Projected implications of climate change for rainfall-related crash risk

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.

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Abstract

It has been well established in previous research that driving during rainfall is associated with increased risk of traffic collision involvement. Of particular concern are heavy rain events, which result in elevated risks up to three times higher than those for light rainfalls. As the global climate changes in the coming century, altered precipitation patterns are likely. The primary objective of this thesis is to estimate the potential impacts of climate change on traffic safety in two large Canadian urban regions: the Greater Toronto Area and Greater Vancouver. A secondary objective is to provide a framework or methodology for exploring this question. In accomplishing the primary objective, daily collision and climate records are utilized to establish an empirical estimate of present-day rainfall-related crash risk. This estimate is combined with results of a climate modelling exercise to arrive at a possible traffic safety future for urban Canada over the next 40 years. For the second objective, several important decisions related to data acquisition, compatibility, and completeness are considered, and the tradeoffs are mapped out and discussed, in order to provide guidance for future studies. Results indicate that over the next 40 years, Toronto is likely to see a mean annual increase in rain days of all intensities, resulting in marginally more collisions and casualties each year. Substantially more rainfall days are projected for Vancouver by mid-century, resulting in a small increase in annual incident counts. In both study regions, the greatest adverse safety impact is likely to be associated with moderate to heavy rainfall days (≥ 10 mm); this estimate is consistent with the greater risk increases associated with these conditions today, and suggests that attention should be paid to future changes in the frequency and intensity of extreme rainfall events. Indeed, heavy rain days are likely to account for approximately half of all additional collision and casualty incidents.

Acknowledgements

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List of Abbreviations

AR4 – IPCC Fourth Assessment Report

CCCSN – Canadian Climate Change Scenarios Network

CMA – Census metropolitan area

CMIP-3 – 3rd generation Coupled Model Inter-comparison Project

ECS – Equilibrium climate sensitivity

GCM – Global climate model (or general circulation model)

GTA – Greater Toronto Area

IPCC – Intergovernmental Panel on Climate Change

IPCC-TGICA – IPCC Task Group on Data and Scenario Support for Impact and Climate Assessment

NARCCAP – North American Regional Climate Change Assessment Program

NCDB – National Collision Database

OECD – Organization for Economic Co-operation and Development

PDO – Property damage only

RCM – Regional climate model

RR – Relative risk

RWIS – Road weather information system

SRES – Special Report on Emissions Scenarios

TCR – Transient climate response

TRB – Transportation Research Board

WMO – World Meteorological Organization

Chapter 1

Introduction

This thesis explores weather-related traffic crashes, both in terms of current weather and projected future conditions under climate change. As such, it is a climate impact assessment as described in the international climate change literature (e.g., Parry et al., 2007). However, its primary focus is on road safety, which itself is a well-developed field of risk analysis.

The field of road safety, or traffic safety as it is sometimes referred to, is a multidisciplinary field of inquiry that at its core attempts to mitigate one of the most prevalent technological risks facing contemporary western society. The field is dominated by two main disciplines, engineering and psychology, although many other fields have made significant contributions, including medicine and public health, law, and geography and planning. Geography's contribution to the road safety community draws on the dual pillars of physical and human geography, and typically involves analysis of environmental risks as well as the spatial patterns of risk.

Environmental or situational risks, ranging from inclement weather to time of day, seasonality, and the overall driving environment (e.g., roadway, distractions, presence of other drivers), are a key issue in traffic safety, as it is within the context of these that travel, and therefore risk exposure, occurs. Environmental factors (including roadways) represent one of the three central foci of road safety, the others being human factors (i.e., driver behaviour) and vehicular factors (i.e., engineering and design).

One significant environmental risk is inclement weather. In Canada's major cities, adverse weather conditions (e.g., rain, snow, and fog) are observed as much as one-third of the time (Andrey et al., 2005). Accordingly, a high proportion of travel takes place during conditions that are less than ideal. As weather-related hazards affect both the driving task (e.g., reduced visibility and vehicle handling) and the driving environment (e.g., slippery roads), it is not surprising that a substantive increase in crashes tends to occur during inclement conditions. Indeed, a sizeable body of empirical research has found that collision and casualty rates (the latter refers to fatal and non-fatal injuries) typically increase by 50 to 100 percent during precipitation (Qiu and Nixon, 2008). Weather-related crashes are a major problem today, and there is good reason to believe that mitigative measures or changes in mobility notwithstanding, the problem will persist in the coming decades. However, the spatial and temporal patterns of weather-related risks may change as the global climate changes.

Anthropogenic (i.e., human-caused) climate change, one of the most pressing issues in the history of humankind, has the potential to alter global weather and climate patterns. A significant trend of warming temperatures has long been established, with major implications for future climate variability and weather extremes (Solomon et al., 2007). In addition to possibly damaging effects on transportation infrastructure, more frequent and intense storms have the potential to adversely affect roads and drivers, adding to the existing traffic safety threat associated with inclement weather.

Detailed multi-stakeholder assessments of climate change impacts have been ongoing for many years, with knowledge and practices particularly well established in areas such as tourism, agriculture, and water resources management. In addition, a growing body of work in recent decades has examined possible climate change impacts on transportation infrastructure and operations worldwide. In Canada, work has focused primarily on inland waterways, coastal areas vulnerable to sea level rise, northern regions, and heat-related infrastructure degradation (Warren et al., 2004; Mills et al., 2007; Millerd, 2011). Road safety in the context of climate change has received extremely limited attention both in Canada and abroad. The current thesis aims to contribute to the emerging field of climate impact assessment in transportation by addressing this knowledge gap.

The thesis has two objectives. The primary objective is to estimate the potential impacts of climate change on traffic safety in two large Canadian urban regions: the Greater Toronto Area and Greater Vancouver. The secondary objective is to provide a framework or methodology for exploring this question. The primary objective draws upon daily collision and climate records to establish an empirical estimate of present-day rainfall-related crash risk; this estimate is combined with results of a climate modelling exercise to arrive at a possible traffic safety future for urban Canada over the next 40 years. For the second objective, several important decisions related to data acquisition, compatibility, and completeness are considered, and the tradeoffs are mapped out and discussed, in order to provide guidance for future studies.

The key contribution of the thesis arises from its novel combination of traffic safety and climate impact assessment. While weather-related travel risks are well understood, there has thus far been little research relating climate change to weather and collision occurrence. Indeed, the author is aware of only one study (a dissertation by Andersson, presented as a series of articles) to have so far examined this relationship. Andersson's work (Andersson, 2010; Andersson and Chapman, 2011a; 2011b) focused on daily minimum air and road surface temperatures in order to investigate the possible effects of climate change on the incidence of slippery winter roads, and therefore crash rates, in the UK and Sweden. This thesis treads new ground by focusing on climate change and safety with respect to changing precipitation patterns; the focus is on precipitation that falls in entirely liquid form. The empirical approach taken in this thesis is a matched pair study design, which is used to control for possible confounding variables, thereby producing robust estimates of present-day rainfall-related crash risk at a daily scale. In addition, high-resolution regional climate models are employed to estimate possible changes in future climate at a fine spatial scale. Accordingly, the thesis establishes a framework for similar safety analyses and vulnerability assessments in other regions.

Following this introductory chapter, which outlined the problem statement and research scope, the thesis is organized into four chapters. Chapter two provides a literature review that establishes the research context by examining the current state of knowledge in three key areas: traffic safety, in general and in a Canadian context; weather-related travel risks; and climate change, variability, and extremes. Next, chapter three describes the empirical research, including the spatial and temporal study context, characteristics and credibility of data sources, and the analytical methodology followed in completing the thesis. Chapter three also addresses the secondary objective of the thesis, which is to develop a methodology for exploring the implications of climate change for road safety. The fourth chapter contains the empirical results of the study, including an analysis of present-day rainfall-related collision risk as well as the potential implications of future climate change on this relationship. Finally, chapter five concludes the thesis by providing a summary and discussion of the empirical and methodological research results; it also outlines practical implications and possible future research directions.

Chapter 2

Literature Review

2.1 Road safety

2.1.1 Introduction to the road safety problem

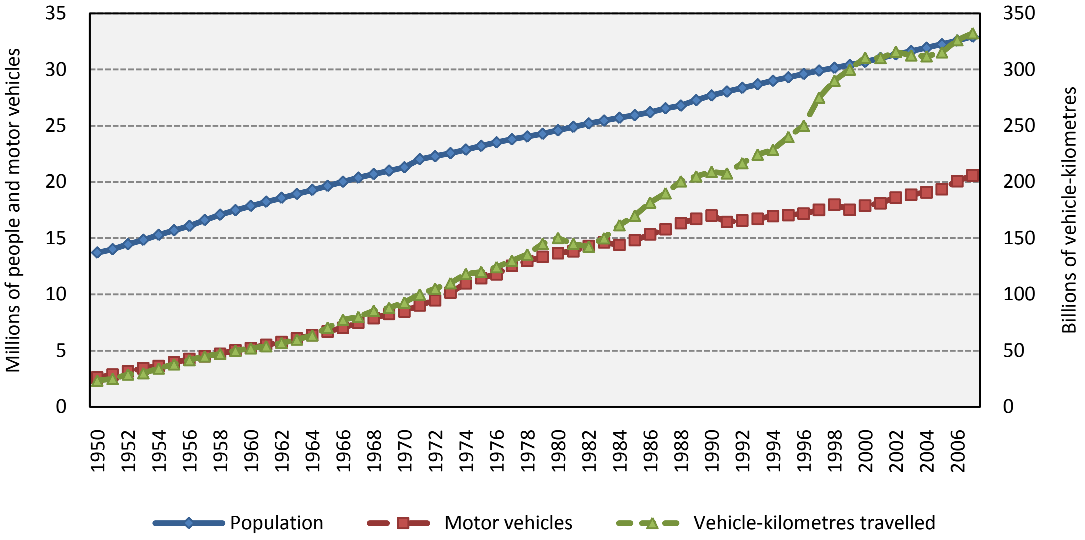
The past half century has seen exponential growth in motorized transport, driven in large part by increased population, affluence, and the emergence of a global economy. Greater mobility, however, has spurred an associated rise in exposure to travel risks including traffic collisions (Andrey, 2010). Despite many technological improvements and safety interventions since mass adoption of the automobile in the post-war years, crashes remain a significant issue. Indeed, more than 1.2 million people die and tens of millions are injured each year in road crashes worldwide, with an estimated economic cost of over $US 500 billion (Peden et al., 2004).

As auto use continues to increase, it is important to understand the related risks and their potential effects on human life and economic loss. Accordingly, this section examines the literature on road safety, beginning with a look at trends in population and mobility, economic losses, and human casualties, in Canada and globally. The wide range of possible collision risk factors is then outlined, followed by a review of several safety measures and their effectiveness in addressing crashes.

2.1.2 Canadian and international collision trends

For the past 60 years, automobile use has outpaced population growth in Canada. Between 1950 and 2007, Canada experienced a 140 percent growth in population, the number of passenger vehicles increased nearly sevenfold, and the annual distance travelled grew by 1300 percent (Figure 2-1). Although there are definite advantages associated with modern transport systems and high societal mobility, there are, arguably, unacceptably high negative externalities. These include pollution and environmental degradation, habitat destruction and wildlife loss, noise and light disturbance, traffic congestion, decreased energy security, carbon emissions, and, perhaps most important, road crashes.

Andrey (2000) argued the existence of an ‘automobility imperative’ – essentially, that cars are so entrenched in our contemporary lifestyle that demand for mobility trumps most other considerations (e.g., safety, environmental effects) in the provision and use of road transport systems. However, the problem of road safety is distinctly related to mobility: with zero mobility there would be no crashes, and with increasing (decreasing) mobility, more (fewer) collisions occur. Indeed, mobility is closely tied to safety as a driver’s risk exposure is determined by how much, where, and when driving occurs as well as how he or she drives (Summala, 1996). Thus, safety is influenced both by the quantity (i.e., how much driving occurs) and quality (i.e., in what circumstances driving occurs) of exposure to risks (Andrey, 2000). As mobility and risk exposure increase, there is a greater chance that safety will be compromised – in the form of collisions or near-misses – and lead to economic loss, injury, or death.



Data sources: Environment Canada (1995); Transport Canada (1998, 2007a)

Figure 2-1: Population and mobility trends, Canada, 1950-2007

Indeed, there are several types of loss associated with traffic collisions. Usually, comprehensive assessments attempt to translate all losses, ranging from vehicular damage to pain and suffering, into monetary costs. One way to organize crash-related economic losses is to look at who pays. In this case, costs might be classified as insurance claims (health and property insurance), public costs (e.g., health care, road maintenance/repair, policing), costs to individual drivers (e.g., towing, injury), and costs to the public at large (e.g., lost productivity of victims). Ted Miller (Miller, 1993; Miller and Blincoe, 1994), the leading expert on road collision costs in the US, outlined a wide range of monetary costs associated with injuries: medical care, emergency services, lost wages and productivity, workplace disruption, and legal and insurance administration services.

While property damage and resources (material and time) expended in association with crashes are relatively easy to quantify in monetary terms, it is more difficult to place a value on the human consequences of a crash, including death, injury, and related costs (Vodden et al., 1994). Two common approaches are used to quantify the human consequences of crashes (Andrey and Mills, 2003). The first, and most inclusive, measures society's willingness to pay to prevent or avoid crash losses from occurring. This comprises the comprehensive costs outlined above, and should represent the full cost that society incurs from crashes (Vodden et al., 1994). The second approach measures discounted future earnings, an estimate of "the value of death or injury based on the lost productive services of affected individuals" (Vodden et al., 1994, p. 5), and thus is less inclusive (Andrey and Mills, 2003). Some argue, therefore, that the comprehensive measure should be utilized in decision-making, as it better reflects society's preferences (Miller, 1993; Vodden et al., 1994).

No matter the costing approach used, it is clear that traffic crashes have a substantial economic impact on society. Using a comprehensive approach, Vodden et al. (1994) estimated the social cost of motor vehicle crashes in Ontario to be \$9.1 billion in 1990 (\$14.0 billion in 2011 dollars), or a significantly lower \$3.2 billion (\$4.9 billion in 2011 dollars) based on discounted future earnings. By 2004, the societal cost (i.e., human consequences, property damage, and time and material expended dealing with these crashes) in Ontario had increased by almost 50 percent to \$17.9 billion (\$20.6 billion in 2011 dollars), contributing to a national total of \$62.7 billion (\$72.1 billion in 2011 dollars) – approximately five percent of Canada's gross domestic product (Vodden et al., 2007; Statistics Canada, 2009). Several other works have estimated the international economic impact of crashes in highly motorized and developing countries (e.g., Miller, 1993; Elvik, 1995, 2000; Al-Masaeid et al., 1999; Blincoe et al., 2002; Trawen et al., 2002). Determining absolute global costs, however, is difficult, as less than half of 178 countries surveyed by the World Health Organization had conducted studies on the economic cost of deaths and injuries from crashes, and many of these were not national-level studies (Toroyan, 2009). Moreover, inconsistent methodologies and underreporting of costs also hinder attempts at international comparison. Nonetheless, a report by the World Health Organization estimated direct economic costs globally at more than half a trillion US dollars (Peden et al., 2004). Despite the magnitude of this economic burden, the health impacts of collisions are of even greater concern.

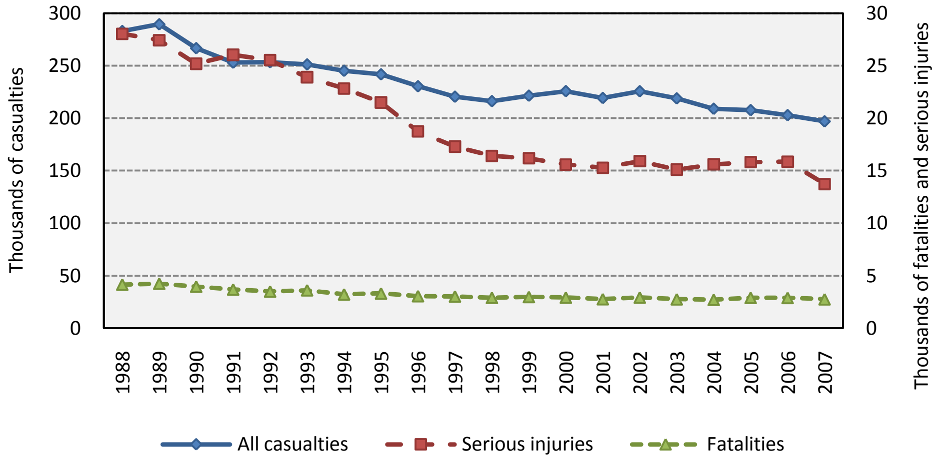
With an annual toll of over 1.2 million deaths and 50 million injuries, traffic crashes are a leading cause of mortality and disabling injury worldwide, particularly among young people (Peden et al., 2004). Globally, crashes were the ninth most common cause of death for all age groups in 2004, and are expected to become the fifth leading cause of mortality by 2030; for people aged 5 to 44 years, traffic injuries are consistently among the top three causes of death (Toroyan, 2009). Similarly, in the

United States, motor vehicle collisions are the number one cause of death for people aged 1 to 34 (CDC, 2010).

The safety problem is disproportionately severe in low-income countries, which have roughly one-third of the world population and less than one-tenth of registered vehicles, but account for 42 percent of traffic deaths. Conversely, high-income countries are home to one-sixth of the global population and over half of registered vehicles, but see less than 9 percent of crash-related mortality (Toroyan, 2009). As developing countries continue to mobilize, this discrepancy is likely to widen.

In Canada, approximately 613,000 crashes were reported in 2004, although it is impossible to know the actual number that occurred due to underreporting of less severe (i.e., minimal injury or property damage only) crashes (Vodden et al., 2007). As crash severity decreases, so does the likelihood that it will be captured in official statistics: in a meta-analysis of studies in 13 countries, Elvik and Mysen (1999) found that mean reporting levels ranged from 95 percent for fatalities to a mere 10 percent for very slight injuries. Further complicating matters is the fact that many countries classify accident and injury severities using different scales that often are not comparable (Evans, 1991; 2004; Elvik and Vaa, 2004). Accordingly, it has been argued that traffic deaths – and possibly severe injuries – are the only reliable measure for comparing road safety between countries (Elvik and Vaa, 2004).

In 2007, across Canada there were 2,767 fatalities and 13,723 serious injuries (i.e., persons admitted to hospital for treatment or observation) (Transport Canada, 2010). Both counts have fallen fairly steadily over the past 20 years – part of a long-term trend of safer Canadian travel (Figure 2-2).

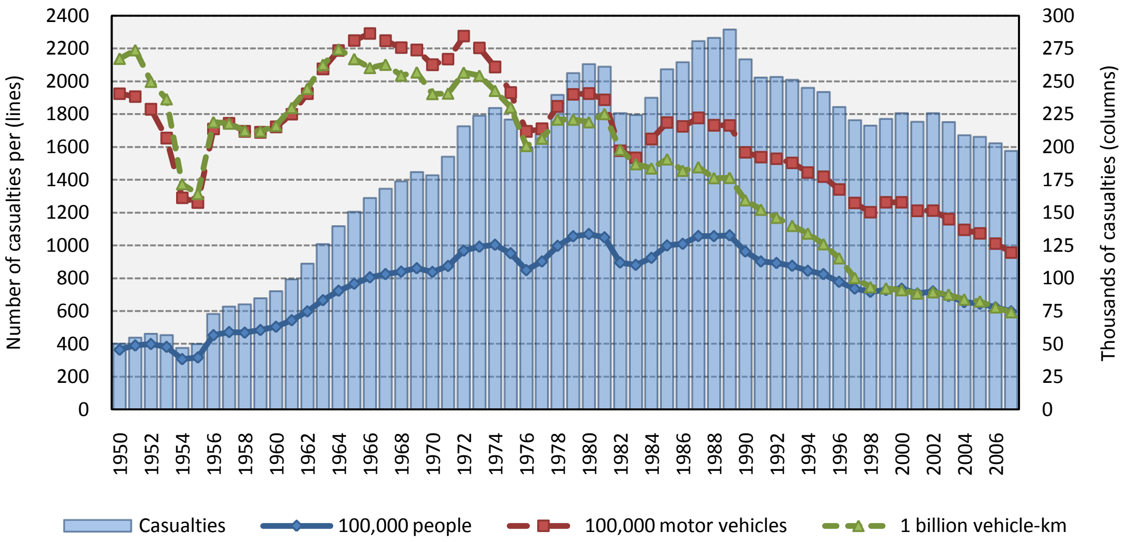


Data source: Transport Canada (2010)

Figure 2-2: Casualty severity trends, Canada, 1988-2007

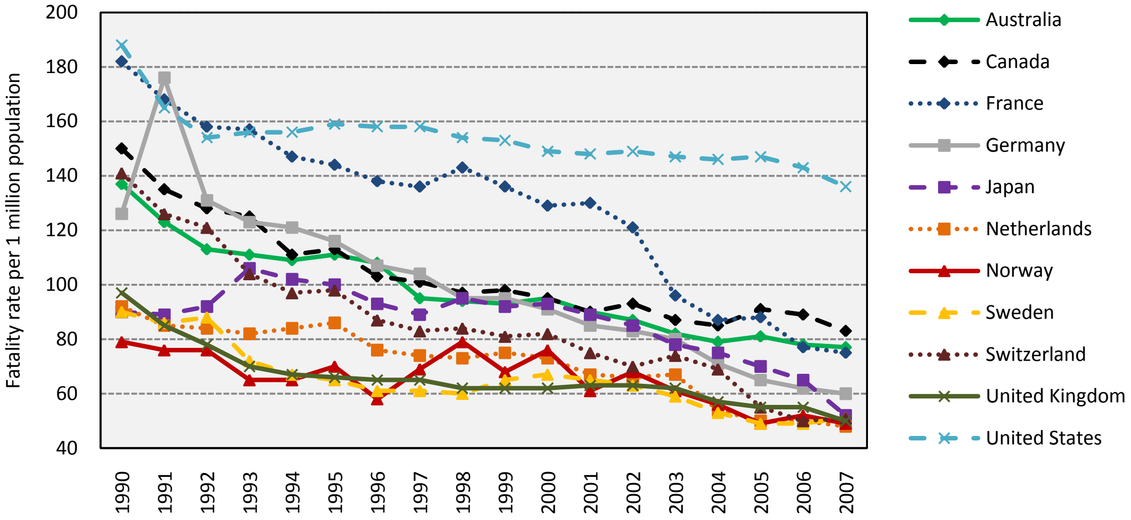
In order to facilitate comparisons over time or space, these counts are expressed as rates. There is some debate within the safety community regarding the most appropriate rate – i.e., whether it should be based on population (per capita) or mobility (e.g., distance travelled per person or vehicle, number of licensed drivers or registered vehicles). Internationally renowned safety expert Leonard Evans (2004) suggested that in general, no particular rate is superior to others, and that the most appropriate indicator depends on the question being asked and the available data. From a health perspective, it may make the most sense to use the per capita rate. However, Elvik and Vaa (2004) proposed that the amount of travel by individuals (i.e., person-kilometres travelled) is the most theoretically correct measure, as it reflects risk exposure.

From 1950 to 2007, the absolute number of Canadian traffic casualties (fatalities and non-fatal injuries) increased threefold, even while the casualty rate per unit of travel decreased substantially. The net effect of these two opposing forces is a per capita casualty involvement rate that is markedly higher now than it was in 1950 (Figure 2-3). Meanwhile, fatalities have fallen dramatically from their peak of over 6,700 in 1973 to less than 2,800 in 2007, indicating that although more crashes are occurring, our ability to mitigate their severity or lessen the damage has improved (e.g., advances in medicine, occupant protection, and vehicle crashworthiness). Similar downward fatality trends have been observed in most highly-motorized countries (Figure 2-4). Nonetheless, traffic crashes remain a significant issue that warrants continued attention.



Data sources: Environment Canada (1995); Transport Canada (1998, 2007a)

Figure 2-3: Long-term casualty trends, Canada, 1950-2007



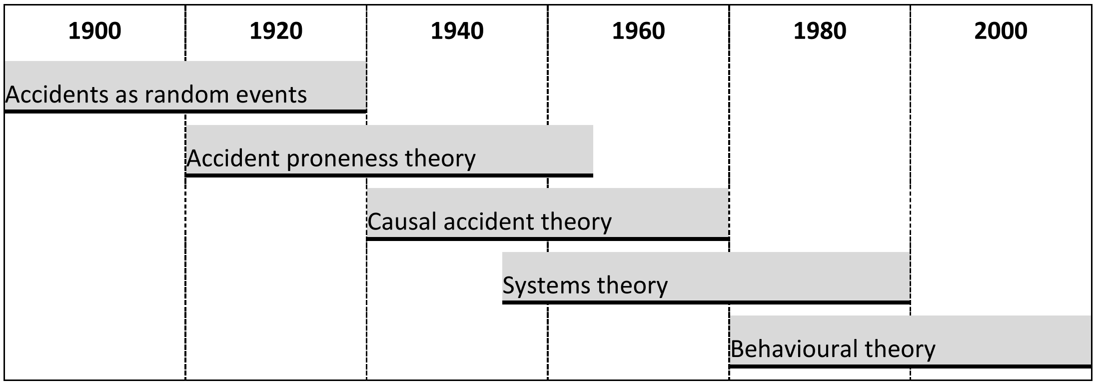
Data source: Organization for Economic Co-operation and Development (OECD,2009)

Figure 2-4: Comparison of fatality trends, selected OECD countries, 1990-2007

2.1.3 Collision risk factors

In moving toward improved road safety, it is important to recognize conditions or situations in which collisions and casualties are more likely to occur. However, for any given crash incident, several factors combine to produce an outcome that might be completely altered if even one factor were different in that moment or situation – essentially leading to a series of 'what if' questions (Evans, 1991; 2004). Thus, it is virtually impossible to isolate any one factor as causing a given collision; a huge body of work has nonetheless endeavoured to conceptualize the contributing factors and 'mechanisms' leading to crashes.

Elvik and Vaa (2004) outlined the evolution of accident causation theories in some detail; a brief summary is presented here and in Figure 2-5. Related studies began more than 100 years ago with the advent of the automobile, and were underpinned by the belief that accidents were completely random events. Later, accident proneness theory assumed that some people were more prone to crash involvement than others; studies began to look at collision variation within certain groups. Following this, a move toward causal accident theory meant that the circumstances surrounding and leading up to collisions became the focus of detailed study. It became clear, however, that road crashes were multi-causal. Nonetheless, human error was identified as a contributing factor in most collisions, and emphasis was placed – misplaced, according to Elvik and Vaa (2004) – on the prevention of accidents through driver behaviour modification. Soon, researchers realized that it was necessary to examine why driver error occurred. Systems theory arose from this need, proposing that inadequate system design led to human error. Thus, research under systems theory focused on highway and vehicle engineering as means of preventing crashes. This approach has been widely successful, as evinced by the downward trends in Western crash and casualty rates. More recently, traffic safety research has shifted once again toward human behaviour, particularly as it pertains to drivers' awareness, perception, and acceptance of travel risks (Elvik and Vaa, 2004).



Reproduced from Elvik and Vaa (2004)

Figure 2-5: Evolution of accident causation theories

While it is difficult to identify the specific 'cause' of most collisions, certain factors definitely increase the probability of one occurring; these are known as risk factors (Elvik and Vaa, 2004). Several frameworks have been suggested for classifying crash risks. Perhaps most widely accepted is the 'Haddon matrix' comprising nine cells in which contributing factors (and safety countermeasures to mitigate them) are categorized as road user, vehicle, or road environment (includes situational factors, e.g., time, weather) according to three time periods: pre-crash, crash, or post-crash (Andrey, 2000). This framework is derived from the medical field of epidemiology, in which a host (i.e., driver) suffers harm resulting from an agent (i.e., vehicle) in the environment (Andrey, 1989). Evans (1987; 1991), on the other hand, employed a broad categorization of risks based on road user (e.g., individual driver behaviour and legislative interventions) and non-road user (e.g., roadways, vehicles, and traffic control systems) factors. Table 2-1 illustrates a detailed collision risk classification scheme comprised of various subcategories within the above frameworks.

Table 2-1: Detailed collision risk classification scheme

Driver	*Vehicle*	*Environment*
Driver characteristics • Age • Sex • Driver experience/skill level • Health and physiology Driver action/behaviour • Unsafe manoeuvres (following too closely, driving too fast or too slow, improper turning or lane changes) • Disobeying traffic controls or road rules • Loss of control • Distracted or inattentive • Risk estimation/awareness Driver condition • Fatigue • Drug or alcohol impairment • Sudden illness or loss of consciousness • Driver confidence Recent activity/travel history • Trip length • Time since last food or sleep • Trip origin purpose • Familiarity with area	Vehicle characteristics • Vehicle size/mass • Repair condition • Safety of load or trailer • Obstructed visibility (dirty windshield) • Colour (affects driver perception) Vehicle engineering and design • Occupant protection devices (seatbelts, airbags) • Visibility (blind spots) • Impact absorption panels	Road engineering and design • Traffic controls • Curvature and gradient • Drainage • Road surface material • Repair condition Environmental factors • Visibility/obstructed view (fog, blowing snow, glare) • Weather condition/physical hazards (e.g., rain, snow, ice, wind) • Light condition Temporal factors • Season • Time of day • Day of week Situational factors • Road location and traffic volume • Traffic rules and legislation • Animal or obstruction in roadway • Road surface friction/winter maintenance condition • Roadside warning or advertising signs (distraction) • Red-light cameras or roadside checkpoints People as situational factors • Social norms • Presence of other inexperienced, impaired, or erratic drivers

In accordance with systems theory, significant past research has focused on the engineering component of collisions. However, Evans (1987) suggested that road user or human factors have greater influence on crash risk than non-road user or engineering factors and that greater safety improvements will therefore be achieved by focusing on the human element. Accordingly, many recent studies (e.g., research on weather and crash risk) have examined driver behaviour and situational interactions with the driving environment. A growing focus on human factors is also reflected in recent years' proceedings of the Canadian Multidisciplinary Road Safety Conference – the country's leading forum for traffic safety issues and research in the professional and academic communities.

Table 2-2: Selected examples of collision risk research

Risk factor	*Author (year)*	*Country*	*Indicator*	*Findings*
Alcohol	Evans (2004)	US	Driver fatalities	Drivers with 0.08% blood alcohol content (legal limit) have 73% higher risk of death (RR=1.73) than drivers with zero blood alcohol
Alcohol and drinking age	Hingson et al. (2002)	US	Collision involvement	Higher risk of alcohol-related crash in one's lifetime with earlier age of drinking onset (RR=3.5 for age 14) relative to legal drinking age of 21
Cell phone use	Redelmeier and Tibshirani (1997)	Canada	Collision involvement	Higher crash risk (RR=4.3) when using a cell phone up to 10 minutes before a crash compared to non phone use; McEvoy et al. (2005) reported similar result (RR=4.1) for Australia
Speeding	Kloeden et al. (2002)	Australia	Casualty collision involvement	For every 5 km/h travel speed increase over a 60 km/h posted speed limit, risk of casualty collision approximately doubles
Drowsiness and fatigue	Lyznicki et al. (1998)	US	Collision involvement	High risk of sleep-related crashes observed among young drivers (aged 16-29), shift workers, impaired drivers, drivers with sleep disorders, and commercial drivers
Young drivers and situational risks	Doherty et al. (1998)	Canada	Collision involvement	Higher crash rates for drivers aged 16-19 compared to 20-24 and 25-29 year olds; especially high on weekends, at night, and with passengers
Age and gender	Massie et al. (1995)	US	Collision involvement	Young drivers (aged 16-19) and women have highest crash involvement rates; drivers aged 75+ and men have highest fatal crash rates
Seatbelt use	Evans (2004)	US	Driver fatalities	Increased (70%) fatality risk for unbelted drivers relative to belted drivers
Road type or design	Evans (2004)	US	Fatalities	Higher fatality rates on rural roads compared to urban, and on local or non-freeway roads compared to freeways

Myriad studies have investigated the effects of different risk factors on collision involvement and injury severity. Of the countless factors that have been examined, Elvik and Vaa (2004) argued that traffic volume is undoubtedly the most important in influencing the number of crashes that occur: with increased traffic comes higher exposure to travel risks and thus a greater overall number of crashes (albeit fewer accidents per unit of travel or exposure). After perusing the literature and recent conference proceedings (as well as from experience as a casual observer), it seems that the most prominent contemporary traffic safety issues – at least from a public awareness, legislation, and enforcement perspective – are related to driver behaviour: impaired driving, cell phone use and other distractions, speeding/street racing, drowsiness/fatigue, driver age/experience, and seatbelt use. Recently, substantial research attention has been devoted in particular to the effects of distracted driving, alcohol, and driver age or experience on crash involvement and injury risk. Other studies, meanwhile, have looked at environmental or situational factors such as road design, light conditions or time of day, and inclement weather. Table 2-2 presents a brief overview of several notable crash risk studies; a review of research on weather and safety follows in Section 2.2 of this chapter.

The large and diverse body of research over the past century has made it clear that traffic crashes are a pervasive problem with a bevy of underlying causes. Improved understanding of risk factors is thus important in planning and decision-making so that safety interventions can be prioritized and limited government resources targeted to achieve the greatest possible safety benefit.

2.1.4 Safety initiatives

A road safety measure, as defined by Elvik and Vaa (2004, p. 3), is “any technical device or programme that has improving road safety as the only objective or at least one of its stated objectives”, and “may be directed at any element of the road system: patterns of land use, the road itself, road furniture, traffic control devices, motor vehicles, police enforcement, and road users and their behaviour”. Absent from this definition, however, is mention of situational or environmental hazards; safety initiatives cannot be directly aimed at these hazards, as they are beyond the realm of human control. Interventions in this area are instead intended to minimize adverse effects on the driver, vehicle, or road.

The road safety research community is largely organized around conducting analyses on disaggregated crash trends (i.e., in certain situations or among certain groups) that will lead to safety improvements based on known problems (Summala, 1996). The majority of interventions are therefore reactive in nature and are intended to mitigate or reduce existing safety issues. Moreover, safety measures generally tend to be designed within the context of contemporary society and the current driving environment, and thus are not intended to challenge the mobility paradigm or change society and social norms. Occasionally, however, a safety program does have this unintended effect. For example, impaired driving legislation, though only intended to stop drunk driving, also contributed to changed societal norms regarding drinking.

In recent years an emerging trend toward a proactive safety approach has become evident. Here, the goal is to anticipate and prevent, rather than mitigate, potential road safety problems before they occur by incorporating safety concerns into the initial mobility planning and road design stage. A leader in this regard is Sweden, whose ‘Vision Zero’ initiative declares that loss of life in traffic is unacceptable (Elvik and Vaa, 2004; Swedish Trade Council, 2010). Canada maintains a similar, although less aggressive, long-term road safety vision: to make Canada’s roads the safest in the world (CCMTA, 2011).

Regardless of whether a reactive or proactive safety approach is taken, the intended outcomes are reduced frequencies and severities of crashes, casualties, and societal costs overall and in specific problem areas. This section presents a review of various safety measures followed by a discussion of their effectiveness.

2.1.4.1 Intervention and the three E’s

In working toward safer roads, the Haddon matrix can again be employed to organize safety measures according to their focus on the road user, vehicle, or road environment as well as on the prevention of crashes or reduction of harm during or following a crash. To address travel-related risks in a comprehensive way, a diverse suite of initiatives, drawing from all cells of the matrix, is necessary.

Safety interventions typically focus on engineering, enforcement, education – known colloquially as the three E’s – or medicine (Andrey and Mills, 2003). However, with the recent emergence of proactive traffic safety planning, a policy-oriented dimension involving land use planning and mobility management has been added to the traditional framework, along with a distinction between pre-mobility and mobility measures. Figure 2-6 presents a conceptual diagram outlining the stages of intervention, which will be briefly examined below. For more detailed discussion, readers should refer to Elvik and Vaa (2004), who provided an extensive list of 124 types of traffic safety measures based on an exhaustive literature review, or the Institute of Traffic Engineers (ITE, 1993).

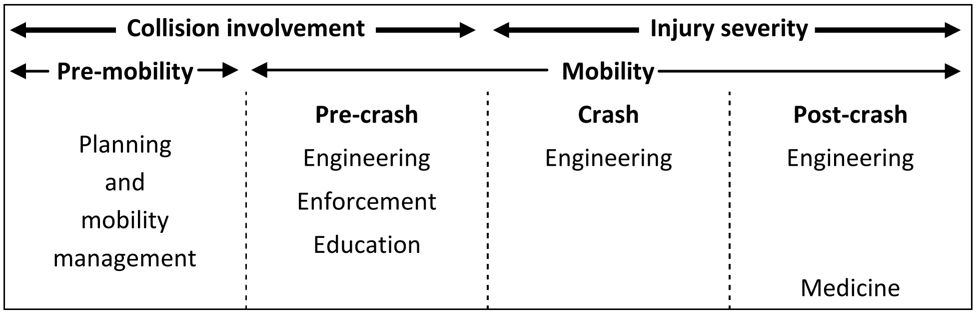


Figure 2-6: Stages of traffic safety intervention

Engineering safety measures tend to address existing hazards or black spots related to technical or situational factors. Consistent with systems theory, the objectives of engineering interventions are twofold: first, to prevent crashes from occurring by overcoming human deficiencies, and failing that, to reduce collision severity and prevent or lessen the severity of human injury (Elvik and Vaa, 2004). Engineers focus on issues related to road and vehicle design. These measures generally are a product of "design process evolution, combined with engineering knowledge and experience", and their introduction is "a gradual process that is rarely accompanied by legislative or regulatory changes" (Zein and Montufar, 2003, p. 1). Several examples of road and vehicle engineering interventions are shown in Appendix A(a).

In accordance with the behavioural theory of accident causation, traffic safety enforcement aims to prevent crashes by modifying driver behaviour. Thus, enforcement measures directly address established behavioural risks while indirectly targeting and attempting to minimize the effects of situational or environmental hazards on drivers and their actions. Enforcement typically involves an on-road police presence operating within a legislative or regulatory framework that stipulates fines or other penalties, and in some cases results in criminal charges, for road users who commit traffic offences. Alternatively, rewards can be given as a motivational tool for positive re-enforcement of good driving practices (e.g., reduced insurance rates). Traffic enforcement initiatives generally arise in response to an existing safety issue that society deems unacceptable (e.g., drunk driving, speeding, seatbelt non-compliance). Examples of enforcement measures are given in Appendix A(b).

Similarly, educational measures are also directed toward road users and are intended to prevent crashes through behavioural modification. Education can be used on its own or in conjunction with enforcement to address known situational and behavioural risks. Educational initiatives sometimes rely on non-profit advocacy groups (e.g., Mothers Against Drunk Driving) working together with police, insurance, and other stakeholders to deliver a message via the media that is intended to make road users more aware of environmental hazards (e.g., wildlife-vehicle collisions, icy roads) or socially intolerable unsafe behaviour (e.g., impaired driving, street racing). These campaigns often use statistics alongside gory details and pictures to focus on and illustrate the outcome of poor driving choices. Appendix A(c) gives several examples of educational measures that have been employed.

Medicine (and emergency response), the fourth 'traditional' group of safety interventions, operates exclusively in the post-crash stage. Thus, while the various other safety measures attempt to prevent collisions, medicine is the 'last resort' to mitigate their impact and minimize injury severity. Thus, improvements in medicine (e.g., faster response time, better hospital care) are intended to repair bodily harm and lessen any long-term disabling effects for persons involved in collisions. Some examples of advancements in medicine and emergency response are shown in Appendix A(d).

Finally, planning and mobility management represent the newest dimension of traffic safety. Operating at the pre-mobility stage, these measures attempt to limit risk exposure by influencing when, where, and in what form (i.e., by what mode) mobility occurs. Thus, this group of interventions is a response to the 'automobility imperative' described by Andrey (2000). The primary objective of planning and mobility management is to bridge the gap between safety and sustainability (social, economic, and environmental) by addressing the conflicting societal goals of mobility and safety. A key component of meeting this goal lies in land use planning and neighbourhood design, as well as the provision of transport infrastructure. In addition, high-level policy programs and legislation can be employed to direct and inform an overall road safety strategy comprised of a diverse suite of interventions. Appendix A(e) presents some examples of safety programs related to planning and mobility management.

2.1.4.2 Effectiveness

It is generally easy to recognize a traffic safety problem and employ some form of intervention to counter it; however, detailed study is required to determine the actual effectiveness of the selected measure and its long-term effect on collisions and casualties (for a detailed review of methods to be used in evaluating intervention effectiveness, refer to Hauer, 1997). Section 2.1.2 showed a downward trend in crashes and fatalities in Canada and most highly motorized countries; but what is responsible for these improvements in recent decades? This section will consider this question with a brief look at the effectiveness of various measures and traffic safety programs that have been employed in Canada and abroad. Once again, Elvik and Vaa (2004) provide a more in-depth discussion.

A wide range of engineering improvements have been made to Canadian roads in recent decades (for a review, see Zein and Montufar, 2003), saving thousands of lives and hundreds of thousands of injuries, but there is little doubt that the greatest safety gains have resulted from better vehicle design and behavioural change. Modern vehicle safety features such as advanced air bags, anti-lock braking systems, electronic stability control, adaptive cruise control, and improvements to vehicle crashworthiness have reduced crash frequencies and injury severities (CARSP, 2010).

Meanwhile, seatbelts – a technological intervention accompanied by legislation requiring inclusion in vehicles and use by motorists – have been found to be the single most effective means of saving lives and reducing injury severities (Dinh-Zarr et al., 2001). It has also been well established that alcohol is involved in roughly half of fatal collisions (Evans, 1990). Therefore, it is likely that the downward trend in fatalities is primarily a reflection of evolved social norms regarding seatbelt use and impaired driving (Evans, 1987). These social changes, along with others related to graduated licensing, speeding, and distracted driving, have been encouraged through a combination of legislative intervention, driver education, and police enforcement (Williams, 2006). Finally, advances in medicine and emergency response have lessened long-term health effects for persons involved in crashes (Nathens et al., 2000); emergency medicine in particular is linked to the significant downward trend in fatalities. For greatest effect, it is important that individual initiatives be employed as part of a broader safety program. In addition, countries serious about improving road safety have typically adopted some form of overall safety vision and/or quantitative targets (see Gutoskie, 2001, for a summary of safety goals and programs in OECD member countries). Perl and Berry (2007) suggested that these targets fall into two categories: concrete goals involving a specific numerical target or milestone (e.g., Netherlands: no more than 750 annual deaths by 2010), and relative goals in relation to a particular reference point (e.g., United Kingdom: 40% reduction in fatalities and serious injuries by 2010). The former is considered more ambitious and attainable, often with great public support and recognition, while the latter reflects government concern regarding the legitimacy of safety action and the administrative capacity to address the problem, and reduces policy makers' exposure to criticism for failing to meet their targets (Perl and Berry, 2007).

Since 1996, Canada's vision has been to have "the safest roads in the world" (CCMTA, 2011). Broad objectives of this strategy, which has recently been updated to 2015, are increased public awareness, improved communication and collaboration between safety stakeholders, enhanced enforcement, and improved safety information to support research and evaluation. The country's previous safety vision included the same broad objectives as well as a number of quantitative targets, particularly a 30 percent reduction in fatalities and serious injuries by 2010; additional sub-targets were related to contemporary problem areas: seatbelt and child restraint use, impaired driving, speed and intersection-related crashes, young and high-risk drivers, vulnerable road users, commercial vehicles, and rural roads (Gutoskie, 2001). However, an independent review reported that progress (as of 2005) was lagging for all established quantitative targets and concluded that they were unlikely to be met by 2010 (Johnson and Howard, 2007). In fact, Canada's relative safety performance decreased between 2000 and 2005 as several countries made greater gains, leaving Canada 11th among the 30 OECD countries for fatalities based on distance travelled (Johnson and Howard, 2007). Moreover, Canada ranked 18th among OECD counties for per capita fatality rate in 2007, with the 16th best improvement since 1990 (OECD, 2009). Accordingly, Canada's new 2015 strategy eschews hard reduction targets in favour of seeking a downward trend in fatalities and serious injuries using rate-based measurements (CCMTA, 2011).

On the other hand, France exemplifies a highly successful national road safety program, having seen a 43 percent reduction in fatalities between 2000 and 2007 (and the 3rd best per capita improvement among OECD countries since 1990), part of a long-term downward trend that began in 1972 with the appointment of a national road safety delegate (Kwasniak and Kuzel, 2009; OECD, 2009). Key to early improvements were the introduction of speed limits, seatbelt laws, and impaired driving legislation. In 2002, when road safety was recognized by the French president as the top priority of his mandate, earlier programs were revisited and significant media attention devoted to safety issues. Enforcement of speeding and other traffic offences increased substantially, with tougher penalties and the introduction of speed cameras. Aggressive new penalties for drunk driving and non-compliance with seatbelt laws were imposed along with license point deductions for cell phone use while driving. Finally, the government set a firm target of no more than 3,000 traffic fatalities by 2012[1]. Thus, the French approach involved a strong focus on behavioural change to minimize driver errors through a combination of regulation, sanctions, and driver awareness. This approach is consistent with the work of Leonard Evans (1987, p. 213), who argued that "the largest safety benefits can be achieved by assisting the evolution of social norms that are conducive to safety, and discouraging those that decrease safety". Indeed, France's aggressive program spurred

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[1] France's hard target of 3,000 fatalities per year represents a per capita rate of 46 deaths per million inhabitants (based on 2011 population data: INSEE, 2011). In 2007, France had 75 traffic fatalities per million population, compared to 83 in Canada; Iceland and the Netherlands led all OECD countries with 48 deaths per million people (OECD, 2009).

substantial short-term fatality reductions between 1972-1974 and 2001-2005 that were maintained over the long-term.

Finally, Sweden, fifth among OECD members for per capita fatalities, is among the world leaders in traffic safety (OECD, 2009). Behind its 'Vision Zero' program, enacted into law in 1997, is an ambitious view that safety cannot be compromised in favour of mobility as well as a simple philosophy: that "it can never be ethically acceptable [or defensible] that people are killed or seriously injured when moving within the road transport system" (Tingvall and Haworth, 1999, p. 1). Sweden's vision essentially aims to remove human error from the safety equation by proactively improving vehicle (e.g., intelligent speed limiters, vehicle interlocks to ensure seatbelt use) and road system design (e.g., road design speeds based on infrastructure type and possible traffic user conflicts) so that deaths and major injuries can be completely eliminated. Due to the program's long-term and idealistic nature it is too early to determine whether it has been successful, but Sweden has seen a downward fatality trend in recent years despite increasing traffic volumes (Elvik et al., 2009; OECD, 2009; Swedish Trade Council, 2010).

Moving forward from the mostly reactive programs to date, it is anticipated that future road safety advances lie in proactive planning and mobility management. In part, this involves land use and the design of cities and transport infrastructure. Summarizing the link between the built environment and traffic safety, Ewing and Dumbaugh (2009) proposed that development patterns affect traffic volumes (and to a lesser degree speeds), which in turn are a major determinant of collision frequency. Roadway design, on the other hand, has a substantial impact on traffic speed (and to some extent volume) and thus is a key factor in determining collision severity. Accordingly, compact and sustainable communities with a variety of land uses and transportation alternatives could modify transport demand and mobility patterns to reduce exposure to auto-related risks while simultaneously improving the viability and presence of other travel modes.

Finally, a proactive approach to road safety might also involve modelling and automated safety analysis (e.g., video sensors) so that potential safety conflicts can be identified and corrected in the design stage or as they appear, rather than waiting for a long-term trend to develop before taking action; such methods are an important component of programs such as Vision Zero (Sayed et al., 2010).

Moving forward, a blend of different intervention strategies will be needed based on a detailed understanding of how various risk factors contribute to unsafe outcomes. The next section presents a review of research on the interaction between weather and traffic safety.

2.2 Weather and safety

With the incredible range of environments in which transport systems have been established worldwide, it is hardly surprising that transportation is affected by weather and climate. Indeed, local weather conditions can have dramatic impacts on transport infrastructure and operations, while longer term climatic processes primarily affect infrastructure. Accordingly, adverse weather conditions present numerous challenges for mobility and safety, particularly with respect to roads. This section discusses the issue of weather and traffic safety, beginning with an overview of weather processes that affect drivers and the road environment, which is followed by a review of the empirical literature on rainfall and crash risk.

There are two main ways in which weather influences road safety: weather affects traffic volume, or road user exposure to weather-related driving hazards, and weather is associated with increased crash risk per unit of exposure (Codling, 1974; Musk, 1991; Andrey et al., 2005). Moreover, weather-related driving risks are typically characterized in one of two ways; in any study of weather and safety, this is a key consideration in framing the research approach. From an applied climatology perspective, it is perhaps best to look at individual weather hazards or atmospheric events (direct weather effects – e.g., rain, snow, frozen precipitation, or fog) before considering their different effects on road users and the driving environment. Conversely, the traffic safety community typically looks first at road hazards (indirect weather effects – e.g., impaired visibility, slipperiness) affecting drivers, vehicles, and the road environment – that is, the impacts of the aforementioned weather hazards. The weather hazards approach is applied in this thesis, primarily for compatibility and incorporation with existing historical climate records and future climate projections. In addition, this approach better allows rainfall-related hazards to be quantified in terms of severity and frequency, which Musk (1991) suggested is an important requirement in traffic safety planning and design.

2.2.1 Typology of weather hazards

Fog, blowing snow, and intense rainfall events produce significant visibility problems. Wet or icy roads reduce tire traction and make vehicle handling more difficult. Winter storms can have a crippling effect on mobility and traffic flow, snarling vital highways with gridlock. Strong winds, particularly on bridges, can adversely affect vehicle control and handling, and also increase the risk of trucks overturning. Periods of extreme heat can result in increased heat stress or driver aggression and instances of road rage. Weather thus represents a frequent and costly threat to transport systems, and weather-related travel risks vary by type of hazard. Risk increases (relative to clear conditions) have been found to be highest during winter conditions, as reduced friction and visibility effects are exacerbated by icy roads and blowing snow (Qiu and Nixon, 2008; Andrey et al., 2010).

There are several scales or metrics with which the importance of weather to traffic safety can be examined; these vary in time and space (Table 2-3). Individual crashes or collision-prone locations may be examined in detail to gain a specific understanding of the possible contributions of weather; however, findings at this scale are not easily generalized (Andrey and Olley, 1990). The opposite problem exists at a regional scale, where aggregated effects of extreme weather events or long-term precipitation patterns may be examined to answer questions such as how often inclement weather is present and the percentage of collisions that occur during adverse weather (Andrey and Olley, 1990).

Table 2-3: Spatial-temporal scales for examining weather-safety relationships

	Hourly or daily comparisons	*Monthly or seasonal comparisons*
Individual site	Detailed investigations of individual accidents	Analysis of accident-prone locations
City or highway	Estimates of relative accident risk during inclement weather made	
Region	Extreme storms examined	General summary of accident characteristics
Reproduced from Andrey and Olley (1990)		

The intermediate spatial scale (i.e., city or highway segment) is well suited to addressing the extent to which crashes increase during poor conditions relative to clear conditions – i.e., the number or proportion of collisions during adverse weather conditions that occur because of the presence of weather. Indeed, at this scale, an estimate of relative collision risk can be made that incorporates some measure of exposure to weather hazards (Andrey and Olley, 1990). Three general approaches have been employed to answer this question (Andrey and Olley, 1990). Temporally and spatially aggregated comparative studies allow investigators to examine the proportion of collisions during adverse conditions in comparison with the proportion of time during which the condition was present; this is the most general calculation. Alternatively, multivariate statistical techniques (e.g., regression analysis), can been used to investigate how different weather variables affect crash rates. Finally, crash frequency on wet versus dry days may be compared; this approach, the most common, is adopted for use in this thesis, as detailed in Section 3.2.2.

2.2.2 Rainfall and associated road hazards

Overall, rain is perhaps the most commonly occurring weather hazard, particularly in areas with high traffic volumes (OECD, 1976). In urban areas across the country, rainfall is observed approximately eight percent of the time (i.e., in eight percent of all hours) on average, with cities on both coasts (Vancouver, 15.7%; Victoria, 12.9%; St. John's, 10.8%) experiencing the most frequent rainfall (Andrey et al., 2005). Accordingly, a significant proportion of driving can be assumed to take place during rainfall, exposing road users to elevated safety risks.

Many studies have established that rainfall is associated with increased collision and casualty risk, with crash rates typically 50-100% higher than normal (i.e., clear) seasonal conditions (e.g., Qiu and Nixon, 2008; Andrey, 2010). Moreover, risk increases tend to be higher for more intense rainfall events than for lighter showers, and the greatest risk increases are typically associated with less severe (i.e., property damage only, or PDO) collisions, although elevated risk has been observed for all crash severities. Crashes involving vulnerable road users are of particular concern, as pedestrian crash risk increases are estimated to be several times higher during rainfall, especially at night (OECD, 1976). Indeed, generally weather effects tend to be greater when they occur in combination with darkness (Musk, 1991).

Andrey and Yagar (1993) found that despite the lingering effect of wet roads, crash risk quickly falls to normal levels following cessation of rainfall. However, risk increases often become greater as the number of days since the last rainfall increases; for example, crash risk is approximately two to three times higher, across all crash severities, for rain after a 21-day dry spell relative to a two-day dry spell (Eisenberg, 2004). The impact of a dry spell is also heightened as the amount of the first rain increases (Keay and Simmonds, 2006). These findings are probably related to oil accumulation on the roadway – as rainfall resumes following an extended dry spell, the oil mixes with water and becomes more hazardous, whereas rain on the preceding day typically washes off this layer of oil (Eisenberg, 2004).

The primary driving-related hazards associated with rainfall are reduced visibility and loss of surface friction due to slippery roads. Key implications of reduced visibility for drivers are shorter forward sight range, decreased ability to distinguish other objects or road users, and therefore reduced reaction time to hazards in the road ahead (OECD, 1976; Morris et al., 1977); reduced efficiency of drivers' eye movement patterns (i.e., fixations and scanning behaviour) has also been observed (Konstantopoulos et al., 2010). Drizzle, defined as water droplets less than 0.5 mm in diameter, is of particular concern, with visibility levels potentially as low as 200 metres; small raindrops of this nature are associated with greater visibility reductions than large drops, and these are especially troublesome at night (OECD, 1976; Morris et al., 1977). The interactive effect of darkness was confirmed by Morris et al. (1977), who reported a significant decrease in drivers' visual acuity (i.e., clearness of vision) during higher intensity rainfall at night compared to a minor reduction in visual acuity during similar daytime rainfalls. In general, forward sight distance is also reduced as rainfall intensity increases and as luminance and wiper speeds decrease (Bhise et al., 1981).

Most visibility problems, however, are caused by the indirect effects of rain (OECD, 1976). During intense rainfall events (e.g., convective Southern Ontario summer thunderstorms) in which vehicle windshield wipers can become overwhelmed, a film of water on the windshield is a key factor in reduced visual performance (Morris et al., 1977). Dirty spray thrown up by other vehicles, especially trucks, can have a detrimental effect on frontal visibility and vehicle headlamps during heavy rain conditions (OECD, 1976; Yager et al., 2009). In nighttime conditions, light reflecting from a slightly wet road surface may lead to vision impairment due to reduced contrast and lower luminance (OECD, 1976; Musk, 1991). Moreover, retroreflectivity of road markings is lower in wet rather than dry conditions, and decreases as rainfall intensity increases (Pike et al., 2007).

Wet or slippery roads are the other common effect of rainfall, and the resulting decrease in surface friction tends to increase a vehicle's safe stopping distance by as much as 75 percent (Table 2-4); this distance tends to increase with rainfall intensity and vehicle speed (Huebner et al., 1999). On wet roads, the average thickness of liquid film on the road surface is 0.1 to 1 millimetre (Mortimer and Ludema, 1972). Heavy rainfall events in particular can result in water accumulation on the roadway, or even flooding in areas with poor drainage, greatly increasing hydroplaning potential – that is, the risk of completely losing tire traction and sliding across the water surface. With racing slick tires in a controlled setting, hydroplaning can occur with water depths as little as 0.76 millimetres; as rainfall intensity and, therefore, water depth increase, the speed at which hydroplaning occurs is reduced (Huebner et al., 1999; Yager et al., 2009). Moreover, the duration of rainfall and pavement wetness tends to increase with hourly rainfall amount – that is, an hour with more measured rainfall typically involves rain falling for a greater period of time during that hour (Harwood et al., 1988). Upon cessation of rainfall, the hazard associated with wet roads remains during a drying period. Andrey and Yagar (1993) found that pavement drying times in Calgary and Edmonton often exceeded one hour, while Harwood et al. (1988) estimated that drying times can range from five minutes to one hour after rainfall, depending on atmospheric conditions.

Table 2-4: Example of stopping distances under dry versus wet road conditions

Vehicle speed	*Stopping distance (metres)*	
	Dry road	*Wet road*
50 km/h	14.1	24.6
100 km/h	56.2	98.4
120 km/h	81.0	141.7
Based on coefficients of friction of 0.7 (dry) and 0.4 (wet) for regular all season tires on dry and wet roads, respectively (Nave, 2010a;b)		

While both reduced visibility and decreased pavement friction have notable impacts on the driving task and road environment, it is difficult to definitively separate the effects of these two phenomena as both occur together, particularly in heavy rainfall (OECD, 1976). Moreover, difficulty is likely to be encountered in attempts to directly identify the impact of one or the other in causing a collision. However, Andrey and Yagar (1993) suggested that drivers are able to adapt more easily to wet roads than to visibility reductions based on observed crash rates during and after rainfall events. In general, it has been estimated that traffic volumes are reduced approximately two percent during rainfall relative to normal driving conditions (Qiu and Nixon, 2008), and some trips, particularly those for leisure, are postponed (Kilpeläinen and Summala, 2007). Specific driver adaptations observed during rainfall include lower average speeds, decreased speed variations, increased vehicle headways, and more frequent vehicle platooning (Hogema, 1996; Andrey et al., 2005; Unrau and Andrey, 2006; Billot et al., 2009; Camacho et al., 2010). These adaptations tend to be more pronounced with increasing rain intensity (Billot et al., 2009), suggesting that drivers do indeed compensate for weather-related driving hazards. However, the highly elevated crash rate associated with precipitation indicates that this adaptation is insufficient (Hogema, 1996).

2.3 Climate change, variability, and weather extremes

Substantial research by the international scientific community has shown that the average global temperature has been warming at an unprecedented rate for the past century. Moreover, there is near universal agreement among climate researchers that the observed warming falls outside the range that can be attributed to natural climatic variability. Indeed, increasing global mean temperatures have coincided with the rapid human development that followed – and has not slowed since – the industrial revolution, and there is little doubt (> 90% probability) that the warming is related to anthropogenic causes, particularly greenhouse gas emissions (Hegerl et al., 2007; Solomon et al., 2007).

As the global climate warms in the coming century, it is likely to have significant impacts on human systems and settlements. Experts contend that as mean temperatures rise, so will the frequency and intensity of extreme events (e.g., heat waves, droughts, floods, tropical storms), with potentially devastating impacts on human life and the global economy. This section presents a review of the climate change literature, including possible responses, approaches to impact assessment and climate modelling, and potential impacts, with particular emphasis on transportation-related impacts.

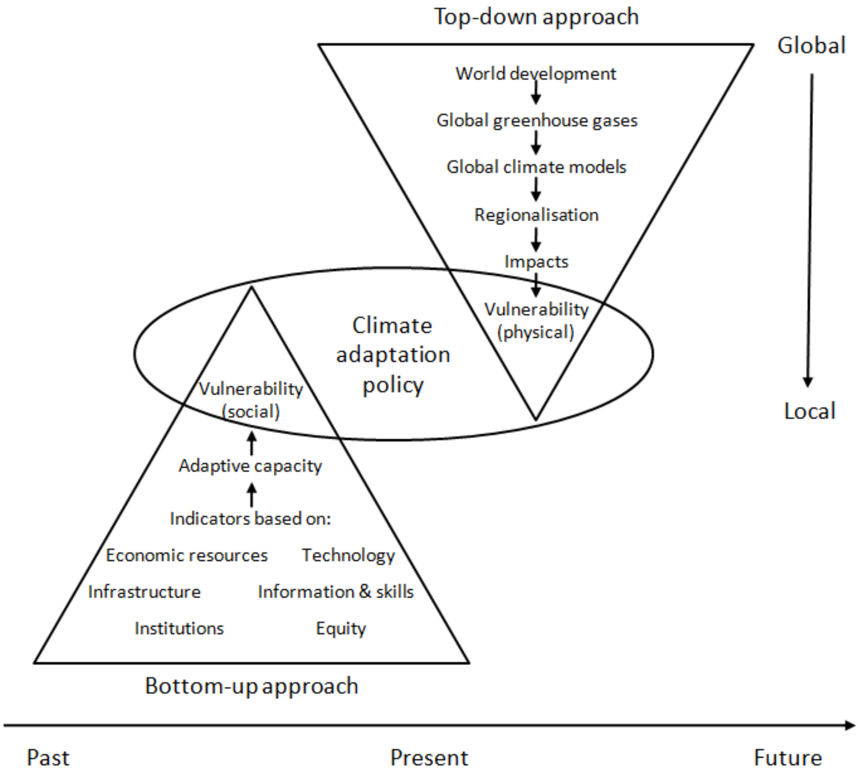
2.3.1 Climate impact assessment

There are two basic societal responses to climate change and its anticipated impacts. The first, mitigation, attempts to lessen the rate and magnitude of climate change by reducing global greenhouse gas emissions or concentrations through measures such as sustainable development or alternative energy sources (Warren, 2004). Mitigation is the focus of a huge amount of research and a core component of international climate change policy (e.g., Kyoto Protocol emissions reduction targets). To be effective, however, mitigation requires a concerted global effort to reduce emissions due to the circulatory nature of atmospheric systems (e.g., reductions in Canada will be meaningless if Chinese or other inputs continue to increase). For an extremely thorough catalogue – indeed, the ‘standard reference’ – of the leading scientific literature on mitigating climate change, refer to the volume prepared by Working Group III of the Intergovernmental Panel on Climate Change (IPCC; Metz et al., 2007). In addition, some degree of climate change is ‘locked in’ to the trajectory already established by current CO_2 levels. Accordingly, mitigation will not prevent climate change from occurring; emission reductions and other mitigation efforts can only be used to alleviate further changes over the long term, so a complementary approach is thus needed (Warren, 2004).

The second major response to climate change is adaptation. This involves adjusting activities or practices so that society can enhance its adaptive capacity to better cope with future changes – that is, to minimize adverse impacts and take advantage of opportunities resulting from projected changes in climate (Warren, 2004). Thus, the main goal of adaptation is to increase systemic and societal resilience while simultaneously reducing vulnerability. Adaptive activities can be either planned, to enable a proactive response to anticipated impacts, or reactive in light of impacts that have already been felt; similarly, adaptation can follow deliberate policy decisions or otherwise occur spontaneously (Warren, 2004; Cohen and Waddell, 2009). Warren (2004) noted two primary concerns regarding adaptation to climate change. First, as the rate of climate change increases, our ability to adapt declines. In addition, increased frequency and intensity of extreme events are anticipated. In order to successfully and cost-effectively alleviate these concerns, proactively planned adaptation responses will be required (Warren, 2004). Working Group II of the IPCC (Parry et al., 2007) produced what is to date the most comprehensive scientific reference volume on climate change impacts and adaptation.

In summary, mitigation comprises technological advances or behavioural shifts to avoid or lessen the magnitude of future climate change (and therefore proactively limit the impacts of that change), while adaptation efforts assume that some degree of change is unavoidable and seek to adjust human systems to better cope with anticipated changes. More simply, mitigation targets the causes of climate change and adaptation focuses on the consequences. Although adaptation represents a distinct research and policy direction from mitigation, both responses should be employed as part of a two-pronged climate change response strategy. This thesis, with its examination of projected traffic safety impacts based on different climate scenarios, focuses almost exclusively on adaptation, though it is recognized that mitigation plays a role in determining possible climate futures and possible transport futures.

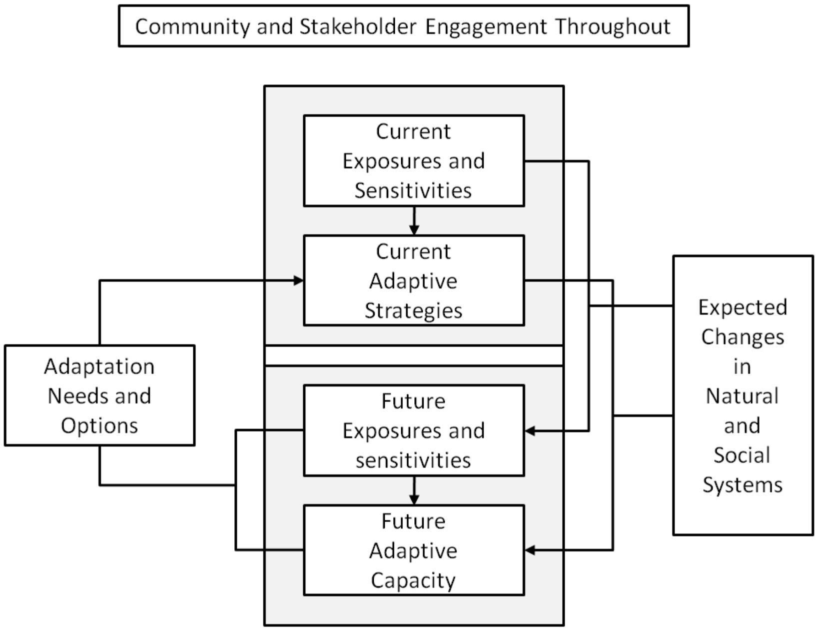
Several different names and classification schemes have been used to describe approaches to adaptation research (cf. Dessai and Hulme, 2004; Warren and Barrow, 2004; Smit and Wandel, 2006; Carter et al., 2007; Wall et al., 2007; Cohen and Waddell, 2009). However, there is general agreement on a dichotomy of processes, each operating at different spatial and temporal scales (Figure 2-7). First, and most common, is the top-down or impact-based approach, which has typically been the standard approach recommended by the IPCC (Dessai and Hulme, 2004; Carter et al., 2007). Analyses of this nature focus on projections of mid- to long-term future climate change impacts at a local or regional level, which are derived from macro-scale global circulation models driven by a range of possible world development and emissions scenarios (i.e., from ‘top’ to ‘bottom’, or a global to local scale). Due to its predictive nature, this approach lends itself particularly well to long-term adaptation policy and planning decisions related to infrastructure with a long operational life, such as dams, bridges, or port facilities (Dessai and Hulme, 2004). Indeed, much of the research on transportation impacts has utilized a top-down approach (e.g., TRB, 2008; see below); in addition, several examples related to Canadian agriculture were reviewed by Wall et al. (2007). However, there are scale issues with the top-down approach, as macro-level global scenarios must be downscaled to a regional or local level and projected impacts transformed into useful parameters for the specific analysis (Brklacich et al., 2007); these issues are discussed in greater detail in the following section.



Reprinted from Dessai and Hulme (2004), p. 112.

Figure 2-7: Approaches used to inform climate adaptation policy

There is also a great deal of uncertainty associated with climate change impacts; the level of uncertainty can ‘explode’ as work progresses from initial emission scenarios toward projections of impacts (Cohen and Waddell, 2009). Thus in some circumstances, such as in developing countries with limited financial and human resources to devote toward impacts research and adaptation decisions, a focus on present rather than future vulnerability might be more prudent (Dessai and Hulme, 2004). Accordingly, the bottom-up approach (Figure 2-8) begins with an assessment of present-day climate-related vulnerability (i.e., recent or historical climate variability and extreme events) at a community or system level before considering the potential impacts of near-future climate change. Detailed reviews of this approach have been published by Smit and Wandel (2006) and Wall et al. (2007).



Reprinted from Smit and Wandel (2006), p. 288.

Figure 2-8: Conceptual framework for vulnerability assessment using the bottom-up approach

Both approaches are similar in that both arrive at an estimation of future vulnerability, from which adaptation decisions can be made; however, they do so from different perspectives, known as biophysical and social vulnerability, respectively (Dessai and Hulme, 2004). Top-down analyses examine the vulnerability of physical or natural systems by looking at exposure units such as a watershed, ecosystem, building, or transportation network, while bottom-up researchers prefer to focus on the socio-economic well-being of society by identifying human vulnerability at a household, community, or national level (Dessai and Hulme, 2004). Cohen and Waddell (2009) suggested that the lines between the two basic approaches are beginning to blur as stakeholder engagement becomes more common – indeed, a requirement – in adaptation decision-making of every nature. Further, they argued that the linear progression suggested by the names top-down and bottom-up is no longer prevalent; ‘scenario-first’ and ‘vulnerability-first’ are put forth as more appropriate names to delineate the starting point of analysis. Finally, in addition to many advances in the traditional approaches to adaptation research, Carter et al. (2007) reported an emerging body of integrated assessments, which employ a hybrid approach involving both top-down and bottom-up analysis; Cohen and Waddell (2009) called these second-generation studies.

In the transportation sector, there is a need for such a hybrid approach to adaptation research, as short-term operational and long-term infrastructural decisions will need to consider adaptation in the face of climate change. This is also true of the traffic safety community, where a combination of short-term (e.g., safety policy, public awareness, and traffic enforcement to manage currently experienced and near-future risks) and long-term (e.g., vehicle and roadway design improvements to cope with anticipated climate changes in coming decades) adaptations will be necessary to effectively cope with climate variability and extremes. However, a great deal is already known about present-day weather-related vulnerabilities and travel risks. Thus in road safety a bottom-up or vulnerability-first approach is, essentially, already underway and ready to proceed to the future impacts stage, where the top-down approach begins. This thesis continues toward the next step in this progression by combining long-term weather-related risk estimates with projected future rainfall frequencies in order to derive a first estimate of the possible effects of climate change on road safety in urban Canada.

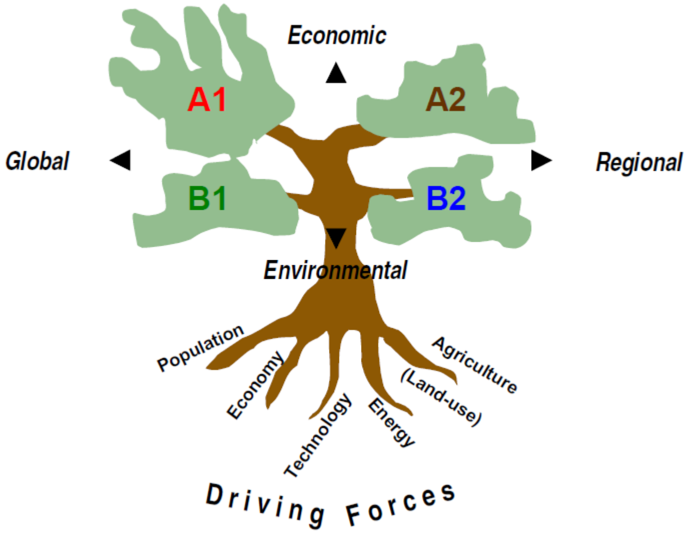
2.3.2 Scenarios for climate impact assessment

While there is agreement within the international climate science community that global temperatures are rising because of increased greenhouse gas emissions, there remains considerable uncertainty regarding estimates of regional or local-scale climate change – the level at which most impacts will be felt (IPCC-TGICA, 2007). The standard approach to addressing this uncertainty is the use of climate scenarios to represent possible future climates over several decades or centuries, based on assumptions about emissions, energy use, human development, and atmosphere-ocean processes (IPCC-TGICA, 2007). Scenarios, however, are not intended to forecast or predict the future, as this cannot be done with any certainty, and these terms imply greater probability of a particular outcome (Warren and Barrow, 2004). Rather, a scenario is “a coherent, internally consistent and plausible description of a possible future state of the world” (IPCC, 1994, p. 3). A range of different socioeconomic and climate scenarios have been developed to address the uncertainties associated with future assumptions.

The most common method of producing climate scenarios involves output from global climate models (GCMs; also known as general circulation models) – numerical representations of physical Earth-atmosphere-ocean processes at coarse spatial resolutions (Warren and Barrow, 2004). As scientific knowledge of climate processes has increased exponentially in recent decades, climate models have consistently become more complex by incorporating additional physical processes (Le

Treut et al., 2007). Indeed, current fourth-generation models simulate complex interactions and feedbacks within and between the atmosphere, ocean, cryosphere, and land surface (Le Treut et al., 2007). However, many key climate processes (e.g., clouds, vegetation) occur at relatively small spatial scales, so difficulty is associated with modelling them in a global context (Le Treut et al., 2007). Thus, in recent years an emphasis on a ‘hierarchy of models’ has arisen, with detailed models limited to a small number of processes or specific regions nested within large-scale global models (Le Treut et al., 2007).

GCM experiments typically rely on a prescribed input measure of radiative constituents (e.g., CO_2, ozone, aerosols) to drive the numerical simulation of biophysical system processes to produce an estimate of radiative forcing. However, human systems are incredibly difficult to predict, so it is impossible to determine future emissions and radiative constituents with any degree of certainty or probability. Accordingly, a range of standardized socio-economic scenarios have been developed by the IPCC for use in climate change studies in order to ensure a common starting point, consistent analyses, and effective intercomparison between different climate models. The scenarios, known as the SRES series (Special Report on Emissions Scenarios; see Nakićenović et al., 2000), are based on different narrative storylines that characterize and quantify possible futures in terms of demographic, socioeconomic, and technological driving forces of anthropogenic greenhouse gas and aerosol emissions (IPCC-TGICA, 2007). Thus the scenarios are useful tools for examining how these driving forces could influence future emissions, while also assessing related uncertainties (Nakićenović et al., 2000). From the storylines, four scenario families have been established (Figure 2-9), each representing an increasingly irreversible divergence from the current state of human development (IPCC-TGICA, 2007). A total of 40 scenarios were developed, with each considered plausible and equally valid. From these, six illustrative ‘marker scenarios’ (Table 2-5; Figure 2-10) were selected and recommended for use in climate modelling to provide a realistic range of future emissions affecting atmospheric concentration and radiative forcing (IPCC-TGICA, 2007). The SRES scenarios do not include or account for climate change interventions (i.e., mitigation and adaptation), and thus are useful as means of estimating the degree of unchecked future climate change to inform policy decisions. It is generally recommended that impact analyses should utilize two or more scenarios (i.e., high and low emissions, with different assumptions on driving forces) to examine a range of possible impacts in light of high uncertainty (Nakićenović et al., 2000).

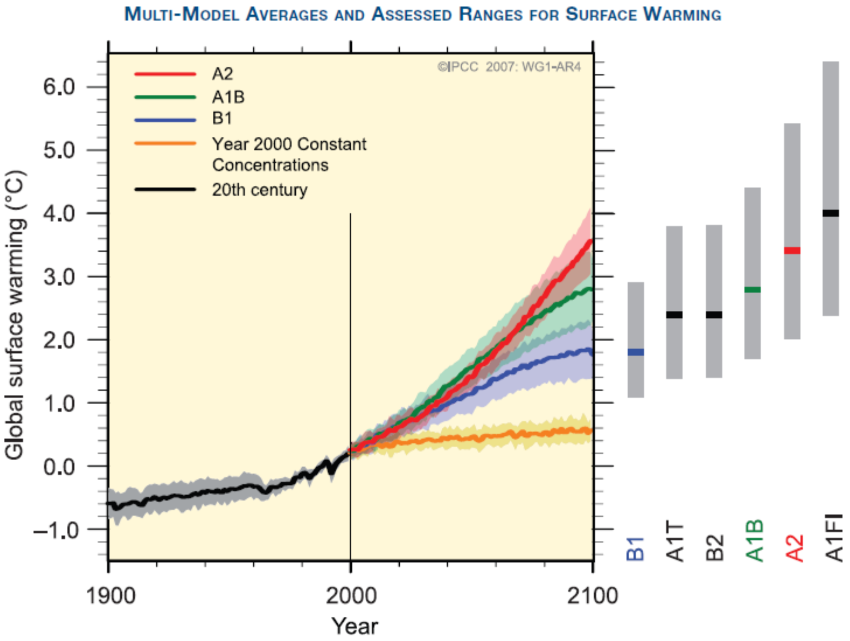


Reprinted from Nakićenović et al. (2000), p. 170.

Figure 2-9: Schematic of IPCC SRES scenario storylines

Table 2-5: Overview of SRES scenario characteristics to 2100

Family	*A1*			*A2*	*B1*	*B2*
Scenario group	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*
World relations	Global			Regional/local	Global	Regional/local
Development focus	Economic development				Social and environmental sustainability	
Population growth	Low			High	Low	Medium
GDP growth	Very high			Medium	High	Medium
Energy use	Very high	Very high	High	High	Low	Medium
Land use changes	Low-medium	Low	Low	Medium-high	High	Medium
Resource availability	High	Medium	Medium	Low	Low	Medium
Pace and direction of technological change favouring	Rapid; coal, oil, gas	Rapid; balanced	Rapid; non-fossils	Slow; regional	Medium; efficiency and dematerialization	Medium; 'dynamics as usual'
Cumulative emissions	High	Medium-high	Low	Medium-high	Low	Medium-low
Adapted from Nakićenović et al. (2000)						



Bars show range of projected temperatures for GCM simulations using each SRES scenario.
Reprinted from IPCC (2007), p. 14.

Figure 2-10: Global temperature scenarios

In addition, uncertainty is typically encountered when modelling future precipitation changes. A much greater degree of uncertainty is associated with precipitation projections than with temperature. Most models agree at least on the sign of temperature changes, if not the magnitude; however, climate models vary greatly in their estimates of precipitation change. Randall et al. (2007) reported that GCMs are fairly good at simulating observed mean annual precipitation, although a drizzle effect is apparent in the models as light precipitation events tend to be overestimated and heavy ones underestimated. In addition, model simulations of the most intense or extreme precipitation events typically involve too little precipitation compared to actual observations. However, it is recognized that the ability to simulate precipitation improves with increasing model resolution (Randall et al., 2007).

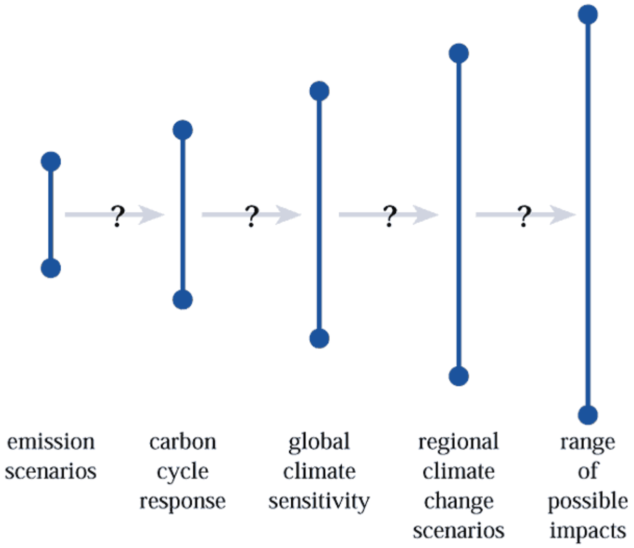
Another key limitation of GCMs is resolution. As they involve extremely intensive computing operations, GCMs must be run at coarse spatial and temporal scales and cannot resolve small-scale landscape features that influence precipitation (e.g., local geography and elevation). Thus, on their own, GCMs have limited utility for location-specific analyses of climate change impacts. In studies requiring fine spatial resolution (e.g., road network, city, or watershed), model outputs can be downscaled.

Two standard approaches have been applied to the problem of downscaling; while theoretically they represent an improvement over global models, there is still great uncertainty involved. First, dynamical downscaling uses regional climate models (RCMs) driven by GCM output. Essentially, GCMs provide a set of boundary conditions within which nested regional models operate, thereby distributing impacts throughout the larger area based on a finer-scale understanding of climate processes and local geography. With RCMs, coarse GCM grid cells (200 by 200 km) can be subdivided into several smaller ones (50 by 50 km). For examples of studies utilizing regional climate models to simulate precipitation changes, refer to Messager et al. (2006), Kjellström and Ruosteenoja (2007), and López-Moreno and Beniston (2009).

Alternatively, statistical downscaling methods can be utilized to estimate localized climate change effects based on statistical relationships that have been established through calibration with observed historic time series data. Statistical downscaling has been applied in several sectors, most notably agriculture and watershed management, to look at temperature and precipitation (e.g., Mills et al., 2007; Régnière and St-Amant, 2007; Chu et al., 2010).

An alternative to the above model-based approaches is the use of temporal or spatial analogues to evaluate possible climate change effects based on current or historical conditions experienced in one location that are reasonably likely to represent future conditions in a different study location (Warren and Barrow, 2004). For example, present-day conditions in the southern US might be representative of future climate in the Canadian prairie provinces. Similarly, paleoclimatic evidence (e.g., warm periods several thousand years ago) or recent historical droughts affecting a region could be used as analogues for future warming or drought conditions. While analogues have the advantage of using real, physically plausible datasets, it has also been suggested that historical extreme events were not the result of anthropogenic forcing and therefore may not represent future deviations from climatic means (Cohen and Waddell, 2009). Alternatively, synthetic scenarios, though arbitrary, can be utilized to examine sensitivity and vulnerability of different systems (e.g., fisheries production, forestry) to future changes in climate (Warren and Barrow, 2004). This might involve, for example, incrementally adding several degrees to all values in the historical temperature record in order to model systemic response. Many studies have utilized analogue and synthetic scenarios; however, GCM-based analysis has emerged as the dominant approach in climate impact assessment.

Regardless of the method used to estimate future changes, a common problem in climate impact research is uncertainty. Indeed, as Figure 2-11 shows, uncertainty increases at every step of the process, from initial estimates of emissions through to projections of possible climate change and associated impacts. As human behaviour and its impacts on natural systems are inherently unpredictable, care must be taken to ensure that a range of possible futures and impacts are evaluated and incorporated into policy, planning, and management decisions; this can be accomplished by analyzing output of several different models or climate scenarios.



Reprinted from Ahmad et al. (2001), p. 130.

Figure 2-11: The 'uncertainty explosion'

2.3.3 Climate change and transportation

The design and operation of transportation infrastructure reflects the diverse range of environmental conditions found across the globe. Indeed, our ability to adapt to different environments has allowed us to develop efficient transport systems in virtually all conditions to meet society's transportation needs. However, as the global climate continues to change in the coming decades, we will need to adapt further so that we can continue to provide safe, efficient, and reliable transportation systems.

There are two general ways in which climate change and transportation are linked. First, the transport sector is a major contributor to anthropogenic climate change through emission of greenhouse gases. Non-renewable, carbon dioxide-emitting oil accounts for 97 percent of fuel use in the transportation sector while the most polluting and fastest-growing transport modes, road and air, comprise 81 and 13 percent shares of travel, respectively (IEA, 2002). The transportation sector as a whole is responsible for 23 percent of global carbon dioxide emissions – more than the industrial, residential, or commercial/service sectors, and second only to electricity and heat generation (IEA, 2009). Thus, transportation will necessarily play a key role in attempts to mitigate greenhouse gas-induced climate change; see Chapman (2007) for a detailed review of transportation impacts on climate change. In addition to being a major contributor to ever-rising greenhouse gas emissions, transport systems are highly vulnerable to the effects of climate change; this second relationship forms the basis of this section and underpins the remainder of the thesis.

If greenhouse gas emissions continue at a rate equal to or higher than present, warming of global mean temperatures will continue into this century at a rate that is very likely higher than observed over the past 100 years (Meehl et al., 2007b). This will likely be accompanied with sea level rise, changes in temperature extremes (more intense, more frequent, and longer lasting heat waves; decreased cold episodes; smaller day-night temperature ranges; fewer frost days), increased mean global precipitation (particularly in tropical and high latitude regions), modified precipitation and storm patterns (more intense and variable precipitation events; more frequent, and more intense, tropical storm and hurricane activity – see Bender et al., 2010), reduced snow cover and sea ice extent, and increased thaw depth in northern permafrost regions (Meehl et al., 2007b).

In North America, warming during the next century is likely to exceed the global mean, with the greatest winter warming expected in northern regions and largest summer warming in the southwest United States (Christensen et al., 2007). Annual mean precipitation is projected to increase in Canada and the northeastern states while decreasing in the southwest states. Moreover, southern Canada is likely to see increased winter and spring precipitation and less summer precipitation, while snow depth and snow season length are projected to decrease across the continent, notwithstanding increased snow depths in the northernmost reaches of Canada (Christensen et al., 2007).

The anticipated changes in climate over the next century are likely to have a range of impacts, both positive and negative, on transport infrastructure and operations in Canada and worldwide (Warren et al., 2004; Peterson et al., 2006). Transportation infrastructure is built according to typical local weather and climate conditions, with the ability to withstand a reasonable range of extremes, such as a 24-hour precipitation or 100-year flood event (TRB, 2008). Slight changes to mean climatic conditions are thus likely to have limited impact, as they are within the design range of most transport systems (Peterson et al., 2006). However, changing climate extremes can be expected to have significant impacts if environmental conditions are pushed outside of the system's design range (TRB, 2008). Accordingly, it is changing weather and climate extremes – in addition to, and in conjunction with, rising sea levels – that are most likely to impact transportation systems (TRB, 2008). A recent report by the Transportation Research Board (TRB, 2008) examined the potential impacts of climate change for the US transportation system, and suggested that the changes of greatest relevance to transportation are, broadly speaking: warming temperatures and temperature extremes; sea level rise; increased heavy precipitation; and more intense tropical storms.

According to the IPCC, increased mean and extreme temperatures are among the most certain changes expected (Meehl et al., 2007b). More frequent periods of excessive heat could have significant and costly impacts on land transport infrastructure, such as compromised pavement integrity (Mills et al., 2007), deformation of rail lines (Rossetti, 2002; Dobney et al., 2009; Baker et al., 2010), and thermal expansion of bridge joints (TRB, 2008). In the winter months, however, warming temperatures will likely result in reduced winter maintenance (i.e., deicing and snow removal) costs (Warren et al., 2004). Fewer freeze-thaw cycles in southern Canada might reduce pavement cracking and frost damage, while milder winters in northern regions could increase freeze-thaw-related road deterioration and maintenance costs, in addition to requiring spring load restrictions that reduce operational efficiency (Mills et al., 2007). Northern regions are also likely to see degradation of permafrost, threatening the stability of road and rail infrastructure (U.S. Arctic Research Commission Permafrost Task Force, 2003), while a shorter ice road season is anticipated due to winter warming (Warren et al., 2004); these problems could be offset by longer open-water and ice-free shipping seasons in arctic waters (ACIA, 2004; Peterson et al., 2006). In southern and mid-continental regions, inland waterways such as the Great Lakes-St. Lawrence Seaway and Mississippi River will likely see lower water levels resulting in cargo restrictions and increased shipping costs; these impacts, however, might be offset by a longer shipping season (Quinn, 2002; Millerd, 2011).

Also among the more certain anticipated impacts of climate change is sea level rise (Meehl et al., 2007b). Flooding due to elevated sea levels, together with high tides, more intense precipitation, and storm surges, presents a particularly strong threat to vulnerable coastal infrastructure such as road and rail networks (many of which serve as emergency evacuation routes to inland areas) and ports, harbours, and other marine freight facilities (Caldwell et al., 2002; Warren et al., 2004; Becker et al., 2010). In addition, many airports are built in low-lying coastal floodplains and river deltas, protected by levee and dyke systems that could be overrun by floodwaters (Titus, 2002; Warren et al., 2004; Peterson et al., 2006). Underground urban transportation infrastructure (e.g., subways, road tunnels) in large coastal metropolitan areas are also highly vulnerable to flooding from storm surges and heavy precipitation (Compton et al., 2002; Titus, 2002; Arkell and Darch, 2006; Chan, 2007). Thus, operational delays and interruptions for all transport modes are expected to become more common in coastal regions as flooding increases in frequency (Suarez et al., 2005; TRB, 2008). Furthermore, it has been predicted that some coastal areas (i.e., Atlantic and Gulf of Mexico) will see transport infrastructure become permanently inundated as a result of rising sea levels (Titus, 2002; TRB, 2008).

More intense precipitation, like sea level rise, could lead to flooding; however, precipitation-related flooding will not be constrained to coastal areas (TRB, 2008). Intense rainfall events may overload urban stormwater management and drainage facilities, leading to flash flooding and high storm loads in river systems, which will flood roads and low-lying riverine areas, causing infrastructural damage and operational delays (Changnon, 1999; Suarez et al., 2005). Shipping on key inland waterways (e.g., Mississippi River) could also suffer significant delays associated with increased flooding (TRB, 2008). Heavy rainfalls and associated runoff could lead to landslides and washouts in mountain and coastal regions, with substantial effects on road and rail infrastructure (duVair et al., 2002; Rossetti, 2002). Finally, it is likely that tropical storms and hurricanes will increase in frequency and intensity, with potentially devastating impacts on transportation infrastructure and operations due to intense precipitation, strong winds, and wind-induced storm surges (Meehl et al., 2007b; Bender et al., 2010). In addition to the aforementioned effects, these storm components can have significant impacts on road and rail networks, displacing bridge decks and blocking emergency access (Rossetti, 2002; TRB, 2008). Shipping and aviation are also likely to suffer substantial delays and facility damages (Caldwell et al., 2002; TRB, 2008; Becker et al., 2010). Meanwhile, damage to minor infrastructure such as signs, lighting, and roadside furniture is also likely, and can have significant costs when occurring on a large scale (TRB, 2008). All modes of transportation are vulnerable to tropical storms, as evinced by the massive damage and delays associated with Hurricanes Katrina and Rita in 2005 (Grenzeback and Lukmann, 2007). Indeed, more intense storms associated with climate change represent a substantial hazard to transport systems and human health.

The above discussion has looked generally at the possible impacts of climate change on transport systems, but with little regard to geography. The effects of climate change will be manifested differently in each country, region, or city, with some locations vulnerable to substantial adverse impacts while others stand to gain. Broad national or state assessments of climate change impacts on transportation have been published or initiated for several jurisdictions, including Canada (Warren et al., 2004, Lemmen et al., 2008), the United States (national: U.S. DOT, 2002; TRB, 2008; California:

duVair et al., 2002; Alaska: Smith and Levasseur, 2002), Australia (national: Austroads, 2004; Victoria: Holper et al., 2006), Scotland (Galbraith et al., 2005), Norway (Petkovic and Larsen, 2009), India (Shukla et al., 2004), and the Arctic (U.S. Arctic Research Commission Permafrost Task Force, 2003; ACIA, 2004). However, only a few studies – none in Canada – have examined regional or city-specific transportation impacts in detail. Among the locales that have been studied are London (Mayor of London, 2005; Arkell and Darch, 2006), New York City (Jacob et al., 2000; Gornitz et al., 2002; Zimmerman, 2002), Boston (Suarez et al., 2005; Kirshen et al., 2006), Seattle (Soo Hoo and Sumitani, 2005), and the Atlantic and Gulf coasts (Burkett, 2002; Titus, 2002).

In Canada, work has been ongoing for the past two decades to assess the national implications of climate change. The focus in the transportation sector has primarily been on inland waterways, coastal areas vulnerable to sea-level rise, and northern regions. More recently, transport professionals have begun to take interest in heat-related pavement degradation of southern roads. With its great diversity of environmental conditions, Canada is likely to see wide variation in regional impacts. Indeed, Canada's northern territories are particularly vulnerable to climate change and the effects of melting permafrost and fewer cold days, while the highly urbanized southern regions will likely see rising coastal waters, reduced lake and river levels, and more intense rainfall events. On a whole, however, Canada's transportation system could benefit from climate change, with reduced safety risks and maintenance costs associated with winter conditions, longer shipping and construction seasons in the south, and greater access to northern waters.

2.3.4 Climate change and road safety

Despite the quickly growing body of climate change research related to transportation, little research has thus far examined road safety in the context of climate change. Rowland et al. (2007) broadly discussed the possible safety implications of altered precipitation patterns, weather extremes, and warming temperatures under climate change; the discussion was based on a review of present-day empirical safety research. Moreover, in a survey of empirical literature on climate change and weather effects in the transport sector, Koetse and Rietveld (2009) suggested that the implications of climate change for road safety are uncertain in both direction and magnitude, and called for additional insights so that more accurate assessments can be made.

To the author's knowledge, only one study (comprised of a series of articles: Andersson, 2010; Andersson and Chapman, 2011a; 2011b) has thus far attempted an empirical estimate of climate change impacts on traffic safety. The research focused on winter (December to February) daily minimum air and road surface temperatures in order to investigate the possible effects of climate change on the incidence of slippery roads, and therefore crash rates, in the UK and Sweden; a brief summary is provided in this section.

Using temperature distributions derived from a stochastic weather generator, Andersson and Chapman (2011a) estimated that by 2080, West Midlands, UK, will experience fewer annual frost days (≤ 0 °C) and a shorter winter season; this could lead to a 43 percent reduction in crashes caused by slipperiness as well as a decreased need for salting and winter maintenance. In another article, Andersson and Chapman (2011b) compared crashes throughout Sweden during a warmer than average January 2005 with those in January 2006, which was cold and dry, as a temporal analogue for future climate change. Four different road slipperiness types associated with road surface temperature < 0 °C were examined. It was concluded that, with a general warming of climate, the number of severe crashes attributable to slipperiness will be reduced. However, this reduction could be partially offset by greater driver complacency in a warmer climate as well as an increase in marginal nights with temperature close to zero degrees, where ice is most slippery. Finally, Andersson (2010) estimated that Gothenburg, Sweden, could see 20 percent fewer crashes during sub-zero temperatures by 2080, as well as a 15 percent reduction in the need for winter road maintenance. Conversely, it is also possible that more annual days with minimum temperature above zero degrees could lead to an increase in crashes on these days.

However, it should be noted that the above studies relied on an empirical relationship between weather and crashes that may not be transferable to other climates or study areas. This relationship is based on a simple ratio where the number of crashes at temperature X is divided by the number of days per winter with minimum temperature X. However, the time steps used in the ratio are incompatible: the numerator appears to include observations or crashes at a given temperature throughout the entire day, whereas the denominator relies on the time of day at which a specific temperature occurs. Despite this shortfall, it is the only research to have thus far provided an empirical estimate of potential climate change impacts on traffic safety, and Andersson's work thus represents a valuable contribution to the climate impact assessment literature.

In summation, the present-day relationship between weather-related hazards and traffic safety has been clearly established by a wide body of work. Moreover, climate change is expected to increase the frequency, intensity, and variability of some of the conditions of greatest safety concern. Detailed analysis of weather and safety in the context of climate change is thus needed; this thesis is the result of one such attempt.

Chapter 3

Data and Methods

This chapter describes the empirical thesis research, and comprises three main sections:

- First, Section 3.1 describes the spatial and temporal context of the study, including basic characteristics of the study cities, the current state of traffic safety, and weather and climate patterns historically and throughout the 2003-2007 study period.
- Section 3.2 outlines the safety analysis for the five-year study period. This includes a discussion of collision and weather data sources and credibility as well as a detailed description of the analytical approach.
- Finally, Section 3.3 details the future climate analysis, primarily focusing on a series of decisions regarding the selection of appropriate climate scenarios and model outputs.

The general steps taken are illustrated in Figure 3-1.

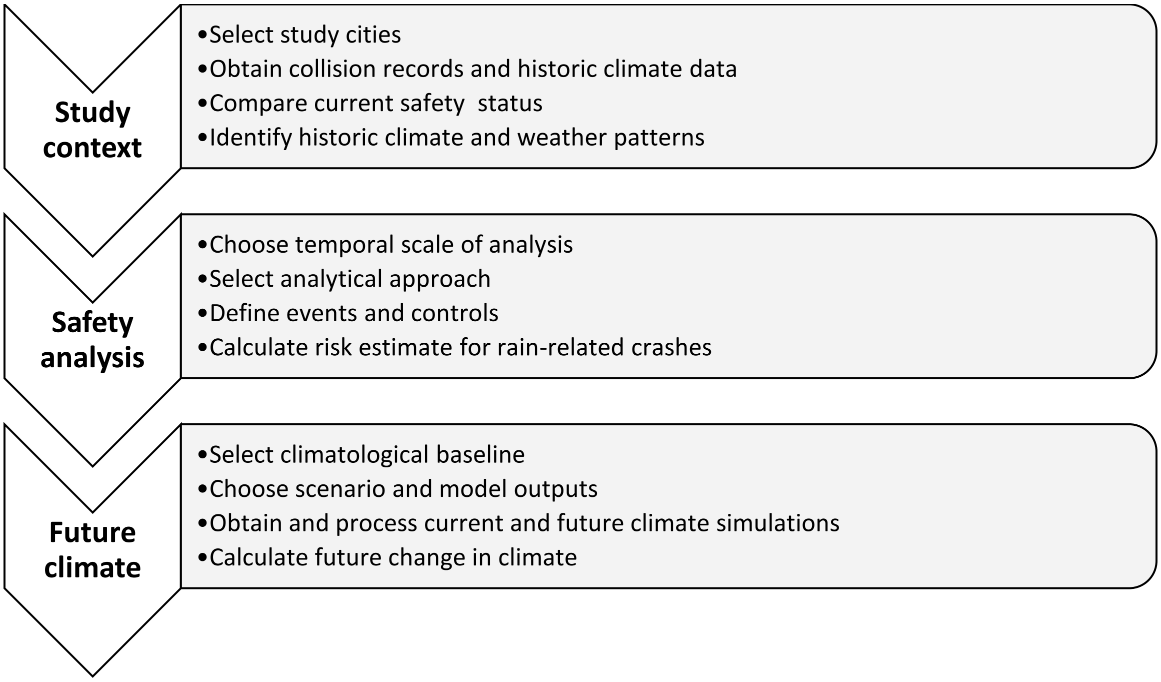


Figure 3-1: Steps taken in conducting the thesis research

3.1 Spatial and temporal context of the study

Canada, despite its huge geographical extent, is a highly urbanized nation: 80 percent of the population lives in urban areas, and two-thirds reside in the country's 33 census metropolitan areas (CMA) – that is, urban agglomerations with at least 100,000 inhabitants (Statistics Canada, 2008). It follows then that most travel – and crashes – occur in urban areas. Indeed, 70 percent of national casualty collisions take place on roads with speed limits of 60 kilometres per hour or lower (Transport Canada, 2007b).

Two large urban regions, the Greater Toronto Area and Greater Vancouver, were selected as study locations for this empirical investigation of the present-day relationship between rainfall and collision risk and the projected implications of future climate change for traffic safety. The regions, which largely coincide spatially with the Toronto and Vancouver CMAs defined by Statistics Canada, are the nation's largest and third most populous urban agglomerations, respectively. A substantial number of collision incidents occur annually in each region, and both experience fundamentally different climates, making Toronto and Vancouver attractive foci for a study of this nature. Data referenced in the following sections are drawn from Statistics Canada (2007), Transport Canada (1994), and Environment Canada (2010; 2011).

3.1.1 Population, mobility, and spatial extent

With over 5.1 million people, the Greater Toronto Area (GTA) is Ontario and Canada's largest urban region, accounting for 42.0 and 16.2 percent of the provincial and national populations, respectively. Made up of 23 local and regional municipalities[2] (Figure 3-2, Table 3-1), the GTA covers an area of approximately 5,900 square kilometres on the north shore of Lake Ontario. Several major highways crisscross the region, including a number of Ontario's 400-series divided freeways and two municipal expressways owned by the City of Toronto. The region is characterized by a heterogeneous development pattern, from a dense high-rise core in downtown Toronto to sprawling suburban and rural fringes in the outer municipalities. Modal shares vary greatly from 43.2 percent of trips using public transit and active transportation in the City of Toronto to over 95 percent auto reliance in

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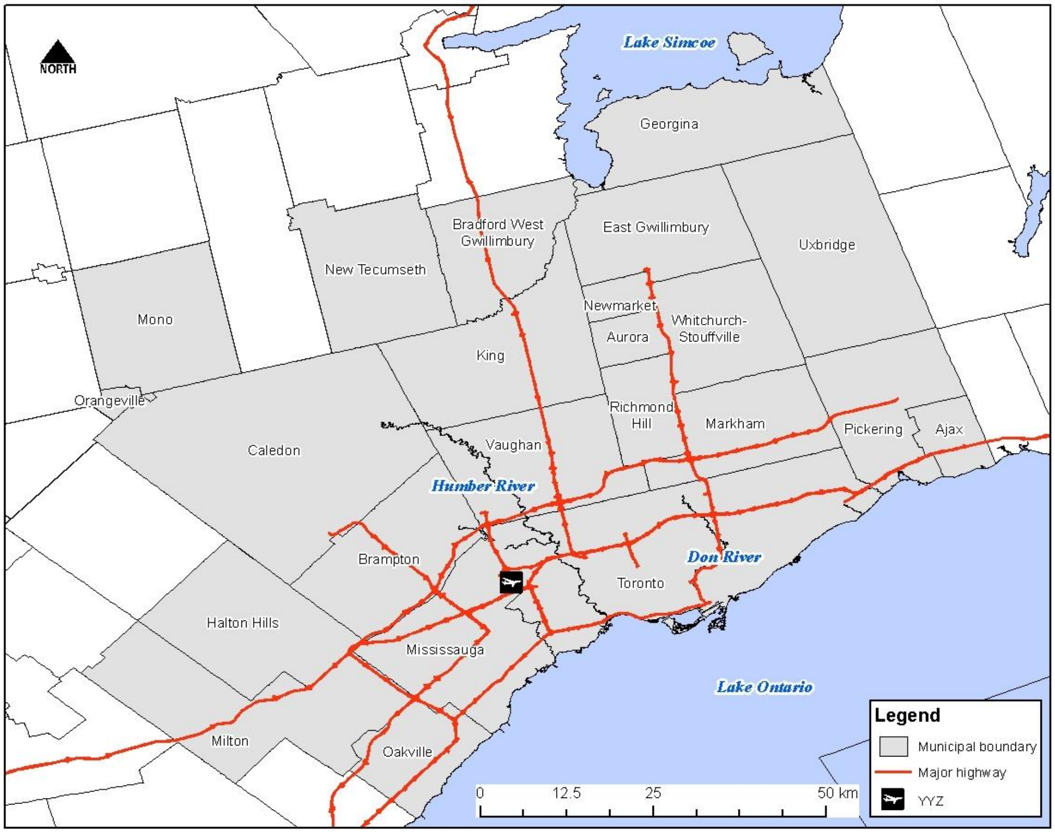
[2] For the purposes of this thesis, the GTA refers specifically to communities within the Toronto CMA boundaries (population 5.1 million) so that demographic comparisons can be made using Statistics Canada community profiles. However, the GTA in common parlance refers collectively to the City of Toronto and all municipalities within the neighbouring regions of Halton, Peel, York, and Durham (population 5.6 million); some of these municipalities are officially included in the Hamilton and Oshawa CMAs. In addition, the towns of Bradford West Gwillimbury, Mono, New Tecumseth, and Orangeville are included in the Toronto CMA but not in the colloquial GTA.

surrounding rural centres. Overall, more than 70 percent of all trips in the GTA involve private automobiles, contributing to a high number of traffic crashes.



Data sources: DMTI (2010a; 2010b); Statistics Canada (2006)

Figure 3-2: Greater Toronto Area

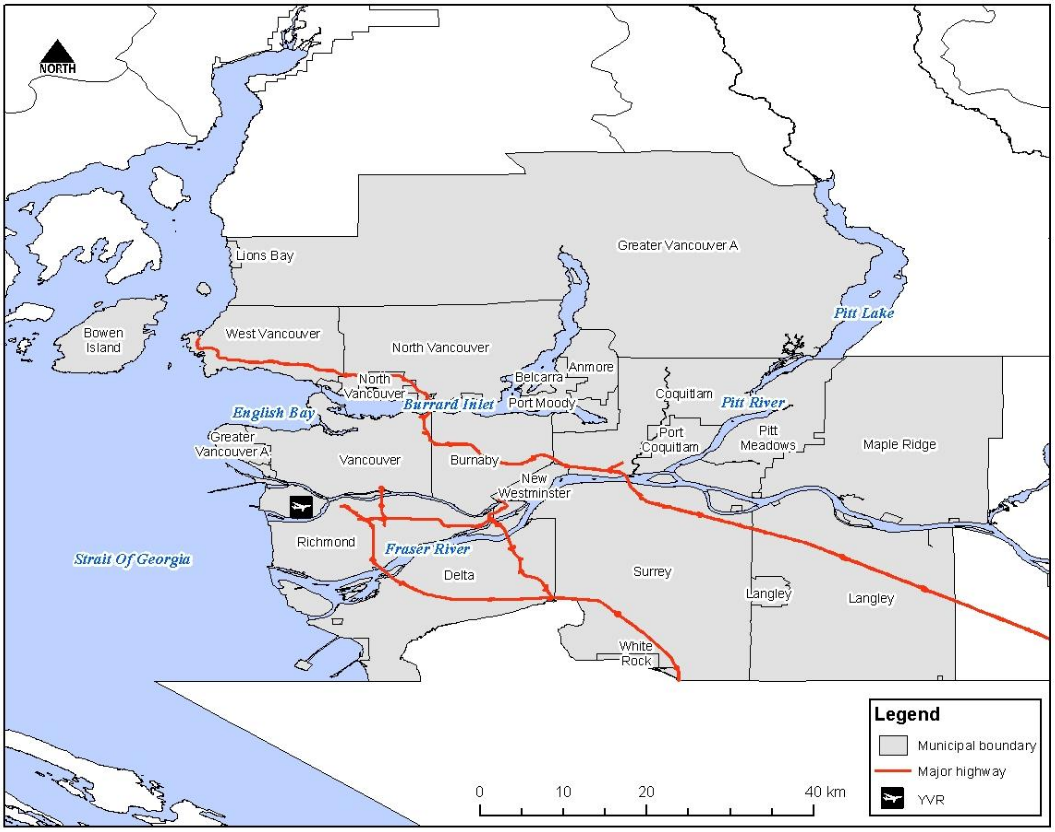
Table 3-1: Toronto CMA municipalities

Municipality	*Population*	*% of CMA population*	*Population density (per km^2)*	*Modal share*			*Police detachment code*	*Collision count*	*% of CMA collisions*
				% car	*% transit*	*% bike or walk*			
Ajax	90,167	1.8%	1,344.0	82.6%	13.4%	3.2%	080140	6,578	1.3%
Aurora	47,629	0.9%	959.9	87.2%	7.9%	4.3%	540500	2,459	0.5%
Bradford West Gwillimbury	24,039	0.5%	119.6	92.8%	3.3%	3.3%	441239, 443869	2,829	0.6%
Brampton	433,806	8.5%	1,626.5	86.6%	10.2%	2.3%	361257	32,383	6.6%
Caledon	57,050	1.1%	83.0	95.2%	1.3%	2.6%	361537	6,519	1.3%
East Gwillimbury	21,069	0.4%	86.0	93.6%	2.9%	2.8%	543865	1,941	0.4%
Georgina	42,346	0.8%	147.2	93.1%	2.4%	3.7%	543563, 547779	4,524	0.9%

Municipality	*Population*	*% of CMA population*	*Population density (per km^2)*	*Modal share*			*Police detachment code*	*Collision count*	*% of CMA collisions*
				% car	*% transit*	*% bike or walk*			
Halton Hills	55,289	1.1%	200.1	91.4%	3.2%	4.5%	171576	3,703	0.8%
King	19,487	0.4%	58.5	91.9%	3.7%	3.7%	544736	3,507	0.7%
Markham	261,573	5.1%	1,230.5	82.6%	14.4%	2.3%	545382	17,168	3.5%
Milton	53,939	1.1%	147.1	90.5%	4.9%	3.6%	175732	6,862	1.4%
Mississauga	668,549	13.1%	2,317.1	80.5%	15.8%	3.0%	365753	55,383	11.3%
Mono	7,071	0.1%	25.5	95.7%	0.3%	3.5%	075782	1,113	0.2%
New Tecumseth	27,701	0.5%	101.0	90.2%	0.7%	8.4%	447278	189	0.0%
Newmarket	74,295	1.5%	1,951.0	87.9%	6.0%	5.3%	545981	4,366	0.9%
Oakville	165,613	3.2%	1,195.2	80.7%	14.3%	4.1%	176082	14,908	3.1%
Orangeville	26,925	0.5%	1,729.3	90.4%	1.2%	7.4%	076136	1,545	0.3%
Pickering	87,838	1.7%	379.3	83.4%	13.0%	3.0%	086350	8,364	1.7%
Richmond Hill	162,704	3.2%	1,612.7	83.4%	13.2%	2.7%	546612	9,790	2.0%
Toronto	2,503,281	49.0%	3,972.3	55.8%	34.4%	8.8%	542746, 542975, 546056, 546834, 547390, 547392, 547780	278,209	56.9%
Uxbridge	19,169	0.4%	45.6	91.4%	2.4%	4.5%	087492	1,435	0.3%
Vaughan	238,866	4.7%	873.1	87.8%	9.6%	1.9%	547511	20,140	4.1%
Whitchurch-Stouffville	24,390	0.5%	118.0	91.8%	4.0%	3.6%	547631	2,073	0.4%
Peel Region*							366293*	2,792	0.6%
CMA Total	5,113,149		866.1	71.1%	22.2%	5.8%		488,780	

Data years: 2006 (demographics); 2003-2007 (collisions).
*The Peel Region police detachment (366293) does not coincide with an individual municipality; its crashes are shared among the lower tier municipalities of Brampton, Caledon, and Mississauga.

Greater Vancouver, meanwhile, is the largest urban region in British Columbia and third largest in Canada, with approximately 51.5 and 6.7 percent of the provincial and national populations, respectively. Its 2.1 million inhabitants occupy 21 municipalities and one electoral district (Figure 3-3, Table 3-2), spanning 2,900 square kilometres in BC's Lower Mainland region at the mouth of the Fraser River – coinciding exactly with the Vancouver CMA defined by Statistics Canada. A number of provincial highways traverse the region's inner and outer suburbs, including the Trans Canada Highway. Vancouver's downtown peninsula is among the most densely developed communities on the planet while the suburban and rural fringes are characterized by similar population densities as are found in the outer GTA. Comprising 74 percent of all trips, the Vancouver region overall has a slightly higher reliance on automobiles than the GTA; this varies from 85 to 90 percent in the outer suburbs to roughly 58 percent in the urban core. Differences likely reflect a more expansive public transit and commuter rail network throughout the Toronto region, although Vancouver sees a greater overall active transportation share supported by a more developed pathway and bike lane infrastructure.



Data sources: DMTI (2010a; 2010b); Statistics Canada (2006)

Figure 3-3: Greater Vancouver

Table 3-2: Vancouver CMA municipalities

Municipality	*Population*	*% of CMA population*	*Population density (per km^2)*	*Modal share*			*Police detachment code*	*Collision count*	*% of CMA collisions*
				% car	*% transit*	*% bike or walk*			
Anmore**	1,785	0.1%	65.1	86.9%	10.4%	2.2%	709**		
Belcarra**	676	0.0%	123.8	87.5%	12.5%	0.0%	709**		
Bowen Island	3,362	0.2%	67.3	75.6%	13.3%	9.0%	742	62	0.1%
Burnaby	202,799	9.6%	2,275.6	68.7%	25.0%	5.3%	704	6,991	8.4%
Coquitlam**	114,565	5.4%	941.4	81.0%	13.9%	4.3%	709**, 710	4,986	6.0%
Delta	96,723	4.6%	526.5	85.3%	9.1%	4.3%	407	5,403	6.5%
Greater Vancouver A	11,050	0.5%	13.5	40.7%	14.5%	43.6%	727	364	0.4%

Municipality	*Population*	*% of CMA population*	*Population density (per km^2)*	*Modal share*			*Police detachment code*	*Collision count*	*% of CMA collisions*
				% car	*% transit*	*% bike or walk*			
Langley	23,606	1.1%	2,309.8	85.7%	6.0%	7.2%	716	1,807	2.2%
Langley DM	93,726	4.4%	305.4	92.1%	2.9%	3.9%	717	5,189	6.3%
Lions Bay*	1,328	0.1%	520.8	87.8%	7.0%	6.1%			
Maple Ridge	68,949	3.3%	259.4	87.1%	7.4%	4.0%	712, 713	3,532	4.3%
New Westminster	58,549	2.8%	3,799.4	65.2%	26.8%	7.0%	409	3,121	3.8%
North Vancouver	45,165	2.1%	3,811.4	67.6%	20.3%	11.3%	720	2,664	3.2%
North Vancouver DM	82,562	3.9%	513.9	83.9%	9.9%	5.0%	721, 748	2,297	2.8%
Pitt Meadows	15,623	0.7%	183.0	85.9%	9.9%	3.6%	741	766	0.9%
Port Coquitlam	52,687	2.5%	1,826.2	84.3%	10.7%	3.7%	711	1,965	2.4%
Port Moody	27,512	1.3%	1,073.8	81.6%	13.7%	3.9%	412	1,720	2.1%
Richmond	174,461	8.2%	1,354.9	82.3%	11.8%	5.0%	722	6,022	7.3%
Surrey	394,976	18.7%	1,245.2	84.9%	10.9%	3.0%	726, 739	18,910	22.8%
Vancouver	578,041	27.3%	5,039.2	57.6%	25.1%	15.9%	401	13,793	16.6%
West Vancouver	42,131	2.0%	483.5	82.1%	9.4%	6.9%	410	2,730	3.3%
White Rock	18,755	0.9%	3,634.7	83.1%	8.3%	6.9%	729	597	0.7%
CMA Total	2,116,581		735.6	74.4%	16.5%	8.0%		82,919	

Data years: 2006 (demographics); 2003-2007 (collisions).

*It is not clear which police detachment is responsible for Lions Bay; it is likely included in one of the nearby provincial detachments operated by the RCMP, such as North Vancouver (748) or Bowen Island (742).

**Police detachment 709 (Coquitlam Provincial) covers several communities, including Anmore, Belcarra, and Coquitlam. In this table, collision counts for this code have been included under Coquitlam.

3.1.2 Traffic safety

In Ontario, vehicle registration and licensing, traffic safety programs, and the provincial highway network are administered by the province's Ministry of Transportation. Similarly, the Ministry of Transportation and Infrastructure is responsible for BC's highways; however, the Insurance Corporation of British Columbia – a provincial Crown corporation – oversees vehicle registration, driver licensing, and road safety. Municipalities in both provinces maintain the local and regional road networks. Traffic safety enforcement in Ontario is carried out by a combination of provincial and municipal police forces. BC, however, does not have a provincial police force, and only a handful of its communities have their own municipal forces; most of the province falls under federal RCMP jurisdiction.

Crash data are readily available for the two study regions. According to the National Collision Database (NCDB), during the 2003 to 2007 period, Toronto and Vancouver averaged approximately 98,000 and 17,000 reported collisions and 31,000 and 11,000 casualties (defined as fatalities and non-fatal injuries) each year, respectively (Table 3-3). Moreover, the CMAs account for approximately 14.7 and 2.5 percent, respectively, of annual reported crashes in Canada and 42.2 and 33.6 percent of those in their respective provinces[3]; reportable collisions are defined as those resulting in death, personal injury, or property damage in excess of $1,000 (ICBC, 2007; MTO, 2007).

Table 3-3: Incident counts by jurisdiction, 2003-2007

Incident type	*Toronto*	*Ontario*	*Vancouver*	*British Columbia*	*Canada*
Collisions					
Fatal	855	3,543	495	1,922	12,537
Injury	105,487	246,706	39,004	100,184	722,559
Property damage only	382,438	907,008	43,420	144,513	2,581,200
Total collisions	488,780	1,157,257	82,919	246,619	3,316,296
Victims					
Fatalities	934	3,942	538	2,157	14,055
Injuries	152,110	358,703	55,105	142,413	1,020,240
Total casualties	153,044	362,645	55,643	144,570	1,034,295

On a per capita basis, these data suggest that Vancouver is safer than Toronto, while both CMAs perform better than the national average in terms of casualty collision rates (Figure 3-4). Toronto has a marginally higher crash rate than the rest of Ontario, possibly because of significant commuter traffic. Vancouver has a substantially lower casualty rate than the rest of BC, likely in part because of the challenging terrain throughout most of the province.

In terms of property damage only (PDO) crashes, the NCDB tells a very different story – but this is almost certainly due to the lack of complete data for these minor crashes, especially in BC. For example, based on the NCDB, Toronto and Ontario are quite close to the national average of 3.5 PDO collisions per casualty collision (Figure 3-4); this metric provides a measure of crash severity: a higher ratio indicates that a smaller proportion of collisions involve death or injury. Vancouver and BC, however, fall well below the national rate. This suggests that PDOs occur far less frequently than casualty collisions or are significantly underreported. However, because the per capita casualty

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[3] According to 2003-2007 NCDB records, property damage only (PDO) collisions comprise a smaller share of total reported collisions in Vancouver (52.4 percent) than in Toronto (78.2 percent); and, as of 2006, Vancouver's per capita PDO involvement rate (401 per 100,000 population) was substantially lower than that for Toronto (1,339 per 100,000 population).

collision rate for Vancouver is similar to that in other jurisdictions and based on conversations with another BC municipality, Prince George, it is almost certain that underreporting of PDOs in BC is responsible for the discrepancy (J. Andrey, pers. comm., 2011). This has implications for the types of calculations that can be done with confidence (i.e., comparisons of absolute collision counts should therefore focus only on casualty collisions), although it is still reasonable to consider PDO crashes in relative risk calculations.

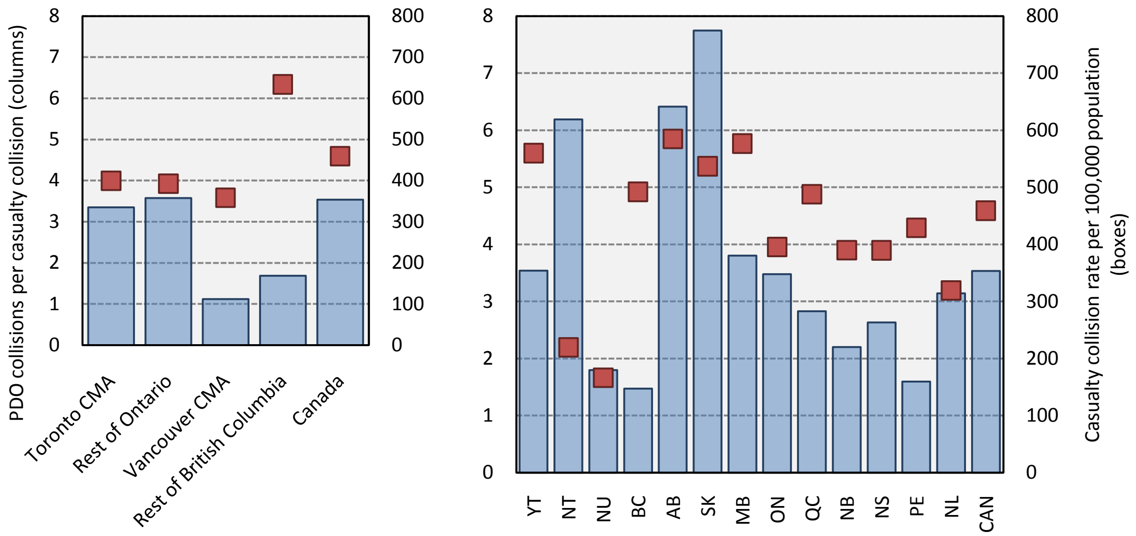

Figure 3-4: Safety comparison, CMAs and provinces, 2006

Table 3-4 highlights some general characteristics of the collisions that occurred in the two regions between 2003 and 2007. First, it is evident that there are differences in road mix between the study cities. Indeed, almost three-quarters of the nearly half million collisions in the Toronto CMA occurred on roads classified as ‘urban’, defined in the NCDB as having a speed limit of 60 km/h or less. Conversely, over 90 percent of the 83,000 crashes in Greater Vancouver took place on ‘urban’ roads. The difference is possibly because there are fewer high-speed highways crossing the Vancouver area. Nonetheless, the two regions are dominated by crashes that occur on low-speed roadways; this suggests that the higher design standards for high-speed roads play a significant role in reducing crash rates on these roads.

Table 3-4: Collision characteristics for study locations, 2003-2007

Collision characteristic	*Toronto*	*Vancouver*
Posted speed limit		
% less than 50 km/h	7.8	5.5
% 50 km/h	34.5	72.0
% 60 km/h	30.3	15.9
% 70 km/h	5.8	2.9
% 80 km/h	6.7	2.8
% 90 km/h	1.7	0.6
% 100 km/h or more	13.3	0.3
Seasonal pattern		
% Winter (Dec-Feb)	28.4	25.0
% Spring (Mar-May)	22.0	24.1
% Summer (Jun-Aug)	23.6	23.9
% Autumn (Sep-Nov)	26.0	27.0
Day of week		
% Monday	14.2	13.1
% Tuesday	15.0	13.5
% Wednesday	15.3	14.2
% Thursday	15.7	14.5
% Friday	17.0	16.1
% Saturday	12.9	15.5
% Sunday	9.9	13.1
Time of day		
% Late night (0:00-5:59)	6.8	12.8
% A.M. rush (6:00-9:59)	19.7	14.1
% Midday (10:00-14:59)	26.8	25.3
% P.M. rush (15:00-18:59)	31.1	27.2
% Evening (19:00-23:59)	15.5	20.6
Light condition		
% Daylight	72.1	58.5
% Dawn/dusk	4.7	6.7
% Darkness	23.2	34.8
Weather condition		
% Rain	11.1	22.5
% Snow	7.6	1.6
% Frozen precipitation	0.9	0.1
% Visibility limitation	1.1	1.0
Road surface condition		
% Wet	19.6	35.7
% Snow, slush, or ice	10.7	3.3

In terms of seasonality, both CMAs have a similar pattern, with close to one-quarter of annual crashes occurring in each three month period. The biggest difference is apparent in the winter months, during which 28.4 percent of Toronto crashes occur, as opposed to 25 percent in Vancouver;

this is likely attributable to the effect of snow, frozen precipitation, and icy roads. Crash distributions are also similar by day of the week, with the highest and lowest crash counts on Friday and Sunday, respectively. Notable time of day differences are evident between the two regions; a higher proportion of Toronto crashes take place in the morning and afternoon rush hours, probably because of heavy commuter traffic, while more crashes occur in Vancouver between 7:00 p.m. and 6:00 a.m. This trend is confirmed by light conditions: slightly more than one-third of Vancouver crashes happen after dark, compared to 23 percent in Toronto. Precipitation was present for one-fifth of Toronto crashes, compared to one-quarter of those in Vancouver. Finally, the GTA has fewer collisions than Vancouver on wet, snowy, or icy roads. To a large extent, these differences are explained by the two regions' fundamentally different climates, as detailed in Section 3.1.3.1. Overall, therefore, the crash characteristics of these two regions are fairly similar – with some notable differences in weather-related risks.

3.1.3 Weather and climate

From a climatological perspective, Toronto and Vancouver represent ideal study locations as both have a relatively complete historical record of weather dating back to 1937. Each city has a major international airport that includes a principal climate station meeting World Meteorological Organization (WMO) equipment and reporting standards. The airports are situated relatively centrally within each region, such that reported conditions are likely to be mostly representative of the greater urban area (cf. Andrey and Olley, 1990). In addition, the cities have distinctly different climates (Table 3-5) and thus are likely to provide interesting insights when results for the two urban regions are compared.

Table 3-5: Climate summary for study locations, 1971-2000

Station	*Toronto Pearson International Airport*	*Vancouver International Airport*
Climate station ID	6158733	1108447
Latitude, longitude	43°40' N, 79°37' W	49°11' N, 123°10' W
Elevation (m)	173.4	4.3
Annual # rain days	111.8	161.3
Annual # snow days	46.5	10.9
Annual rainfall (mm)	684.6	1154.7
Annual snowfall (cm)	115.4	48.2
Daily average temp., Jan (°C)	-6.3	3.3
Daily average temp., July (°C)	20.8	17.5
Annual days with max temp ≤ 0 °C	57.2	4.5
Annual days with max temp > 30 °C	12.6	0.2

3.1.3.1 Climate normals, 1971-2000

Toronto is located in the Great Lakes-St. Lawrence Lowlands climatic zone and is characterized by a temperate continental climate with short, cold winters and warm, humid summers as well as reasonably consistent year-round precipitation (Bone, 2005). The nearby Great Lakes have a moderating effect on temperature, with warmer winters and slightly cooler summers than similar inland locations (Phillips, 1990). As Figure 3-5 illustrates, a clear seasonal temperature pattern is observed, with a 25 to 30 degree difference between average winter and summer temperatures. Roughly 16 percent of all days fall below zero degrees Celsius while a handful of days each year have extremely hot temperatures. The GTA tends to see great variation in day-to-day weather systems resulting from the convergence of several air masses with high and low pressure systems (Phillips, 1990). During the winter months cold, dry, and stable Continental Arctic air comes from the northwest, bringing snow and frozen precipitation as it follows the primary North American storm track (jet stream) eastward over the Great Lakes and surrounding lowlands (Phillips, 1990). Hot, humid, and unstable Maritime Atlantic and Maritime Tropical air comes from the southeast in the summer, bringing frequent thunderstorms as it clashes with cooler, more stable Arctic and Pacific air from the northwest (Phillips, 1990). In terms of total accumulation, a fairly uniform precipitation distribution is found throughout the year: precipitation is measured on approximately 40 percent of all days and Pearson Airport receives roughly 40 to 80 millimetres each month. As with temperature, however, there is a distinct seasonal pattern to Toronto’s precipitation mix. Some rain is measured year-round (occurring on 31 percent of all days and observed on seven percent of all hours; Andrey et al., 2005), although it is most common from mid spring to late fall, where monthly accumulation typically approaches or exceeds 75 millimetres (Figure 3-6). May and October in particular experience the peak annual number of rain days, while fewer occur in the warm summer months despite the July to September period having the greatest total accumulation and highest number of heavy rain days (i.e., those with at least 25 millimetres) associated with thunderstorms and convective storm activity. The winter months, from December to early March, are typically not as wet as summer and receive a greater share of precipitation as snow or freezing rain. Overall, snow falls on roughly 13 percent of all days and winter precipitation is observed during six percent of all annual hours (Andrey et al., 2005); snow represents about 15 percent of total precipitation accumulation.

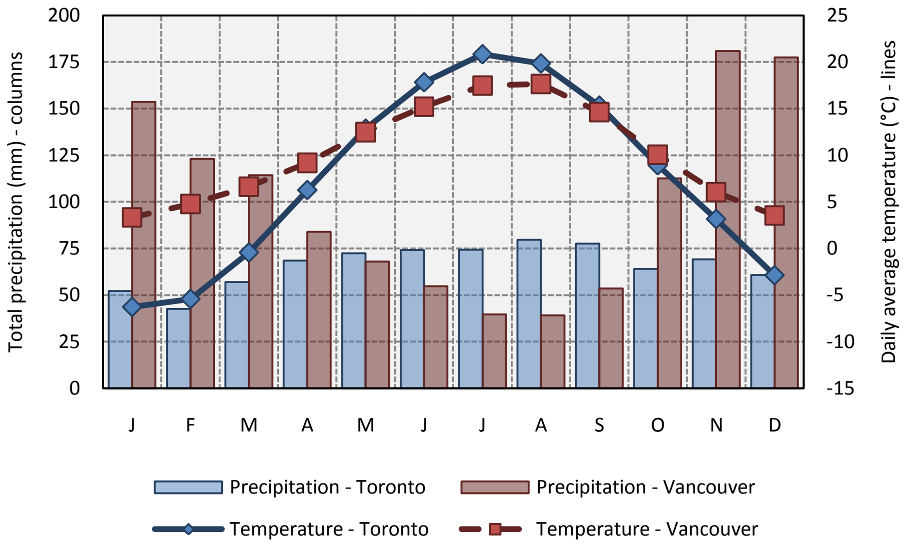

Figure 3-5: Mean monthly total precipitation and air temperature, 1971-2000

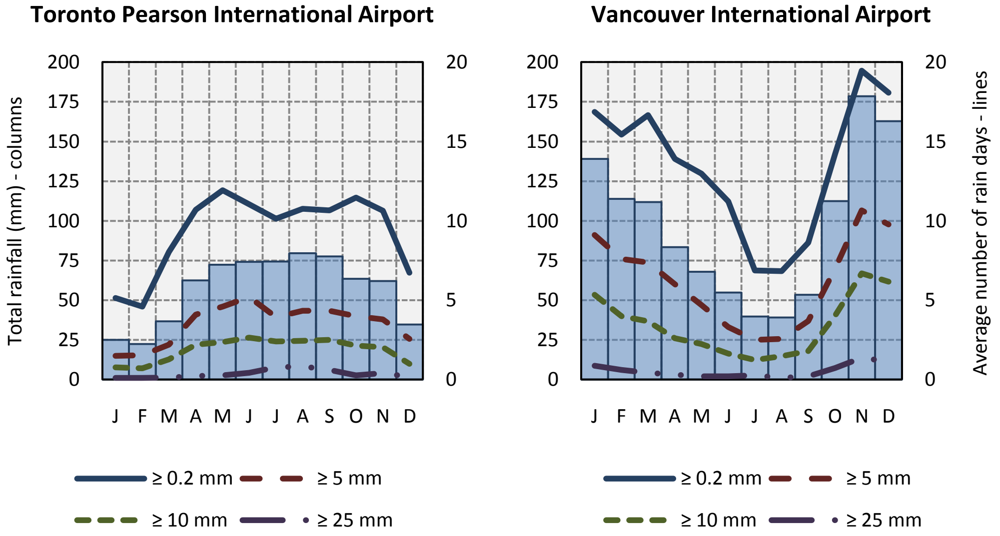

Figure 3-6: Mean monthly total rainfall and number of rain days, 1971-2000

Vancouver, with its mild winters, pleasant summers, and high annual precipitation, has a maritime temperate climate and lies within the Pacific Coast climatic zone (Bone, 2005). A year-round moderating effect is provided by the warm Alaska Current flowing northward in the nearby Pacific Ocean and warm Pacific air carried onshore by the jet stream (Phillips, 1990). During the winter months the mild, stable Maritime Polar and unstable Maritime Arctic air masses combine to bring cloud cover and frequent showers, while the Maritime Polar air mass provides a warm, dry summer climate (Phillips, 1990). Vancouver sees a more consistent and less drastic seasonal temperature range than Toronto, with a difference of roughly 14 degrees Celsius from January to July average temperatures (Figure 3-5). Average winter temperatures are typically 3 to 4 degrees, while mean summer temperatures are 17 to 18 degrees. Only a handful of days fall below freezing each year, and the region experiences very few extremely hot days. Compared to Toronto, Vancouver Airport sees 45 percent more rain days each year, 70 percent more rainfall accumulation, only one-quarter of the snow days, and about 40 percent of the total snowfall. Rain falls throughout the year in Vancouver (measured on 44 percent of all days and observed in 16 percent of all hours; Andrey et al., 2005), although there are notably drier conditions during the summer months (Figure 3-6). Only 11 percent of annual precipitation is received between June and August compared to roughly 43 percent between November and January, the peak months of the October to April rainy season. In addition, heavy rainfall days (i.e., at least 25 millimetres) occur most often in the late fall and early winter. Each year, snow tends to fall on less than three percent of days and it is observed in approximately one percent of all hours (Andrey et al., 2005); snowfall accounts for about four percent of total annual precipitation accumulation. Finally, it should be noted that the northern portion of the Vancouver region experiences significantly more annual precipitation (upwards of 1700 millimetres) than the airport weather station due to the strong orographic effect of the Coast Mountains; with increasing distance north and east of the airport precipitation increases greatly (Phillips, 1990). Nonetheless, the Vancouver Airport climate station is used in this study due to its long historical record and proximity to the most populous areas of the urban region.

3.1.3.2 Study period, 2003-2007

To establish the implications of rainfall for road safety, a five-year study period (2003-2007) was selected; this decision was based on the availability of collision data, as detailed in Section 3.2.1.1. Overall, this period is slightly warmer than the 1971-2000 climate normals for both Toronto and Vancouver (Table 3-6). Moreover, the study years, on average, are marginally drier for Toronto, despite having more rain days than normal, while Vancouver had more rain days and greater rainfall accumulation than normal. Annual graphs for each city are provided in Appendix B.

Table 3-6: Climate summary for five-year study period, 2003-2007

Station/variable	*5-year average*	*2003*	*2004*	*2005*	*2006*	*2007*	*1971-2000 normal*
Toronto Pearson International Airport							
Daily average temperature (°C)	8.7	7.9	8.2	9.0	9.7	8.9	7.6
Total precipitation (mm)	775.1	895.6	755.0	766.7	865.7	592.7	792.8
Total rainfall (mm)	663.9	752.0	643.3	612.2	833.9	478.2	684.6
Annual # rain days	115.8	111.0	124.0	98.0	140.0	106.0	111.8
Annual # snow days	47.8	51.0	53.0	57.0	24.0	54.0	46.5
Vancouver International Airport							
Daily average temperature (°C)	10.8	10.9	11.4	10.8	10.7	10.2	10.1
Total precipitation (mm)	1215.9	1,106.1	1,210.6	1,215.2	1,225.2	1,322.4	1,200.1
Total rainfall (mm)	1184.2	1,086.2	1,200.8	1,183.8	1,176.0	1,274.4	1,156.2
Annual # rain days	173.6	159.0	178.0	158.0	176.0	197.0	161.2
Annual # snow days	7.2	7.0	3.0	9.0	6.0	11.0	10.9

Toronto saw above average annual temperatures in all five study years, while precipitation trends varied from year to year.

- During 2003, Toronto experienced a colder, drier winter than normal followed by a slightly cool spring in which May precipitation was double the average. A warm, dry summer was extended into September, kicking off a mild and wet fall season that included several days with over 20 millimetres of rain and two of Toronto's top ten rain days for 2003-2007. December was several degrees warmer than normal.
- The winter of 2004 started late, and was short but cold. Spring came early, with February and March temperatures two to three degrees Celsius above average, before returning to normal levels through August. Following a wet spring, rainfall decreased before peaking in July. As with the previous year, fall 2004 was uncharacteristically mild, but saw 40 percent less rainfall than normal.
- Heading into 2005, which is among Toronto's ten highest recorded snowfall years – and, interestingly, also the sixth warmest – temperatures alternated between being above and below normal every month from December through May, before a markedly hotter than usual summer and fall. Rainfall in 2005 was well below average, with a particularly dry period from early spring through mid summer, until higher than normal rainfall – including

the study period's first and third largest accumulations – came in August. Autumn rainfall was marginally above average, leading into a wet, rainy winter.

- As would be expected for the second hottest year on record, every month of 2006 saw higher than average temperatures, with January especially mild at 6.5 degrees Celsius above normal. The year also holds the distinction of having the lowest snowfall total in Toronto's recorded history, a mere 32 centimetres. A fairly dry summer – notwithstanding rainfalls of 33.4 and 35.2 millimetres on July 10th and 12th – was followed by a wetter than normal fall.
- A mild December 2006 was a prelude to above normal temperatures for most of 2007, despite a cold February. Rainfall in 2007 – the fourth lowest total on record – was substantially below average in almost every month, save a rainy autumn season to finish the year.

As with Toronto, Vancouver experienced above average annual temperatures in all five study years. Moreover, all but one year were wetter than normal.

- After a mild January, the year 2003 saw above average spring rainfall as well as summer and fall seasons that were warmer and drier than normal, notwithstanding an especially wet October in which 140.8 millimetres of rain fell over a two-day period. Moreover, the third heaviest rain day of the study period (with 62.6 millimetres) occurred in late November.
- Temperatures were one to two degrees Celsius above normal and rain marginally less abundant throughout most of 2004 – the city's second hottest year on record – but August and September rainfall accumulation that was two to three times the average amount contributed to an elevated total for the year. An event of particular note occurred in September, when over 90 millimetres of rain was measured; this represented almost eight percent of the entire year's total and was the highest single-day rainfall accumulation of the study period.
- Mild temperatures in December 2004 began an average winter 2005 in which January and February saw rainfall that was 60 percent above and below normal, respectively; the January increase is largely attributable to one week during which 202 millimetres fell – nearly 90 percent of the monthly total. Temperatures throughout most of the year were slightly above seasonal, while a noteworthy trend in rainfall was not apparent.

- In 2006, a warm, rainy January – with rain on 29 of 31 days – was followed by a prolonged dry period with elevated temperatures until November, when higher than average rainfall was accompanied by several snow days to close out the month.
- Finally, 2007 saw temperatures that were only marginally above average, mostly because of a slightly warmer spring and July. Precipitation for the year was fairly average, aside from spikes in March, June-July, and September-October; these were offset by less than normal accumulation in May, August, and November.

3.1.3.3 Future climate, 2050s

Looking ahead, GCM projections suggest that Toronto and Vancouver are likely to experience climate change differently. In broad terms, Toronto is likely to become warmer and slightly wetter over the next 40 years. It is anticipated that Vancouver will also experience a slightly warmer climate, although models differ in their precipitation projections: some project increased annual precipitation while others suggest a marginal drying trend. Detailed discussion of possible climate futures for the two regions follows in Section 4.2.2. The distinct climatic differences between the two study regions are likely to remain into the near future, making Toronto and Vancouver suitable for comparison from a present and future climatological perspective.

3.2 Safety analysis, 2003-2007

3.2.1 Data sources

3.2.1.1 Collisions

The empirical analysis of present-day rainfall-related crash risk is based on the integration of two large government datasets. Collision data were obtained from the National Collision Database (NCDB) maintained by Transport Canada for the years 2003 to 2007, which is the most recent period for which data are available (Transport Canada, 1994). Although previous Canadian studies (e.g., Andrey, 2010) have utilized longer time series, the current study period is limited to the most recent five years due to data compatibility issues (i.e., available NCDB data are in a different format as of 2003) as well as the availability of PDO collision records for this period.

NCDB data are compiled from provincially assembled police records, which are based on forms completed by the investigating officer at a crash scene or by involved parties at collision reporting centres. The hierarchical database – with three levels: collisions, vehicles, and persons – contains detailed information on all reported collisions nationwide, including timing and location, collision configuration, driver and vehicle characteristics, injury or damage severity, and general environmental context. It is the most readily accessible source of Canadian crash information.

It should be noted that the completeness of police data has been questioned in comparisons with hospital records (Aptel et al., 1999; Lopez et al., 2000; Amoros et al., 2008), social surveys (Harris, 1990), and insurance claims (Kallan et al., 2009; Mills et al., 2011). In a meta-analysis of official crash statistics from 13 countries, Elvik and Mysen (1999) found average reporting levels of 95, 70, 25, and 10 percent for fatal, serious, slight, and very slight injuries, respectively. Reporting rates for PDO collisions are uncertain due to data limitations, but are likely even lower (Evans, 1991). This is because, in part, less severe collisions tend to be self-reported; drivers may choose not to report minor PDO crashes so that insurance company involvement can be avoided (Evans, 1991). Despite the issues identified with police data, the NCDB represents a valuable information source due to its wide spatial and temporal coverage and the likelihood that it captures casualty collision rates with reasonable accuracy (cf. Roberts et al., 2008). Indeed, recent work by Mills et al. (2011) reported similar estimates of precipitation-related casualty collision risk in Winnipeg, Canada, using two independent datasets: the NCDB and public insurance records.

Data completeness remains an issue for estimating PDO rates and counts, especially given the apparent differences in reporting between the two study areas. Figure 3-7 presents a breakdown of the PDO rate per casualty collision for each police detachment in the two study regions. With the exception of a few detachment codes that have very low collision counts[4], most Toronto-area jurisdictions fall within a range of three to six PDOs per casualty collision. This and the fact that the aggregate CMA rate is nearly identical to the provincial and national averages of 3.5 (Figure 3-4) suggest that reporting of PDO collisions in the Toronto region occurs at roughly the national rate. Figure 3-7 is also indicative of significant PDO underreporting in Greater Vancouver, where no police detachment has a PDO per casualty collision rate higher than 2.1. Moreover, the overall CMA

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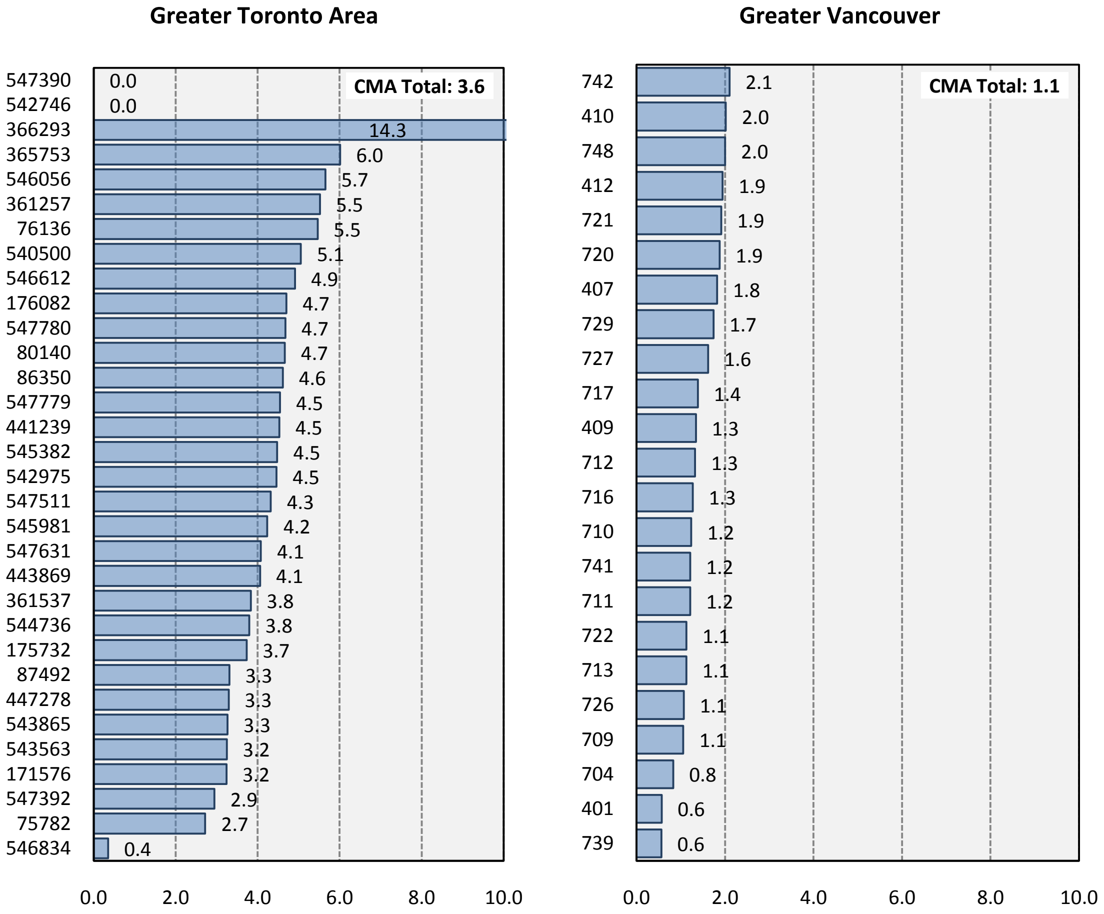
[4] In the Toronto CMA, police detachment codes 547390 and 542746 refer to CFB Toronto and East York, respectively. These have a PDO per casualty collision ratio of zero because each includes only one PDO crash and no casualty collisions over the study period. Similarly, code 546834 represents Scarborough, where the majority of crashes involved casualties (231), compared to 82 PDO incidents. These three detachment codes are underutilized and crashes within these areas have been assigned to the less geographically specific Toronto detachment (547392), which covers the entire City of Toronto proper. Conversely, the high ratio (14.3) for Peel Region (code 366293) reflects underutilization in favour of more specific spatial location, as most crashes within the region fall within its constituent municipalities of Brampton (361257), Caledon (361537), and Mississauga (365753).

rate of 1.1 PDO collisions per casualty collision is substantially lower that the national average, although similar to BC's rate (1.5). Accordingly, it is estimated that approximately two-thirds of Vancouver PDO collisions are missing from the NCDB dataset. This approximation is consistent with insights provided by collision data for the City of Prince George, BC, where insurance claims for collisions outnumber those reported in the NCDB by three to four times (J. Andrey, pers. comm., 2011). Any comparison of absolute incident rates or counts should therefore not rely on PDOs and should focus only on casualty collisions. However, use of PDOs in relative risk calculations is appropriate because there is no apparent trend in the underreporting bias; rates are roughly the same across the geographic regions and are not affected by weather condition (Table 3-7).



Numbers on y-axis are police detachment codes; refer to Table 3-1 and Table 3-2 for corresponding municipality and police detachment names. For each study region, CMA total refers to the overall ratio of PDO collisions per casualty collision across all police detachments in the region.

Figure 3-7: PDO collisions per casualty collision across police detachments, 2003-2007

Table 3-7: Prevalence of weather condition in collision reports by crash severity, 2003-2007

	Toronto			*Vancouver*		
Collision severity	*No weather*	*Weather*	*Unknown*	*No weather*	*Weather*	*Unknown*
Total collisions	78.7%	20.9%	0.4%	73.6%	25.1%	1.3%
Fatal	79.9%	20.0%	0.1%	77.4%	21.8%	0.8%
Injury	81.4%	18.2%	0.4%	74.5%	24.7%	0.8%
PDO	78.0%	21.6%	0.4%	72.7%	25.4%	1.9%

3.2.1.2 Weather

NCDB records provide basic information on the environmental context of each incident, including weather (clear, rain, snow, etc.) and road surface (wet, icy, etc.) conditions at the time of the collision. This information, however, relies on the judgement of the police officer attending a crash scene or, in some cases, the involved parties. Moreover, official crash reports do not contain information on precipitation intensity or other atmospheric variables (e.g., temperature, visibility) that may be associated with inclement weather events. A more detailed source of weather information is therefore necessary for in-depth analysis of weather-related crash risk (Brodsky and Hakkert, 1988). Theoretically, the most accurate source is road weather information systems (RWIS) – roadside weather stations that provide real-time data on specific atmospheric conditions in the immediate vicinity. These have the advantage of being temporally and locationally precise and are therefore ideal for analyses focused on individual highway segments; however, RWIS networks do not currently have wide spatial coverage and typically do not provide information on precipitation accumulation.

This thesis relies on historical climate records acquired from Environment Canada's digital archive (Environment Canada, 2010); detailed observational records are available for many variables at different temporal scales (e.g., hourly, six hourly, and daily) from a network of weather stations nationwide. Specifically, daily climate records were obtained for two principal weather stations: Toronto Pearson International Airport and Vancouver International Airport. Although these do not offer the spatial precision of RWIS, they provide an excellent historical record over more than 70 years and are reasonably representative of weather conditions experienced throughout their greater urban regions. Indeed, previous research by Andrey and Olley (1990) reported almost 85 percent agreement between weather conditions as identified in crash records and from hourly observations at airport weather stations. Table 3-8 illustrates this point for the two study regions by comparing daily weather condition as recorded in NCDB crash reports and at airport weather stations. Despite a modest difference in annual days with precipitation, both study locations have nearly identical weather reporting trends. On days with zero percent of CMA collisions reporting weather, it is virtually certain that the airport received no precipitation. Similarly, when over half of a given day's total crashes indicate the presence of inclement weather, it is almost certain that precipitation was measured at the airport. The middle category (days with more than zero but less than half of crashes indicating weather) is illustrative of days where the two data sources do not universally agree (i.e., no rain measured at the airport but collisions reporting rain in other parts of the region, or vice versa). Of the three situations, this middle category is most frequent, though it occurs substantially more often (85 percent of days, i.e., 1,545/1,826) in Toronto than in Vancouver (half of days, i.e., 905/1,826).

Table 3-8: Weather condition as recorded in collision reports and climate data, 2003-2007

*% of daily collisions reporting weather**	*Daily precipitation occurrence at airport*		*Count of days*
	No precipitation	*Precipitation ≥ 0.2 mm*	
Toronto			
0%	100.0%	0.0%	100
> 0 to 50%	61.9%	38.1%	1,545
≥ 50%	3.9%	96.1%	181
All days	58.2%	41.8%	1,826
Vancouver			
0%	98.9%	1.1%	376
> 0 to 50%	60.7%	39.3%	905
≥ 50%	3.3%	96.7%	545
All days	51.4%	48.6%	1,826

*Percentage of daily crashes with valid weather condition that reported the presence of inclement weather (rain, snow, or frozen precipitation)
All percentages sum to 100% across rows.

3.2.2 Analytical approach

3.2.2.1 Matched pair approach

To estimate the risk associated with rainfall, a matched-pair (or case-comparison) study design is adopted (as described in Andrey et al., 2003, after Codling, 1974). In the absence of real travel exposure data, this approach reasonably controls for the influence of time-dependent variables such as seasonality, time of day, and traffic volume by assuming that travel patterns are similar from one week to the next, when averaged over many observations. It does not, however, account for the slight reductions in travel that are typically observed during inclement weather conditions. Risk estimates, therefore, are likely to be conservative in nature.

A range of temporal scales have been examined in previous studies, from variable-length individual storms (Andrey, 1989) to six hourly (Andrey, 2010; Sherretz and Farhar, 1978; Changnon, 1996), daily (Eisenberg, 2004; Codling, 1974), and monthly (Eisenberg, 2004) time steps. Generally, as the temporal resolution becomes coarser, the effect of weather on collision rates becomes diluted as more dry hours are included in each event period. Thus, storm-level analysis is ideal as it best represents the true driving conditions experienced throughout the entire duration of a precipitation event. The present research, however, is based on a daily analysis to facilitate comparison with climate change scenarios. Accordingly, crash data were aggregated to a daily level based on a 24-hour climatological day beginning at 0600 GMT (1:00 a.m. local time in Toronto and 10:00 p.m. in Vancouver). Next, the two datasets were merged to facilitate the definition of matching control days.

3.2.2.2 Event and control definitions

Historical climate records include hourly weather observations and rainfall amounts as well as daily temperature and precipitation measurements. However, climate change scenarios typically produce only daily projections of minimum, maximum, and mean temperature and total precipitation amount, with no indication of precipitation type (i.e., rain, snow, sleet, etc.). Accordingly, a surrogate indicator of rainfall was necessary, and the criteria used in defining events and controls had to be relaxed from those used in previous studies (e.g., Andrey et al., 2003; Andrey 2010) so that a sufficient sample size was retained.

Here, a rainfall event is defined as a 24-hour day with at least 0.2 millimetres total precipitation and daily minimum temperature of at least one degree Celsius; the same criteria are also used to identify future rain days from the climate model outputs. A minimum precipitation amount of 0.2 millimetres was selected for several reasons. This amount represents the common definition of measurable precipitation and is also used as the minimum threshold for counting annual rain days in climate normals (Phillips, 1990; Environment Canada, 2011). Moreover, several previous studies have used 0.2 millimetres as the lower limit for light rainfall events (e.g., Andrey, 1989; Changnon, 1996; Eisenberg, 2004). Finally, Harwood et al. (1988) suggested that as little as 0.01 inches (0.254 mm) of rain in an hour (i.e., any measurable hourly rainfall amount) is likely to wet the road surface and reduce tire friction, possibly contributing to collisions.

Table 3-9: Number of days with at least 0.2 mm measured rainfall, 1938-2007

Daily minimum temperature	*# days with measured rain*	*# days with measured rain and snow*	*% of rain days with snow*
Toronto			
>0 °C	5,702	94	1.65
≥1 °C	5,379	28*	0.52
≥2 °C	4,976	10	0.20
Vancouver			
>0 °C	10,258	113	1.10
≥1 °C	9,886	40**	0.40
≥2 °C	9,208	11**	0.12
*Two during five-year study period: December 1, 2004, with 9.7 mm rain, 2.5 cm snow, and two hours of observed frozen precipitation; April 15, 2007, with 0.8 mm rain, 0.8 cm snow, and five hours of observed frozen precipitation. **One during study period: April 4, 2003, with 5.6 mm rain, 0.2 cm snow, and zero hours of observed frozen precipitation.			

A second criterion, daily minimum temperature of at least one degree Celsius, is also used in order to eliminate snow and other frozen precipitation, as well as icy roads, from the analysis while maintaining the ability to examine rainfall year-round. Norrman (2000) suggested that winter-time precipitation that falls while the air temperature is above zero degrees and the road surface temperature is below freezing is likely rain or sleet that freezes to the road surface. Moreover, as air temperature increases, the probability of snowfall quickly decreases (Norrman, 2000). To arrive at the cut off of one degree, the historical daily climate record was checked for days in which both rain and snow were measured, as shown in Table 3-9, where a clear breaking point is evident between zero and one degree. For both cities, the count of such days relative to the overall number of rain days proved to be sufficiently small (roughly half a percent) that analysis could proceed. The removal of days with below freezing temperatures ensured that the analysis examined a subset of rainfall days that is in entirely liquid form, with no danger of freezing. However, it should be noted that even with this criterion, two days within the study period for Toronto (and none for Vancouver) contained some hourly observations of frozen precipitation. Moreover, because of the second criterion, results based on this subset of rainfall events are unavoidably conservative in terms of the number of rain days included in the analysis: approximately one-fifth of all rain days and total accumulation are removed from the analysis for Toronto and just under ten percent for Vancouver (Table 3-10). Indeed, this definitional criterion has a greater impact on Toronto than Vancouver because more Vancouver rain days inherently meet the daily minimum temperature threshold of one degree, while Toronto has a greater number of days during which rain is measured and temperatures fluctuate above and below freezing. In order to avoid confusion throughout the remainder of the thesis, the terms ‘rainfall’ or ‘rain day’ generally refer to liquid rain days (i.e., daily minimum temperature ≥ 1°C), unless specifically noted otherwise.

Table 3-10: Rain days and liquid rain days, 2003-2007

	All rain days		*Liquid rain days (≥ 1°C)*	
Rainfall amount	*# days*	*Total mm*	*# days*	*Total mm*
Toronto				
0.2 to 4.9 mm	362	576.7	282	459.1
5.0 to 9.9 mm	104	698.3	80	535.0
10.0 to 19.9 mm	73	1,007.2	57	779.4
≥ 20.0 mm	40	1,037.4	36	935.6
Sum	579	3,319.6	455	2,709.1
Vancouver				
0.2 to 4.9 mm	503	905.1	454	807.2
5.0 to 9.9 mm	160	1,110.2	154	1,070.6
10.0 to 19.9 mm	144	1,958.2	135	1,845.8
≥ 20.0 mm	61	1,947.7	58	1,879.5
Sum	868	5,921.2	801	5,603.1

In Toronto, 455 days (one-quarter of all days) met the event criteria, compared to 801 (44 percent of all days) for Vancouver. Controls are defined as days with zero precipitation, either one week immediately before or after the event day. Statutory holidays and associated weekends are excluded from both events and controls (refer to Appendix C for holiday definitions), as these periods typically involve altered traffic patterns (Andrey et al., 2003). This reduced the number of events by approximately eight to nine percent and primarily affected the summer months, although the holidays are fairly evenly distributed throughout the year. During the matching process, each event was checked in chronological sequence for an available control seven days prior. When a match was found, the control was removed from the pool of available days for matching, as each control day could be used only once. A second stage of matching followed, in which remaining unmatched events were checked for corresponding controls one week later. Events for which a suitable control could not be found are removed from the analysis; in Toronto, 114 of 419 events (27 percent) were dropped for this reason, while Vancouver lost 315 of 731 events (43 percent). Overall, roughly two-thirds and one-half of all liquid rain days are included in event-control pairs for Toronto and Vancouver, respectively.

Table 3-11 indicates a seasonality in matched pairs for Toronto, with nearly 90 percent falling within the April to November period; however, this is not surprising as 90 percent of liquid rain days also occur in this period. There is, in fact, a remarkably good match between the distributions of event-control pairs and rain days throughout the year. The winter months experience greater temperature fluctuations and fewer days meet the temperature requirements for liquid rainfall. Moreover, the prevalence of short but intense convective rainfall activity in the summer allows matches to be found relatively easily in this period for the Toronto region. On the other hand, event-control pairs are distributed relatively evenly throughout the year for Vancouver, suggesting that slightly fewer matches occurred in the rainy fall-winter period than would be expected along with a higher than expected proportion of matches in the dry summer months. It is no surprise, however, that it is more difficult to find control days in a month with more rain events, and vice versa for dry months. Working at a finer temporal scale (e.g., three- or six-hourly) would likely result in more matches, and relative risk estimates would almost certainly be higher because events would be less diluted by the presence of non-rainfall hours.

Table 3-11: Seasonal distribution of event-control pairs, 2003-2007

	Toronto		*Vancouver*	
Month	*% of matched pairs*	*% of rain days**	*% of matched pairs*	*% of rain days*
Jan	2.0%	2.6%	8.4%	11.2%
Feb	0.3%	0.2%	9.1%	7.7%
Mar	4.6%	4.0%	9.6%	11.7%
Apr	8.2%	9.0%	9.4%	9.9%
May	12.8%	13.6%	9.4%	7.9%
Jun	11.8%	10.1%	8.7%	7.6%
Jul	12.1%	12.7%	6.0%	3.9%
Aug	12.5%	10.5%	6.3%	3.7%
Sep	12.5%	11.4%	7.9%	6.0%
Oct	11.5%	14.3%	9.4%	10.9%
Nov	8.9%	8.8%	8.9%	10.2%
Dec	3.0%	2.6%	7.0%	9.2%
Count	305	455	416	801
*Includes all annual days with ≥ 0.2 mm liquid rainfall				

Previous studies have utilized somewhat more restrictive criteria for defining event-control pairs; for example, Andrey (1989) required that no precipitation was observed in the 6 hours preceding controls in order to allow sufficient time for wet roads to dry. Moreover, previous attempts have been made to ensure representativeness of single-point airport station weather observations across an entire city or region by reconciling weather variables in crash data with climate records. As per Codling (1974), this has typically required that at least 50 percent of crash reports indicate the presence of precipitation during a given event period – and no more than 10 percent during controls. While this tends to remove a significant number (e.g., one-third; Andrey, 1989) of event-control pairs from the sample, it ensures a good match between weather reported in climate records and that identified in crash reports. In this thesis, this step was not taken because the temporal unit of analysis is the day, and in any 24-hour period it is unusual for it to rain continuously. Accordingly, it is recognized that events herein are likely to include more non-rain hours than those in previous research.

3.2.2.3 Relative risk calculation

In order to estimate rainfall-related collision risk for the 2003-2007 period, odds ratios are calculated, as per Johansson et al. (2009). These represent the probability of a collision occurring during one condition (i.e., inclement weather) relative to the odds of a crash during a different condition (i.e., clear conditions). Each matched pair produces four counts, as shown in Table 3-12.

Table 3-12: Description of counts for calculating odds ratios

Count	*Description*
A	Collisions during the control period
B	Collisions during the event period
C	Estimate of safe outcomes* during the control period
D	Estimate of safe outcomes* during the event
*Safe outcomes represent the number of trips during which no collision occurred; these are large in urban areas, and can therefore be estimated somewhat arbitrarily (e.g., one million).	

From these counts, an odds ratio is calculated for each matched pair as follows:

$$Odds\ ratio = \frac{(B/D)}{(A/C)} = \frac{(Collisions\ during\ rainfall\ /\ Safe\ outcomes\ during\ rainfall)}{(Collisions\ on\ clear\ days\ /\ Safe\ outcomes\ on\ clear\ days)}$$

The logarithm of the odds ratio (y_i) is then computed, for which the variance (v_i) is calculated as:

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

Estimates of risk can be combined from odds ratios for individual matched pairs using one of two methods: the fixed-effects model and the random-effects model. The fixed-effects model assumes that the variation in risk estimates is random only, while the random-effects model adds a variance component to each matched pair's statistical weight. Using the fixed effects model, the statistical weight (w_i) – which is inversely proportional to the variance – is calculated for each matched pair as:

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

The weighted mean effect on a set of g matched pairs is then calculated:

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

An overall relative risk estimate is obtained by taking the antilog of this value. To test the validity of the variation assumption in the fixed-effects model, a Q test is performed as follows (with $g - 1$ degrees of freedom); if the test statistic is statistically significant, a random-effects model is used instead.

$$Q = \sum_{i=1}^{g} w_i y_i^2 - \frac{\left(\sum_{i=1}^{g} w_i y_i\right)^2}{\sum_{i=1}^{g} w_i}$$

In this thesis, all Q test statistics were found to be statistically significant, so a variance component (σ_θ^2) is calculated for use in the random-effects model:

$$\sigma_\theta^2 = \frac{[Q - (g - 1)]}{c}$$

Where c, an estimator, is:

$$c = \sum_{i=1}^{g} w_i - \left[\frac{\sum_{i=1}^{g} w_i^2}{\sum_{i=1}^{g} w_i}\right]$$

In the random-effects model, the variance for each event-control pair becomes:

$$v_i^* = \sigma_\theta^2 + v_i$$

And each pair's statistical weight becomes:

$$w_i^* = \frac{1}{v_i^*}$$

A new weighted mean estimate for the set of matched pairs is calculated as:

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

Again, an overall estimate of relative risk is obtained by taking the antilog of this value. The standard error of the risk estimate is calculated as:

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

The standard error is used to calculate 95% confidence intervals for the weighted mean estimate of effect:

$$95\%\ confidence\ interval = risk\ estimate\ \pm 1.96 \times SE$$

Finally, anti-logging these values produces upper and lower confidence limits for the risk estimate. The latter two steps can also be illustrated as:

$$95\%\ C.I. = exp\left[\left(\sum_{i=1}^{g} w_i^* y_i \,/ \sum_{i=1}^{g} w_i^*\right) \pm 1.96 * \left(1/\sqrt{\sum_{i=1}^{g} w_i^*}\right)\right]$$

3.2.2.4 Rainfall categories

Many studies have examined the effects of different hourly rainfall intensities (e.g., millimetres per hour) on driver performance and crash risk; however, some difficulty is typically encountered in analyses using a daily temporal resolution. Such difficulty comes primarily from the fact that only measures of total rainfall accumulation, and not intensity throughout the course of a rainfall event, are available at the daily level. This masks the fact that different types of rain days may occur that result in similar accumulations (e.g., low intensity rainfall for many hours versus one or two hours of intense thunderstorms and precipitation). Accordingly, to better understand the changes in risk associated with different daily rainfall amounts, care must be taken to select rain categories that reasonably capture a range of rain event types while simultaneously ensuring a sufficient sample size for robust analysis.

Table 3-13 provides selected examples of rain categories used in previous safety studies. Generally speaking, it is evident that most investigations have employed fairly broad (e.g., light, medium, heavy) categories with somewhat arbitrary break points, such as intervals of 5 or 10 millimetres (or inches). Regardless of category limits, most studies report a trend of increasing crash rates with more intense rainfalls. For example, Keay and Simmonds (2006) reported that, with traffic volumes normalized, collision counts increased by 5, 10, 20, 30, 40, and 60 percent over the dry day mean rate for days with 0 to 1, 1 to 2, 2 to 5, 5 to 10, 10 to 20, and greater than 20 millimetres of rainfall, respectively. Similarly, Eisenberg (2004) found that crash rates (all severities included) increased by 7, 17, 23, and 30 percent during very light, light, medium, and heavy or very heavy precipitation.

Table 3-13: Rainfall categories from previous safety studies

Author (year)	*Focus*	*Temporal resolution*	*Rainfall categories (mm)*
Andrey (2010)	Crash risk	Six hourly	i) 0.39-2 mm (low) ii) >2-10 mm (moderate) iii) >10 mm (high)
Billot et al., (2009)	Drivers' behaviour (e.g., speed, headways)	Hourly	i) 0 mm/h (no rain) ii) >0-2 mm/h (light) iii) >2-3 mm/h (medium) iv) >3 mm/h (heavy)
Keay and Simmonds (2006)	Crash rates	Daily (and daytime/nighttime)	i) >0-1 mm ii) >1-2 mm iii) >2-5 mm iv) >5-10 mm v) >10-20 mm vi) >20 mm
Eisenberg (2004)	Crash rates	i) Monthly	Total monthly accumulation
		ii) Daily	i) 0 mm (no rain) ii) >0-5 mm (very light) iii) >5-10 mm (light) iv) >10-20 mm (medium) v) >20-50 mm (heavy) vi) >50 mm (very heavy)
Changnon (1996)	Crash frequency and severity	Rain days and non-rain days (based on afternoon/evening rush hour, 1600-2100)	i) 0 mm (no rain) ii) 0.2-12.7 mm (light - moderate) iii) 12.8-50.8 mm (moderate - heavy) iv) >50.8 mm (heavy/very heavy)
Sherretz and Farhar (1978)	Crash frequency and severity	Rain days and non-rain days (based on afternoon/evening rush hour, 1600-2100)	i) 0 mm (no rain) ii) 0.3-5 mm iii) 5.1-10 mm iv) 10.1-15 mm ... xi) 45.1-50 mm xii) >50 mm

Daily rainfall categories of 0.2 to 4.9 mm (very light), 5 to 9.9 mm (light), 10 to 19.9 mm (moderate), and greater than 20 mm (heavy) have been selected for use in the current analysis (Table 3-14). These represent roughly one-half to one-third, one-fifth, one-eighth, and one-twelfth of liquid rainfall days over the five year study period, respectively. In general, as the categories increase in intensity the number of days decreases while accounting for a greater share of total rainfall accumulation. For Toronto, nearly two-thirds of all rain days in each category are captured in matched pairs, with a particularly high match rate of 80 percent for heavy rainfall days. Vancouver suffers a lower capture rate across the board, with roughly half of the days in each category included in event-control pairs; this is probably a result of the difficulty in finding suitable controls throughout much of the year.

Table 3-14: Liquid rain days, 2003-2007

Daily rainfall intensity	*# days*	*Total mm*	*% of total days*	*% of total mm*	*% of days captured in matched pairs*
Toronto					
Very light (0.2-4.9 mm)	282	459.1	62.0%	16.9%	66.0%
Light (5.0-9.9 mm)	80	535.0	17.6%	19.7%	65.0%
Moderate (10.0-19.9 mm)	57	779.4	12.5%	28.8%	66.7%
Heavy (≥ 20.0 mm)	36	935.6	7.9%	34.5%	80.6%
All intensities (sum)	455	2,709.1			
Vancouver					
Very light (0.2-4.9 mm)	454	807.2	56.7%	14.4%	54.2%
Light (5.0-9.9 mm)	154	1,070.6	19.2%	19.1%	50.0%
Moderate (10.0-19.9 mm)	135	1,845.8	16.9%	32.9%	49.6%
Heavy (≥ 20.0 mm)	58	1,879.5	7.2%	33.5%	44.8%
All intensities (sum)	801	5,603.1			

3.3 Future climate

3.3.1 Climate scenarios

In order to assess future climate change impacts at any scale (i.e., single site, regional, or global), a quantitative description of expected changes in climate must be obtained. Thus, it is necessary to establish a recent climatological baseline from which future climate scenarios will deviate (IPCC-TGICA, 2007). The outcome of an impact assessment can be greatly influenced by the selection of both the baseline and climate scenarios, so great care must be exercised when making these decisions. For the present study, current and future climate simulations were obtained from the North American Regional Climate Change Assessment Program (NARCCAP), an international program that aims to provide high-resolution regional climate change scenarios in order to explore uncertainties in regional projections of future climate and for use by the impacts and adaptation community (Mearns et al., 2009).

In 2007, the IPCC's Task Group on Data and Scenario Support for Impact and Climate Assessment (IPCC-TGICA, 2007) published a guidance document on the interpretation and application of scenarios for climate impact assessment. The guidelines within are intended to improve consistency in the selection and application of scenarios while fostering more efficient information exchange within the climate change research community. Accordingly, the decisions in this section of the thesis are consistent with the guidelines outlined in the task group's document. Some decisions, however, are constrained by the availability of data from NARCCAP. To avoid confusion throughout this section and the remainder of the thesis, the following naming conventions are used to denote 30-year period averages: 'Obs' refers to historic climate observations for the 1971-2000 normal period; '20C' refers to the baseline, i.e., the model representation of current climate (again, 1971-2000); and '21C' refers to the modelled future climate (2041-2070, i.e., 2050s). Finally, 'ΔC' refers to the difference (for temperature and number of rain days) or ratio (for precipitation amount) between 21C and 20C.

3.3.1.1 Climatological baseline

The IPCC-TGICA document outlines several issues to be considered when selecting a climatological baseline: types of data required, duration of the baseline period, data sources, and the application of baseline data in an impact assessment. The current analysis of rainfall-related crash risk requires surface measurements of temperature and precipitation for several large Canadian urban areas at a daily temporal resolution. From these basic variables, precipitation type (e.g., liquid rainfall) can be inferred, and rainfall intensities categorized.

Although the safety component of this analysis comprised the years 2003-2007, a baseline period of 1971-2000 was selected by default for the climate change component, as this is the period for which present-day climate conditions were simulated by NARCCAP. The 1971-2000 period is ideal for the current impact assessment as it satisfies the criteria in the guidance document: this baseline is representative of the study area's recent and present-day climate; is of sufficient length to include a range of climate variability and weather anomalies; includes high quality data for the variables of interest at appropriate spatial and temporal resolutions; and is consistent with climatological baselines used in other impact studies. Finally, it is a 30-year 'normal' period, as defined by the WMO; while the current official WMO normal period is 1961-1990, the 1971-2000 period has been adopted by Environment Canada.

Several sources can be used to obtain baseline climatological data, including national archives and meteorological agencies, global data sets, climate model outputs, and weather generators (IPCC-TGICA, 2007). As discussed above, daily climate records were obtained from Environment Canada's CDCD archive for principal weather stations near each study location (Environment Canada, 2010). Environment Canada's observed climate normals were also acquired for the 1971-2000 baseline period (Environment Canada, 2011) for comparison with 20C baselines produced by NARCCAP models.

3.3.1.2 Scenario selection

After establishing a climatological baseline, climate scenarios are selected to quantify and evaluate future climate changes. The choice of scenarios is important, and can affect an impact assessment's outcome; indeed, moderate and extreme scenarios might produce moderate and extreme impacts, respectively (IPCC-TGICA, 2007). Thus it is recommended that impact analyses employ a range of scenarios to identify the sensitivity of systems to climate change and address the high uncertainty associated with climate futures. Guidance on the selection and construction of climate scenarios is provided in the IPCC-TGICA document. As with the baseline period, choice of scenario is constrained by the availability of NARCCAP modelling results.

The IPCC-TGICA (2007; after Smith and Hulme, 1998) outlines five criteria that should be met in order for climate scenarios to be useful for impacts researchers and policymakers. Scenarios should be consistent with the range of global warming projections associated with increasing greenhouse gas emissions; be physically plausible and follow the established laws of physics, with changes in one region related to and consistent with changes elsewhere; provide output of sufficient variables at spatial and temporal scales appropriate for a given impact assessment; be representative of the range of potential changes in future climate; and be readily accessible and straightforward to obtain, interpret, and apply in impact studies.

Of the three types of climate scenario (i.e., synthetic, analogue, and model-based), global climate model (GCM) outputs are most applicable for the current study, as they can provide geographically and physically consistent climate change estimates at global and continental scales. Moreover, GCM output data are readily available with sufficient documentation at online repositories such as the

Canadian Climate Change Scenarios Network (CCCSN) and the IPCC's data distribution centre. For inclusion at these centres, GCMs must be well documented in the peer-reviewed literature, must have performed climate control runs, and must have participated in model inter-comparison projects (IPCC-TGICA, 2007). The models provided – including those used by NARCCAP – are also of generally high resolution and represent the current state-of-the-art.

At coarse resolutions (horizontal grid cells typically around 200 kilometres by 200 kilometres) GCMs can, to a limited extent, simulate present and future climate at a local scale (e.g., an individual city or region); however, their true utility lies in modelling global mean changes. To better resolve small-scale features that influence variables such as precipitation (e.g., clouds, local geography and elevation), GCM output can be downscaled using dynamical or statistical techniques. In this fine-scale analysis of individual urban areas, downscaling was accomplished by obtaining data from NARCCAP, which utilized a suite of regional climate models (RCMs) driven by different GCMs to investigate projections of regional climate change over North America at a finer spatial resolution (50 kilometres by 50 kilometres) than is currently possible with GCMs alone (Mearns et al., 2009).

Finally, a future (21C) period of 2041-2070 (i.e., 2050s) has been selected by default, as this is the focus of NARCCAP modelling efforts. This period is beneficial because it is distant enough that a clear climate change signal should be evident, but near enough that results will be useful for an impact assessment related to transportation, a system in which change comes slowly and infrastructure investments have a lifespan of several decades. Ideally, shorter-term projections would also be available to better inform near-term (i.e., 10 to 20-year) traffic safety programs and decisions; however, this period is sufficient for decisions related to engineering and infrastructure planning and design that are made on a longer timeline (i.e., up to 50 years).

3.3.1.3 Model output selection

The choice of which model output scenarios to use in undertaking a climate impact assessment is a challenging one, as a wide range of climate change experiments involving different GCMs and SRES scenarios have been performed by modelling centres worldwide. In selecting a model, it is suggested that vintage, resolution, validity, and representativeness of results be considered (IPCC-TGICA, 2007; after Smith and Hulme, 1998). Moreover, the CCCSN recommends that selected scenarios should be constructed from a minimum of two different models (CCCSN, 2011c).

Again, the choice of model outputs is restricted to those available from NARCCAP. The project utilized four state-of-the-art GCMs (referred to in this thesis as the ‘NARCCAP models’ or ‘NARCCAP GCMs’, although it is recognized that they were not actually run by NARCCAP) to drive six different RCMs (Table 3-15). These third-generation GCMs (Table 3-16) are considered more reliable than those of earlier generations (cf. Reichler and Kim, 2008) because they incorporate more scientific knowledge of natural processes and feedbacks and typically are run at higher resolutions.

Table 3-15: NARCCAP RCM/GCM combinations

	Global climate models			
Regional models	*CCSM3*	*CGCM3*	*GFDL*	*HadCM3*
CRCM	X	X ▨		
ECP2			O	O
HRM3			O	X
MM5I	X			O
RCM3		X ▨	X ▨	
WRFG	X	X		
Status as of June 11, 2011: run completed (X); run planned or in progress (O). Shading represents models used in the thesis.				

Table 3-16: Details of GCMs used as inputs for NARCCAP RCMs

Short name	*CMIP-3 ID*	*Model*	*Sponsoring agency*	*Reference*
CCSM3	CCSM3	Community Climate System Model, version 3	National Center for Atmospheric Research (USA)	Collins et al. (2006)
CGCM3	CGCM3.1(T47)	Third Generation Coupled Global Climate Model (T47 Resolution)	Canadian Centre for Climate Modelling and Analysis (Canada)	Kim et al. (2002)
GFDL	GFDL-CM2.1	Geophysical Fluid Dynamics Laboratory Climate Model, version 2.1	Geophysical Fluid Dynamics Laboratory / National Oceanic and Atmospheric Administration (USA)	GFDL GAMDT (2004); Delworth et al. (2006)
HadCM3	UKMO-HadCM3	Hadley Centre Climate Model, version 3	Hadley Centre for Climate Prediction and Research / Met Office (UK)	Gordon et al. (2000); Pope et al. (2000)
Note: for ease of reference throughout the thesis, models are referred to by the above short names.				

As the focus of NARCCAP is uncertainty across different RCM/GCM combinations rather than uncertainty related to different emissions scenarios, only the A2 marker scenario was used (NARCCAP, 2007). The A2 scenario falls at the higher end of the SRES scenarios (Figure 2-10);

according to the project's documentation, this was ideal for two main reasons. First, the current global emissions trajectory appears to be heading toward a high emissions scenario in the absence of immediate mitigative action. Moreover, a high emissions scenario, representing a larger degree of climate change, is more useful from an impacts and adaptation perspective: if adaptive measures are taken to address a more severe change scenario, then smaller changes in climate can also be adapted to (NARCCAP, 2007). Finally, although A2 projections fall slightly below those of the highest SRES scenario (A1FI) – and indeed, current emissions are on track to outpace both high-end scenarios – it is likely that the differences will not be evident until the emissions trajectories diverge in the latter half of this century.

To examine the uncertainty and sensitivity associated with different RCMs and GCMs, two types of RCM/GCM combinations are selected for comparison in this thesis: a single GCM driving two RCMs (1GCM x 2RCM), and two GCMs driving a single RCM (2GCM x 1RCM). Based on the current completion status of NARCCAP modelling runs at the time of writing (Table 3-15), the HadCM3 model is excluded from further consideration because it cannot satisfy either combination. The remaining three GCMs are evaluated in terms of validity and representativeness, as suggested by IPCC-TGICA criteria.

Validity, or the ability of a model to accurately simulate present-day climate, is an important criterion in GCM selection, as it is assumed – though not guaranteed – that this may indicate the reliability of future climate projections (IPCC-TGICA, 2007). Several model inter-comparison projects have been completed, most notably CMIP-3 (the third-generation Coupled Model Inter-comparison Project; see Meehl et al., 2007a), which evaluated the models used in the IPCC's Fourth Assessment Report (AR4), including the NARCCAP models. However, previous studies have largely avoided quantitative performance assessments. Reichler and Kim (2008) assessed the performance of three generations of GCMs in this regard, and suggested that increasing confidence can be placed in climate projections from recent models. The NARCCAP models fared well on Reichler and Kim's performance index, and were found to be on the higher end relative to other third-generation models in accurately simulating current mean global climate observations. The performance index varies around one, with greater values representing underperforming models, while models scoring less than one are considered more accurate. The GFDL, CGCM3, and CCSM3 models had values of approximately 0.64, 0.77, and 0.82, respectively, ranking first, sixth, and seventh among 22 CMIP-3 models (Reichler and Kim, 2008).

Table 3-17 illustrates the ability of three NARCCAP GCMs to accurately simulate observed local-scale mean annual climate variables for Toronto and Vancouver relative to the NCEP reanalysis grid and observed conditions from airport weather stations; boxplots showing monthly and seasonal differences are provided in Appendix D. The GFDL most closely simulates three of the four precipitation observations, while the CCSM3 is most accurate for temperature in three of four instances. The CGCM3 tends to be more middle of the road.

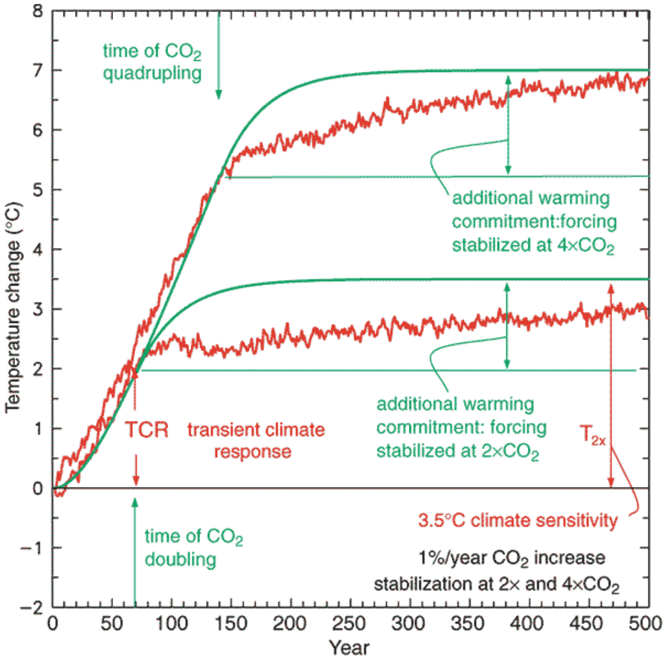
Table 3-17: Accuracy of GCMs in simulating mean annual climate, 1971-2000

	Toronto				*Vancouver*			
	Temperature (°C)		*Precipitation (mm/day)*		*Temperature (°C)*		*Precipitation (mm/day)*	
Model	*NCEP*	*YYZ*	*NCEP*	*YYZ*	*NCEP*	*YVR*	*NCEP*	*YVR*
CCSM3	-0.279	0.496	-0.649	0.153	0.035	-7.097	0.402	1.067
CGCM3	-0.839	-0.064	-0.337	0.465	-0.815	-7.947	0.479	1.144
GFDL	-2.821	-2.046	0.113	0.915	-0.387	-7.519	0.045	0.710

Values represent difference between model-simulated (20C) and observed historic (Obs) climate. Shading indicates best performing model (i.e., smallest difference) in each category. NCEP refers to observations at centre of NCEP/NCAR reanalysis grid (a model of the atmosphere based on the assimilation of local station observations and numerical weather prediction model output over a series of grid cells). YYZ and YVR refer to observations at local climate stations (i.e., Toronto and Vancouver airports, respectively).
Data Source: CCCSN (2011b)

For most months of the year, the three NARCCAP models fall within the inter-quartile range (between the 25th and 75th percentiles) of all GCM experiments for reproducing NCEP reanalysis observations of precipitation accumulation and daily average temperature in both study cities. Moreover, the models accurately simulate the month-to-month trend in observed precipitation at Toronto airport. Seasonal temperature observations are also modelled reasonably well relative to Toronto climate station means. Similarly, the models simulate Vancouver airport precipitation means with decent accuracy throughout most of the year, notwithstanding a relatively large difference of two to three millimetres per day in October. None of the GCMs (used by NARCCAP or otherwise) appear able to reproduce Vancouver airport temperature observations, possibly because of the airport's low elevation and close proximity to the moderating effect of water, while the models are averaged over a larger area of several hundred square kilometres that is centred further inland and includes mountainous terrain. However, they do reproduce NCEP temperature patterns fairly well, which share a similar grid to that used by the models.

Another criterion on which GCMs can be compared is representativeness of results – that is, the range of projected changes relative to other models. One measure of representativeness is climate sensitivity, a characterization of the global climate system's feedback or response to a given level of radiative forcing (Figure 3-8). Climate models differ in their estimation of climate sensitivity, leading to a range of projections of future change (Randall et al., 2007). To sample the spread or range of uncertainty in potential future climates for a given study area, it is prudent to sample two or more GCMs having higher and lower climate sensitivities; this is of particular importance for the current analysis, where only the A2 emissions scenario is available.



Global mean temperature change for 1%/yr CO$_2$ increase with subsequent stabilization at 2xCO$_2$ and 4cCO$_2$. Red curves from coupled AOGCM simulation; green curves from simple illustrative model with no energy exchange with deep ocean. 'TCR' indicates transient climate response; 'T2x' indicates equilibrium climate sensitivity. Reprinted from Cubasch et al. (2001), p. 534.

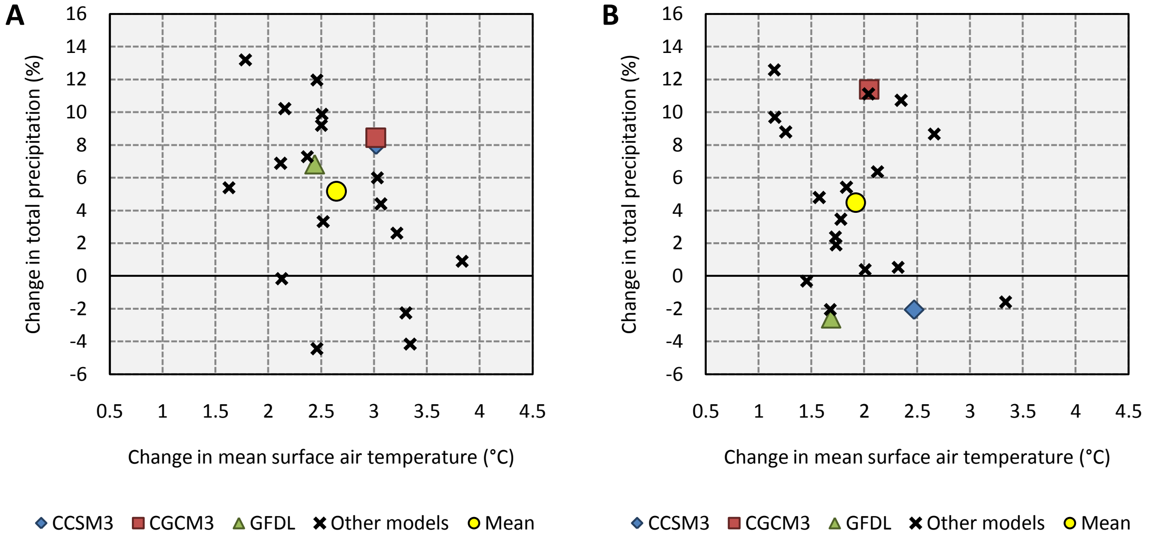
Figure 3-8: Illustration of climate sensitivity

Equilibrium climate sensitivity (ECS) is defined as "the global annual mean surface air temperature change experienced by the climate system after it has attained a new equilibrium in response to a doubling of atmospheric CO$_2$ concentration" (Randall et al., 2007, p. 629). The full range of ECS for all AR4 models is between 2.1 and 4.4 degrees Celsius; the NARCCAP models fall in the middle of this range (Table 3-18) on either side of the most likely value, which has been estimated at 3.0

degrees Celsius (Meehl et al., 2007b). Similarly, transient climate response (TCR) refers to the change in global annual mean temperature at the time of atmospheric CO_2 doubling, before equilibrium has been reached (Randall et al., 2007). For all of the AR4 models, TCR falls between 1.2 and 2.6 degrees Celsius; the NARCCAP models fall in the mid-to-low area of this range (Table 3-18). Transient climate response is considered more pertinent to this thesis research because equilibrium is not likely to be reached until long after the mid 2050s analysis period.

Table 3-18: Climate sensitivity estimates for NARCCAP GCMs

Model	*Equilibrium climate sensitivity (°C)*	*Transient climate response (°C)*
CCSM3	2.7	1.5
CGCM3	3.4	1.9
GFDL	3.4	1.5
Reproduced from Randall et al. (2007)		



Difference between 21C and 20C, i.e., ΔC, for (A) Toronto and (B) Vancouver. All points represent A2 scenario. Data provided by CCCSN (2011a)

Figure 3-9: Projected changes in annual mean climate, 2050s

In addition to looking at model estimates of global climate sensitivity, it is important to compare prospective models at a local scale. Figure 3-9 shows the projected changes in annual mean temperature and total precipitation for all AR4 GCMs to the 21C period for Toronto and Vancouver. In both cities, the CCSM3 is on the higher end of models for average temperature change, while the CGCM3 is among the leaders in projections of increased precipitation. Little difference between the three NARCCAP models is evident in estimating annual precipitation change for Toronto, while a substantial difference can be seen in Vancouver. For temperature change, the three models fall within approximately 0.6 to 0.8 degrees of each other in both cities.

Based on the above discussion of validity and representativeness, the CGCM3 and GFDL models have been selected for use in the thesis research. These have a higher and lower transient climate response, respectively, and represent a range of precipitation and temperature changes at a local scale while accurately simulating present day observed climate, both globally and locally. Accordingly, the model combinations chosen for comparison are the CGCM3 driving the CRCM and RCM3 (1GCM x 2RCM); and the RCM3 driven by the CGCM3 and GFDL (2GCM x 1RCM). These combinations are referred to as 'CRCM_cgcm3', 'RCM3_cgcm3', and 'RCM3_gfdl'.

3.3.2 NARCCAP data

3.3.2.1 Data format and variables

Following model selection, RCM/GCM output data were downloaded from NARCCAP; throughout this section, constant reference is made to both the NARCCAP web documentation (NARCCAP, 2007) and dataset (Mearns et al., 2007). A collection of several dozen surface and atmospheric variables are available with different spatial (e.g., 2-D, 3-D) and temporal (3-hourly, daily) structures. Data are stored, one variable per file, in NetCDF format – a robust climate data system that situates thousands of individual data points in time and space across a projected model grid using progressive timesteps (i.e., time since a given date/time) and a three-dimensional (x, y, z) coordinate system. A command line interface is used to extract and manipulate data for grid points and timesteps of interest.

As climate models operate, they constantly (i.e., every 900 seconds for CRCM and 150 seconds for RCM3) log instantaneous measurements of surface and atmospheric conditions. However, the resulting data files are massive, so model outputs must be compiled at a coarser time scale by the home modelling team prior to submission to NARCCAP and distribution to end users. NARCCAP offers several variables related to precipitation and surface air temperature; all are initially provided in 3-hourly timesteps, with some converted to a daily scale (Table 3-19).

Table 3-19: Description of NARCCAP climate variables

Variable	*Unit*	*Native timestep*	*Daily conversion*	*Unit conversion*
pr	$kg/m^2/s$	3-hourly	Mean of 3-hourly	mm = $kg/m^2/s$ * 86400 seconds
tas	K	3-hourly	Mean of 3-hourly	°C = K - 273.15
tasmax	K	Daily	Max of 3-hourly*	°C = K - 273.15
tasmin	K	Daily	Min of 3-hourly*	°C = K - 273.15
*Daily tasmax and tasmin recalculated from 3-hourly tas				

Precipitation ('pr') data are provided as an average instantaneous flux rate (in $kg/m^2/s$) over each 3-hourly timestep; to transform into the more useful measure of total accumulation (in mm), the average rate is multiplied by the number of seconds in the timestep (i.e., 10,800 seconds in a 3-hour timestep). In addition, the daily average precipitation flux rate can be calculated by averaging the reported values for each 3-hour timestep during a day; to convert to daily total accumulation (in mm) the daily average flux rate is multiplied by 86,400 seconds.

Surface air temperature ('tas') is reported instantaneously at the beginning of each 3-hour timestep (i.e., 0300, 0600 UTC/GMT, etc.); averaging this value over the eight timesteps in a day produces daily average surface air temperature. Variables related to daily temperature range are also provided by the models. In the CRCM, daily maximum and minimum surface air temperature ('tasmax' and 'tasmin') are calculated from instantaneous temperature measurements every 900 seconds (15 minutes) during the model run; these represent true maximum and minimum temperatures throughout the day. Conversely, the RCM3 calculates tasmin and tasmax from the 3-hourly tas values, providing estimates, though not true measures, of daily maximum and minimum temperature. Accordingly, in the current research daily tasmax and tasmin for the CRCM are recalculated from 3-hourly tas measurements in order to maintain consistency with RCM3 calculations. Temperature measurements are provided in Kelvin (K); to convert to degrees Celsius, 273.15 is subtracted from each value.

The existence of NARCCAP and its RCM data were brought to the author's attention late in the research process, when decisions had already been made to work at a daily scale for the analysis. Previously, the methodology was to utilize coarse-scale GCM outputs in combination with downscaling by statistical weather generators (cf. Mills et al., 2007); these data were only available at a daily resolution. To this end, historical climate and collision data had already been retrieved, aggregated to a daily level, and analyzed by the time NARCCAP data were obtained; essentially, the safety component of the analysis had already been completed by this point. Accordingly, while 3-hourly data are readily available for all selected NARCCAP model combinations, a decision was made to continue working at daily resolution. However, this decision was also beneficial from a computational perspective, as conversion to daily from 3-hourly timesteps reduces file size by a factor of eight.

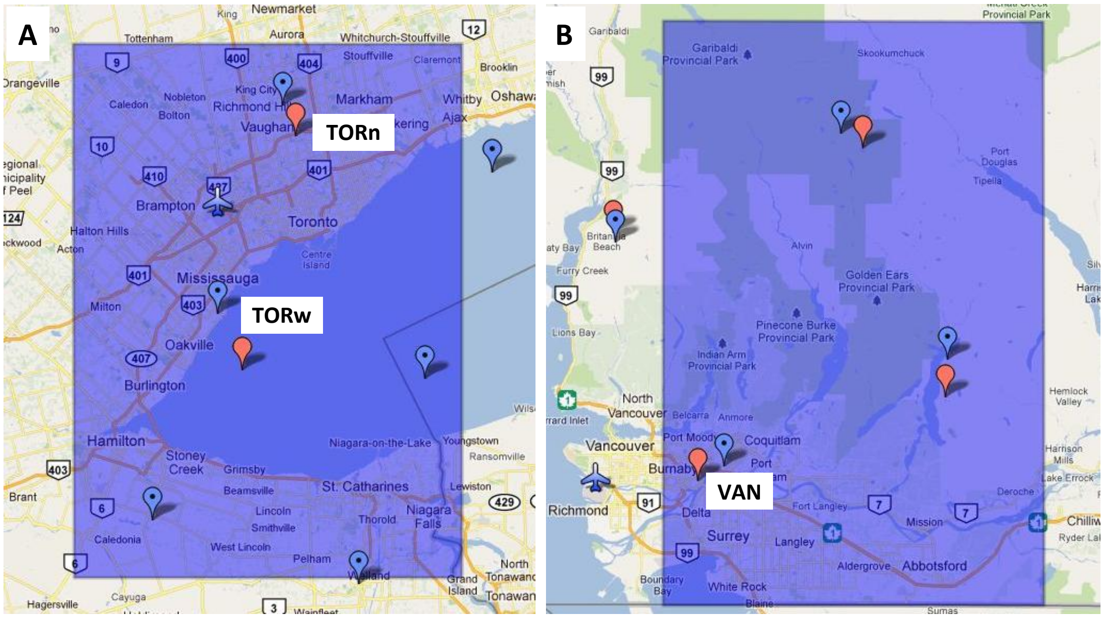
3.3.2.2 Processing

After data retrieval and conversion to daily timesteps, a series of transformations were necessary before the data could be analyzed. Outputs for each RCM/GCM combination are stored in 5-year blocks for each individual variable; these blocks were combined for each 30-year period (current, 1971-2000, and future, 2041-2070) using a ‘mergetime’ command. Data include an initial ‘spin-up’ period, beginning in 1968 and 2038, during which models are equilibrated; NARCCAP documentation recommends removal of this period from the analytical dataset. Accordingly, a ‘seldate’ command was used to extract all data between December 1, 1970 and November 30, 2000 (2040 and 2070 for future); these include a one month offset from year-end so that seasonal (i.e., DJF) averages will not be affected by a fractional winter at the beginning and end of the two periods.

3.3.2.3 Grid point selection

Each RCM uses its own projected x-y-z coordinate grid system, and these are not square in terms of latitude or longitude. As precipitation and temperature are surface variables, only the x and y coordinates are considered here. The CRCM grid covers 16,100 points (140 x by 115 y) over North America, compared to 13,936 (134 x by 104 y) for the RCM3. Grid points can be selected by defining a latitude/longitude box (i.e., select all grid points that fall within a given lat/lon range), a grid index box (i.e., select all grid points that fall within a given model grid box), or individually (i.e., specify the point for which data are to be extracted). Figure 3-10 illustrates the difference between the two model grids relative to one degree-by-one degree latitude/longitude boxes containing Toronto and Vancouver, respectively. RCM analyses typically examine climate changes averaged over a larger (i.e., sub-continental) scale; however, the current fine-scale analysis of two large urban agglomerations required the use of specific grid points in close proximity to local airport climate stations. The use of such modelling techniques over such a small study area is rather novel.

The choice of grid points to represent the Vancouver area is a rather simple one, as both the CRCM and RCM3 have points located relatively centrally within the urban area (labelled ‘VAN’ in Figure 3-10), and should therefore reasonably simulate the local climate. The grid points are located further inland than Vancouver airport, so they should also experience the moderating climatological effects of water to a lesser extent than the airport station. Conversely, in both models the Greater Toronto Area is represented by two sets of points: one in the southwestern GTA, centred near the shoreline or slightly off shore in Lake Ontario (i.e., Toronto West: 'TORw' in Figure 3-10), and the other further inland near the north central area of the GTA (Toronto North: 'TORn'). The area's principal weather station at Pearson Airport is located roughly halfway between these two points, and thus is generally representative of the entire urban region's climate.



(A) Toronto; (B) Vancouver. Airplane symbol denotes location of principal weather station. CRCM grid points are shown in blue (with black dots); RCM3 in red (without dots). Blue shading indicates 1° by 1° latitude/longitude box (Toronto boundaries: 43°N, 80°W by 44°N, 79°W; Vancouver boundaries: 49°N, 123°W by 50°N, 122°W)

Figure 3-10: Location of RCM grid points relative to latitude/longitude box

There are essentially three possibilities for selecting an appropriate point for the Toronto region (Table 3-20). Ideally, the third option (C) would be used due to the spatial difference between the two grid points. However, this is not feasible, as geocoded location-specific crash data are unavailable. Instead, crashes could be arbitrarily assigned to Toronto North or West based on police detachment codes nearest to each grid point, but there is only one principal climate station that is centrally located and roughly representative of the overall regional climate. Two climate stations, with long-term records, would be needed – one near each model grid point – for this approach to work. Therefore, options A are B are most appropriate in the current analysis.

Table 3-20: Selection of Toronto RCM grid points

Option	*Description*
A	1 set of results based on average of TORn and TORw points over entire study area
B	2 sets of results, using TORn and TORw points individually to represent entire study area
C	1 set of results, with TORn and TORw points each representing half of the study area

To choose between the two remaining options (A and B) for simulating Toronto's 20C climate, an examination of differences was undertaken for the two sets of grid points. Both a Paired t-Test (which assumes a normal distribution of differences, which is not the case) and Wilcoxon Matched-Pairs Signed-Ranks Test (which is a non-parametric test) showed differences in daily precipitation amount that are statistically significant ($p<0.000$) as well as substantive (mean differences as shown in Table 3-21). In addition, there are notable differences for several major storm events (e.g., days with differences greater than 50 mm); the vast majority of large differences occur in the summer months, probably indicative of localized convective storm activity. This difference is perhaps expected, as the Toronto region sees a relatively high degree of spatial variability in precipitation. For example, 1971-2000 climate normals indicate that nearby Hamilton and Waterloo receive approximately 765 mm and 910 mm of annual rainfall and precipitation, respectively, compared to 685 mm and 790 mm in Toronto, 730 mm and 890 mm in Orangeville, and 760 mm and 880 mm in Oshawa. It was decided, therefore, that separate climate simulation outputs would be analyzed for the Toronto area using the two sets of grid points individually, rather than averaging between them or selecting only one point as representative of the entire region. Finally, data were extracted for each grid point for the 20C and 21C periods in order to estimate the magnitude and direction of future change.

Table 3-21: Examination of precipitation differences between Toronto RCM grid points

Model	*Mean difference between TORn and TORw points (mm)*	*Mean difference expressed as % of daily mean precipitation*
CRCM_cgcm3	-0.15	5.7%
RCM3_cgcm3	-0.36	12.5%
RCM3_gfdl	-0.35	11.8%

3.3.2.4 Climate change estimation

Climate impact assessments typically begin with the observed historic climate record (Obs) and then come up with an estimate of how the climate might be expected to change. To obtain this estimate, the difference (for temperature or number of rainfall days) or ratio (for precipitation amount) between modelled future (21C) and baseline (20C) climates is calculated for each grid point and RCM/GCM combination. To estimate future changes in safety, the projected change in climate (or delta, referred to as ΔC) is applied as an offset to current rainfall-attributable crash rates determined from risk estimates in the safety analysis; results of this process are presented in Section 4.3.

Chapter 4

Results

4.1 Rainfall-related crash risk, 2003-2007

This section presents the empirical results of the traffic safety analysis for the Toronto and Vancouver CMAs during the five-year study period, 2003 to 2007. Following a matched-pair research design, estimates of rainfall-related crash risk were produced for different collision severities at a range of rainfall intensities. The reader is reminded that ‘rainfall’ and ‘rain days’ in this section refer specifically to the subset of liquid rain days having a daily minimum temperature of at least one degree Celsius, thereby ensuring the removal of snowfall and winter precipitation from the analysis.

The matching process resulted in 305 and 416 event-control pairs for Toronto and Vancouver, respectively. Nearly one-third of all Toronto collisions were included in the pairs, compared to almost 45 percent for Vancouver (Table 4-1). The difficulty in finding matching control periods for Vancouver’s rain days is reflected here: the region had 75 percent more liquid rain days than Toronto during the study period, yet only 36 percent more matched pairs. Moreover, it is evident that a substantially higher proportion of collision and casualty incidents occur during rainfall in the Vancouver CMA relative to Toronto. This difference is expected, however, due to the higher number of rain days that Vancouver receives each year (Table 3-10).

Table 4-1: Summary of incident counts, 2003-2007, and matched pair inclusiveness

Incident type	*Total for all days*	*Rainfall days*		*Matched events*		*Controls*		*E-C pairs*
		Sum	*% of total*	*Sum*	*% of total*	*Sum*	*% of total*	*% of total*
Toronto								
Total collisions	488,780	123,963	25.4	84,778	17.3	74,966	15.3	32.7
Casualty collisions	106,342	28,018	26.3	19,081	17.9	17,507	16.5	34.4
PDO collisions	382,438	95,945	25.1	65,697	17.2	57,459	15.0	32.2
Casualties	153,044	40,320	26.3	27,246	17.8	25,245	16.5	34.3
Vancouver								
Total collisions	82,919	38,844	46.8	20,517	24.7	16,619	20.0	44.8
Casualty collisions	39,499	18,373	46.5	9,766	24.7	8,086	20.5	45.2
PDO collisions	43,420	20,471	47.1	10,751	24.8	8,533	19.7	44.4
Casualties	55,643	25,993	46.7	13,789	24.8	11,223	20.2	45.0

At a 95 percent confidence level, relative risk estimates for rainfall days were between 1.09 and 1.15 for Toronto and 1.19 and 1.26 for Vancouver, meaning that, on average, collision risk is 9 to 15 percent higher in Toronto and 19 to 26 percent higher in Vancouver on days with rainfall relative to those with normal seasonal (i.e., dry) conditions (Table 4-2). This compares reasonably well with earlier results reported by Andrey (2010), where rain was responsible for a 72 percent increase in casualty risk over six-hour event periods (averaged out over an entire day, this equates to a relative risk of approximately 1.2). It should be noted, however, that in a daily analysis of this nature, the effects of the rainfall are often diluted by non-rainfall hours that are captured within the rainfall day – this phenomenon is particularly likely on days with light rainfall. Thus, when rain is actually present, risk increases are likely to be substantially higher than the 10 to 25 percent observed here. Moreover, the current analysis is restricted to a subset of rain days during which only liquid rainfall is present, whereas the Andrey study examined all days with measured rainfall; this difference also is a probable contributor to the slightly lower risk estimates reported here.

Table 4-2: Comparison of risk estimates, 2003-2007 (95% confidence intervals)

Daily rainfall intensity	*Event-control pairs*	*Total collisions*	*Casualty collisions*	*PDO collisions*	*Casualties (all severities)*
Toronto					
All days with ≥ 0.2 mm	305	1.09-1.15	1.06-1.12	1.10-1.16	1.04-1.11
Very light (0.2-4.9 mm)	186	1.03-1.09	0.99-1.07	1.04-1.11	0.98-1.06
Light (5.0-9.9 mm)	52	1.13-1.22	1.10-1.20	1.13-1.23	1.09-1.21
Moderate (10.0-19.9 mm)	38	1.15-1.33	1.12-1.32	1.15-1.34*	1.12-1.33*
Heavy (≥ 20.0 mm)	29	1.19-1.40*	1.07-1.29*	1.22-1.45*	1.03-1.27*
Vancouver					
All days with ≥ 0.2 mm	416	1.19-1.26	1.15-1.24	1.21.1.30	1.17-1.26
Very light (0.2-4.9 mm)	246	1.10-1.18	1.05-1.15	1.12-1.23	1.05-1.16
Light (5.0-9.9 mm)	77	1.19-1.35	1.17-1.38*	1.19-1.37	1.21-1.44*
Moderate (10.0-19.9 mm)	67	1.31-1.49	1.28-1.49*	1.28-1.54*	1.32-1.54*
Heavy (≥ 20.0 mm)	26	1.31-1.65*	1.29-1.65*	1.27-1.71*	1.32-1.78*
*95% confidence intervals exceed +/- 0.1 due to insufficient incident counts					

Consistent with the findings of previous analyses (e.g., Eisenberg, 2004; Andrey, 2010), a strong progression in risk was identified in conjunction with increasing rainfall intensity (Table 4-2). For Toronto, days with very light rainfall (i.e., less than five millimetres) are associated with little or no increase in incident risk, while moderate and heavy rain events typically see an increase that is twice that of less intense events. A similar trend is observed in Vancouver, where more intense rain days result in elevated risks up to three times higher than those for very light rainfalls. Indeed, although some studies (e.g., Unrau and Andrey, 2006; Qui and Nixon, 2008; Billot et al., 2009) have shown slight reductions in traffic volume as weather conditions worsen, the crash involvement rate remains highly elevated, particularly during intense rain events.

Risk increases for both cities were generally found to be higher for less severe collisions, a trend that was apparent across all rainfall categories. This is most likely explained by the fact that as driving conditions become more hazardous, drivers tend to adjust to some degree (thereby reducing collision severity), though often not enough to avoid a collision altogether (Hogema, 1996). The less elevated risk of casualty and casualty collision involvement identified in Toronto for heavy rainfall relative to moderate provides some evidence of this adjustment, although it is less apparent for Vancouver.

Finally, the results suggest that Vancouver drivers are more susceptible to crashes during rainfall than their counterparts in Toronto. Indeed, for most rain categories and incident types, risk increases in Vancouver tend to be double those identified for Toronto. This is an interesting and somewhat counterintuitive result, as it seems logical that more frequent rainfall on the west coast than in southern Ontario would be expected to make Vancouver drivers more used to driving in rain, and less likely to crash in it. It is not certain why this perverse relationship occurs; however, it could be related to driver maladaptation, i.e., it is possible that Vancouver drivers are so used to inclement weather that they do not adequately recognize and adjust to the hazards associated with it.

Additional insight into the hazards associated with travel during rainfall can be gleaned from an examination of collision characteristics. The incidence of various situational and environmental characteristics, in all crashes as well as those during rainfall and wet road conditions, is provided in Table 4-3. Note that the figures below refer to all crashes over the five-year study period, not just those in matched pairs. Collision severity is markedly similar between the three conditions, the only exception being that PDO crashes occur with slightly greater frequency (and injury collisions slightly less frequently) on wet roads relative to the other two conditions. Again, this is likely indicative of slight driver adjustments. Rainfall and wet roads are associated with marginally more single-vehicle collisions and fewer involving two vehicles; the relative incidence of multi-vehicle crashes is approximately the same. It appears that low-speed roads (≤ 60 km/h) in Toronto see a couple of percentage points more rain and wet road crashes, while no notable difference is evident in Vancouver. In addition, a smaller proportion of rainy and wet-road crashes take place on Toronto-area freeways (≥ 90 km/h) than the overall share for these roads in all conditions.

Table 4-3: Weather and road surface condition as identified in collision reports, 2003-2007

	Toronto			*Vancouver*		
	All collisions	*Raining*	*Wet road*	*All collisions*	*Raining*	*Wet road*
Collision count	488,780	54,099	95,290	82,919	18,436	29,295
Collision severity						
% Fatal	0.2	0.2	0.2	0.6	0.5	0.6
% Injury	21.6	21.7	21.1	47.0	47.4	46.6
% PDO	78.2	78.1	78.7	52.4	52.1	52.9
# vehicles involved						
% Single vehicle	13.9	15.7	14.8	25.4	28.0	28.0
% 2 vehicles	76.7	74.4	75.7	63.3	60.5	60.6
% 3 or more vehicles	9.3	9.9	9.5	11.3	11.5	11.4
Posted speed limit						
% less than 50 km/h	7.8	6.8	6.9	5.5	4.6	4.8
% 50 km/h	34.5	34.5	34.8	72.0	71.5	71.6
% 60 km/h	30.3	33.5	32.7	15.9	16.5	16.7
% 70 km/h	5.8	6.6	6.6	2.9	3.4	3.2
% 80 km/h	6.7	6.0	6.5	2.8	3.0	2.9
% 90 km/h	1.7	1.6	1.6	0.6	0.8	0.6
% 100 km/h or more	13.3	11.0	10.7	0.3	0.2	0.2
Seasonal pattern						
% Winter (Dec-Feb)	28.4	15.0	33.8	25.0	30.3	35.1
% Spring (Mar-May)	22.0	22.8	20.0	24.1	24.3	22.3
% Summer (Jun-Aug)	23.6	19.8	14.1	23.9	11.0	9.8
% Autumn (Sep-Nov)	26.0	42.4	32.1	27.0	34.4	32.8
Day of week						
% Monday	14.2	12.9	13.5	13.1	11.8	12.6
% Tuesday	15.0	16.6	16.3	13.5	12.1	12.7
% Wednesday	15.3	15.7	15.2	14.2	14.9	14.4
% Thursday	15.7	13.7	14.5	14.5	14.3	13.8
% Friday	17.0	17.2	17.3	16.1	15.8	15.6
% Saturday	12.9	14.1	13.6	15.5	16.0	16.2
% Sunday	9.9	9.9	9.6	13.1	15.0	14.7
Time of day						
% Late night (0:00-5:59)	6.8	7.5	7.4	12.8	14.0	14.9
% A.M. rush (6:00-9:59)	19.7	17.7	20.2	14.1	14.2	16.3
% midday (10:00-14:59)	26.8	23.3	24.5	25.3	21.8	22.3
% P.M. rush (15:00-18:59)	31.1	32.4	30.3	27.2	26.7	24.7
% Evening (19:00-23:59)	15.5	19.1	17.6	20.6	23.4	21.8
Light condition						
% Daylight	72.1	61.8	62.7	58.5	45.1	46.6
% Dawn/dusk	4.7	6.8	6.6	6.7	7.7	7.8
% Darkness	23.2	31.3	30.7	34.8	47.2	45.6
Weather condition						
% Rain	11.1	--	55.9	22.5	--	61.2
% Snow	7.6	--	7.3	1.6	--	0.8
% Frozen precipitation	0.9	--	0.8	0.1	--	0.1

	Toronto			*Vancouver*		
	All collisions	*Raining*	*Wet road*	*All collisions*	*Raining*	*Wet road*
% Visibility limitation	1.1	--	2.4	1.0	--	1.5
Road surface condition						
% Wet	19.6	97.8	--	35.7	97.0	--
% Snow, slush, or ice	10.7	2.0	--	3.3	0.6	--

Note: for each variable group, percentages are summed by column; for weather and road surface condition, these do not sum to 100 percent, as clear weather and roads are excluded for redundancy.

A distinct seasonal pattern is observed in the distribution of collisions for which rainfall is indicated. In Toronto, the autumn months see a disproportionate share of annual rainfall crashes (42%) compared to all collisions (26%), while substantially fewer winter crashes occur during rain (15%, versus 28% of total crashes) and a slightly smaller share in summer (20% rainfall and 24% overall); the latter result is especially surprising, as the late summer months are the city's peak rain season, and would be expected to see a greater seasonal share. Meanwhile, Vancouver's seasonal crash distribution in rainy conditions closely matches the city's seasonal rainfall pattern, with higher rainfall collision frequencies (relative to all crashes) in the wet fall and winter months. In both cities, crashes on wet roads occur with much greater frequency in fall and winter, suggesting that warm temperatures in the summer months contribute to faster pavement drying times. Day-of-week distributions are similar across all three conditions, with fewer crashes occurring on Sundays in both regions. Slightly higher shares of rainfall and wet road crashes occur during evening and late night periods (i.e., 7:00 p.m. to 6:00 a.m.); this is indicative of the confounding effect of darkness. Similarly, rainfall and wet road collisions occur substantially more often when light condition is reported as being dark, and less often in daylight. Furthermore, wet roads are slightly overrepresented in the morning rush hour, possibly because temperatures typically have not yet reached their daily maximum at this point; the lower frequency of wet road crashes midday and in the afternoon/evening commute period supports this explanation. Finally, as would be expected, there appears to be strong agreement between collisions simultaneously reporting the presence of rainfall and wet pavement.

A key focus of the thesis research is to provide a first estimate of possible climate change effects on traffic safety in Canadian cities. The above findings demonstrate that rain-related crash risk is highly elevated today; a comparison with projected changes in future rainfall patterns follows.

4.2 Estimates of climate change, 2050s

This section contains the results of the modelling exercise, which estimated changes in the study regions' climates to the mid-21st century. First, however, is a brief discussion of model accuracy in simulating present-day climate. The reader is reminded that the following naming conventions are used for 30-year period averages: 'Obs' refers to historic (1971-2000) climate observations; '20C' refers to the baseline, i.e., the model representation of current climate (1971-2000); and '21C' refers to the modelled future climate (2041-2070, or 2050s). Finally, 'ΔC' refers to the difference (for temperature and number of rain days) or ratio (for precipitation amount) between 21C and 20C.

4.2.1 Simulation of current climate

In general, difficulty is encountered when directly comparing model simulations with observed climate because of differences in spatial scale. GCM measurements are averaged over a coarse grid (200 kilometres by 200 kilometres), while RCM grid cells have greater spatial precision (50 kilometres by 50 kilometres) but are still relatively coarse compared to point-based measurements at weather stations. Moreover, models are not able to accurately resolve local topography and landscape features that may influence precipitation processes. Accordingly, precipitation accumulations at each location within a model grid are averaged over the entire grid box, thereby spreading out or 'smearing' the precipitation as a thin layer, whereas an individual weather station specifically records precipitation amount as received at a specific point.

There is no commonly agreed upon way of comparing precipitation between the different spatial scales. It is generally expected, however, that lower precipitation intensities and accumulation should be apparent at a grid box scale because of the smearing effect and, conversely, that significantly more precipitation days should occur at a grid scale relative to an individual point, as there is a strong likelihood of precipitation occurring at least somewhere within the grid box on days when the point location is dry. A certain amount of model bias is therefore expected when attempting to simulate observed precipitation conditions at a fine spatial scale, as is done in this thesis.

Temperature, on the other hand, tends to see less drastic variation over the area of a grid cell, so models should be more accurate in representing point-based temperature observations. Less model bias should therefore be apparent in temperature measurements, although some bias is still inherently present because models are unable to perfectly replicate local atmospheric processes. Moreover, the ratio of snow or frozen precipitation to that falling in entirely liquid form may be represented differently in Obs and 20C because of model temperature bias.

Broadly speaking, despite earlier evidence that the CGCM3 and GFDL models (20C) reproduce observed Toronto and Vancouver climate (Obs) with reasonable accuracy, it is apparent that, when paired with regional models, this accuracy is reduced to various extents (see Appendix E for detailed figures). In all cases, the models appear biased as they overestimate annual total precipitation and underestimate daily mean temperature (Table 4-4).

Table 4-4: Model simulation of observed climate, 1971-2000

	Total annual precipitation (% difference)			*Daily mean temperature (°C difference)*		
Experiment	*Toronto North*	*Toronto West*	*Vancouver*	*Toronto North*	*Toronto West*	*Vancouver*
CRCM_cgcm3	+26.2%	+19.4%	+96.6%	-3.0	-2.3	-6.4
RCM3_cgcm3	+49.9%	+33.3%	+249.3%	-2.7	-1.7	-4.3
RCM3_gfdl	+51.1%	+35.1%	+164.9%	-3.7	-2.8	-2.1
Table values refer to difference between 20C and Obs.						

Moreover, the models differ in their representation of rainfall extremes (Table 4-5). In Toronto, the models tend to underestimate the intensity of the 90th percentile rainfall event; however, they fairly accurately allocate the total proportion of liquid rainfall that occurs on the top 10 percent of days. Conversely, the two RCM3-based simulations vastly overestimate the intensity of the 90th percentile rain day for Vancouver, while the CRCM more closely simulates this value. In addition, all RCM/GCM experiments overestimate the percentage of total rainfall associated with the most extreme events.

Table 4-5: Model simulation of extreme rainfall events, 1971-2000

	90th percentile rain day amount (mm)			*% of total rainfall accumulation that occurs on top 10th percentile of rain days*		
	Toronto North	*Toronto West*	*Vancouver*	*Toronto North*	*Toronto West*	*Vancouver*
Observed	118.5	118.5	89.4	41.0%	41.0%	36.3%
CRCM_cgcm3	63.4	68.0	90.8	40.5%	41.0%	44.7%
RCM3_cgcm3	99.9	119.4	211.7	42.7%	45.4%	41.5%
RCM3_gfdl	100.6	82.5	170.2	43.4%	44.9%	46.9%
Table values refer to liquid rainfall days.						

This discrepancy or model bias is likely explained in part by geographic differences. The extreme difference in Vancouver precipitation is probably a result of the greater precipitation accumulation with increasing distance north and east of the airport weather station; the climate model grid centres are located further east over higher elevations and therefore probably incorporate orographic precipitation to a greater extent. Moreover, the differences for the Toronto models are possibly an artefact of the regional variation in precipitation normals, as discussed in Section 3.3.2.3; differences in proximity to Lake Ontario between the model grid centres and Pearson Airport may also be a factor.

Total accumulation notwithstanding, general seasonal relationships for precipitation are replicated with reasonable accuracy, except that the wet seasons are substantially wetter according to the models. Similarly, for temperature, model simulations reproduce the normal seasonal curve fairly well, but with cooler cold seasons.

4.2.2 Future climate

The marked difference between observed (Obs) and simulated baseline (20C) climates suggests that the models provide a somewhat biased or incomplete representation of local climatic processes for the study cities. This bias is partly explained by the difference in spatial scale, as point observations are being compared against a grid box average (i.e., ‘apples to oranges’). However, the opposite is also true: local weather stations are not completely representative of the complex climates within their respective model grid boxes due to differences in elevation and spatial context (e.g., land/water, urban/rural).

Accordingly, it is not prudent to directly compare a modelled future (21C) with observed (Obs) climate. Any estimate of future change (ΔC) should therefore be derived from the difference between simulated baseline (20C) and future (21C) climates. This deals with the problem of model bias by assuming that the same biased representation of present climatic processes will continue to exist in future simulations. Estimates of future climate change (e.g., an increase in rain days) derived in this way can then be compared with observed climate in order to proceed with impact assessment.

Table 4-6 illustrates the mean annual projections of climate change (ΔC) for the three RCM/GCM combinations as well as the two driving GCMs at each study location. By mid-century, Toronto could see a moderate overall increase in annual precipitation accompanied by mean warming of 2.4 to 3.1 degrees Celsius. RCM/GCM projections for the northern GTA range from 5.2 to 11.5 percent more total annual precipitation, compared to a slightly smaller 3.4 to 9.5 percent increase in Toronto West. The driving GCMs estimate 6.8 to 8.4 percent more annual precipitation for the region as a whole. Vancouver, on the other hand, could see a slight to moderate increase in annual precipitation, depending on the experiment. The RCM/GCM projections anticipated from 1.7 to 8.8 percent more annual precipitation, while the driving GCMs lie outside of this range: 11.4 percent more and 2.6 percent less precipitation for the CGCM3 and GFDL, respectively. All scenarios estimate a mean temperature increase of 1.7 to 2.4 degrees, notwithstanding the RCM3 driven by GFDL, which projects slight cooling for the Vancouver region.

Table 4-6: Mean annual climate change estimates for GCMs and RCM/GCMs, 2050s

	Total annual precipitation (% difference)			*Daily mean temperature (°C difference)*		
Experiment	*Toronto North*	*Toronto West*	*Vancouver*	*Toronto North*	*Toronto West*	*Vancouver*
GCMs						
CGCM3	+8.44%		+11.39%	+3.02		+2.05
GFDL	+6.82%		-2.58%	+2.44		+1.69
RCMs/GCMs						
CRCM_cgcm3	+5.21%	+3.40%	+8.81%	+3.04	+3.09	+2.39
RCM3_cgcm3	+11.49%	+8.84%	+7.51%	+2.68	+2.69	+2.14
RCM3_gfdl	+9.08%	+9.46%	+1.69%	+2.44	+2.47	-1.43
Table values refer to difference between 21C and 20C, i.e., ΔC.						

General trends in future rainfall days for each of the RCM/GCM experiments and grid points are presented in Table 4-7. It is evident that the highest overall increases in rain days are projected by the two simulations driven by the CGCM3; this is not surprising, as this model falls near the high end of all GCMs in predicting increased precipitation for both study regions (Figure 3-9). The GFDL, on the other hand, projects an annual decrease in precipitation, and is among the lowest of all GCMs in its estimate of future precipitation for the Vancouver area. When paired with a regional model (RCM3), however, it projects a moderate overall increase in rainfall. Moreover, the RCM3 appears to distribute changes in rainfall mostly toward higher intensities (i.e., ≥ 20 mm), whereas the CRCM favours very light rainfall (< 5 mm).

Table 4-7: Model differences in simulating annual rain days, 2050s

Experiment	*Toronto North*	*Toronto West*	*Vancouver*
CRCM_cgcm3	Moderate overall increase; greatest for very light rain	Moderate overall increase; greatest for very light rain	High overall increase, mostly weighted toward very light and heavy rain
RCM3_cgcm3	Moderate overall increase, mostly divided between very light and heavy rain	Moderate overall increase, slightly more in very light and heavy rain	High overall increase, especially for heavy rain
RCM3_gfdl	Slight overall increase, almost all for moderate-heavy rain	Slight overall increase, almost all for moderate-heavy rain	Moderate overall increase, mostly for very light and heavy rain
Table values refer to difference between 21C and 20C, i.e., ΔC.			

4.3 Effects of climate change

For each study location, an estimate of future safety is obtained by calculating the anticipated annual change in the number of rain days and rainfall-related incidents based on established present-day weather-safety relationships. In order to provide more reliable estimates and increase the signal to noise ratio, changes in rain day frequencies and incident counts are reported as a multi-model ensemble mean change for each grid point, incident type, and rainfall intensity. The ensemble change estimate is based on the average of the differences between 20C and 21C rain day counts for each of the three RCM/GCM combinations. High and low estimates are also reported to illustrate the range of uncertainty associated with future projections.

Using an example from Table 4-8, the future safety calculations proceed as follows. In present-day Toronto, the relative risk (e) of casualty collision during heavy rain is 1.174. For each of the roughly 6 annual days on which heavy rain occurs (r), 14.9 percent [(1.174-1.000)/1.174*100] of the collisions that occur may be attributable to the poor weather (p); the remaining 85 percent ($1 - p$) would likely have occurred regardless of the weather condition. Accordingly, 10.8 casualty collisions (n), per rainfall day, are attributable to the occurrence of heavy rainfall [14.9 percent (p) multiplied by an average of 73 crashes per heavy rain day (i)]. Therefore, assuming all other factors (i.e., mobility patterns, crash risk) remain constant, a climate future with an additional 2.4 rain days (Δr) each year (high and low estimates are 1.4 and 3.5) would see an increase (Δi) of approximately 26 casualty collisions annually (estimates range from 15 to 38).

Table 4-8: Projected change in rainfall-related incidents, Toronto North, 2050s

Incident type and daily rainfall intensity	*r*	*i*	*e*	*p*	*n*	*Mean change estimate (range of estimates)*	
						Δr	*Δi*
Casualty collisions							
Very light (0.2-4.9 mm)	49.2	58.0	1.029	0.028	1.6	+4.8 (-1.0 to +10.4)	+7.7 (-1.7 to +16.9)
Light (5.0-9.9 mm)	15.2	63.6	1.152	0.132	8.4	+0.9 (+0.3 to +1.9)	+7.2 (+2.2 to +16.2)
Moderate (10.0-19.9 mm)	12.2	69.2	1.216	0.177	12.3	+1.1 (+0.6 to +1.9)	+14.0 (+7.0 to +23.7)
Heavy (≥ 20.0 mm)	6.3	72.9	1.174	0.149	10.8	+2.4 (+1.4 to +3.5)	+25.6 (+15.2 to +37.5)
All intensities (sum)						+9.1 (+1.2 to +17.7)	+54.6 (+22.7 to +94.3)
Casualties							
Very light (0.2-4.9 mm)	49.2	83.1	1.017	0.016	1.4	+4.8 (-1.0 to +10.4)	+6.4 (-1.4 to +14.1)
Light (5.0-9.9 mm)	15.2	92.4	1.146	0.127	11.7	+0.9 (+0.3 to +1.9)	+10.0 (+3.1 to +22.7)
Moderate (10.0-19.9 mm)	12.2	99.5	1.220	0.181	18.0	+1.1 (+0.6 to +1.9)	+20.6 (+10.2 to +34.7)
Heavy (≥ 20.0 mm)	6.3	106.2	1.147	0.128	13.6	+2.4 (+1.4 to +3.5)	+32.1 (+19.0 to +47.1)
All intensities (sum)						+9.1 (+1.2 to +17.7)	+69.2 (+30.9 to +118.6)

r: average annual number of rainfall days [from Obs]
i: average number of incidents per rainfall day [# crashes on rain days / # rain days in study period]
e: relative risk estimate [calculated as per Section 3.2.2.3]
p: proportion of incidents for each rainfall day that are attributable to weather [(*e* – 1)/*e*]
n: number of incidents 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]
Δi: change in annual number of incidents [*Δr* * *n*]

A breakdown of results for each of the three modelling locations is provided next. For the north-central GTA (Toronto North, Table 4-8), the RCM ensemble projects a mean annual increase (1.4 to 21.4 percent, based on 82.9 rain days per year) in rain days of all intensities over the next half-century, resulting in marginally more (0.1 to 0.4 percent, based on 21,268 annual casualty collisions and 30,609 casualties per year) casualty collision and casualty incidents each year. In terms of rainfall intensity, the ensemble experiment suggests that very light (< 5 mm) rain days will see the greatest increase, accounting for roughly half of new rain days each year. Annual increases in incident counts, however, are more strongly weighted towards higher rainfall intensities, likely because of the more elevated risk associated with these days. Heavy rain days in particular – expected to increase by almost 40 percent – are estimated to account for almost half of the total increase in incidents each year.

Table 4-9: Projected change in rainfall-related incidents, Toronto West, 2050s

Incident type and daily rainfall intensity	r	i	e	p	n	*Mean change estimate (range of estimates)*	
						Δr	Δi
Casualty collisions							
Very light (0.2-4.9 mm)	49.2	58.0	1.029	0.028	1.6	+3.8 (-1.1 to +9.0)	+6.1 (-1.7 to +14.5)
Light (5.0-9.9 mm)	15.2	63.6	1.152	0.132	8.4	+0.8 (-0.2 to +1.4)	+7.1 (-1.7 to +11.7)
Moderate (10.0-19.9 mm)	12.2	69.2	1.216	0.177	12.3	+1.4 (+0.7 to +2.5)	+16.8 (+8.2 to +30.3)
Heavy (≥ 20.0 mm)	6.3	72.9	1.174	0.149	10.8	+2.1 (+1.6 to +2.5)	+22.7 (+17.0 to +27.4)
All intensities (sum)						+8.1 (+1.0 to +15.4)	+52.7 (+21.7 to +84.0)
Casualties							
Very light (0.2-4.9 mm)	49.2	83.1	1.017	0.016	1.4	+3.8 (-1.1 to +9.0)	+5.1 (-1.4 to +12.1)
Light (5.0-9.9 mm)	15.2	92.4	1.146	0.127	11.7	+0.8 (-0.2 to +1.4)	+9.9 (-2.3 to +16.4)
Moderate (10.0-19.9 mm)	12.2	99.5	1.220	0.181	18.0	+1.4 (+0.7 to +2.5)	+24.6 (+12.0 to +44.3)
Heavy (≥ 20.0 mm)	6.3	106.2	1.147	0.128	13.6	+2.1 (+1.6 to +2.5)	+28.5 (+21.3 to +34.4)
All intensities (sum)						+8.1 (+1.0 to +15.4)	+68.1 (+29.5 to +107.3)

r: average annual number of rainfall days [from Obs]
i: average number of incidents per rainfall day [# crashes on rain days / # rain days in study period]
e: relative risk estimate [calculated as per Section 3.2.2.3]
p: proportion of incidents for each rainfall day that are attributable to weather [$(e - 1)/e$]
n: number of incidents 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]
Δi: change in annual number of incidents [$\Delta r * n$]

Model simulations for the western portion of Toronto (Table 4-9) tell a similar story, with an approximately 0.1 to 0.4 percent increase in annual incident counts and 1.2 to 18.6 percent more rain days across the board. The mean estimate is again weighted mostly toward very light rain days, although roughly one-third more heavy days are expected. Increases in incident counts are distributed more in favour of moderate and heavy rainfall days. Compared to Toronto North, it is anticipated that the western GTA will see marginally fewer additional rain days and incident counts each year.

Table 4-10: Projected change in rainfall-related incidents, Vancouver, 2050s

Incident type and daily rainfall intensity	*r*	*i*	*e*	*p*	*n*	*Mean change estimate (range of estimates)*	
						Δr	*Δi*
Casualty collisions							
Very light (0.2-4.9 mm)	76.9	20.8	1.098	0.089	1.9	+8.9 (+5.8 to +11.3)	+16.5 (+10.8 to +21.0)
Light (5.0-9.9 mm)	30.9	24.4	1.267	0.211	5.1	+3.7 (+2.3 to +4.9)	+19.1 (+11.8 to +25.3)
Moderate (10.0-19.9 mm)	26.4	26.1	1.383	0.277	7.2	+5.6 (+3.4 to +7.0)	+40.4 (+24.6 to +50.8)
Heavy (≥ 20.0 mm)	12.2	28.3	1.464	0.317	9.0	+9.5 (+5.0 to +14.9)	+84.7 (+44.5 to +133.7)
All intensities (sum)						+27.7 (+16.5 to +38.2)	+160.7 (+91.6 to +230.9)
Casualties							
Very light (0.2-4.9 mm)	76.9	29.4	1.101	0.092	2.7	+8.9 (+5.8 to +11.3)	+24.1 (+15.7 to +30.6)
Light (5.0-9.9 mm)	30.9	34.7	1.320	0.242	8.4	+3.7 (+2.3 to +4.9)	+31.3 (+19.3 to +41.4)
Moderate (10.0-19.9 mm)	26.4	36.7	1.427	0.299	11.0	+5.6 (+3.4 to +7.0)	+61.3 (+37.3 to +77.1)
Heavy (≥ 20.0 mm)	12.2	40.4	1.535	0.348	14.1	+9.5 (+5.0 to +14.9)	+133.2 (+70.0 to +210.4)
All intensities (sum)						+27.7 (+16.5 to +38.2)	+249.9 (+142.3 to +359.5)

r: average annual number of rainfall days [from Obs]
i: average number of incidents per rainfall day [# crashes on rain days / # rain days in study period]
e: relative risk estimate [calculated as per Section 3.2.2.3]
p: proportion of incidents for each rainfall day that are attributable to weather [(*e* – 1)/*e*]
n: number of incidents 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]
Δi: change in annual number of incidents [*Δr* * *n*]

By mid-century, Vancouver (Table 4-10) is likely to experience a negative safety effect due to substantially more (11.3 to 26.1 percent) annual rainfall days; this is estimated to result in a 1.2 to 3.2 percent increase in annual casualties and casualty collisions. The distribution of additional rainfall days is more even across intensities than that anticipated for Toronto; however, the greatest increases are likely to be observed for very light and heavy rain days. As with the GTA, annual incident increases are skewed toward more intense rainfall. Particularly striking is the more than 75 percent increase in the number of heavy rain days each year, accounting for half of the additional incidents.

Notwithstanding changes in mobility or risk, both sets of experiments agree in suggesting that Toronto will likely see future roads that are marginally less safe (i.e., 0.1 to 0.4 percent more annual incidents) due to increased rain day frequency (Table 4-11). Similarly, by the mid 2050s, Vancouver is projected to experience an increase in annual incident counts of between 1.2 and 3.2 percent as rainfall becomes markedly more frequent in a region already known for its soggy weather. The greatest impact in terms of casualty and casualty collision counts will likely be observed during days with moderate to heavy rainfall (≥ 10 mm), consistent with the more elevated risk estimates associated with these conditions today. This suggests that attention should be paid to future changes in the frequency and intensity of extreme rainfall events.

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

	Average annual incidents	*Mean estimate*	*Low estimate*	*High estimate*
Toronto North				
Casualty collisions	21,268	+0.3%	+0.1%	+0.4%
Casualties	30,609	+0.2%	+0.1%	+0.4%
Toronto West				
Casualty collisions	21,268	+0.2%	+0.1%	+0.4%
Casualties	30,609	+0.2%	+0.1%	+0.4%
Vancouver				
Casualty collisions	7,900	+2.0%	+1.2%	+2.9%
Casualties	11,129	+2.2%	+1.3%	+3.2%
Above estimates are based on change in annual incidents (from Tables 4-8, 4-9, and 4-10) divided by average annual incident count				

At first glance, the estimated increases in total annual crashes for each study location seem small, ranging from 0.1 to 3.2 percent. To better understand the magnitude of the issue, it is useful to also consider them from a different perspective. As shown in Table 4-12, the annual increase in incidents directly attributable to rainfall is more marked. Indeed, the average increase in the GTA is roughly 67 percent compared to an almost 150 percent increase in Greater Vancouver. This complements the initial assessment by specifically highlighting the additional annual crashes that are caused directly by the rain, i.e., while it is actually raining. It should be noted that these estimates do not account for changes in traffic volume during inclement conditions and assume that all aspects of the mobility and safety picture will remain constant over the next 40 years.

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

	Average annual incidents attributable to rainfall	*Mean estimate*	*Low estimate*	*High estimate*
Toronto North				
Casualty collisions	81	+67.4%	+28.0%	+116.6%
Casualties	102	+68.0%	+30.4%	+116.5%
Toronto West				
Casualty collisions	81	+65.1%	+26.9%	+103.8%
Casualties	102	+66.9%	+28.9%	+105.4%
Vancouver				
Casualty collisions	110	+145.5%	+83.0%	+209.1%
Casualties	169	+148.1%	+84.3%	+213.1%
Above estimates are based on change in annual incidents (from Tables 4-8, 4-9, and 4-10) divided by average annual incidents attributable to rainfall. The latter count is calculated based on total rain day sum as [(*r* * *i* * *p*) / *5 years*]				

Chapter 5
Conclusions and Discussion

5.1 Summary of results

The primary objective of this thesis is to provide a first estimate of the potential impacts of climate change on road safety in urban Canada over the next 40 years. In completing this objective, an empirical estimate of present-day rainfall-related crash risk was established based on daily collision and climate records over a five-year study period from 2003-2007. This estimate was then combined with outputs from high-resolution regional climate models in order to arrive at possible climate and traffic safety futures for the Toronto and Vancouver regions.

Key results related to the primary objective are:

- On average, collision risk is approximately 10 to 15 percent higher in Toronto and 20 to 25 percent higher in Vancouver on days with rainfall relative to days during which inclement weather is not present. This compares reasonably well with results of previous analyses. However, the risk estimates reported here are conservative in nature, as the effects of rainfall are diluted by the presence of non-rainfall hours within the 24-hour analysis period. Moreover, the thesis examines only a subset of rainfall events – those which occur in entirely liquid form – thereby resulting in slightly lower risk estimates than would otherwise have been identified.

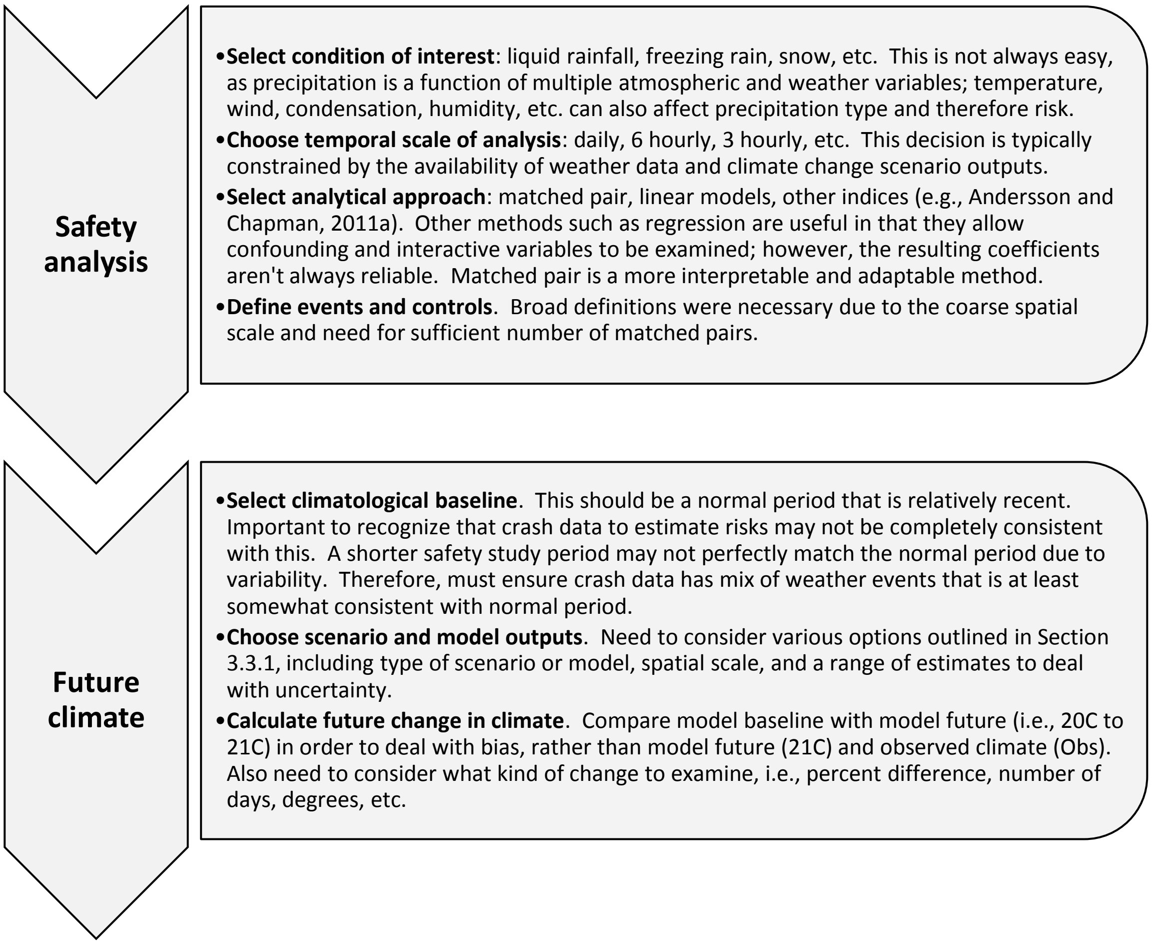
- As found in previous analyses, there is a strong progression in risk as rainfall intensity increases. In Toronto, days with very light rainfall (< 5 mm) are associated with slight increases in collision and casualty risk, and moderate to heavy rainfall events (≥ 10 mm) typically result in risk increases that are twice that of lower intensity rains. A similar progression is apparent in Vancouver, where heavy rainfalls (≥ 20 mm) result in elevated risks up to three times higher than those for very light rain days.

- Risk increases are typically higher for less severe collisions, regardless of rainfall intensity. As driving conditions worsen, it appears that drivers typically adjust to some extent (thereby reducing crash severity), although not enough to completely avoid a collision.

- Vancouver drivers are more susceptible to crashes during rainfall than are Toronto drivers; risk increases in Vancouver are typically double those observed for Toronto, regardless of rain day intensity and incident severity. This is a rather unexpected result, and possibly is indicative of driver maladaptation to weather-related hazards.

- By mid-century, Toronto is likely to see a moderate overall increase in annual precipitation accompanied by mean warming of 2.4 to 3.1 degrees Celsius. In the northern GTA, the RCM/GCM projections range from 5.2 to 11.5 percent more total annual precipitation, compared to a slightly smaller 3.4 to 9.5 percent increase in Toronto West. The two driving GCMs estimate 6.8 to 8.4 percent more annual precipitation for the Toronto region as a whole.
- Vancouver, on the other hand, could see a slight to moderate increase in annual precipitation, depending on the model used. The RCM/GCM projections range from 1.7 to 8.8 percent more annual precipitation, while the driving GCMs lie beyond this range: 11.4 percent more and 2.6 percent less precipitation for the CGCM3 and GFDL, respectively. All scenarios estimate a temperature increase of 1.7 to 2.4 degrees, notwithstanding the RCM3 driven by GFDL, which projects slight cooling for the Vancouver region.
- Over the next 40 years, Toronto is likely to see a mean annual increase (approximately 1 to 20 percent) in rain days of all intensities, resulting in marginally more (0.1 to 0.4 percent) casualty collisions and casualties each year. Roughly half of the additional rain days each year are expected to involve very light rainfall. Slightly more additional rain days and incident counts are projected for the northern GTA compared to the western part of the region.
- Substantially more (11 to 26 percent) rain days are projected for Vancouver by mid-century, resulting in a 1 to 3 percent increase in annual incident counts. Additional rain days are expected for all intensities, with the greatest increases likely to be observed for very light and heavy rainfall days.
- In both study regions, the greatest impact in terms of casualty and casualty collision counts will likely be observed on days with moderate to heavy rainfall; this estimate is consistent with the greater risk increases associated with these conditions today, and suggests that attention should be paid to future changes in the frequency and intensity of extreme rainfall events. Heavy rainfall days are likely to account for approximately half of all additional safety incidents.

As the field of climate impact assessment continues to grow, more and more attention is being paid to standardization of approaches in order to ensure well thought out decisions and comparability of results. Accordingly, the secondary thesis objective is to develop a framework or methodology for exploring the implications of climate change for traffic safety. Several important decisions were made regarding data acquisition, compatibility, and completeness; these, and a number of associated tradeoffs, are summarized in Figure 5-1 in order to provide guidance for future research.



Safety analysis

- **Select condition of interest**: liquid rainfall, freezing rain, snow, etc. This is not always easy, as precipitation is a function of multiple atmospheric and weather variables; temperature, wind, condensation, humidity, etc. can also affect precipitation type and therefore risk.
- **Choose temporal scale of analysis**: daily, 6 hourly, 3 hourly, etc. This decision is typically constrained by the availability of weather data and climate change scenario outputs.
- **Select analytical approach**: matched pair, linear models, other indices (e.g., Andersson and Chapman, 2011a). Other methods such as regression are useful in that they allow confounding and interactive variables to be examined; however, the resulting coefficients aren't always reliable. Matched pair is a more interpretable and adaptable method.
- **Define events and controls**. Broad definitions were necessary due to the coarse spatial scale and need for sufficient number of matched pairs.

Future climate

- **Select climatological baseline**. This should be a normal period that is relatively recent. Important to recognize that crash data to estimate risks may not be completely consistent with this. A shorter safety study period may not perfectly match the normal period due to variability. Therefore, must ensure crash data has mix of weather events that is at least somewhat consistent with normal period.
- **Choose scenario and model outputs**. Need to consider various options outlined in Section 3.3.1, including type of scenario or model, spatial scale, and a range of estimates to deal with uncertainty.
- **Calculate future change in climate**. Compare model baseline with model future (i.e., 20C to 21C) in order to deal with bias, rather than model future (21C) and observed climate (Obs). Also need to consider what kind of change to examine, i.e., percent difference, number of days, degrees, etc.

Figure 5-1: Important considerations in climate impact analyses for traffic safety

The methods employed in this thesis have advantages over those used by Andersson in what is so far the only previous research on climate change and traffic safety (Andersson, 2010; Andersson and Chapman, 2011a; 2011b). The thesis establishes a clear and direct present-day relationship between rainfall and crash risk over several study years based on a robust and widely accepted matched pair approach that uses a common daily scale to control for confounding temporal and situational variables (e.g., time of day, season, light condition, traffic volume), thereby allowing the focus to remain solely on rainfall. Moreover, the matched pair design is highly adaptable and offers the ability to look at changes in risk at various temporal scales and for different event types or intensities. Andersson, meanwhile, relies on one season of crashes and a ratio (number of collisions at temperature X / number of days per winter with minimum temperature X) with incompatible time scales (i.e., numerator based on specific time of collision and denominator on entire days) to establish present-day safety status. Moreover, the thesis uses state-of-the-art high resolution climate models to estimate future changes in climate, while Andersson's work is based on temporal analogues and statistical weather generators.

5.2 Conclusions

The empirical results indicate that climate change is likely to have a slight to moderate impact on annual rainfall-related crash rates in urban Canada over the next 40 years. While the estimated increase in total annual casualties and casualty collisions appears small (0.1 to 0.4 percent in Toronto and 1.2 to 3.2 percent in Vancouver), it is not insignificant. Moreover, the future component of this analysis did not include PDO collisions because of a large underreporting bias; however, these less severe crashes are associated with the greatest risk increases during rain, particularly at higher intensity rainfalls. As such, the increase in total crashes is likely to be substantially higher than the estimates provided here.

Additional future rain days will likely be distributed across all rainfall intensities, although very light rains (< 5 mm) are projected to have among the highest increases. These days are not likely to have a significant safety impact, however. In Vancouver especially, heavy rain days (≥ 20 mm) could increase by 75 percent or more, likely with a strong negative safety effect; in both study cities, roughly half of all additional casualty collisions and casualties are expected to occur on these days. Accordingly, the safety problem is expected to persist at all rainfall intensities, although it is apparent that heavy rain days and extreme events should receive particular attention moving forward.

From an impact assessment point of view, this is a moderate to high priority issue relative to other climate change impacts. Indeed, the nature of the impact being measured is human life and human health, which makes it different than other climate impact analyses that highlight largely economic concerns. The current research is similar to heat stress in that respect; the increased phenomenon may not occur often, but its consequences are of huge concern. In addition, the issue is of moderate concern from a safety perspective because inclement weather accounts for a small percentage of overall crash risk and absolute incident counts, and the additional climate-induced risk and incidents are expected to be smaller still.

However, there is likely to be wide spatial variation in the extent of the future safety problem associated with rainfall, not just because of differences in climate and climate change impacts but also the significant differences in relative risk in different regions, some of which is not fully understood. For example, rainfall-related risk increases in Vancouver are nearly double those for Toronto, despite the fact that Vancouver receives substantially more rainfall. One would expect Vancouver motorists to be more used to driving in rainy conditions, therefore leading to fewer crashes; however, this is not the case. Moreover, the road mix is not the same in every region, so working at a disaggregated spatial scale (e.g., an individual highway segment) could tease out the effect of these differences on risk. Accordingly, not all regions experience rainfall-related crash risk to the same extent and, similarly, not all areas will be susceptible to the same degree of future climate change.

Finally, the analysis is based on the key *ceteris paribus* assumption that the climate is evolving but everything else is static – i.e., that relative risk and mobility will remain constant between now and the future. If this assumption holds true, then modest changes (less safe roads) will be expected. However, the assumption is particularly troublesome in this context because of the long-term trend of safer Canadian roads, both overall, as identified in Section 2.1.2, and during rainfall, as reported by Andrey (2010).

Nonetheless, despite decreasing over the past 25 years, the risk associated with driving during rainfall remains highly elevated today. Thus, there is a need not only for interventions today, but also for additional assessments of local and regional implications of climate change. Through research of this nature, potential safety concerns can be identified and resources directed to best address them. Indeed, the anticipated increase in rainfall-related traffic incidents in Toronto and Vancouver could be partially offset by greater hazard awareness and adequate driver adjustment, improved roadway and vehicle design, or a transition to a more sustainable transport future.

5.3 Discussion

The practical implications of the thesis research relate primarily to safety interventions and cost. Traffic safety is an incredibly complex system with a wide range of risk factors and risk offset interventions. Essentially, the system is a game of incremental changes, where key risk factors of contemporary interest are addressed one at a time. It is widely acknowledged within the safety community that easy interventions or ‘low-hanging fruit’ such as vehicle occupant protection and better road engineering have already been addressed, resulting in substantial safety improvements. The current situation, therefore, involves a focus on smaller changes that will move us slowly in the direction of safer roads. Accordingly, the estimated 0.1 to 3.2 percent increase in annual incidents reported in this thesis has the potential to offset other initiatives that have been put in place (e.g., anti-lock braking systems). Indeed, because most ‘easy’ interventions have already been made, a great deal of effort – and expense – is now required to remove a few percent of collisions. Current and next-generation technological initiatives (e.g., GPS-controlled car trains) are massively expensive, while behavioural interventions such as driver retraining are only partially successful in alleviating the problem. Therefore, a focus on mobility is likely the next required step to significantly reduce collision rates and severities, and to offset the projected safety impacts of climate change. If movement toward more sustainable transportation systems begins to change modal split in favour of active transportation and public transit, then climate change mitigation (fewer greenhouse gas emissions) will occur simultaneously with adaptation (less exposure to travel risks). It is possible that, given such a shift, the climate impacts estimated in this thesis may not materialize, or at least will be adequately and cost effectively offset.

Changes in mobility and risk notwithstanding, the increase in crashes associated with climate change is likely to have a significant social cost. Vodden et al. (2007) estimated the average social cost, in 2004 dollars, of an injury collision and fatal collision in Ontario at $82 thousand and $15.7 million, respectively ($94 thousand and $18 million in 2011 dollars); it is assumed that these values reasonably represent BC as well. If Toronto is to see an additional 22 to 94 casualty collisions each year, this equals an added annual cost of $2 million to $9 million. Vancouver, meanwhile, could experience 92 to 231 more annual crashes, at a cost of $9 million to $22 million. Casualty collisions mostly comprise injury collisions (approximately 99%), but additional fatal crashes will probably occur too. Therefore, using injury collision cost to represent all casualty collisions provides a conservative estimate. In addition, PDO crashes are not accounted for, and risk estimates tend to be lower in daily analyses, so costs are again likely to be higher than those estimated here. When aggregated to a provincial or national scale, it is likely that climate change will have substantial costs related to traffic safety.

While this thesis has provided a first estimate of future rainfall-related crash risk for two Canadian cities, there are a number of limitations associated with climate change analysis. First, the IPCC (2005, 2007) is more confident in projections of warming temperatures and sea level rise, which are considered ‘virtually certain’ (> 99% probability of occurrence), compared to changing seasonal precipitation patterns (‘likely’, > 66% probability of occurrence) and extremes (‘very likely’, > 90% probability of occurrence). Indeed, climate models have a limited ability to simulate precipitation changes, particularly at fine spatial scales, due to the highly localized nature of precipitation and the strong influence of local geography and landscape features. It is likely, however, that this limitation is partly addressed by the use of RCMs to downscale GCM results. Moreover, several different RCM/GCM combinations have been utilized to address some of the uncertainty associated with modelling future climate change. In addition, there is difficulty associated with identifying future precipitation type; thus in most climate scenarios, only total accumulation is simulated. Accordingly, in the current study, daily minimum temperature is used as a determinant of precipitation type so that only liquid rainfall days are examined. However, roughly 20 percent of Toronto rainfall and rain days are removed from the analysis because of this criterion, compared to less than 10 percent for Vancouver.

Additional limitations arise in the safety component of the analysis. The study has assumed that relative risk, traffic volumes, and modal shares will remain constant over the next 40 years, as the matched pair methodology makes it difficult to anticipate the effect of changes in any of these variables. Future work therefore needs to consider such changes, perhaps using a scaling factor to increase or decrease crash counts in conjunction with changing travel patterns. Furthermore, it may be possible to adjust travel exposure (i.e., decrease the estimate of total trips) during event periods by a specified percentage in order to approximate the travel reductions observed during adverse weather conditions. Finally, the daily scale of analysis means that some non-rainfall hours are included in rainfall events, thereby diluting the risk estimates, which results in a lower estimate of incident counts attributable to the rain; future work could address this issue by using a finer temporal scale, such as three-hourly or six-hourly observations.

Moving forward, there is a need to look at overall weather-related crash risk, including winter driving and extreme temperatures, in order to more comprehensively assess the safety implications of climate change for Canada. This is especially pertinent, given that snowfall and frozen precipitation patterns could see a greater degree of change than rainfall. In addition, the period when temperatures fluctuate around zero degrees is particularly troublesome from a safety perspective because of rapid road freezeup; future analyses should consider this in the context of climate change.

Moreover, additional cities and climatic regions, as well as seasonal differences, should be evaluated to establish a cross-country profile of future precipitation patterns and resulting safety impacts. Impact assessments of this nature should also be done in developing countries that are rapidly motorizing, as hazards in these locales have not been assessed and are likely to change for the worse; climate change could exacerbate this effect.

Finally, in future analyses, a wider range of climate scenarios and downscaling methods should be evaluated to provide a sensitivity analysis of the breadth of possible future changes as they relate to traffic safety. This would reduce uncertainty in working toward a ‘best estimate’ of possible future change in order to facilitate informed adaptation decisions. Indeed, massive public expenditures to adapt to a ‘worst case’ climate change scenario may be difficult to justify in the face of uncertainty. Therefore, a robust comparison of different methods would be particularly beneficial to both the modelling and impacts communities.

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Appendix A

Selected examples of safety interventions

Intervention	*Purpose*
A. Engineering	
Highway design	
Breakaway poles and street furniture; energy-absorbing barrier ends	Reduce injury severity upon impact by absorbing energy; significantly reduce or eliminate fatalities
Divided highways	Avoid head on collisions by separating opposing traffic lanes
Roadside fencing and wildlife crossing structures	Prevent wildlife-vehicle collisions in natural movement corridors and other high-risk areas
Roadside and median barriers	Reduce collision severity by avoiding run-off or head-on collisions and preventing vehicle spins; channel collision trajectory in direction of vehicle movement
Street lighting	Prevent collisions by increasing visibility of driving environment and other road users
Separated facilities for different road users (e.g., sheltered bike lanes or paths)	Prevent collisions by reducing possibility of road user conflicts
Road gradient and curvature	Prevent collisions by improving visibility and vehicle handling around curves
Road surface maintenance	Prevent collisions by ensuring that road is in good condition
Traffic controls; roundabouts; channelized intersections (e.g., left and right turn lanes)	Reduce number of intersection collisions by making vehicle movements more predictable
Winter road maintenance (e.g., plowing, salting)	Prevent collisions by improving road surface friction to give drivers better control
Rumble strips	Reduce number of off-road and head-on collisions by making drivers aware of lane violations
Vehicle design	
Daytime running lights	Prevent collisions by increasing visibility of vehicles
Antilock/antiskid brakes	Prevent collisions or reduce their severity by providing better traction when braking suddenly
Adaptive cruise control	Prevent collisions by maintaining steady vehicle speed
Snow tires/studded tires	Prevent collisions by increasing vehicle traction in low-friction winter driving environments
Occupant protection devices (seatbelts, airbags)	Reduce injury severity and keep occupants inside the vehicle upon collision occurrence
Vehicle crashworthiness	Reduce injury severity by absorbing collision energy and maintaining better vehicle integrity

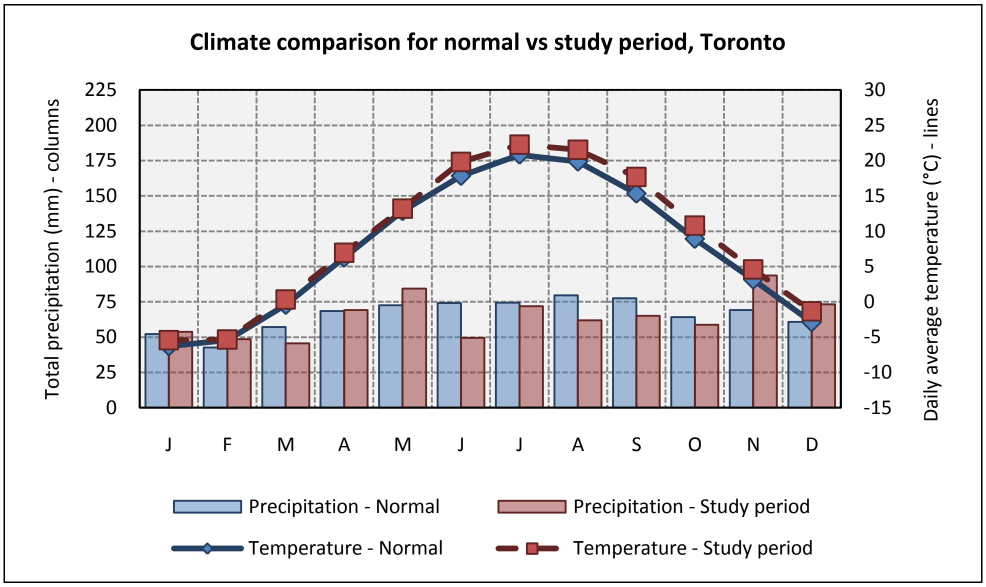
Intervention	*Purpose*
B. Enforcement	
Seatbelt laws	Reduce injury severity by issuing fines for vehicle occupants not wearing seatbelts
Impaired driving enforcement and legislation	Prevent drinking-related collisions by threatening sanctions such as charges, license suspension, or vehicle seizure
Snow tire legislation	Prevent snow-related collisions by requiring all vehicles to have snow tires, with a fine for non-compliance
Patrolling	Reduce unsafe driving behaviour with a constant visible police presence on the road system
Speed limits, roadside speed enforcement, street racing laws, speed cameras	Prevent speed-related crashes by curbing unsafe driving above or below speed limits; fines or vehicle seizure depending on severity of infraction
Red light cameras	Reduce intersection collisions by issuing fines to drivers observed running red lights
Vehicle and garage inspection	Prevent collisions by ensuring that vehicles are in good working order
Age and health limits for drivers	Prevent collisions by keeping inexperienced or unsafe drivers off the road
Regulation for driving and rest hours	Prevent truck collisions by regulating maximum shift lengths and minimum rest hours for professional drivers
Fixed penalties and sanctions	Reduce unsafe driving behaviour and safety infractions by imposing fines, imprisonment, or other penalties (e.g., license demerit points or suspension, vehicle seizure, higher insurance premiums)
Fire safety standards	Reduce collision severity by preventing fire or explosions post-collision
Driver rewards	Encourage good driver behaviour through positive enforcement (e.g., better insurance rates)
C. Education	
Advocacy programs (e.g., MADD, OSAID)	Prevent collisions and unsafe behaviour by making the public aware of major societal safety issues (e.g., impaired driving)
Hazard awareness	Prevent collisions by making drivers aware of situational or environmental hazards (e.g., deer or moose crossing area; need to reduce speeds and drive more carefully in rain, snow, fog)
Variable feedback signs	Prevent collisions by ensuring that drivers are informed on road and traffic conditions
Road user information and campaigns	Improve driver behaviour by alerting drivers to important safety issues
Education in schools	Influence behaviour and improve safety-related knowledge and skills of children so that they can travel safely

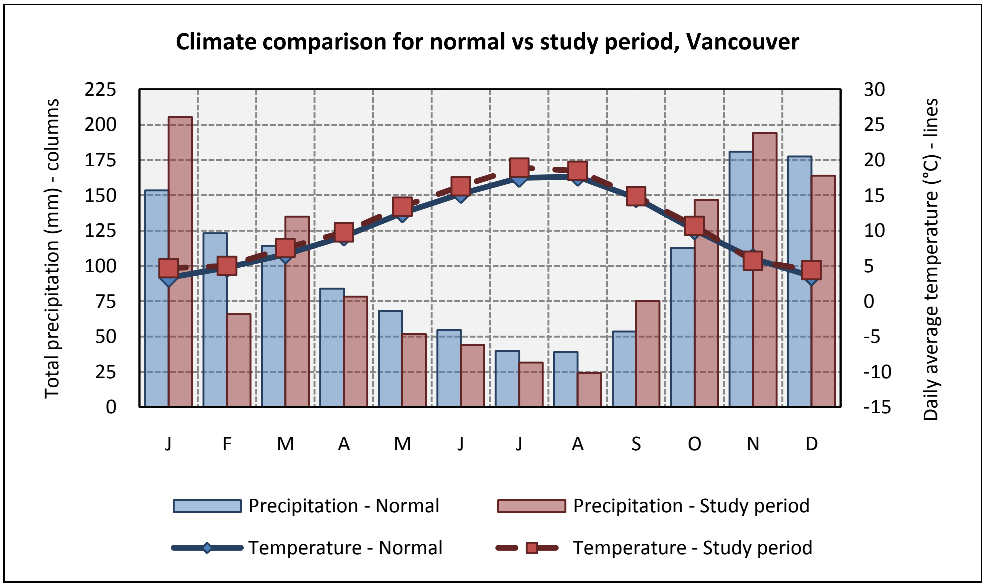
Intervention	*Purpose*
Graduated licensing; training and testing	Reduce difficulty in new drivers’ development of driving skills; lift restrictions as drivers gain experience; ensure that drivers retain knowledge and skills related to road rules and the driving task
D. Medicine	
Access to first aid and ambulance transport	Improve emergency response times and enhance the ability of first responders to quickly intervene in life-threatening situations; increase crash survival rates
Doctors on board ambulance	
Ambulance helicopters	
Faster emergency response	
Access to and quality of hospital treatment	Increase likelihood of recovery from injuries and reduce potential for long-term disability
Long-term care and rehabilitation facilities	
E. Planning and Mobility Management	
Land use planning (e.g., mixed use communities, walkable neighbourhoods)	Attempt to influence travel patterns and reduce road traffic by encouraging the use of other transportation modes while making driving less desirable
Modal split/provision of alternative modes (e.g., transit)	
Road pricing (tolls, congestion fees)	
Vehicle and fuel taxation	
Quantified road safety targets	Provide a clear, publicly recognized target or reference point against which safety progress can be measured; increase accountability and transparency
Information for decision makers (e.g., more complete accident and safety data)	Allow safety practitioners to identify and target important black spot areas where additional intervention measures might be required
Neighbourhood planning; traffic calming	Reduce collision frequencies by slowing traffic

Appendix B

Monthly comparison of climate normals with study period

The below graphs illustrate the average monthly differences between 1971-2000 climate normals and weather during the five-year study period (2003-2007).





Appendix C

Holidays which were excluded from the dataset

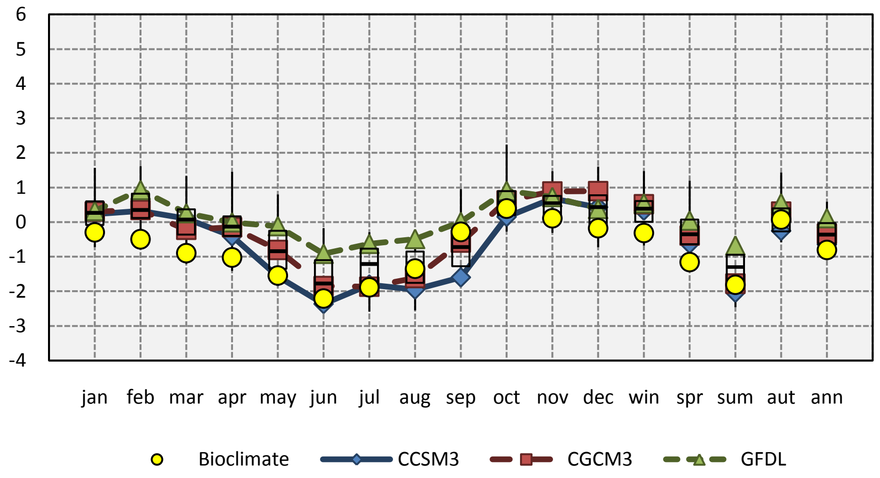
Holiday	*Typical occurrence*	*2003*	*2004*	*2005*	*2006*	*2007*
New Year's	January 1; if falls on Saturday or Sunday, holiday on Monday	Dec 31 - Jan 1	Dec 31 - Jan 1	Dec 31 - Jan 3	Dec 31 - Jan 2	Dec 31 - Jan 1
Easter Weekend (Friday-Monday)	Varies each year	Apr 18-21	Apr 9-12	Mar 25-28	Apr 14-17	Apr 6-9
Victoria Day Weekend (Friday-Monday)	Monday preceding May 25	May 16-19	May 21-24	May 20-23	May 19-22	May 18-21
Canada Day (and/or July 1 Weekend)	July 1; if falls on Sunday, holiday on Monday	Jun 28 - Jul 1	Jul 1-4	Jun 30 - Jul 3	Jun 30 - Jul 3	Jun 29 - Jul 2
Civic Holiday/British Columbia Day Weekend (Friday-Monday)	First Monday of August	Aug 1-4	Jul 30 - Aug 2	Jul 29 - Aug 1	Aug 4-7	Aug 3-6
Labour Day Weekend (Friday-Monday)	First Monday of September	Aug 29 - Sep 1	Sep 3-6	Sep 2-5	Sep 1-4	Aug 31 - Sep 3
Thanksgiving Weekend (Friday-Monday)	Second Monday of October	Oct 10-13	Oct 8-11	Oct 7-10	Oct 6-9	Oct 5-8
Remembrance Day	November 11	Nov 11	Nov 11	Nov 11	Nov 11	Nov 11
Christmas (Dec 24-26 and closest weekend, Saturday-Sunday)	December 24 and 26	Dec 24-28	Dec 24-26	Dec 24-26	Dec 23-26	Dec 22-26

Appendix D

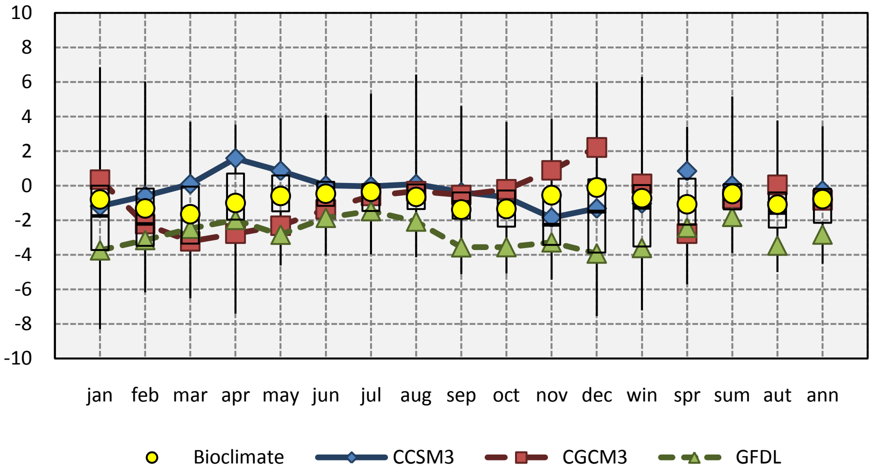
GCM validation boxplots

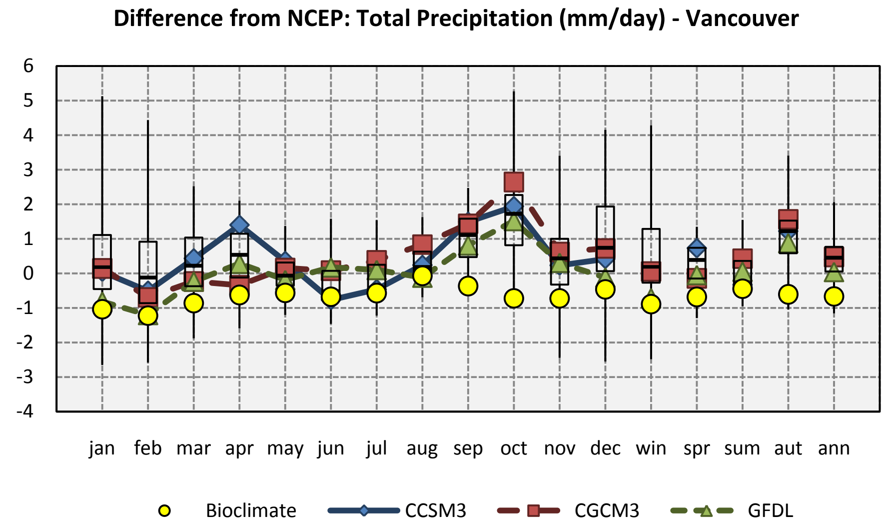
The following boxplots illustrate monthly and seasonal differences in the ability of the NARCCAP GCMs to simulate observed local climate for the 1971-2000 normal (Obs) period. All are plotted relative to (i.e., as differences from) the NCEP reanalysis gridpoint in closest proximity to each city's airport weather station. The plots indicate minimum, 25th percentile, median, 75th percentile, and maximum differences derived from 58 experiments of 24 different GCMs. (Source: CCCSN, 2011b). Bioclimate observations from the two airport weather stations are also plotted for comparison.

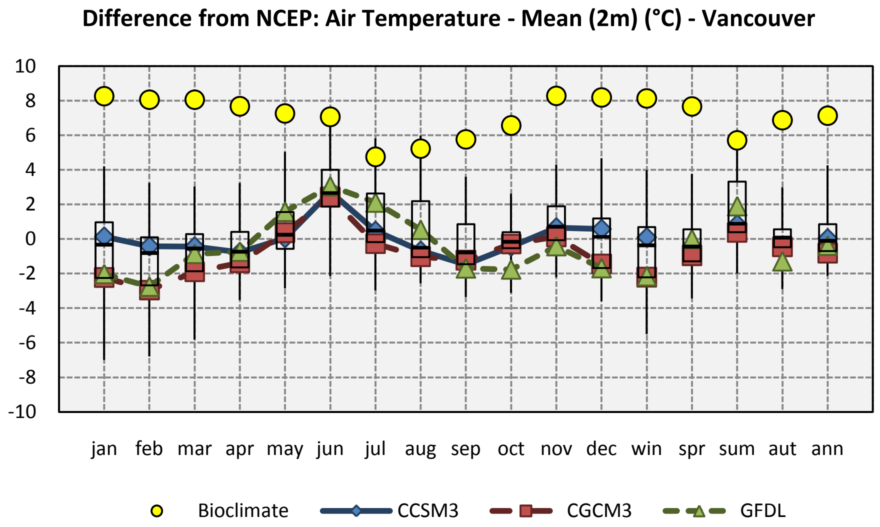
Difference from NCEP: Total Precipitation (mm/day) - Toronto



Difference from NCEP: Air Temperature - Mean (2m) (°C) - Toronto



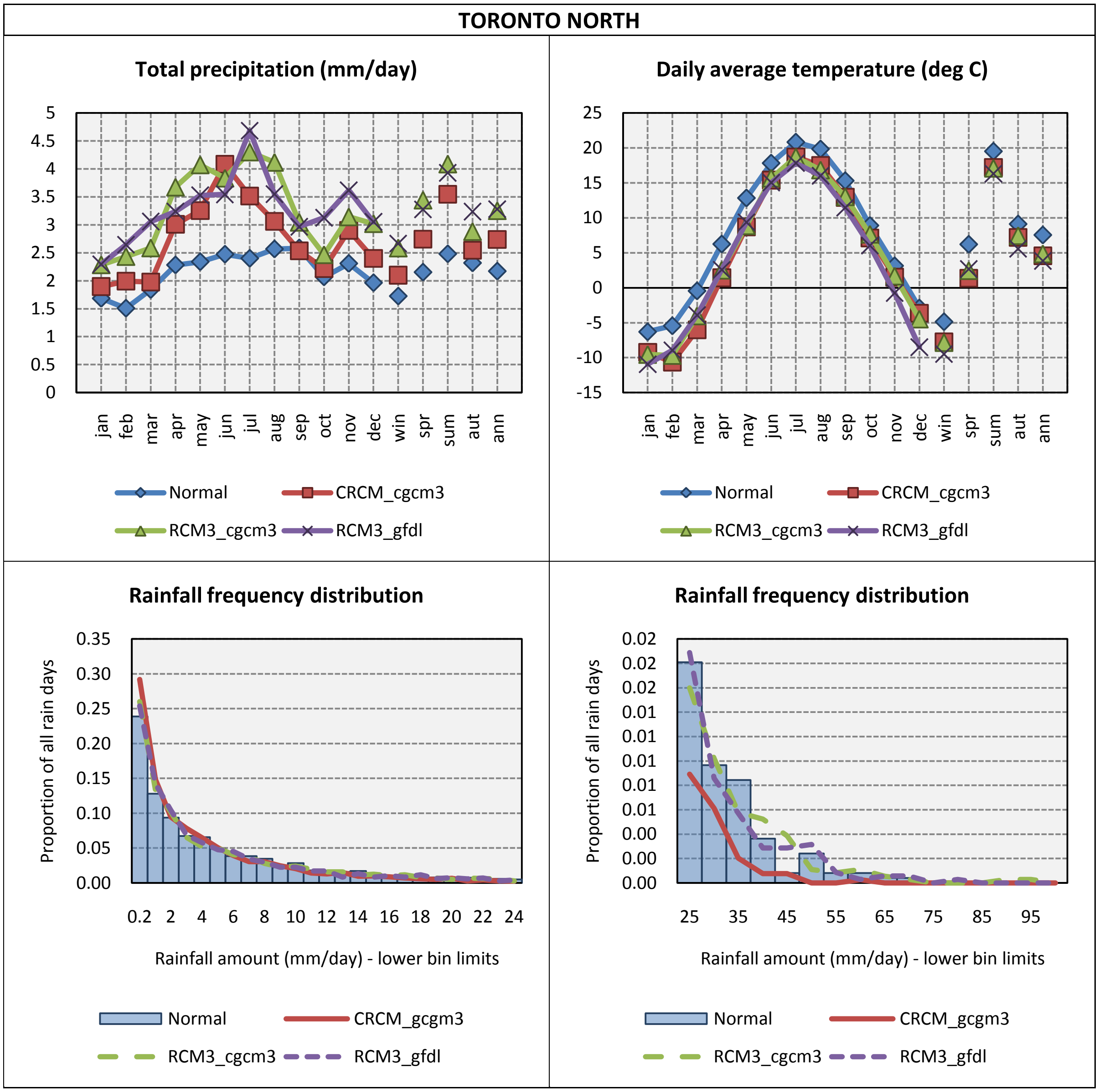

Difference from NCEP: Total Precipitation (mm/day) - Vancouver


Difference from NCEP: Air Temperature - Mean (2m) (°C) - Vancouver

Appendix E

Model simulation of observed climate

The below graphs illustrate the differences between model simulated baseline (20C) and observed (Obs) climates for the 1971-2000 period. The precipitation graphs include all annual precipitation, while the rainfall intensity and rain day distribution graphs include only liquid rainfall (daily minimum temperature ≥ 1 °C).



TORONTO NORTH

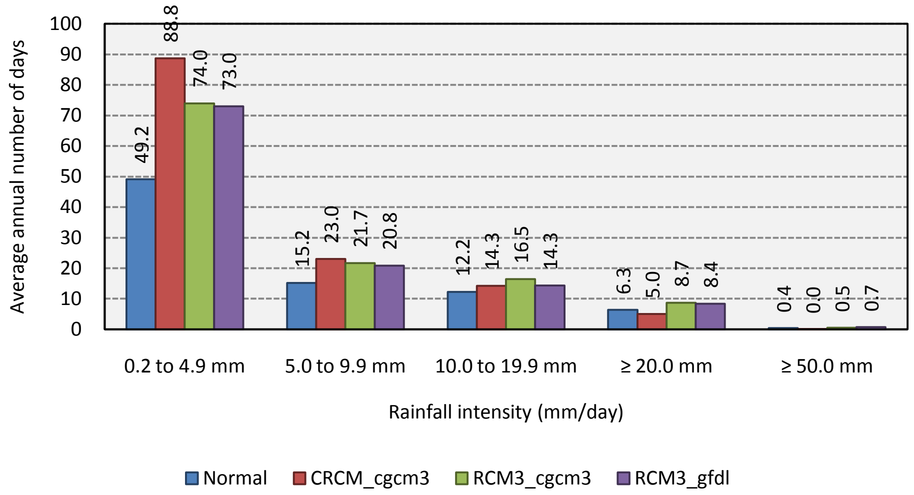
Total precipitation (mm/day)

Daily average temperature (deg C)

Rainfall frequency distribution

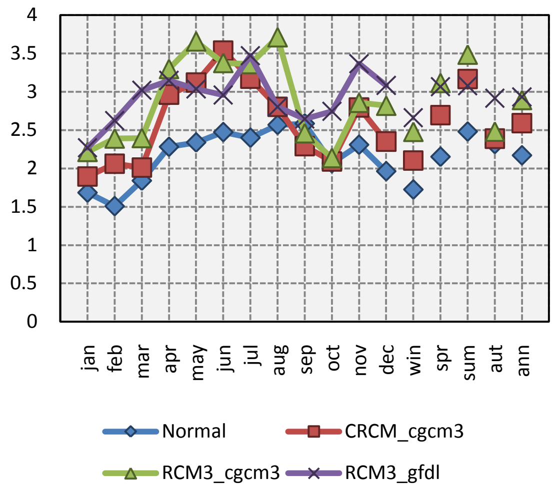
Rainfall frequency distribution

TORONTO NORTH

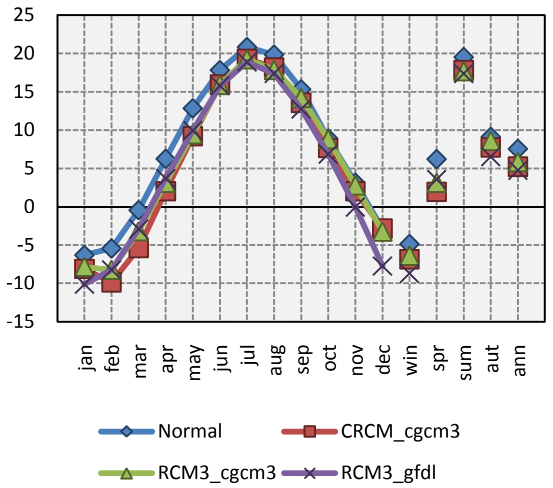


Rain day frequency

TORONTO WEST

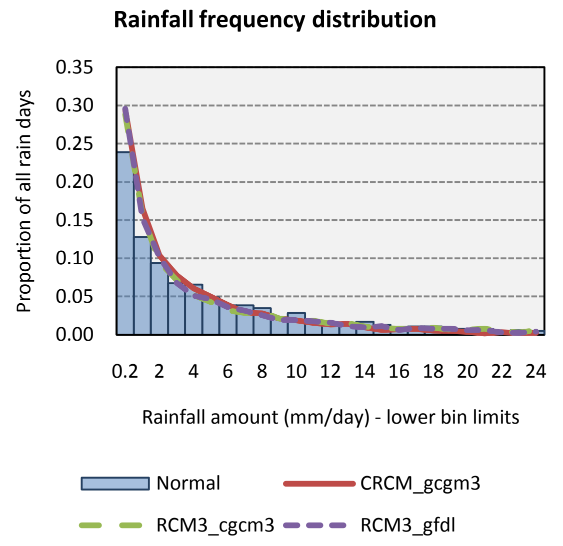


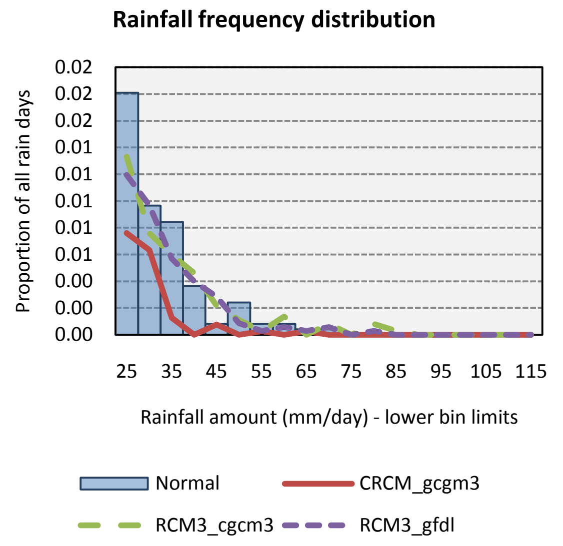
Total precipitation (mm/day)

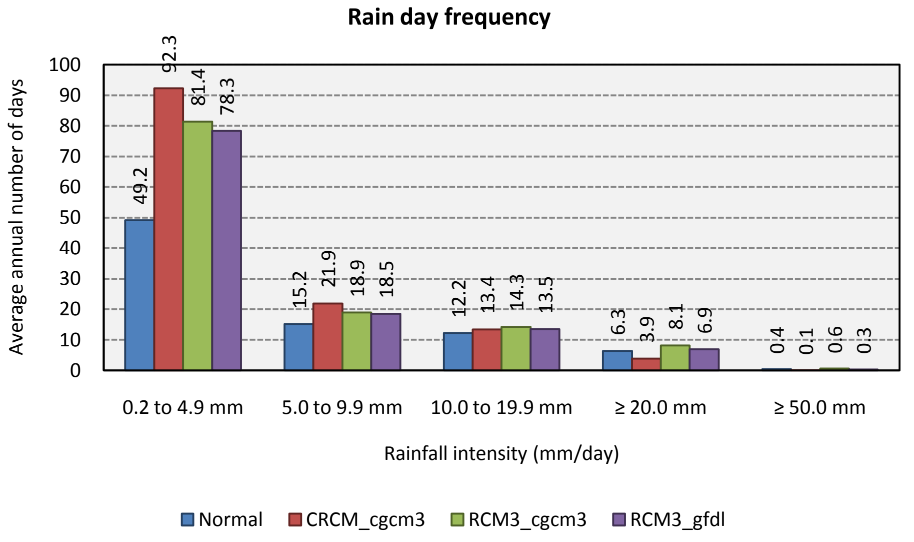


Daily average temperature (deg C)

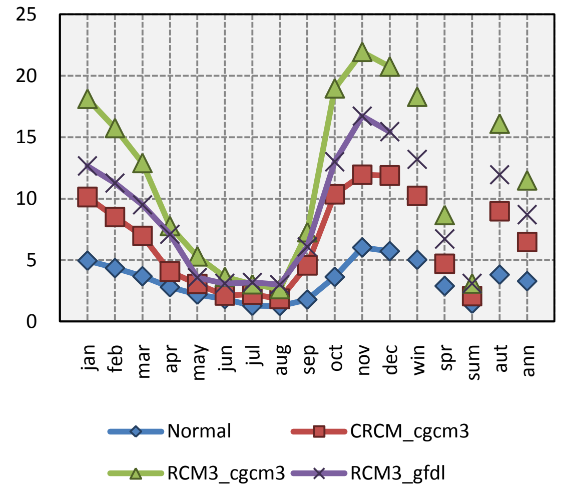
TORONTO WEST

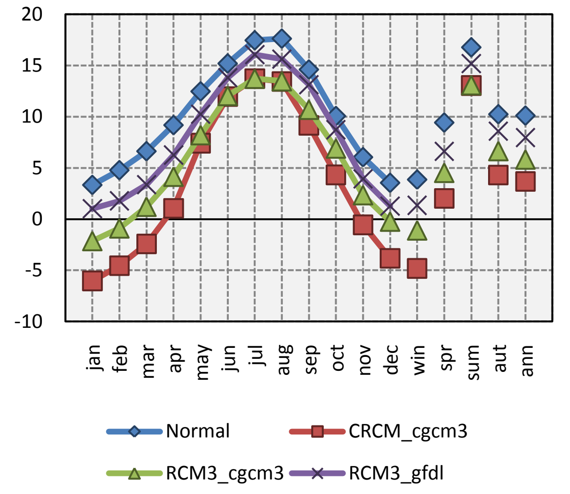

Rainfall frequency distribution

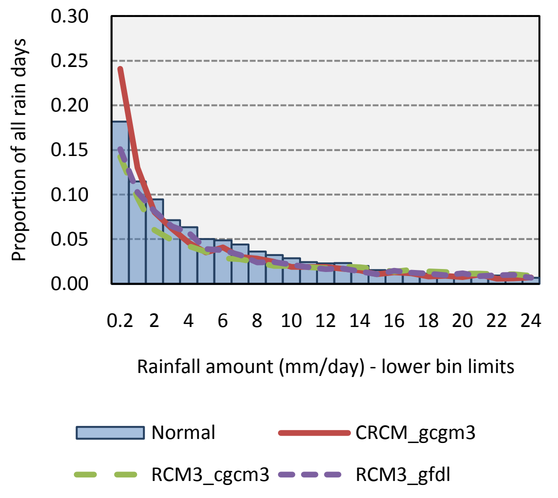

Rainfall frequency distribution

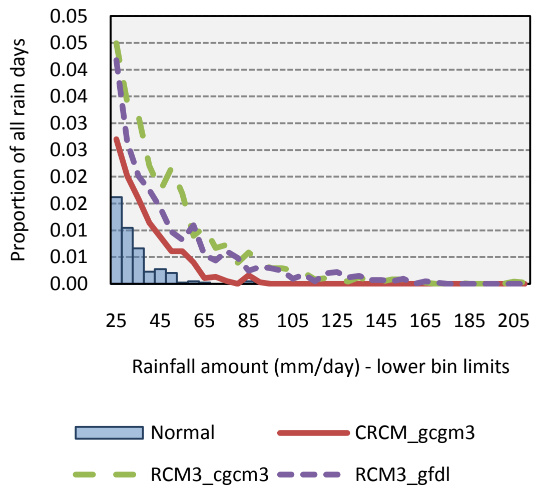

Rain day frequency

VANCOUVER

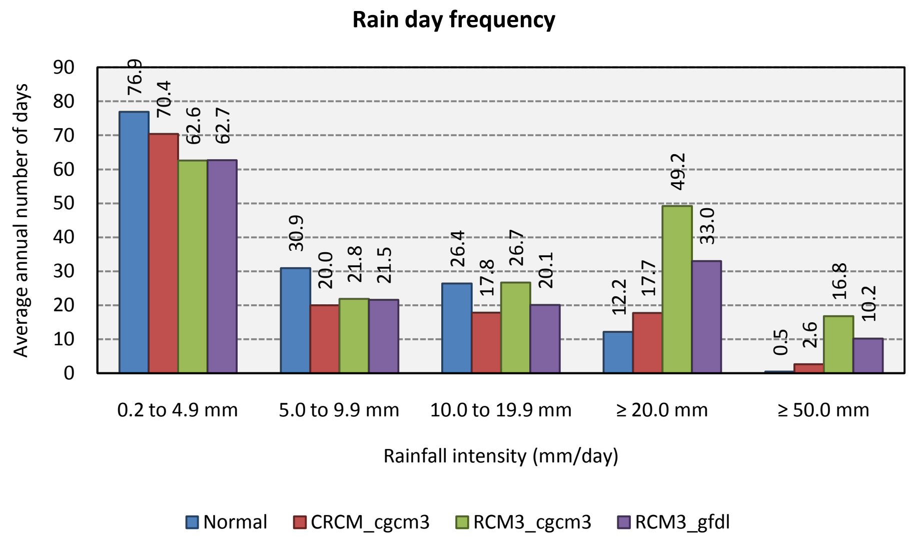

Total precipitation (mm/day)


Daily average temperature (deg C)


Rainfall frequency distribution


Rainfall frequency distribution

VANCOUVER


Rain day frequency
Average annual number of days
0
10
20
30
40
50
60
70
80
90
76.9
70.4
62.6
62.7
30.9
20.0
21.8
21.5
26.4
17.8
26.7
20.1
12.2
17.7
49.2
33.0
0.5
2.6
16.8
10.2
0.2 to 4.9 mm
5.0 to 9.9 mm
10.0 to 19.9 mm
≥ 20.0 mm
≥ 50.0 mm
Rainfall intensity (mm/day)
Normal
CRCM_cgcm3
RCM3_cgcm3
RCM3_gfdl