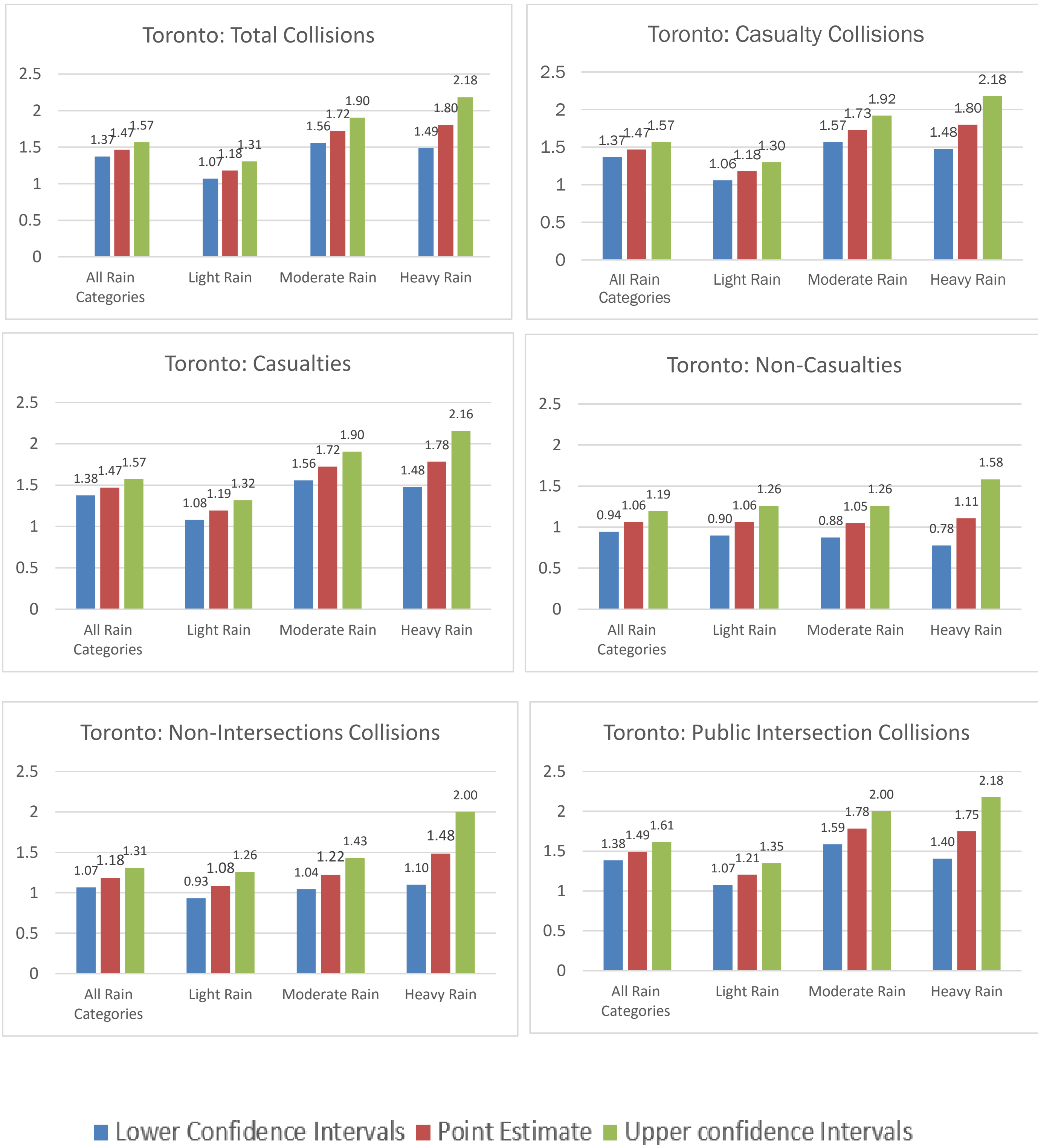

Figure 4-1: Toronto six-hourly relative risk estimates (95% confidence intervals

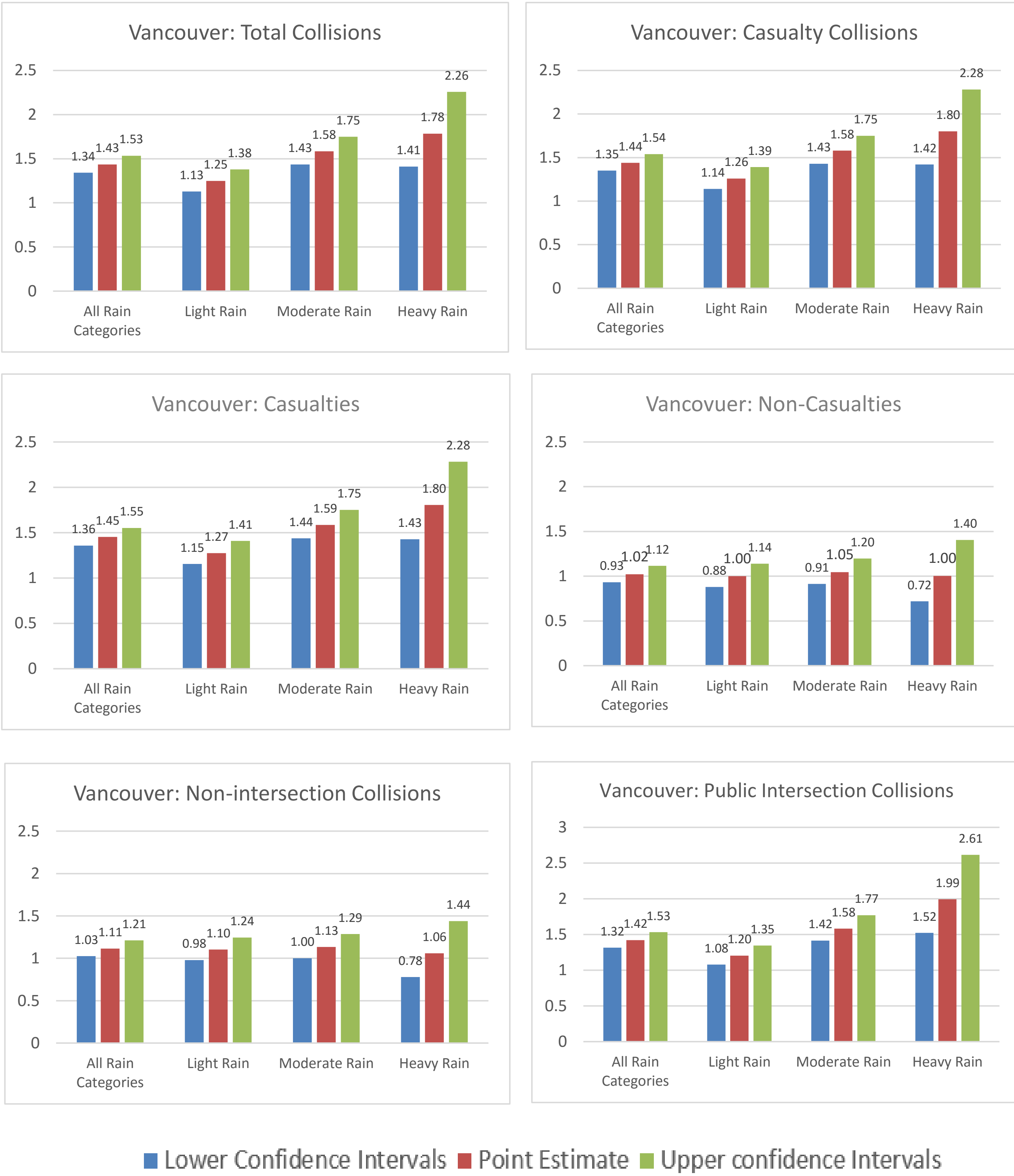

Figure 4-2: Vancouver six-hourly relative risk estimates (95% confidence intervals)

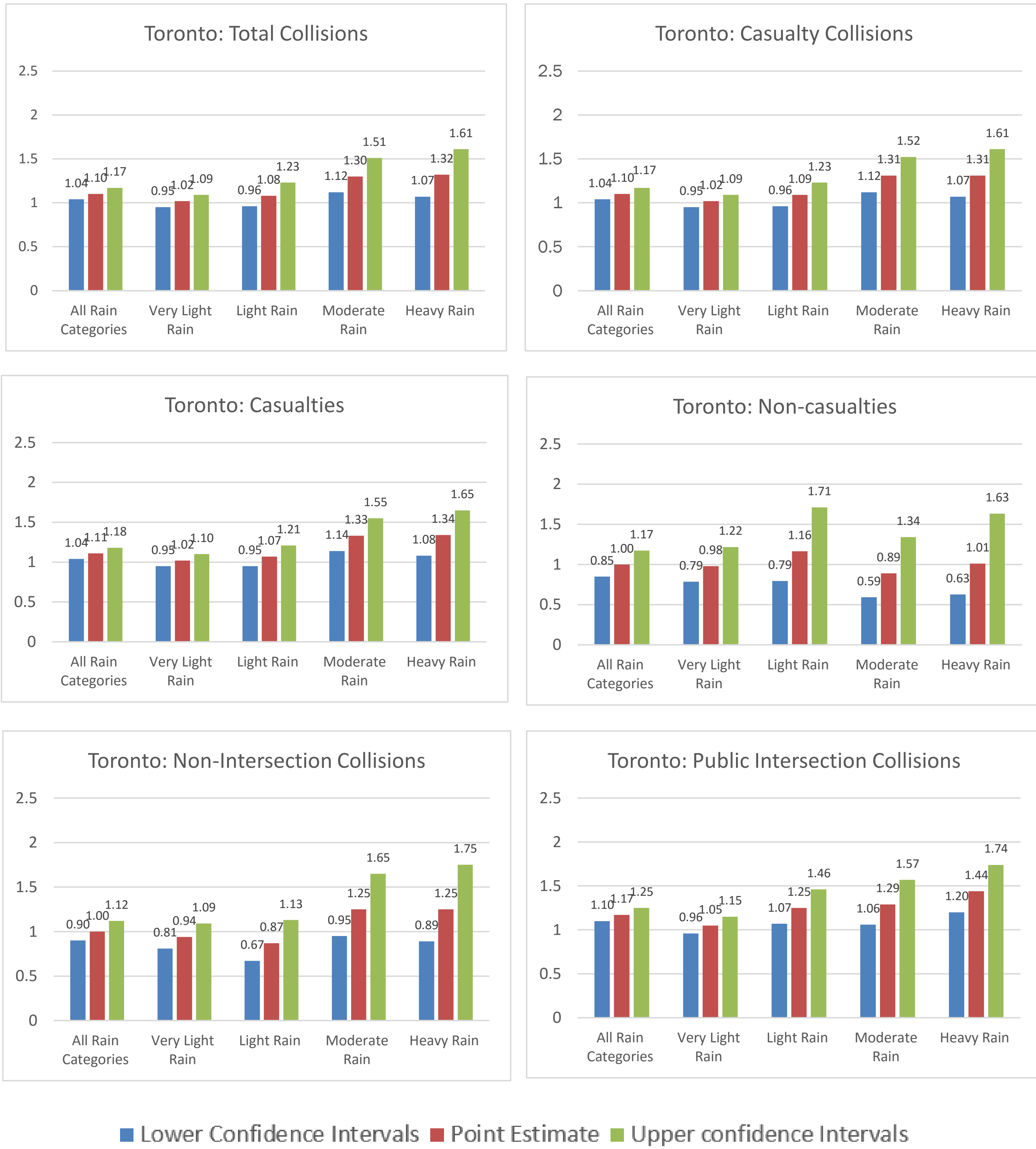

Figure 4-3: Toronto daily relative risk estimates (95% confidence intervals)

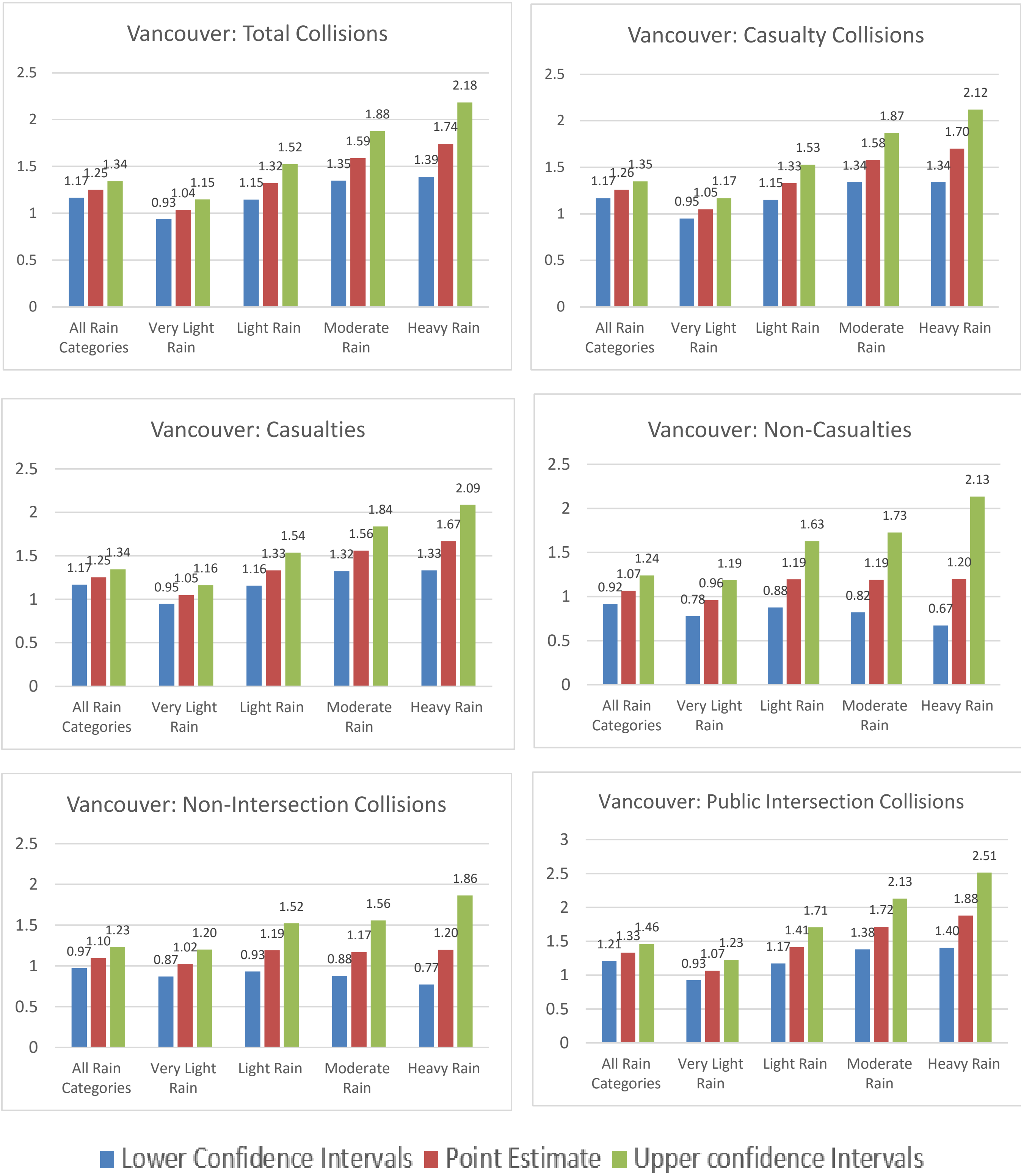

Figure 4-4: Vancouver daily relative risk estimates (95% confidence intervals)

There is a higher risk of collision-related casualties as rainfall intensifies than non-casualties for both areas. Casualties and casualty collisions have four types of injuries in collision reports; minimal, minor, major, and fatal (refer to Appendix A for definitions). The risk of minimal and minor injuries tends to increase and remain elevated as rainfall intensifies (refer to appendix for definitions of minimal, minor, major and fatal injuries). However, there is a less increase in risk for major and fatal injuries, suggesting an adjustment in pedestrian and driver behaviours as conditions worsen. In general, most pedestrian casualty collisions have elevated risk across rainfall categories, which is expected due to the higher probability of an unsafe incidents combined and the unprotected nature of a pedestrian. Naturally, it is unclear if there is any risk for non-casualty collisions in both regions. This is expected due to the small number of pedestrian collisions that do not result in any casualty as demonstrated by the sample size of Table (4-1).

There is a higher relative risk of pedestrian collision in public intersections than any other type of intersection, except for roundabouts and small intersections which are not included in the analysis due to the small number of collisions reported in these roadways. During moderate and heavy rainfall, there is a significant increase in risk for pedestrians crossing public intersections in both regions. Public intersections in Toronto have a slightly higher risk, which suggests that pedestrians are less acclimatized to intense rainfall than their Vancouver counterparts. Local factors that are not controlled for, such as road design and population demographics would also influence this conclusion. At the six-hourly level, there is a higher risk in non-intersection collisions at moderate rainfall levels in Toronto (Figure 4-1). The results imply that current traffic safety measures at public intersections may not be effective in protecting pedestrians from collisions during weather events.

Table 4-4: Pedestrian Collision Characteristics, 2003-2009

	Toronto		**Vancouver**	
	All Collisions	**Raining**	**All Collisions**	**Raining**
Collision Count	16,634	2,512	7,759	2,028
Collision Severity				
Fatal	1.9%	2.4%	2.8%	3.0%

Injury	96.8%	96.3%	94.8%	95.2%
Non-casualty	1.3%	1.3%	2.4%	1.9%
Speed				
Less than 50 km/hr	16.8%	14.9%	7.4%	6.4%
50 km/hr	51.9%	50.8%	69.2%	75.0%
60 km/hr	28.0%	31.1%	5.3%	4.9%
70 km/hr	1.7%	2.1%	0.4%	0.2%
80 km/hr	0.8%	0.5%	0.4%	0.6%
Location				
Urban	96.7%	96.9%	96.9%	97.8%
Rural	3.3%	3.1%	2.1%	1.8%
Roadway Type				
Non-intersection	23.5%	17.2%	26.7%	20.9%
Public intersection	67.7%	77.5%	55.2%	67.4%
Small intersection	8.6%	5.2%	5.4%	3.6%
Roundabout	0.0%	0.0%	0.0%	0.0%
Visibility				
Daylight	66.3%	34.8%	56.1%	30.2%
Dawn	1.9%	3.1%	2.2%	3.1%
Dusk	3.2%	3.9%	4.7%	5.0%
Darkness	28.5%	58.1%	36.1%	61.4%
Road Surface Conditions				
Wet	23.3%	99.3%	36.3%	96.4%
Fresh Snow	1.5%	0.2%	0.8%	0.2%
Slush, ice, wet snow	2.4%	0.4%	1.0%	0.3%

Table (4-4) provides an overview of the characteristics of collisions reported by road authorities over the seven-year period. Note that the values in the table refer to all collisions during the period, not just the matched pairs. Collision severity is similar in both regions in total collisions and while it is raining. Fatal collisions occur at a slightly greater frequency in Vancouver when it is raining. Regarding the speed limits, in both regions, most crashes during rainfall occur in 50 km/hr roads which are most likely urban areas. Toronto has a slightly greater proportion of rain collisions in 60 km/hr roads than the total. It appears that 50 km/hr roads are problematic in Vancouver where 75 percent of crashes are occurring during rainfall. It is possible that Vancouver has a greater proportion of 50 km/hr roads in pedestrian and motor-vehicle conflict areas.

In both regions, almost all collisions during rainfall are occurring in urban areas (Table 4-4). This is expected due to the higher relative risk of collisions occurring in busy public intersections which are more common in urban areas in comparison to rural areas. With regard to the type of roadway reported, Small intersections and roundabouts have an insignificant number of collisions, especially during rain. Overall, public intersections have two to three times more collisions in both regions than collisions at non-intersections especially during rainfall. The percentage of collisions in public intersections is slightly higher than total collisions.

Finally, according to the literature, visibility is one of the main factors leading to pedestrian-vehicle collisions. Table (4-4) demonstrate that most of the total collisions occur during daylight hours since majority of vehicle trips occur at that time. There is a smaller proportion of collisions during darkness compared to daylight, however, once rainfall occurs, a disproportionate share of annual rainfall collisions occur during darkness compared to all collisions. Moreover, in both cities, the figures are quite similar. This signifies that rainfall hazards such as reduced visibility is one of the leading factors in pedestrian-vehicle collisions along with reduced tire-pavement friction from precipitation. As expected, there is a strong association between collisions with reported presence of rainfall and wet road surfaces. Other than the collisions that takes place in dry weather, the greatest share of total collisions is occurring on wet roads.

Table 4-5: Relative risk estimate by six-hourly interval

6- Hourly Time Interval	Toronto	Vancouver
12 am to 6 am (0)	1.41-2.07	1.20-1.65
6 am to 12 pm (6)	0.99-1.29	1.19-1.58
12 pm to 6 pm (12)	1.24-1.51	0.98-1.26
6 pm to 12 am (18)	1.91-2.60	1.68-2.14

Andrey et al. (2010) examined the time of day effect on relative risk at the six-hourly level. Evenings and late nights / early mornings, demonstrated a significant increase in relative risk of vehicle collisions, especially during rainfall. The time-of-day effect also was considered in the current study. A higher risk of pedestrian collisions during rainfall is evident for early mornings and late nights for both study areas (Table 4-5). But, it is unclear if there is any elevation of risk during rainfall in Toronto during the hours of 6 am to 12 pm. The same applies for Vancouver. It is unclear if there is a higher risk for 12 pm to 6 pm. This is due to the disproportionate number of unrepresentative control periods which have above average number of collisions per six-hour. Most of these unrepresentative control periods were entirely attributable to these time intervals.

As revealed, both Vancouver and Toronto's pedestrians are susceptible to a higher risk of collisions during rainfall. Specifically, the risk increases as rainfall intensifies indicating insufficient adaptability to rainfall hazards. The risk of certain variables elevates suggesting a need for increased awareness and implementation of safety interventions. The next objective of the thesis is to demonstrate how climate change will influence precipitation, and pedestrian safety, in turn.

A decision has been made to analyze the effects of future climate change using the relative risk estimates based on the daily unit of analysis instead of the presented six-hourly relative risk estimates. There is more certainty in daily level climate change projections and the data was more easily attainable. Also, current weather generators provide climate projections only at the daily level.

4.2 Future Climate Change

This section contains the results of the climate change analysis. The modelling analysis was conducted to estimate changes in climate by the 2050s for Toronto and Vancouver. The climate change projections were produced at the daily level in order to use the daily relative risk estimates (2003 to 2007) calculated as per section 3.2.2. In this section, the reader is reminded that "Obs" refers to the 1971-2000 historical baseline period observed at airport stations, "20C" is simulated baseline (1971-2000) by GCMs, and "21C" is the projected future period by GCMs. The delta change represented as "ΔC", is the difference between 21C future projections and the simulated baseline 20C.

4.2.1 Accuracy of Simulations

The first output is the simulated 1971-2000 baseline by the weather generators, LARS-WG. The weather generator calibrates the observed weather data to produce a set of statistical characteristics describing observed data. This include: the distribution of wet and dry series, hot and cold spells, frequency of precipitation, maximum and minimum precipitation totals, minimum and maximum temperatures, and statistical characteristics of solar radiation. The statistics are recorded by month and seasonality from observed data. Temperature is modeled by constructing parameters such as mean value. Precipitation is modeled using seasonal and monthly histograms of event frequency and number of dry and wet spells. LARS-WG uses this information to produce a synthetic artificial weather series or a simulation (20C). These observed weather parameters are later adjusted by the weather generator using the delta change in climate according to emission scenarios (in this case A2) from GCMs to produce stochastic realistic future climate data (21C). Therefore, it is important to have the simulated baseline similar to the observed data to determine if LARS-WG is suitable for the study area and analysis, and to have the best representation for climate change by the 2050s.

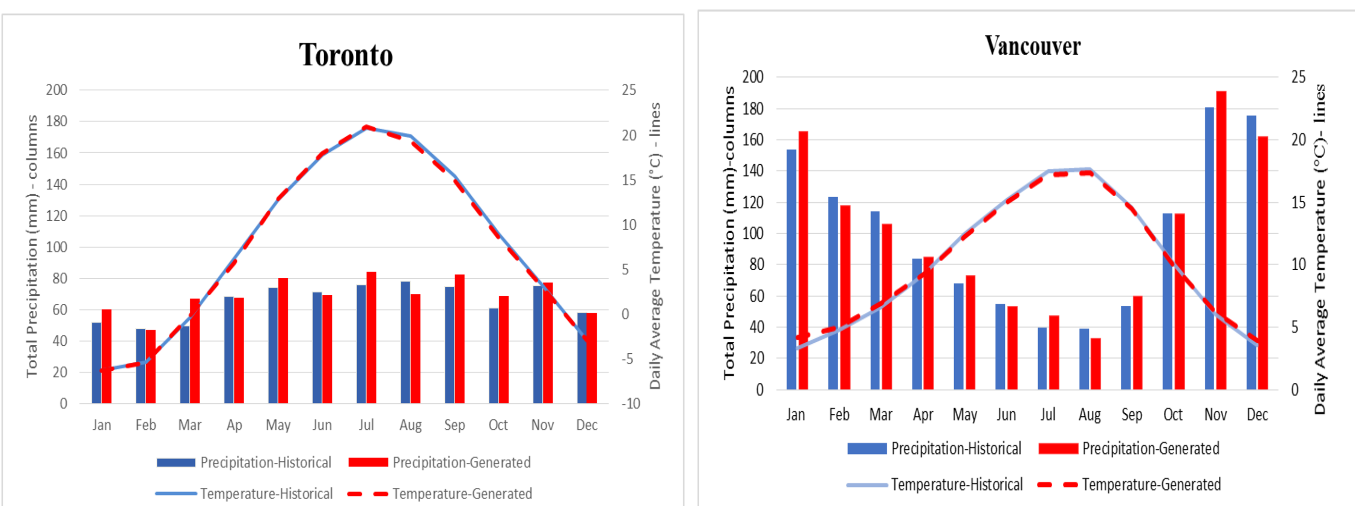

Figure 4-5: Climate Comparison of LARS-WG Generated Baseline vs. Historical Observations

Figure (4-5) illustrates the simulation of LARS-WG (20C) against the historical observations (Obs). The weather generator simulated historical observations with reasonable accuracy for both areas. Differences in results were mostly statistically insignificant ($p > 0.01$). The calibrated model simulated the average monthly temperature values quite well for both areas. In Toronto, average daily temperatures are lower by 1 degree Celsius in August than observed. Vancouver's temperatures are slightly lower than observed during the summer and slightly higher during the winter, but for the year the average temperature values are almost identical. The results for temperature simulation are satisfactory. Precipitation amounts are slightly overestimated for Toronto for most of the months in the year. The total amount of precipitation generated is higher by approximately 6 percent. Conversely, in Vancouver the precipitation generated is higher for half of the months in the year, especially July and January. Overall the results are satisfactory as the precipitation amount simulated is only 0.5 percent higher than the baseline. At the annual level, temperatures are quite similar, and precipitation statistics are not too far off the historical value which implies the accuracy of the weather generator in simulating the local climate.

Table 4-6: LARS-WG Generated Baseline differences in rainfall amounts (mm) by intensity

Rainfall Intensity	Toronto rainfall (% difference)	Vancouver rainfall (% difference)
Very light rain (0.4 to 4.9 mm)	-12.1%	5.5%
Light Rain (5 to 9.9)	-9.4%	6.7%
Moderate rain (10 to 19.9 mm)	-2.5%	5.5%
Heavy rain (≥ 20 mm)	-2.4%	-5.4%
The values are differences between 20C and Obs total annual rainfall.		

Upon a closer investigation of liquid precipitation or rainfall (>= 2 degrees Celsius), LARS-WG is either over or under estimating accumulation of the rainfall intensities (Table 4-6). Very light rainfall (0.4 to 4.9 mm) and light rain (5 to 9.9) is underestimated in Toronto by larger amounts than other intensities. The generator has overestimated most rainfall intensities except for the heavy rain days (≥20mm) in Vancouver. Overall, the agreement between simulated and observed climate indicated that LARS-WG is able to generate synthetic data that is similar to the observed climate especially for temperature, despite differences in precipitation amounts.

4.2.2 Changes in Climate, 2050s

Through the LARS-WG generator, nine GCMs were used to project climate information for 2041-2070 under the A2 scenario. Regarding annual precipitation amounts, a few models project a decrease in precipitation. There is a challenge in predicting changes in precipitation amounts by a single GCM. Therefore, having a combination is prudent to the analysis. The delta change values (ΔC) or estimate of future change in climate is calculated for each model as per Table (4-7). This change is the difference between future climate (21C) and the simulated baseline (20C) produced. This method is used because LARS-WG operates with some degree of uncertainty and limitation. Moreover, LARS-WG calibration used a set of parameters calculated from historical observations. These parameters were adjusted based on GCM predictions of future climate to produce the 2050s baseline. The estimate or delta change (e.g. increase in temperature) derived this way can then be compared to historical observations if needed for the assessment.

Table 4-7: Mean annual climate change estimates for GCMS, 2050s

	Toronto		Vancouver	
Model	**Total annual precipitation (% difference)**	**Daily mean temperature (°C difference)**	**Total annual precipitation (% difference)**	**Daily mean temperature (°C difference)**
NCPM	+6.2%	+1.7	-0.3%	+1.7
NCCCSM	+1.1%	+2.8	+1.8%	+2.3
MPEH	+13.1%	+2.0	+7.0%	+2.0
IPCM	-5.1%	+3.1	+8.6%	+1.6
INCM	-5.4%	+2.4	+12.0%	+2.2
HADGEM	+0.2%	+3.8	-5.3%	+3.3
HADCM3	+8.9%	+2.4	-4.8%	+1.7
GCFM	+4.2%	+2.0	+1.2%	+1.9
CNCM3	+11.6%	+2.1	+4.1%	+1.5
The values are differences between 21C and 20C				

As illustrated in Table (4-7), by mid-century, Toronto's annual mean temperature is estimated to increase by 1.7 to 3.8 degrees Celsius. Most models are projecting an increase in total annual precipitation. The increase in annual precipitation is from 0.2 to13 percent. Similarly, Vancouver is expected to have higher temperatures by mid-century where the annual mean temperature increase is between 1.5 to 3.4 degrees Celsius. An increase in annual precipitation is projected in Vancouver. The range is from 1.2 to 12 percent. In both areas, all models agree on an increase in annual mean temperature.

Some models in Table (4-7) projected a decrease in annual precipitation in both regions. However, upon examination of rainfall days, all models indicated an increase in rainfall days (Table 4-8). This is possibly due to the unanimous increase in annual temperatures that all models are projecting, which would naturally increase the number of liquid precipitation days and amounts. Therefore, all the models are projecting an average increase in rainfall amounts, the amounts varying from 1 to 25 percent in Vancouver, and 7 to 24 percent in Toronto.

Table 4-8: Annual change in rainfall days by model, 2050s

Model	Toronto	Vancouver
NCPM	+11.0	+10.3
NCCSM	+15.5	+11.9
MPEH	+11.0	+11.4
IPCM	+17.0	+12.5
INCM	+13.1	+8.7
HADGEM	+22.7	+12.2
HADCM3	+11.6	+7.1
GCFM	+10.3	+11.8
CNCM3	+12.5	+7.0
The values are the differences between 21C and 20C		

4.3 Impact of climate change on pedestrian safety

The last phase of the study estimated the change between present and future traffic safety based on the anticipated change in annual rainfall days by the 2050s. The change in annual rain days is the difference between simulated baseline (20C) and the projected climate (21C) (Table 4-8) in Toronto and Vancouver. This phase also uses the present-day risk estimates calculated in section

3.2.2 as an input in the calculation. Due to uncertainty and variation in model projections, the overall average change in rain days, and its subsequent influence on collision frequency, is calculated with low and high estimates. This change is then reported in terms of rainfall intensity and collision type.

Future traffic safety calculations are completed based on Hambly's (2011) methods. Using an example from Table (4-8), the calculation for a light rainfall day in Toronto, with a present-day relative risk of 1.09 is as follows:

- ❖ For each of the 13.8 days that rainfall occurs *(r)*, roughly 8 percent [(1.09 -1)/1.09] of the collisions that occur may be attributable to weather *(p).*
- ❖ The average casualty collisions per rainfall days is 6.79 *(i),* therefore, the number of collisions for each rainfall day that are attributable to moderate rainfall (*n*) is 0.54 [6.79 *(i)* * 8 percent *(p)*].
- ❖ An additional 2.7 days *(Δr)* each year, by the 2050s, (low estimate 1.7 and high estimate is 4.9) would increase annual collisions by approximately 1.4 *(Δc),* with a high estimate of 2.6 and a low estimate of 0.9.

This approach assumes that mobility patterns and collision risk will remain constant until this future period. Comprehensive results of this analysis are demonstrated in Table (4-9) for Toronto and (4-10) for Vancouver. A reminder that types of collisions that demonstrated a notable increase in relative risk were selected for the climate change analysis. The tables demonstrate the change in traffic safety for casualty collisions, casualties, and collisions in public intersections.

Table 4-9: Anticipated change in rainfall-related collisions, Toronto, 2050s

Collision Type and rainfall intensity	r	i	e	p	n	Δr	Δc
Casualty collisions							
Very light rain (0.4 to 4.9 mm)	37.10	6.19	1.02	0.02	0.12	+9.7 (+6.0 to +16.2)	+1.2 (+0.7 to 2.0)
Light Rain (5 to 9.9)	13.80	6.79	1.09	0.08	0.54	+2.7 (+1.7 to +4.9)	+1.4 (+0.91 to 2.61)
Moderate rain (10 to 19.9 mm)	11.60	8.76	1.31	0.23	2.05	+0.4 (-0.1 to +1.7)	+0.8 (-0.82 to +3.6)
Heavy rain (≥ 20 mm)	5.97	8.81	1.31	0.24	2.08	+1.1 (-0.1 to +2.5)	+2.4 (-0.9 to +5.3)
All intensities (sum)						+13.9 (+10.3 to +22.7)	+5.8 (+2.8 to +7.9)
Casualties							
Very light rain (0.4 to 4.9 mm)	37.10	6.40	1.02	0.02	0.13	+9.7 (+6.0 to +16.2)	+1.3 (+0.8 to 2.2)
Light Rain (5 to 9.9)	13.80	6.98	1.07	0.07	0.46	+2.7 (+1.7 to +4.9)	+1.2 (+0.8 to 2.2)
Moderate rain (10 to 19.9 mm)	11.60	9.16	1.33	0.25	2.28	+0.4 (-0.1 to +1.7)	+0.9 (-0.9 to +3.95)
Heavy rain (≥ 20 mm)	5.97	9.12	1.34	0.25	2.29	+1.1 (-0.1 to +2.5)	+2.6 (-1.0 to +5.8)
All intensities (sum)						+13.9 (+10.3 to +22.7)	+6.0 (+2.5 to +8.4)
Public intersections							
Very light rain (0.4 to 4.9 mm)	37.10	4.18	1.05	0.05	0.19	+9.7 (+6.0 to +16.2)	+1.8 (+1.2 to +3.1)
Light Rain (5 to 9.9)	13.80	4.92	1.25	0.20	0.97	+2.7 (+1.7 to +4.9)	+2.6 (+1.7 to +4.7)
Moderate rain (10 to 19.9 mm)	11.60	6.33	1.29	0.22	1.42	+0.4 (-0.1 to +1.7)	+0.6 (-0.57 to +2.47)
Heavy rain (≥ 20 mm)	5.97	6.49	1.44	0.31	2.00	+1.1 (-0.1 to +2.5)	+2.3 (-0.87 to +5.1)
All intensities (sum)						+13.9 (+10.3 to +22.7)	+7.2 (+4.6 to +10.1)

r - average annual number of rainfall days [from obs]
i - average number of collisions per rainfall day [# of collisions on rain days/# rain days in study period]
e - relative risk estimate
p - proportion of collisions for each rainfall day that are attributable to weather [e-1/e]
n - number of collisions for each rainfall day that are attributable to weather [i*p]
Δr - change in annual number of rainfall days [r for 21C - r for 20C]
Δc - change in annual number of collisions [change in r *n]

Table 4-10: Anticipated change in rainfall-related collisions, Vancouver, 2050s

Intensity	r	i	e	p	n	Δr	Δc
Casualty collisions							
Very light rain (0.4 to 4.9 mm)	62.60	2.80	1.05	0.05	0.14	+3.9 (-1.9 to +7.9)	+0.5 (-0.3 to +1.1)
Light Rain (5 to 9.9)	28.77	3.79	1.33	0.25	0.93	+1.7 (+0.9 to +2.4)	+1.6 (+0.81 to +2.27)
Moderate rain (10 to 19.9 mm)	25.00	4.31	1.58	0.37	1.59	+2.2 (+0.1 to 3.7)	+3.6 (+0.1 to +5.8)
Heavy rain (≥ 20 mm)	11.50	6.09	1.70	0.41	2.51	+2.5 (-0.5 to +6.2)	+6.3 (-1.6 to +15.7)
All intensities (sum)						+10 (+7.0 to +12.5)	+12.0 (+1.1 to +21.5)
Casualties							
Very light rain (0.4 to 4.9 mm)	62.60	2.91	1.05	0.05	0.14	+3.9 (-1.9 to +7.9)	+0.5 (0.3 to 1.1)
Light Rain (5 to 9.9)	28.77	3.97	1.33	0.25	0.99	+1.7 (+0.9 to +2.4)	+1.7 (+0.8 to + 2.4)
Moderate rain (10 to 19.9 mm)	25.00	4.51	1.56	0.36	1.62	+2.2 (+0.1 to 3.7)	+3.6 (+0.1 to +5.9)
Heavy rain (≥ 20 mm)	11.50	6.30	1.67	0.40	2.52	+2.5 (-0.5 to +6.2)	+6.3 (-1.3 to + 15.7)
All intensities (sum)						+10 (+7.0 to +12.5)	+12.1 (+1.2 to +21.7)
Public intersections							
Very light rain (0.4 to 4.9 mm)	62.60	1.49	1.07	0.06	0.09	+3.9 (-1.9 to +7.9)	+0.4 (-0.2 to +0.7)
Light Rain (5 to 9.9)	28.77	2.37	1.41	0.29	0.69	+1.7 (+0.9 to +2.4)	+1.4 (+0.6 to +1.7)
Moderate rain (10 to 19.9 mm)	25.00	2.84	1.72	0.42	1.18	+2.2 (+0.1 to 3.7)	+2.6 (+0.1 to +4.3)
Heavy rain (≥ 20 mm)	11.50	4.23	1.88	0.47	1.98	+2.5 (-0.5 to +6.2)	+5.0 (-0.9 to +12.3)
All intensities (sum)						+10.3 (+7.0 to +12.5)	+9.1 (+0.7 to +16.7)

r - average annual number of rainfall days [from obs]
i - average number of collisions per rainfall day [# of collisions on rain days/# rain days in study period]
e - relative risk estimate
p - proportion of collisions for each rainfall day that are attributable to weather [e-1/e]
n - number of collisions for each rainfall day that are attributable to weather [i*p]
Δr - change in annual number of rainfall days [r for 21C - r for 20C]
Δc - change in annual number of collisions [change in r *n]

The breakdown of the results for Toronto is illustrated in Table (4-9). For Toronto, based on 62 rain days per year, the models project a substantial mean annual increase (from 16 to 36 percent) in rain days for all intensities by the 2050s. According to Table (4-11), the annual casualty collisions is expected to increase from 0.1 to 0.3 percent, based on average annual collisions of 2,346. The casualties would increase from 0.1 to 0.3 percent as well, based on an average annual number of 2,439. The public intersection collisions are anticipated to have the largest increase from 0.3 to 0.6 percent, based on 1,609 average collisions per year. Regarding rainfall intensity, light rain days will have the greatest increase, accounting for more than half of new rain days each year. Except for public intersections, the annual increase in collisions is highest for heavy rainfall. This is likely due to the higher risk of collisions associated with heavy rainfall days. Almost 40 percent of the increase in annual collisions is expected to come from heavy rainfall days in the 2050s.

The anticipated results portrays a similar story in Vancouver (Table 4-10). By mid-century, the annual number of rain days are projected to increase (by a range of 5 to 9 percent) based on 135 rain days per year. According to Table (4-11), this is estimated to increase annual casualty collisions and casualties from 0.1 to 2.0 percent, based on 1,082 and 1,132 average annual collisions, respectively. The annual public intersection collisions are estimated to increase from 0.1 to roughly 3 percent, based on current 611 average annual collisions. Similarly to Toronto, the greatest increase will occur in light rainfall days, accounting for half of all additional rain days. But, light rainfall days will have the lowest number of additional collisions. Again, due to risk, the highest increase in the annual number of collisions would be observed during moderate and heavy rainfall days. This increase accounts for roughly 80 percent of additional collisions.

Table 4-11: Annual change in total collisions, 2050s

	Average annual incidents	Mean estimate	Low estimate	High estimate
Toronto				
Casualty collisions	2,346	+0.2%	+0.1%	+0.3%
Casualties	2,439	+0.2%	+0.1%	+0.3%
Public intersections	1,609	+0.5%	+0.3%	+0.6%
Vancouver				
Casualty collisions	1,082	+1.1%	+0.1%	+2.0%
Casualties	1,132	+1.1%	+0.1%	+1.9%
Public intersections	611	+1.5%	+0.1%	+2.7%
Estimates are based on change in annual collisions (Δc, Table 4-9 & 4-10) divided by average annual collisions.				

Assuming that mobility patterns and risk remain constant until the mid-century, both analyses agree on a decrease in pedestrian safety by 2050 as rain frequency increases. The highest increase in collisions for both areas will be observed on moderate and heavy rainfall days. Table 4-11 summarizes the findings and the change in the annual total number of collisions by the 2050s. The change in total collisions at first glance might seem to be a negligible amount, from 0.1 to 3 percent. But to demonstrate the importance of the issue, it is useful to investigate the change in collisions entirely attributable to rainfall. Table (4-12) demonstrates that the average increase in collisions during rainfall is roughly 67 percent in Toronto and 65 percent in Vancouver.

Table 4-12: Average annual change in collisions attributable to rainfall, 2050s

	Average annual incidents attributable to rainfall	Mean estimate	Low estimate	High estimate
Toronto				
Casualty collisions	9	+64.3%	+30.4%	+87.9%
Casualties	9	+63.8%	+26.7%	+88.8%
Public intersections	10	+74.0%	+46.3%	+102.5%
Vancouver				
Casualty collisions	19	+64.3%	+6.0%	+115.0%
Casualties	19	+62.7%	+6.3%	+112.1%
Public intersections	14	+66.7%	+5.3%	+122.6%
Estimates are based on change in annual collisions (Δc, Table 4-9 & 4-10) divided by the average annual collisions attributed to rainfall, calculated as [(r*i*p) / 5 years].				

The results compare well with Hambly's (2011) vehicle collisions analysis. Similarly to this analysis, Hambly found that the greatest increase in additional casualty collisions and casualties will be observed on moderate and heavy rainfall days. Overall, the average increase in vehicle-vehicle collisions occurring while it's raining in Toronto is the same as the average increase in vehicle-pedestrian collisions, about 67 percent. However, in Vancouver, Hambly anticipated a much higher average increase in rainfall vehicle-vehicle collisions of 150 percent, roughly 80 percent higher than pedestrian-vehicle collisions. This difference is possibly due to the greater increase in heavy rain days projected for Vancouver. Hambly's models projected a remarkable 75 percent increase in the number of heavy rain days each year. However, just as in this analysis, light rainfall days are accountable for almost half of new rain days each year in Toronto. Both studies emphasise that future safety related changes should consider the influence of moderate and heavy rainfall days on traffic safety.

On a more positive note, winter precipitation in Toronto could see a change due the influence of climate change. In Canada, over the past 60 years, events such as blowing snow have decreased significantly (Andrey & Hambly, 2012). With warming winter temperatures, it is likely that pedestrian collisions during winter may be become a lesser concern in Toronto.

Chapter 5: Summary and Discussion

5.1 Summary and Conclusion

The overall purpose of this thesis was to explore the impacts of rainfall and climate change on pedestrian safety. Exploration of this issue is limited in the pedestrian literature despite the likely negative implications of climate and weather on pedestrian health and wellbeing. The first objective of the study was to estimate the relative risk of pedestrian collisions under present climate conditions (2003-2009). The second objective was to evaluate the influence of climate change on collisions and pedestrian safety by mid-century. The empirical results of these analyses were presented for different types of collisions (total collisions, non-casualties, casualty collisions (i.e. number of collisions with casualty), casualties (i.e. number of persons who sustained any type of injury), non-intersections and public intersections. This helped demonstrate how collision types are influenced by rainfall and climate change. To achieve the objectives of the thesis, and to be able to compare results with vehicle-collisions, the analysis implemented methods elaborated by Hambly (2011). Two urban Canadian regions with different meteorological climates were selected for the study, namely Toronto and Vancouver.

The first objective, estimating the relative risk of pedestrian collisions, had the following key results:

- ❖ For the current climate analysis, the relative risk estimates were calculated using a daily and six-hourly unit of analysis to explore the risk through different temporal scales. On days with measurable rainfall, pedestrian collision risk was estimated to be by 4 to 17 percent higher in Toronto and 17 to 34 percent higher in Vancouver in comparison to days with normal weather. At the six-hourly level, the risk of collisions during rainfall is 37 to 57 percent higher in Toronto and 34 to 53 percent higher in Vancouver relative to normal hours.
- ❖ The risk estimates are higher for both areas at the six-hourly level because, on average, there is a lower number of dry hours that would influence and dilute the risk. The presence of dry hours during the rainfall “event days” is more prevalent in in Toronto, since it has a drier climate than experienced in Vancouver.

- As rainfall intensifies, the relative risk of collisions increases, a trend evident in both study areas. In Toronto, there is an insignificant increase in risk at the daily level for very light (< 5mm) and light rainfall (<10mm), and there is a slight increase in risk for light rainfall (< 2mm) at the six-hourly level. The same is true for Vancouver, where there is a slight increase in risk for light rainfall days and a significant increase in risk at six-hourly light rainfall periods. In both regions, at moderate and heavy intensities (> 20 mm) the risk is almost three times higher than very light rainfall. In both units of analysis, the progression of risk as rainfall intensifies is evident.

The second objective using the present-day relative risk estimates explored how climate change would impact pedestrian road safety in Canada by mid-century. Through a statistical downscaling method, several models were used to produce climate change projections for both regions. Using more than one model is imperative in impact assessment studies due to the inherent biases and uncertainties in each model.
This analysis demonstrated the following:

- By mid-century, Toronto will likely encounter a mean warming of 1.7 to 3.8 degrees Celsius. Most of the models projected an increase in precipitation, but the amounts varied from 0.2 to 13 percent.
- Vancouver will likely also see an increase in annual temperatures and precipitation. The models projected an annual mean temperature warming from 1.5 to 3.4 degrees Celsius. Precipitation is projected to increase in most models; the range is from a 1.2 to 12 percent increase.
- Looking at the change in rainfall by mid-century, the mean annual increase of rain days for Toronto is roughly 16 to 36 percent for all rainfall intensities. This increase in rain days is projected to increase annual pedestrian-vehicle collisions from 0.1 to 0.3 percent. Half of the additional rain days by mid-century are very light rainfall days. However, almost 40 percent of additional collisions are to occur during heavy rainfall days.
- For Vancouver, the mean annual increase of rain days is approximately 5 to 9 percent for all rainfall intensities. This would increase annual collisions from 0.1 to 3 percent. Like Toronto, 50 percent of Vancouver's additional rainfall days are very light rainfall. The

highest increase in pedestrian collisions would likely be for moderate and heavy rainfall days. Roughly 80 percent of additional pedestrian collisions are expected to occur on days with these intensities.

Through these analyses, different types of collisions that could be influenced by rainfall and future climate change are analyzed. A reminder is given to the reader that the relative risk was also calculated for overall collisions, non-casualty, and non-intersections, but the types of collisions that had evident increase in risk during rainfall were selected for the climate change analysis (casualty collisions, casualties, and public intersections). The findings are as follows:

- ❖ The relative risk estimates did not show a notable increase in risk of non-casualty collisions and non-intersection collisions during rainfall. The analysis of collision characteristics demonstrated that only 1.3 and 2.4 percent of collisions occurring during rainfall were non-casualty in Toronto and Vancouver, respectively. And, About 23 and 27 percent of collisions during rainfall occurred in non-intersections in Toronto and Vancouver, respectively. The relative risk of non-casualty and non-intersection collisions did not demonstrate a notable increase. Analysis for the effect of climate change proceeded with casualty collisions, casualties, and public intersection collisions.
- ❖ At the daily level, in Toronto, public intersection collisions and involving casualties have a high risk during moderate and heavy rainfall. In Vancouver, the risk of casualties and casualty collisions is similar. However, in both regions, collisions at public intersections show a higher risk than other types of collisions, especially during intense rainfall amounts.
- ❖ At the six-hourly level, in Toronto, the relative risk of casualty collisions and casualties is similar. The risk for these collisions in public intersections is highest for moderate rain (> 10 mm). In Vancouver, casualties are slightly higher than casualty collisions. But similarly to Toronto, collisions in public intersections have the highest risk during moderate and heavy rain fall.
- ❖ By mid-century, in Toronto, collisions taking place in public intersections has the highest increase due to climate change, roughly 7 additional collisions annually. Casualty collisions and casualties have similar increases since the risk is the same for both types.

> For Vancouver, climate change will increase the number of collisions and casualties by similar amounts, about 12 additional collisions. Collisions taking place in public intersections have a lesser increase, around 9 additional collisions.

The results of the study demonstrate that the risk of casualty collisions, casualties and collisions in public intersections is higher in rainfall periods than normal periods. The risk is significantly higher for moderate and heavy rainfall during six-hourly periods and days, where the increase is two or three times higher than very light and light rainfall periods. Climate change is likely to have minimal impacts on this risk. The number of rainfall days is projected to increase by mid-century, thereby, increasing the annual number of collisions (0.1 to 0.3 percent for Toronto, and 0.1 to 3 percent for Vancouver). Light rainfall (< 5 mm) will have the highest increase in days, however, the anticipated additional accidents will largely be attributed to moderate and heavy rainfall days. The relative risk for casualty collisions and casualties is similar and this is expected because pedestrians involved in a collision are susceptible to injury. The results for public intersections show that regardless of the city, there is a high risk for collisions occurring at major intersections, especially as rainfall intensifies. The results unequivocally demonstrate that moderate and heavy rainfall events are very problematic to pedestrian safety, requiring attention from the traffic safety community in present weather and future climate.

Walking as a mode of transport is an important part of urban cities, sustainability, standard of living, and human health. The influence of weather and climate on walking and pedestrian safety is barely addressed in the literature, despite the changes in mobility patterns, increasing population, urbanizing centers, and the likely modal shift to sustainable transportation. This thesis attempted to fill this gap, and to evaluate the vulnerability of the pedestrian in present and future climate conditions. The conclusion is that it is imperative to design safety interventions that can reduce pedestrian collisions such as modifications to the built environment.

5.2 Discussion

This study attempts to understand and create awareness of the issue of pedestrian collisions and its relation to weather and climate change. The implications of the findings relates primarily to the issue of road safety. Traditionally, road safety has focused on increasing the survival rate of motor vehicle occupants, this resulted in a remarkable decline in fatal vehicle-vehicle collisions (Andrey, 2000). However, specific interest grew in pedestrian safety due to their intrinsic vulnerability and sensitivity to injuries from vehicle impact, especially in children and the elderly. Pedestrian safety became particularly important since the ability to walk and cross roads safely is critical to public health, quality of life, and sustainability. Walking as a form of transport has been proven to reduce chronic illnesses, rates of obesity, heart disease and overall health care spending in Canada (Transport Canada, 2011). In many countries, and mainly in Europe, considerable progress in safety of vulnerable road users was achieved because pedestrians and cyclists safety became the top priority of road safety (Pucher & Dijkstra, 2003). In Canada much of the progress in road safety is attributable to motor-vehicles with little progress in pedestrian safety. In comparison to European countries, Canada has further advancements to make. In 2008, the pedestrian fatality rate per 100,000 people was 0.34 in the Netherlands and 0.49 in Sweden, compared to 1.1 in Canada (Arason et al., 2013).

It is widely acknowledged in the motor vehicle safety literature that different types of weather create different types of hazardous driving conditions, increasing the risk of collisions for some of these types of weather (Andrey & Hambly, 2012). The defenseless nature of the pedestrian against vehicle impact collisions creates a vulnerable group of road users in urban and urban-sprawl locations. This intrinsic vulnerability is problematic during times when risk levels are especially high, such as during inclement weather conditions.

The study demonstrated the elevated levels of pedestrian risk under rainfall conditions in Toronto and Vancouver. Days with moderate and intense rainfall have a particular significant increase in risk. This issue will likely become more problematic as climate change takes place. The implications of climate change for pedestrian safety has been barely investigated and therefore are largely unknown. If mobility patterns and current road practices remain the same for the next 35 or years, there likely will be only minimal increases in annual pedestrian collisions in Toronto and Vancouver. The increase is estimated to be 0.1 to 3 percent of total annual collisions. This number may be a negligible amount, but it's useful to think about the percentage in a different way. When the change in annual collisions entirely attributable to rainfall is calculated under climate change scenario, the total percentage increase in all collision types is between 5 to 122 percent. Another way to think of the significance of the results is the resulting social costs due to the increase in pedestrian collisions. According to the City of Vancouver, the average cost of a casualty pedestrian-vehicle collision in Vancouver in 2012 is $234,000 ($244,190 in 2016) including human error, medical care, lost earnings, administration fees and other indirect costs (Lightman et al., 2012; Sayed, 2012). If Vancouver has an additional 21 casualty collisions per year (high estimate since the low estimate is 1.1), this is equals an added cost of approximately $5 million per year. These figures are representative of Toronto as well. Toronto could possibly experience between 2.8 to 7.9 more casualty collisions, this would be an added annual cost of $700,000 to $2 million. These figures are likely underestimating the true cost of additional collisions because the growth in population is not included which likely drive these values even higher. Investing in pedestrian safety could reduce the anticipated additional financial burden of collisions.

Most impact assessments on the implications of climate change on transport have focused on economic issues relating to transportation infrastructure, with prominent and alarming financial and societal costs such as sea-level rise, permafrost degradation, and freeze-thaw cycles. Little has been discussed on the implications of climate change for road users and even less for vulnerable road users. The study provided evidence of interaction between aspects of pedestrian safety and anthropogenic climate change. For the region of Toronto and Vancouver, the first signal from GCMs regarding temperature is clear. There will be an increase in average annual temperatures for both regions. Higher temperatures translates into extreme heat risks. Research on the effects of extreme heat on vehicle drivers has been explored, with results indicating an increase in collisions as ambient temperatures reaches 32 degrees Celsius due mainly to psychological effects of heat (Andrey & Hambly, 2012). This issue will likely require further attention since an increase in annual temperatures is projected under climate change. The second projections is the changes in precipitation amounts and annual rainfall days. The projections of precipitation changes by mid-century is less clear than temperature. Most models indicated an increase in precipitation amounts, while two to three models projected a decrease in precipitation amounts in both regions. However, all models of Toronto and most models of Vancouver clearly indicated an increase in annual rainfall days for both regions. Because of the strong progression of risk as rainfall intensifies, it was important to consider the risk associated with different accumulations of rainfall. The models projected an increase in very light (0.4 to 4.9 mm) and light rainfall days (5 to 9.9 mm) in both regions. Therefore, an increase in rainfall and rain days is the highly plausible outcome. Given the high risk of collisions during rainfall and the natural vulnerability of the pedestrian to casualty collisions, it is imperative to implement safety initiatives by to reduce future negative implications of climate change.

One of the main differences between this study and Hambly (2011) is the projected heavy rainfall days (≥20 mm) in Vancouver. In his study, Hambly (2011) demonstrated a remarkable 75 percent increase in heavy rainfall days in Vancouver by mid-century. While, the weather generator in this study reproduced the baseline rainfall data with reasonable accuracy for Vancouver, a 24 percent increase in heavy rainfall days was projected. The possible reason for this differences is the type of GCMs and output method used in each study. There are three reasons for the greater increase in heavy rainfall days in Vancouver by Hambly (2011). First, Hambly used three GCMs coupled with regional climate models (RCMs). Second, the reproduced simulation of baseline data by RCMs overestimated total annual precipitation in Vancouver by 96.6 to 169.4 percent. Third, Hambly's models also overestimated the percentage of total rainfall associated with extreme events (90^{th} percentile rain day amount) by approximately 4 to 10 percent. Lastly, different types of GCMs were used in both studies, the nine GCMs in this analysis were not used by Hambly (2011). The same applies for Toronto, but the differences in projected rainfall amounts between the two studies is not as remarkable. Overall, both studies agree on more rain days in both areas and a slightly elevated number of collisions as a result.

For present day relative risk, there are a couple of limitations that could be addressed in future studies. The first one is the assumption "*ceteris paribus*" that mobility patterns will remain the same for the next 35 years until mid-century climate change takes place. This is highly unlikely due the rapidly changing nature of our transportation systems. Globally, the urban population is expected to increase to 67 percent by 2050, and more than 90 percent of future population growth is expected to occur in cities (Lohrey & Creutzig, 2015). This means a total of 6 billion out of 9 billion total world population will be urban dwellers. Moreover, about 40 percent of all transport emissions occur at urban areas, and therefore governments of urban regions will need to plan efforts to reduce this contribution (Lohrey & Creutzig, 2015). Several studies have discussed the benefits of high density development on transport energy use. For example, the shift to modes such as public transport, cycling and walking to reduce externalities such as noise, air pollution, and congestion of highly populous areas. If this scenario happens, then this modal shift would likely create safer road environments in the future that would offset this risk.

Large-scale modal shifts may not be the outcome for Canadian cities such as Toronto, which are often characterized by urban expansion through low-density automobile-oriented sprawl (Taylor, 2010). In this case, the *ceteris paribus* assumption maybe be a less of a concern for Toronto due to its type of expansion. However, Vancouver has an urban intensification rate double that of Toronto (Taylor, 2010). Due to the presence of mountains and the ocean, Vancouver has a relatively high-density development within urban areas that may be advantageous for future transport reform.

The second limitation is the consideration of pedestrian exposure in the analysis. It is difficult to answer the question of how many pedestrians are walking outside on a normal day versus a rainy day. This is because spatially comprehensive data of total numbers, kilometres walked, road crossing and trips completed is publically unavailable. Due to the lack of this data, it is impossible to adjust for the likely reduction in pedestrian trips during inclement weather to reflect a more accurate measure of risk.

For future studies, analysis of the influence of weather and climate on pedestrian safety should consider stressors other than rainfall, such as snowfall, wind, extreme temperatures, or fog. Furthermore, there is an opportunity to understand the variation in risk by season. Also, most of the research relating to the influence of weather and climate on pedestrian safety has focused on developed countries. An expansion of such analyses to developing countries is important since pedestrians trends are more marginalized and road traffic laws are less enforced in places such as Sub-Saharan Africa (Sietchiping et al., 2012). Moreover, in developing countries, there are greater numbers of people using walking as a mode of transport, and a growth in the use of motor vehicle usage (Sietchiping et al.,2012;Stocker et al, 2015). These conditions will provide greater insights in the vulnerability of pedestrians in different regions and environmental settings. For a smaller scale, an extension of this research can investigate the influence of pedestrian types such as children and elderly on intersection collisions. This would provide insights into how intersection design contributes to collisions for specific pedestrian groups.

Regarding interventions to the pedestrian-vehicle collision problem. Studies always stress one of the following interventions: education; enforcement or; environmental change (Schuurman et al.,2009; Stoker et al., 2015; Transport Canada, 2011). Implementing strategies that combines these three types of interventions is most effective. Education is useful for children and young pedestrians as it help raise awareness of the joint responsibility of the pedestrian and vehicle drivers. Education programs could include training to improve driving and walking behaviours (Transport Canada, 2011). Enforcement is imperative to pedestrian safety since studies documented the low compliance rate in pedestrians, especially during severe weather (Li & Fernie, 2010). Enforcement requires road authorities to hold pedestrians and drivers accountable to unsafe behaviours such as jaywalking, crossing with no right of way, and speed of vehicles. Environmental change includes physical changes such as frequent sidewalks, wider crosswalks, and interventions for intersections such as countdown signals and red light cameras for speeding vehicles (Zegeer & Bushell, 2012). Environmental changes also includes social changes such as encouraging and promoting pedestrian and active transportation through well-lit or tree filled streets. These interventions are usually easiest to implement in communities since it is difficult to physically modify vehicles to reduce injuries or prevent certain types of pedestrians such as children from walking. A comprehensive approach including education, enforcement and environmental change is more effective.

In conclusion, this study attempted to understand the interaction between safety and the built environment. Although road safety has come a long way through educational campaigns, modifications to the built environment, and vehicular technologies, a challenge still remains when weather and climate change offsets the current safety measures, especially for a group of roads users who have been traditionally overlooked by the safety community. Safety analysis has focused solely on the effectiveness of the built environment without incorporating road users and climatological conditions. Planners within the safety community should consider the role of the built environment in traffic safety, and its effectiveness in reducing traffic conflicts particularly during inclement weather. With climate change, additional collisions will possibly occur if safety interventions and a shift towards sustainable modes of transport in urban regions do not materialize. Since the risk of pedestrian collisions is higher during rainfall, there is an opportunity for safety interventions to be revised and expanded to address the influence of weather and climate on safety. The benefit of this study is ability to generalize some of the methods such as the matched-pair approach, the hazards that occur during rainfall such as loss of tire-pavement friction, and the conclusion that heavy and moderate rainfall days can impose a higher risk of pedestrian-vehicle collisions all around the world.

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Appendix A: Definitions and Excluded Holidays from Analysis

Holiday	2003	2004	2005	2006	2007	2008	2009
New Year's	Dec 31 - Jan 1	Dec 31 - Jan 1	Dec 31 - Jan 3	Dec 31 - Jan 3	Dec 31 - Jan 3	Dec 31 - Jan 3	Dec 31 - Jan 3
Family Day (Ontario Only)	n/a	n/a	n/a	n/a	n/a	Feb 16	Feb 16
Easter Weekend	Apr 18- 21	Apr 9-12	Mar 25-28	Apr 14-17	Apr 6-9 May	Mar 21 - 24	Apr 10 -13
Victoria Day	May 16- 19	May 21-24	May 20-23	May 19-22	May 18- 21	May 16-19	May 15 – 18
Canada Day	Jun 28 - Jul 1	Jul 1-4	Jun 30 - Jul 3	Jun 30 - Jul 3	Jun 29 - Jul 2	June 27 – Jul 1	Jul 1
Civic Holiday (British Columbia)	Aug 1-4	Jul 30 - Aug 2	Jul 29 - Aug 1	Aug 4-7	Aug 3-6	Aug 1- 4	Jul 31-Aug 3
Labour Day	Aug 29 - Sep 1	Sep 3-6	Sep 2-5	Sep 1-4	Aug 31 - Sep 3	Aug 29-Sep 1	Sep 4 - 7
Thanksgiving	Oct 10- 13	Oct 8-11	Oct 7-10	Oct 6-9	Oct 5-8	Oct 10-13	Oct 9 – 12
Christmas Holidays	Dec 24- 28	Dec 24-28	Dec 24-28	Dec 24-28	Dec 24-28	Dec 24-28	Dec 24-28

Injury Type	Definition
Minimal injury	Minor abrasions, bruises and pain. Does not require a visit to the hospital.
Minor Injury	An injury requiring treatment at an emergency room but no hospitalization was necessary for the person involved in a collisions
Major Injury	An injury that was severe enough to result in hospitalization
Fatal Injury	Person was killed immediately following a collision or within 30 days.
Source: Transport Canada, 2011	

Appendix B: Fourth IPCC Report Global Climate Models Used in the Analysis

Center	Center Acronym	Model
Centre National de Recherches Meteorologiques France	CNRMCM	CM3
Max-Planck-Institut for Meteorology Germany	ECHAM5	*ECHAM5-OM
Geophysical Fluid Dynamics Laboratory USA	GFDL	CM2.0
		CM2.1
Institute for Numerical Mathematics Russia	INMCM	CM3.0
Institut Pierre Simon Laplace France	IPSLCM4	CM4
National Centre for Atmospheric Research USA	NCARPCM	*PCM
		*CCSM3
UK Met. Office UK	HadCM3 HadGEMI	*HadCM3
		*HadGEM1
Data sources: IPCC (2014) and CCDS(2015b)		

Appendix C: GCM validation tables

The following table illustrates the differences in mean temperature and precipitation between observed historical data (Obs) and simulated data (20C) by GCMS in absolute value.

Differences between observed and simulated baseline by all GCMs – Toronto

Model	Mean Temp °C Difference from Obs	Model	Precipitation (mm/day) Difference from Obs
ECHAM5OM	0.300	NCARCCSM3	0.031
INMCM3	1.017	NCARPCM	0.416
NCARCCSM3	1.046	INMCM3	0.459
HADCM3	1.206	CNRMCM3	0.513
HADGEM1	1.613	HADGEM1	0.701
CNRMCM3	1.899	GFDLCM2.1	0.782
IPSLCM4	2.326	HADCM3	0.921
GFDLCM2.1	2.777	IPSLCM4	0.969
NCARPCM	2.999	ECHAM5OM	1.214

Differences between observed and simulated baseline by all GCMS – Vancouver

Model	Mean Temp °C Difference from Obs	Model	Precipitation (mm/day) Difference from Obs
INMCM3	1.297	INMCM3	0.231
CNRMCM3	2.002	CNRMCM3	0.551
IPSLCM4	3.170	NCARPCM	0.677
HADGEM1	4.541	IPSLCM4	1.220
NCARPCM	5.205	GFDLCM2.1	1.244
GFDLCM2.1	5.514	NCARPCM3	1.459
NCARPCM3	5.596	HADCM3	2.043
ECHAM5OM	6.276	ECHAM5OM	3.001
HADCM3	8.454	HADGEM1	3.182

Appendix D: Monthly Comparison of Study Period with Climate Normals

Toronto

Baseline 1971-2000		
Month	**Average daily precipitation (mm)**	**Average daily temperature (°C)**
Jan	1.68	-6
Feb	1.50	-5
Mar	1.84	0
Apr	2.26	6
May	2.34	13
Jun	2.47	18
Jul	2.40	21
Aug	2.57	20
Sep	2.60	15
Oct	2.06	9
Nov	2.28	3
Dec	1.96	-3
Study Period 2003-2009		
Month	**Average daily precipitation (mm)**	**Average daily temperature (°C)**
Jan	1.71	-5.44
Feb	2.14	-5.09
Mar	1.65	0.10
Apr	2.54	7.44
May	2.54	13.00
Jun	2.04	19.45
Jul	2.94	21.72
Aug	2.52	21.13
Sep	2.14	17.46
Oct	1.86	10.24
Nov	2.76	4.55
Dec	2.52	-1.76

Vancouver

Historical Baseline 1971-2000		
Month	**Average daily precipitation (mm)**	**Average daily temperature (°C)**
Jan	4.94	3.3
Feb	4.36	4.8
Mar	3.69	6.6
Apr	2.80	9.2
May	2.19	12.5
Jun	1.83	15.2
Jul	4.94	17.5
Aug	1.28	17.6
Sep	1.79	14.6
Oct	1.26	10.1
Nov	6.03	6.0
Dec	5.75	3.5
Study Period 2003-2009		
Month	**Average daily precipitation (mm)**	**Average daily temperature (°C)**
Jan	5.96	4.1
Feb	2.30	4.9
Mar	3.94	6.9
Apr	2.53	9.3
May	1.72	13.2
Jun	1.30	16.2
Jul	0.89	18.8
Aug	1.03	18.3
Sep	2.25	15.0
Oct	4.61	10.5
Nov	6.81	6.3
Dec	5.04	3.6