Evaluation of safety effects of roundabouts in the Region of Waterloo: inclement weather and conversion

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Roundabouts, as a form of intersection traffic control, significantly improve safety and efficiency. In Canada, the benefits of roundabouts have drawn growing interest, and roundabouts are being constructed increasingly in recent years. However, compared with the popularity of roundabouts in other western countries, the Canadian experience with roundabouts is limited.

To enhance the understanding of the safety of roundabouts both overall and during inclement weather, this research first provides risk estimates of collision occurrence at roundabouts and signalized intersections under inclement weather conditions relative to clear weather condition by using the matched-pair approach. This method reasonably controls for the effect of time-dependent variables by assuming that travel patterns are similar from one week to the next. Secondly, the empirical Bayes approach is used to analyze the safety effect of converting signal-controlled intersections to roundabouts. This method is able to estimate the safety impact of the conversion without the disadvantage of the regression-to-mean bias.

There is no evidence of a statistically significant increase in crashes on days with rainfall relative to 'good' weather conditions for roundabouts, whereas there is evidence of such an increase in crash risk estimated to be 7 to 36 percent for signalized intersections. In addition, roundabout installation is shown as an effective safety prevention for severe collisions in the Region of Waterloo. However, roundabouts experience increases in total collisions both overall and during days with precipitation. The results of this study offer explanations regarding the effect of inclement weather on roundabout safety and the safety implications of the conversion from conventional signalized intersections to modern roundabouts in the Region of Waterloo.

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Dedication

This is for my beloved parents. Thanks for always being there for me.

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Chapter 1 Introduction

1.1 Background

Traffic safety is a major public concern globally. There are many safety interventions that are sometimes categorized according to the three E's: education, enforcement and engineering. The design of safe intersections is one of the many challenges that falls under the engineering umbrella, although safety outcomes also are affected by land use, traffic patterns and environmental risk factors, such as inclement weather.

Roundabouts are a popular alternative to intersections with conventional control types, and are adopted by many countries as a common intersection form because of the promise of substantial improvement in safety and efficiency. In Canada, the potential benefits of roundabouts have drawn growing interest, and the number of roundabouts continues to increase. However, compared with the popularity of roundabouts in the United States and some European countries, the Canadian experience with roundabouts is limited (Canadian Institute of Transportation Engineers, 2013), and more research is needed to better understand the safety outcomes at this form of intersection control.

This thesis contributes to roundabout safety research by estimating the safety effect of roundabouts, using Waterloo Region as the focus for empirical research. The analysis has two components. The first pertains to the relative safety of roundabouts during inclement weather relative to 'good' conditions – an issue that has received little attention in the literature. The second deals with the promise of safety improvement overall by considering the safety record at roundabouts in comparison to other control types. The reader should notice that the words "crash" and "collision" are used interchangeably in the transportation articles and this thesis, referring to "a traffic incident which involves at least one vehicle impacting with another road user or object, usually resulting in injury or property damage" (Cleghorn, 2009, p. 10).

With respect to the first theme, adverse weather makes road surface conditions worse and reduces driver visibility, creating challenges for vehicle control. There is emerging consensus that inclement weather generally leads to increased collision frequency (Andrey and Olley, 1990; Andrey et al., 2003; Eisenberg, 2004; Hambly et al., 2013; Koetse and Rietveld, 2009). Even though weather-related collision risks are well explored, most studies concentrate on particular road segments or entire road networks, and little is known about how weather factors affect roundabout safety. In addition, because roundabout operation

and safety performance, to some extent, depend on the geographical location of the study area. For example, the total number of days with rainfall and snowfall in Canada can be different from those of countries with different climates, and the familiarity level of Canadian drivers to roundabouts and driving habits when they navigate roundabouts may be different from those of countries with more roundabouts and longer roundabouts' history. Thus, the safety prediction procedure under different weather conditions currently used in other countries cannot be directly applied to Canadian roundabouts (Rodegerdts et al., 2010).

Installing roundabouts at intersections has been one of the common methods used to enhance safety and efficiency. The National Cooperative Highway Research Program (NCHRP) Report 672: *Roundabouts: An Informational Guide* (2010) outlines state-of-the-art analytical methods to assess the operational and safety effects of roundabouts. In addition, many researchers have studied the safety performance of roundabouts and concluded that roundabouts are able to reduce the number and lower the severity of collisions (Gross et al, 2013; Hauer, 1997; Persaud et al., 2001; Persaud et al, 2012; Retting et al., 2001). However, in terms of converting intersections to roundabouts, very limited attention has been paid to the safety effects of such conversions in Canada. Since the geometric design, the familiarity level and the reaction to roundabouts can be different, effects cannot necessarily be deduced from previous research done in other countries.

1.2 Objectives

This study was initiated because the safety problems at intersections generally and at some roundabouts more specifically are well-known in the Region of Waterloo, and the safety effects of roundabouts in Canada are not well documented. The goal of this research is to enhance the understanding of the safety of roundabouts both overall and during inclement weather.

The research takes an empirical approach, using data from 23 roundabouts as well as a number of comparable intersections with conventional traffic control. The relative risk during rainy days will be estimated for different types of crash severities at the daily level. In addition, the safety implications of converting from signal-controlled intersections to roundabouts will be modeled.

The specific objectives of this thesis are:

1. To analyze the safety performance of roundabouts in the Region of Waterloo.
2. To examine the potential effects of rainfall on roundabout safety in the Region of Waterloo.

3. To evaluate the safety effect of converting signal-controlled intersections to modern roundabouts in the Region of Waterloo.

The first objective is addressed by considering the collision history at roundabouts in the Region of Waterloo from 2005 to 2015. The second objective provides risk estimates of collisions at roundabouts under rainfall conditions relative to 'good' weather conditions based on historical collision data and weather records. The third objective estimates the safety impact of the contemplated conversion from existing signalized intersections to modern roundabouts, which provides a tool for city designers and planners to predict the change in collision frequency expected with the installation of a roundabout.

1.3 Organization

This thesis consists of five chapters. This chapter shows the statement of problem and objectives for the research. The remaining chapters are structured as follows: Chapter 2 provides a review of the scientific literature in terms of the weather-related road safety and before-after studies on roundabout safety. Chapter 3 describes the study area and the historical weather conditions throughout the study period, followed by the data used in this study. This chapter also outlines the analytical methods used in estimating risk. Chapter 4 documents the results of the study, including the estimates of relative risks at roundabouts in rainy days and the predicted changes of the safety performance in the conversion process. Finally, Chapter 5 presents the conclusions, discussions, and implications of this study.

Chapter 2 Literature review

Quantifying weather-related collision risk at roundabouts and evaluating the safety effects of the installation of roundabouts at intersections with traffic signals are the main foci of this research. Thus, in this chapter, a comprehensive literature review is conducted by studying weather-related road safety and before-after studies on safety interventions, such as roundabout conversion.

2.1 Road safety

2.1.1 Introduction to road safety

Road safety is a challenging research field due to the unpredictable nature of collision occurrences (Rodegerdts et al., 2010). With rapidly growing populations, urban and rural development, and technological development, the increase in traffic volume results in high exposure to the risk of traffic collisions. Thus, road safety is a serious global challenge.

Road collisions are a leading cause of the death globally. According to the global status report of The World Health Organization (WHO) (2015) on road safety, despite general improvements in road safety, the total number of road fatalities is still over 1.2 million worldwide each year, with millions more experiencing serious injuries and long-term consequences to health.

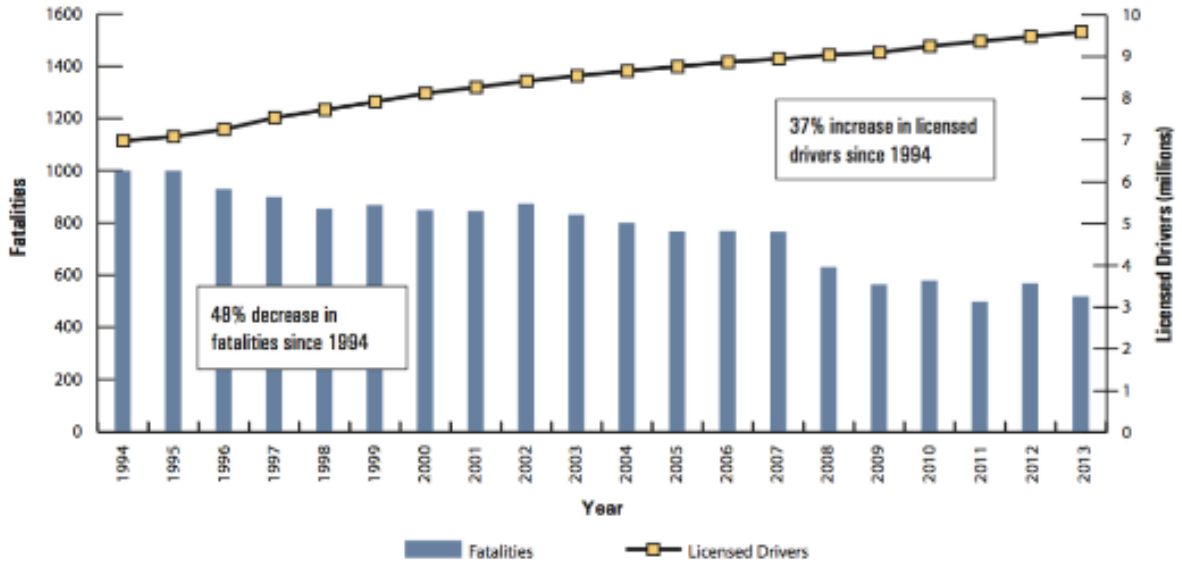
2.1.1.1 Canadian and Ontario collision trends

In Canada, road safety is a priority for all levels of government. A national goal is to have the safest roads in the world (Transport Canada, 2015).

Like many other 'western' countries, a decrease in the number of fatalities and injuries by transportation collisions has been achieved in Canada, despite the fact that there are more vehicles on the road each year. Government reports indicate that 1,834 people were killed and 149,900 people were injured in traffic crashes on the road in 2014, which is the latest year for which data are available. These counts are down 45 percent and 37 percent, respectively, from the year 1995 (Transport Canada, 2014).

Ontario is the most populous province of Canada, with a strong record of the road safety. Over the past 15 years, the fatality rate places Ontario first or second for road safety in North America (Ministry of Transportation, 2013). Notwithstanding the annual increases in the number of licensed drivers, reductions in fatalities have been successfully accomplished. As shown in Figure 2-1, the number of licensed drivers

increased by 37 percent from 1994 to 2013, while the number of deaths decreased to 518 in 2013, which is the second lowest count since 1944 (Ministry of Transportation, 2013).



Reprinted from Ministry of Transportation (2013), p. 14

Figure 2-1 The number of licensed drivers and deaths in Ontario, 1994-2013

2.1.1.2 Contributing factors to collisions

Over the years, many researchers have studied the road safety problem in an attempt to identify and mitigate the contributing factors that influence road safety. Findings highlight that traffic crashes frequently involve complex interactions among geometric design, human factors (demographic characteristics and the human behavior of road users such as, failure to yield to right-of-way, speeding, medical conditions, and distractions, etc.), environmental conditions such as weather and daylight, vehicle characteristics, and traffic volume/composition (Caliendo et al., 2007; Chin and Quddus, 2003; Ladron de Guevara et al., 2004; Naderan and Shahi, 2010; Noland and Oh, 2004; Poch and Mannering, 1996; Pulugurtha and Nujjetty, 2012; Pulugurtha et al., 2013).

Many studies have shown that roadway design matters. For example, Zakowska (1995) showed that improved safety performance in rural areas of Poland was associated with small curve angles and large radii on rural highways. Similarly, Berhanu (2004) showed positive correlations between roadway width and traffic safety, as well as sidewalks width and traffic safety in Ethiopia, using Poisson and negative binomial regression. Normally, collision investigations focus on driver factors, and, as such, the role of road design or other road-related factors may be underestimated (ITF, 2016). However, regardless of how

a collision happened, the severity of the collision is inevitably more or less affected by the road infrastructures. Thus, traffic engineers never stop improving road design guidelines is an attempt to reduce the number of collisions and their effects (ITF, 2016).

In terms of human factors, the *National Highway Traffic Safety Administration (NHTSA) report* claimed that human factors contributed to 94 percent of crashes in the United States in 2002. In recent years, human factors related to road safety have attracted more researchers' attention. Many studies have been completed in different driving contexts – in Europe (Oltedal and Rundmo, 2006; Shen et al., 2013; Sumer, 2003), North America (Cinnamon et al., 2011; Woodcock et al., 2005), and Australia (Department of Infrastructure and Regional Development, 2015; Hughes et al., 2015).

From a human behaviour perspective, common problems are excessive speed, inattention, failure to observe other vehicles, and improper evasive action (Shinar, 1978). Other factors mentioned in previous research papers include alcohol use, drug impairment, drowsiness, physical disability and driver inexperience (Cinnamon et al., 2011). The eye movement of drivers is critical for road safety, which contributes to proper direction and lateral vehicle position (Reason, 1990; Reason, 2000). For vehicle drivers, auditory distractions, such as listening to music, the radio, or talking with others can be important factors in collisions. Mobile phone conversations (McEvoy et al., 2005; Schwebel et al., 2012) and texting (Drews et al., 2009) also have been proven to be distraction factors for drivers that lead to the increasing risk of vehicle crashes. It should be noted that human behaviour is managed not only by the drivers' experiences and skills, but also by the surrounding context or environment in which the behaviour happens (Rumar et al., 2004).

The correlation between some demographic and personality traits, such as age, gender, anxiety, and high anger, and collisions was also demonstrated in prior studies (Buss, 2004; Costa and McCrae, 1992; Deffenbacher et al., 2003; Whissell and Bigelow, 2003). However, human behaviour is complex, measurement is challenging, and the effects of public policy and rule enforcement is only partially understood.

Environmental factors also are known to be important risk factors. More specifically, inclement weather conditions have been found to have a mostly consistently negative effect on road safety (Andreescu and Frost, 1998; Graham and Glaister, 2003; Koetse and Rietveld, 2009). More details will be discussed in the section 2.2.

2.1.2 Introduction to intersection safety

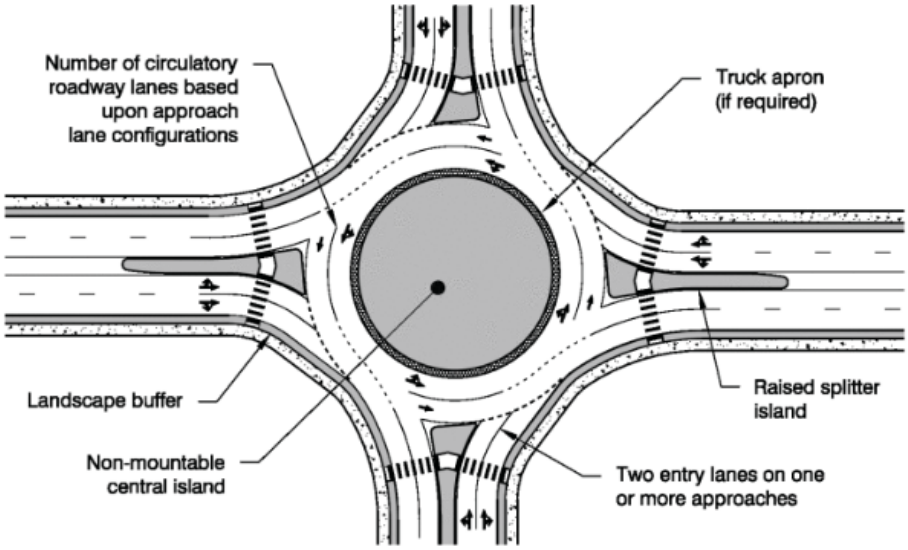
Intersections are widely accepted as the most dangerous locations in the road network. Not surprisingly then, intersection collisions represent a large proportion of the total number of collisions. According to the *Ontario Road Safety Annual Report*, intersection-related collisions (e.g., a collision may be close to an intersection but not at the intersection) and collisions at intersection account for 43.2% of total collisions in Ontario (Ministry of Transportation, 2013). It is not surprising that collisions are concentrated at intersections, since they are the junctions of roads on the traffic network where conflicts between traffic movements are most likely to happen (Antonucci et al., 2004).

In order to prevent collisions between conflicting traffic movements, intersections are 'controlled'. Stop signs and traffic signals are two primary tools used to control traffic flow at intersections.

The most heavily traveled intersection typically are signalized. These are operationally complex, with conflicts between through traffic with different maneuvers and many other factors inducing potential safety problems (Antonucci et al., 2004). As stated in the U.S. Fatality Analysis Reporting System, signalized intersections almost account for 30 percent of fatal collisions at intersections (National Highway Traffic Safety Administration, 2002).

The *National Cooperative Highway Research Program Report 500, Volume 12,* addressed the potential methods to improve safety at signalized intersections. Objective 17.2B stated that geometric improvements are effective approaches to ameliorate safety at signalized intersections. Specifically, the directive was given to "construct special solutions" (Antonucci et al., 2004, p. V-43). One of these special solutions is the conversion of signalized intersections to roundabouts.

In right-hand drive jurisdictions, a roundabout is a form of circular intersection in which all the traffics circulate anticlockwise in the lanes around a central island (Transportation Research Board, 2010). The entering traffic is required to yield to the circulating traffic. In other words, the vehicles already in the circulatory roadways have priority. The vehicles in the entry lanes are not allowed to enter the intersection until a sufficient gap in the circulating traffic is available (Transportation Research Board, 2010).



Reprinted from Rodegerdts et al. (2010), p. 1-15

Figure 2-2 Design elements of a roundabout

There are some traffic circles that have similar characteristics, which could be confusing. However, the design speed is the principal disparity between roundabouts and other traffic circles or rotaries. Generally, roundabouts are intended to have lower entry speed (<25 mph), while traffic circles or rotaries allow higher speed (> 25 mph) (Robinson et al., 2000). Also, compared with other types of traffic circles, roundabouts have some essential characteristics in terms of their operation and design that is demonstrated in Figure 2-2. No control equipment is installed on the circulatory roadway, but a yield control sign is installed at each entry (Canadian Institute of Transportation Engineers, 2013). The traffic moves anticlockwise on the circulatory roadway and has the right-of-way. No pedestrian access is allowed within the roadway but rather is allowed only to cross the legs, which are behind the yield line of the roundabout (Robinson et al., 2000). No parking is permitted "within the circulatory roadway or at the entries" (Rodegerdts et al., 2010, p.1-11). Although some traffic circles have many characteristics that are connected with roundabouts, one or more vital features is absent. However, these distinctions between roundabouts and other circular intersections may not be always clear for the public, and the terms may be misused or confused. In addition to the design elements pointed out above, roundabouts often include some additional characteristics to improve the safety and/or capacity of the intersection, such as an apron for the appropriate design vehicles (e.g., larger vehicles such as buses and trucks), splitter islands to separate vehicles with opposite directions and to help pedestrians to cross traffic, and entry flares to increase the capacity at the entrance (Rodegerdts et al., 2010).

The use of roundabouts is found to have various advantages.

1. Roundabouts have been shown to improve safety by reducing collisions, especially for severe injury collisions. More details of safety benefits will be discussed in section 2.1.2.2 (National Highway Traffic Safety Administration, 2002; Robinson et al., 2000; Rodegerdts et al., 2010; Troutbeck, 1993).
2. Contrary to many people's perceptions, roundabouts shorten the overall delays and queue lengths of the intersections, so they promote an uninterrupted traffic flow and move traffic more quickly (Canadian Institute of Transportation Engineers, 2013)
3. The long-term costs of a roundabout are lower. Although the construction costs of a roundabout are relatively high, the costs of hardware, electrical and maintenance associated with conventional signalized intersections are removed (Transportation Research Board, 2000).
4. Compared to conventional intersections, roundabouts are more environmentally friendly. A relative continuous traffic flow at a roundabout lowers emission. In addition, the elimination of electrical devices saves energy (Canadian Institute of Transportation Engineers, 2013).

2.1.2.1 Roundabouts in Canada

In the 1960s, the modern roundabout was originally developed in the United Kingdom (Rodegerdts et al., 2010). Since they were associated with a substantial improvement in efficiency and safety, they were adopted by many other countries as a common intersection form.

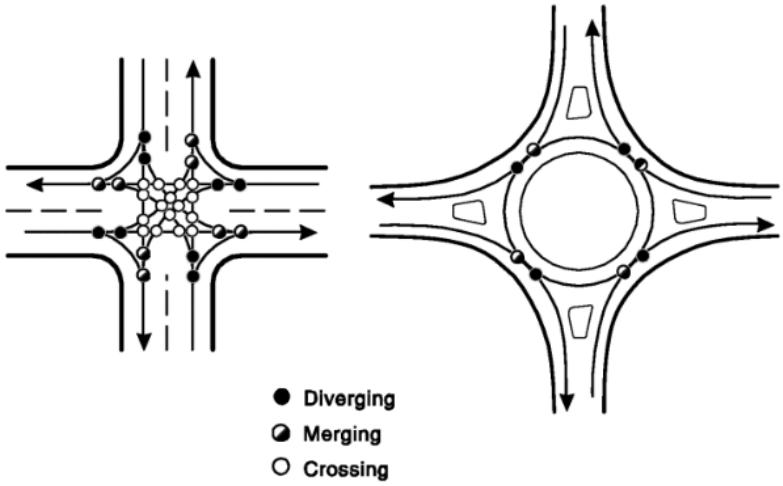
Roundabouts are becoming more popular in Canada. However, compared with the popularity of roundabouts in the United States and some European countries, the Canadian experience with roundabouts is limited (Canadian Institute of Transportation Engineers, 2013). Nevertheless, the benefits of roundabouts have drawn growing interest, and roundabouts are being constructed more and more frequently in Canada.

The city of Edmonton, the traffic circle pioneer of Canada, constructed a dozen traffic circles on arterial roads in the 1950s (Herzog, 2015). However, the first "real" roundabout as defined previously in Canada, which was installed at the intersection of Highway 63 and King Street in Fort McMurray, Alberta, was constructed starting in the summer of 2001 and opened to traffic in July, 2003 (Bassi et al., 2004). Based on an investigation by the Canadian Institute of Transportation Engineers, estimates of the total number of existing roundabouts in Canada ranged from 117 to 237 at the end of 2013 (Canadian Institute of

Transportation Engineers, 2013). It is not easy to get a precise total number of roundabouts currently implemented in Canada, because up-to-date inventories are not recorded in literature or reports. Consequently, a Canadian roundabout database was built by collecting government reports, searching online information, finding on Google Maps, and contacting government staffs for each province. To the author's knowledge, there are at least 350 roundabouts in Canada in 2017, and this form of intersection is becoming gradually more common across the country. Quebec and Ontario have about 100 of them, and British Columbia also has constructed dozens of them. It has been shown that the distribution of roundabouts in Canada is concentrated, with the majority located in the urbanized areas of the most densely populated provinces. Interestingly, the Region of Waterloo has almost the highest density with more than 20 roundabouts.

2.1.2.2 Safety of Roundabouts

The number of vehicle-to-vehicle conflict points drops from 32 at a conventional four-leg intersection to eight at a typical roundabout. As shown in figure 2-3, diverging conflicts caused by the separation of two traffic volumes decrease from eight to four, merging conflicts caused by the joining of two traffic volumes decrease from eight to four, and crossing conflicts caused at the intersection of two traffic volumes were eliminated by the implementation of roundabouts.



Reprinted from Rodegerdts et al. (2010), p. 5-7

Figure 2-3 Comparison of potential conflict points at conventional four-leg intersections and modern roundabouts

As noted in the previous section, in terms of safety, roundabouts are reported as an effective alternative to conventional intersections, improving safety performance by decreasing vehicle speed as drivers navigate the intersection, changing or even eliminating conflicts, and reducing the severity of collisions. In general, previous studies can be categorized in two ways. On the one hand, many studies in Australia, the United States, and some European countries investigated the safety performance of roundabouts, and concluded that the implementation of roundabouts is an effective method to ameliorate road safety, particularly for the decrease of fatal and injury crashes (AASHTO, 2001; Brown, 1995; Daniels et al., 2008; De Brabander and Vereeck, 2007; Gross et al., 2013). For example, Persuad et al. (2001) concluded that roundabouts reduce by 35 percent total collisions and 74 percent injury collisions, compared to intersections with traffic signal control. On the other hand, some studies explored how roundabouts affect particular types of vulnerable road users' safety by analyzing the collisions that involved pedestrians and cyclists (Daniels and Wets, 2005; Hels and Orozova-Bekkevold, 2007).

From the perspective of geometric design, Daniels et al. (2010a) evaluated the safety performance of different roundabout characteristics in Flanders-Belgium, but no clear relationships was found between roundabout measurements and safety, such as the circle diameter of roundabouts, the number of lanes, lane width, and central island diameter. However, Kim and Choi (2013) found that, in South Korea, the relationship between geometric elements, such as the number of approaches, the number of lanes, lane width, and the angle of the entering lanes, and crash rates of roundabouts can be estimated using the Poisson distribution and the negative binomial distribution. Their work showed that the crash rate is expected to decrease when the circulating lane width increases. In addition to the influence of geometric elements, Daniels et al. (2010b) also mentioned that there is a tendency toward more severe crashes in night conditions according to the logistic regression that used the time of day as an explanatory variable.

The safety benefits of roundabouts can be summarized as follows:

1. According to Gregoriades's (2010) research, there is a balance between the number of cognitive resources and the information processing efficiency. Once the demand for cognitive resources exceeds information resources, drivers may fail to pay attention to the most important information. The implementation of roundabouts generally reduces the absolute speed of all conflicting traffic movements so that it allows more time for drivers to process the information received and react to potential conflicts while entering a roundabout. Thereby, it decreases the likelihood of injury when a collision occurs (Rodegerdts et al., 2010).

2. Compared to conventional intersections, roundabouts have fewer potential vehicular conflict points. This reduces the number of high-severity collisions by eliminating some conflict types (e.g., head-on, high angles) (Gross et al., 2013). For signalized intersections, roundabouts also eliminate red-light running situation.
3. Roundabouts lower the relative speed for all vehicles travel through roundabouts so this reduces serious injury collisions (Rodegerdts et al., 2010).
4. The raised splitter islands provide vulnerable pedestrians a refuge to cross traffic safely (Robinson et al., 2000).

2.1.2.3 Safety of Roundabouts in Canada

At the national level, the Transportation Association of Canada (TAC) developed a synthesis document to focus attention on current design and operating practices and experiences of roundabouts in Canada and the United States in 2009. One year later, in 2010, Transport Canada (TC) partnered with Ryerson University and the Ministry of Transportation, Ontario (MTO) to establish tools for estimating the safety and operational impacts of roundabouts in Canada. They provided a general way to evaluate the cost-effectiveness of the conversion from a conventional stop-controlled intersection or signal-controlled intersection to a modern roundabout. Weber and Button (2009) concluded that, in addition to the improvement of the safety performance, roundabouts also demonstrated benefits on environmental, economic, and social aspects. The latter conclusion was based on telephone interviews in Canada and the United States as well as a review of previous literatures.

At the provincial level, Ontario used "*Roundabouts: An Informational Guide*" (2000) developed by the Federal Highway Administration (FHWA) as a guidance for roundabouts planning and geometric design on provincial highway in Ontario (Canadian Institute of Transportation Engineers, 2013).

At the regional level, the Region of Waterloo is one of the regions with highest number of roundabouts. The Region of Waterloo also disseminates considerable roundabouts education in the form of delivered background information, education material, and maneuverability at roundabouts via diverse methods such as maps, cartoons, and videos, to promote the public have a better understanding of the roundabout and its safety. Additionally, the Transportation Administration of the Region of Waterloo has prepared an annual collision report that includes collision data on roundabouts.

Although the majority of prior studies suggests that roundabouts have better performance than other forms of intersections on road safety, the improvements in safety related to conversion varies in magnitude. In addition, most research has been carried out in the United States and European countries but little has been done in Canada, where driving conditions and culture may vary to some extent. Hence, the safety of roundabouts in Canada is not fully understood, and the effectiveness of the roundabouts in the Region of Waterloo cannot be directly deduced from previous research.

2.2 Weather and safety

Transportation systems are well established all over the world. Given the variation in physical and cultural conditions across the globe, it seems reasonable to assume that geographical differences may influence the safety of roads (Page, 2001).

Weather has a discernible impact on transport. Sudden adverse weather conditions can affect transport operations, and long-term climatic patterns can determine transportation infrastructure requirements.

This section discusses the relationship between weather and traffic safety, beginning with a summary of why weather is a factor affecting road safety. Also, a review of previous literature on the effect of weather characteristics on road safety was completed.

2.2.1 Weather impacts on road safety

"Adverse weather" is a common experience in virtually every location on earth. Such adverse conditions are capable of affecting traffic volume by influencing the performance of vehicles and the behaviour of drivers in different ways. Wet pavement or pavement covered with ice can lead to a reduction in road-surface friction (Andrey, 2010), and thus to less controlled acceleration and deceleration (Maze et al., 2006; Prevedouros and Chang, 2005). Wet pavement conditions caused by precipitation can affect drivers' behaviour and consequently the safety and capacity of roadways and intersections (Tenekeci et al., 2010). Inclement weather, such as heavy rain or snow, causes windscreens to become covered by raindrops or snow, which brings about poor visibility (Prevedouros and Chang, 2005). Since drivers have a limited perception of the surroundings, there will be an increase in speed variability, leading to a higher risk of tailgating and lower capacity of the road (U.S. Department of Transportation, 2016).

Normally, as noted in the Highway Capacity Manual (2000), the fundamental conditions for current traffic analysis are "good weather, good pavement conditions, users familiar with the facility, and no impediments to traffic flow" (p. 2-3), which means the analysis of traffic operations and performance, as

well as the formulation of policy and standards for traffic, generally begin with a focus on clear conditions. As a result, current practices may not sufficiently address weather-related risks.

Research showed that weather conditions have a significant effect on road safety (Koetse and Rietveld, 2009). According to Hambly's (2011) research, crash risk related to different weather circumstances normally is considered in one of two ways. From an applied climatology point of view, analyzing specific weather type or atmospheric events directly caused by weather effects, such as rainfall and snowfall, is a prerequisite for studying the effects of them on road safety (Hambly, 2011). On the contrary, from a human factors perspective, the focus tends to be on the indirect effects of weather, such as the extent to which driver visibility is reduced by rainfall rate. This thesis adopted the first approach that consolidates historical weather records and quantifies the relationship between weather occurrences of different types and severities to collision outcomes.

Many different weather conditions have been considered as potential risk variables for road travel. For example, Stern and Zehavi (1990) explored the relationship between hot weather conditions and road safety. They found that the risk of 'run-off-road' collisions is the most frequent type of collisions occurring under heat stress conditions. As a second example, Hermans et al. (2006) considered the influence of fog, wind, and precipitation on hourly number of collisions in the Netherlands, finding that the increase of maximum wind gust can lead to the increase of collision. Overall, however, the most important variable affecting road safety is precipitation.

2.2.2 Precipitation as a weather hazard

Weather is an environmental factor that affects road safety. Generally, rainfall and snowfall are two of the most frequently occurring adverse weather conditions that have been studied in previous research. Precipitation can be measured by intensity, which is defined as the ratio between the total volume of precipitation and the duration of precipitation (Theofilatos and Yannis, 2014). Precipitation can be quantified in different time scales such as annually, seasonally, monthly, weekly, daily or even hourly, relying on the type of data resources.

2.2.2.1 Precipitation-related road collisions

Looking into the future, the National Research Council et al. (2008) evaluated the possibility of changes in weather most relevant for transportation in the United States. They identified increases in intense precipitation events as being highly likely, which means the probability of their occurrence is no less than

90 percent. Canadian studies also have highlighted the potential effects of climate change for intense precipitation and the second-order effects on road safety. Andrey et al. (2013a) comprehensively summarized the implication of the changes in precipitation extremes, showing that there is a general increase in annual maximum precipitation, which will affect traffic collision patterns. They also provided results of the safety analysis for present-day heavy precipitation-related risks (daily amount of precipitation is greater than 20.0 mm), indicating that the relative risk on days with heavy rain is generally 1.31, which means that the collision rates are 31 percent higher relative to days with clear conditions. It is worth noting that the relative risk estimates during days with heavy rain is much higher than results on days with lower precipitation.

In terms of current climates, precipitation occurs frequently in virtually all parts of North America and Canada (Bonnin et al., 2006). In urban areas in Canada, precipitation is observed almost eight percent of the time, on average, (Andrey et al., 2003). Based on the climate data published by Environment Canada for more than 20 years, the average number of days annually with at least 0.2 mm of precipitation (rain or snow) for some major cities in Ontario is around 150 days (Government of Canada, 2017). In addition, most parts of Canada normally experience snow and ice during winter seasons. Therefore, it is not fully unexpected that a significant number of road users are exposed to higher levels of risk associated with their driving during less-than-ideal weather conditions.

Considerable attention has been paid to precipitation-related collision risks in previous studies. The influence of precipitation is reasonably consistent and leads commonly to significant increases in collisions frequency (Andreescu and Frost, 1998; Andrey and Olley, 1990; Andrey and Yagar, 1993; Andrey et al., 2003; Brodsky and Hakkert, 1988; Caliendo et al., 2007; Edwards, 1996; Eisenberg, 2004; Hambly et al., 2013; Hermans et al., 2006; Koetse and Rietveld, 2009; Shankar et al., 2004). Table 2-1 summarizes some relevant studies carried out in many countries. Where possible, estimates of relative risk are provided. A relative risk of 1.0 shows that there is no difference in the safety outcome observed during a particular weather type relative to 'good' conditions. A relative risk that is larger than 1.0, shows that crash rates are elevated during the stated weather condition. For example, a relative risk of 2.2, as found in the Brodsky and Hakkert (1988) study indicates that collision frequency during rainfall is 2.2 times higher than during 'good conditions'.

Table 2-1 Summary of research on effects of precipitation on road safety

Author	Year	Study area	Study period	Method	Weather type	Relative risk
Brodsky and Hakkert	1988	Israel	1979–1981	Difference in means	Rainfall	2.2 for injury crashes
		United States	1983-1984			2.18 for fatal crashes
		Israel	1979–1981	Wet pavement index		6 for injury crashes
		United States	1983-1984			3.75 for fatal crashes
Andrey and Olley	1990	Edmonton	1983	Matched-pair	Rainfall	1.6
Andrey and Yagar	1993	Calgary and Edmonton, Canada	1979-1983	Matched-pair	Rainfall	1.7
Fridstorm et al.	1995	Denmark, Finland, Norway, Sweden	1973-1987	Generalized Poisson regression	Rainfall	Increase injury crashes
						Decrease injury crashes
					Snowfall	Increase fatal crashes in Denmark
						Decrease fatal crashes in Denmark, Norway, and Sweden
Andreescu and Frost	1998	Canada	1990-1992	Correlation estimation	Rainfall	Increase crashes
					Snowfall	Increase crashes
Andrey et al.	2003	Six cities in Canada	1995-1998	Matched-pair	Rainfall	1.59
						1.41 for injury crashes
					Snowfall	1.73
						1.47 for injury crashes
Eisenberg	2004	United States	1975-2000	Negative binomial regression	Precipitation	Decrease fatal crashes
Andrey	2010	Canada	1984-2002	Matched-pair	Rainfall	1.72 (from 1.9 in 1984 to 1.5 in 2002)
					Snowfall	1.87
Antoniou et al.	2013	Greece	1997-2005	Generalized linear model/ dynamic generalized linear model	Rainfall	Decrease crashes

However, as shown in the table, the increase of risk varies from study to study, which might be caused by the differences in the weather types, the driving conditions, and the temporal unit of observation (Andrey et al., 2003). As a matter of fact, some studies predicted that the number of collisions increased by a hundred percent or even more during rainfall (Bertness, 1980; Brodsky and Hakkert, 1988), while most

research concluded more moderate increases of between 50 and 100 percent (Andrey and Yagar, 1993; Andrey et al., 2003; Andrey et al., 2013b; Keay and Simmonds, 2005; Qiu and Nixon, 2008).

Eisenberg (2004) found that "lagged" precipitation appears to mediate the influence of precipitation on road collisions. He also showed that, if rainfall occurs daily for an extended period of time, collision risks were higher on the first day of rainfall than on subsequent days. According to Koetsen and Rietveld (2009), this is most likely because the roads are less slippery after the precipitation washes away the oil accumulated during dry days. Also, drivers may adjust their driving behaviour, but this process can be slow, indicating high relative risk on days with rainfall after a dry spell.

In order to study precipitation-related road collisions, prior research has employed a variety of data and approaches. Some studies considered the effects of weather on specific collision subsets, focusing for example on one severity group: property-damage-only (PDO), injury, or fatal collisions (Fridstorm et al., 1995; Khattak et al., 1998). Some studies investigated different storm intensities (Fridstorm et al., 1995), and others employed different methods like the matched-pair approach, Poisson and negative binomial regressions, mean differences and least squares (Andrey et al., 2003; Brodsky and Hakkert, 1988; Eisenberg, 2004; Eisenberg and Warner, 2005; Fridstrom et al., 1995; Shankar et al., 2004).

Most studies concluded a positive relationship between precipitation and collision frequency, but risk levels differ, and the results of a few studies instead suggest that precipitation leads to fewer collisions (Eisenberg, 2004; Shankar et al., 2004). To elaborate:

- Yannis and Karlaftis (2010) found that a high amount of precipitation might be associated with a decreased number of crashes in Athens.
- Eisenberg (2004) summarized that increased precipitation is associated with a decreased number of fatal collisions in the United States during 1975 to 2000.
- Khattak et al. (1998) concluded that the severity of crashes decreased slightly during rainfall.

Risks associated with snowfall also provide variable risk estimates.

- Khattak et al. (1998) summarized that variables of inclement weather such as snow and fog, also have a small negative impact on collision severity which is statistically significant.
- A similar finding was presented by Fridstrom et al. (1995) that the number of collisions decreases with an increase of snowfall days for both injury and fatal collisions.

- For PDO collisions, however, the evidence overwhelmingly indicates that collision rates increase (Andrey et al., 2013a).

2.2.2.2 Precipitation related roundabout collisions

Research on roundabout safety under inclement weather conditions is limited. Even though a large number of studies had investigated the extent to which weather conditions influence collision risk, to the author's knowledge, most of them concentrated on highways or urban networks. Very little attention has been given to the effects of adverse weather conditions on intersection safety, whether it is a stop-controlled intersection, a signal-controlled intersection or a roundabout.

While it is commonly believed that intersection operations on the whole may perform worse under inclement weather conditions (Rodegerdts et al., 2010), it is important to ask "how much worse" and whether roundabouts are at all immune from this weather deterioration of safety. It is important to conduct this research in Canada at this time, while roundabouts are relatively unfamiliar, in order to create a benchmark against which future findings can be compared. This thesis is directed toward addressing this knowledge gap with a particular focus on Canadian roundabouts.

2.3 Before-after studies on road safety

This section addresses questions related to the safety effect of converting conventional intersections to roundabouts. The review begins with a more general discussion of before-after studies in road safety, drawing mainly on the book, *Observational Before-After Studies in Road Safety*, written by Erza Hauer in 1997.

Roads are continually being repaired and reconstructed. When features are added to a road segment, or when an intersection control type is changed, the severity and frequency of collisions can be affected (Hauer, 1997). According to Hauer's (1997) research, usually, a cross-section study is used to evaluate the safety impact of a common feature by comparing the safety performance of one group of entities that have this characteristic to the group of entities without the characteristic. Alternatively, before-after studies focus on the change in safety from the before condition to the after condition of the entities that are changed by some treatment (Hauer, 1997). The latter is considered as the simplest way of evaluating the safety effect of a treatment, and it has been widely used in professional safety-related research (Hauer, 1997).

Normally, the safety of a site during a certain period can be described as the anticipated number of crashes per unit of time to take place on this site (Hauer, 1997). Although Pendleton (1991) considered that three years might be too much for the research because more external factors are likely to be changed, a three-year period is typically used for the before and the after period (Shen, 2007).

Before-after studies use different approaches: the naïve before-after study, the before-after study with comparison group, and the empirical Bayes (EB) approach. The first two are relatively straightforward, while the latter is more advanced but has the advantage of accounting for regression-to-mean (RTM) bias and other external factors.

However, no matter what approach is selected, there are two essential questions that need to be solved.

1. "What would have been the safety of the entity in the after period" (Hauer, 1997, p. 61) without the treatment, π?
2. What is the safety of the treated entity after the treatment was applied, λ ((Hauer, 1997)?

2.3.1 Naïve before-after study

The naïve before-after study, the simplest approach to evaluate the safety effect, compares the count of crashes in the before period to that in the after period. This method is still commonly used. With this procedure, how much the safety has changed is essentially described as the difference between the collision frequency in the before period and the collision frequency after the treatment is applied. The weaknesses of this method include:

1. The naïve before-after method assumes that all factors, other than the treatment, are the same in the after period as in the before period. When this is not the case, the measured change in safety reflects not only the treatment but other factors as well such as traffic volume, collision trend, environmental conditions (weather, and road surface condition), vehicle fleet, and drivers' behaviors.

2. There is an assumption that the number of crashes at an entity before the treatment can be recognized as a good estimate of the number of crashes that would occur at this entity in the after period if the treatment had not been employed. However, the sites may have been selected as treatment entities because of their safety records. If so, this will cause a biased estimate, i.e., one that overestimates or underestimate the magnitude of the reduction of crashes. The problem is that if the treatment had not been implemented, crash rates could be affected by the RTM or any

change in other external factors like annual average daily traffic (AADT) and weather (Hauer, 1997; Hauer et al., 2002; Hauer et al., 2004; Persaud, 2001; Retting et al., 2001). In other words, since RTM is at play, crash rates could easily decrease if an entity was selected only because of its unusual high crash counts. That is to say, the unusual collision experience before the treatment may be not a good estimate for forecasting the anticipated number of collisions in the after period had treatment not been implemented.

Some factors mentioned change gradually, but some change sharply. Therefore, shortening the length of the before and after periods does not effectively reduce the effects of sharp-changed factors. This is why the naïve approach mixes the safety effect of the treatment and other factors and cannot distinguish which part of the change is caused by which factor.

Measuring the change in safety only by counting the number of collisions in the before and after period is not a reliable method to determine the effect of a treatment in most cases.

2.3.2 Before-after study with comparison group

The before-after study design that uses a comparison group is another popular way to predict the effect of a treatment on safety. It identifies a group of untreated entities that are similar to the treated entities in geometry and traffic volume as a "comparison group", and assumes that the change of the safety effect of the comparison group between the before and after period reflects the magnitude of the change in associated with factors other than treatment.

Compared to the naïve before-after study, the comparison-group study design does a better job at considering the effects of some external natural time-related factors such as crash trends, weather, and traffic volume and therefore yields more precise estimates. The greater the similarity between the comparison group and the treatment group, the more accurate the estimates will be.

This method is based on two essential assumptions (Hauer, 1997).

1. Between the before and the after period, the factors that influence safety have an equal change on both the treatment group and the comparison group.
2. The changes in these factors have the same effects on the safety of both the treatment and the comparison groups.

However, it is unlikely that the factors that influence safety have the exact identical impact on the treatment and the comparison group. Also, it is unlikely to find an adequate number of similar entities that

remained untreated in most practical cases. On the contrary, it is likely that there is a link between the collision history and the decision to make some treatments, which usually refers to "selection bias" or "RTM". Accordingly, the before-after study with comparison group still is not ideal for obtaining accurate insights into the effect of treatment.

2.3.3 Before-after study with empirical Bayes method

A third alternative is the before-after study design using the EB method to predict the safety impact of the treatment without the disadvantage of the RTM bias, which is a statistical phenomenon that usually takes place when a sample is selected because of some certain reasons (e.g., for road safety study, it occurs when a site with abnormally high collisions is selected for treatment). This method accounts for the time trend in AADT, crash counts, and external factors which may influence changes in crashes (Bhim, 2005). In addition, it has been interpreted thoroughly by Hauer (1997) and adopted as one of the most established research methods for before-after studies (Council et al., 2005; Persaud et al., 2010).

Compared to other conventional methods, the EB method has three outstanding advantages.

1. Eliminates the effects of the RTM bias
2. Produces more accurate estimates than other conventional approaches
3. Allows the estimation of the expected collision frequency in a specified period of time (κ) of the entire time series

Recall that the chief mission of the before-after study is to predict how many target collisions would have taken place in the after period where the treatment had not been implemented. There are several ways to estimate the anticipated number of collisions (Hauer, 1997; Mountain et al., 1992), but all of them consist of two successive steps.

1. Predicting the anticipated collision frequency in the before period to build the foundation of the prediction (Attah, 2012).
2. Estimating how the anticipated number of collisions would have changed between the before and the after period based on the foundation established in step 1, according to the changes in weather, traffic and other external factors (Attah, 2012).

In terms of the EB approach, the anticipated number of crashes that would have taken place at treated sites without treatment is estimated by the crash counts observed at treated entities in the before period

combining a negative binomial crash prediction function for untreated reference population with similar traits. Then, it is compared to the crash counts at treated entities in the period after the conversion to evaluate the effect of the implemented safety improvement (Persaud et al., 2010).

However, the point is that the count of collisions occurring at the treated site A is not "a neutral estimate of its anticipated number of collisions" when there are some certain reasons to select site A as the treated site (Hauer, 1997, p. 185), and the prior information in the EB procedure comes from the calibration process of the safety performance function (SPF), which is based on a reference group of entities similar to treated entities.

Hauer (1997) raised two kinds of clues that can be jointly used in the EB approach to account for the RTM and to estimate the safety performance:

1. Contained in traits

   Traits here are referring to traffic, geometry, and demographic characteristics of the entity, etc. Safety of entities is influenced by the traits of themselves.

2. Derived from the collision counts occurrence

   The collision history of an entity of interest before the treatment is applied includes valuable information about the safety.

If the safety estimation is only based on the traits of entities, some relevant information will be ignored and the prediction will be conducted using reference populations. If the safety estimation is placed on collision counts, the prediction solely depends on this arbitrary time period. Accordingly, it is wise to adopt both kinds of clues: one derived from the traits, and another derived from the history of collision occurrence for the site of interest. The joint use of these two clues is shown as follows (Hauer et al., 2002):

$$E\{\kappa|\mathrm{K}\} = \alpha\mathrm{E}\{\kappa\} + (1-\alpha)\mathrm{K} \tag{2.1}$$

In Equation 2.1, the anticipated mean and the variance were calculated and combined with the crash counts for a specific intersection in order to get a better-quality estimate of a long-term expected number of collisions at a treated entity (Persaud et al., 2010).

K = the number of crashes recorded at the entity in the period of interest

κ = the estimation of the anticipated crash frequency in a specified period of time

Therefore $E\{\kappa|K\}$ is the expected value of κ when the number of crashes K of the entity is given. α is weight between 0 to 1. If α is close to 0, the κ of the entity of interest, which is estimated as $E\{\kappa|K\}$, is close to the recorded crash history K. Conversely, if α is close to 1, the κ of the entity of interest is close to the mean of safety in the reference population $E\{\kappa\}$.

α, the most important part here, is computed as:

$$\alpha = \frac{1}{1+r\frac{\mathrm{VAR}\{\kappa\}}{\mathrm{E}\{\kappa\}}} \tag{2.2}$$

In this, $E\{\kappa\}$ and $\mathrm{VAR}\{\kappa\}$ are the mean and the variance of the κ respectively. Since one must be able to get the weight α before the κ of an entity specified can be estimated, it is necessary to obtain the estimates of $E\{\kappa\}$ and $\mathrm{VAR}\{\kappa\}$.

For Eq. 2.2 to be valid, K and κ must belong to the exactly same time period. However, the information of the collision count K might be different from the data for the reference population in practice. Therefore, r represents the number of years that K relates to, divided by the number of years that κ relates to.

The variance of the estimate of the anticipated number of collisions at the treated entities is defined as follows:

$$\mathrm{VAR}\{\kappa|K\} = (1-\alpha)\mathrm{E}\{\kappa|K\} \tag{2.3}$$

Hauer (1997) suggested that a model of the entire probability distribution function of κ|K is important since the way to estimate $E\{\kappa|K\}$ and $\mathrm{VAR}\{\kappa|K\}$ is already demonstrated. He also assumed that the distribution of the estimates of the expected collision frequency (κ) in the sites of the reference population follow a Gamma probability density distribution and the number of crashes recorded at the treated sites (K) can be described by the Poisson distribution. Thus, for κ ≥ 0, there are:

$$g(\kappa) = \frac{a^b \kappa^{b-1} e^{-a\kappa}}{\Gamma(b)} \tag{2.4}$$

$$P(K|\kappa) = \frac{\kappa^K e^{-\kappa}}{K!} \tag{2.5}$$

Where 'a' and 'b' are two parameters and can be expressed with reference to the mean and the variance of itself.

$$a = \frac{\mathrm{E}\{\kappa\}}{\mathrm{VAR}\{\kappa\}} \tag{2.6}$$

$$b = \frac{(\mathrm{E}\{\kappa\})^2}{\mathrm{VAR}\{\kappa\}} \tag{2.7}$$

The derivation of the probability density function of the κ in the reference population is based on the Bayes theorem (Hauer, 1997). The process can be expressed by the following equations:

$$g(\kappa|\mathrm{K}) = (constant)P(K|\kappa)\mathrm{g}(\kappa) \tag{2.8}$$

Using the equations for g(κ) and P(K|κ) in the equation g(κ|K), the new equation g(κ|K) is expressed as:

$$g(\kappa|\mathrm{K}) = (constant_1)\frac{\kappa^K e^{-\kappa}}{K!} \times \frac{a^b \kappa^{b-1} e^{-a\kappa}}{\Gamma(b)} = (constant_2)\kappa^{K+b-1} e^{-\kappa(1+\mathrm{a})} \tag{2.9}$$

The constant$_2$ can be normalized as $(1+a)^{K+b}/\Gamma(K+b)$, and recall that $\kappa \geq 0$ in the equation g(κ), the updated equation, which assumes the distribution of the count of crashes at the treated entity follows the Poisson distribution and the κ in the reference population is Gamma distribution, can be defined by:

$$\mathrm{g}\{\kappa|\mathrm{K}\} = \frac{(1+\mathrm{a})^{\mathrm{K+b}}\kappa^{\mathrm{K+b-1}}\mathrm{e}^{-\kappa(1+\mathrm{a})}}{\Gamma(\mathrm{K+b})} \tag{2.10}$$

And the mean and the variance are:

$$\mathrm{E}\{\kappa|\mathrm{K}\} = \frac{\mathrm{K+b}}{1+\mathrm{a}} \tag{2.11}$$

$$\mathrm{VAR}\{\kappa|\mathrm{K}\} = \frac{\mathrm{K+b}}{(1+\mathrm{a})^2} \tag{2.12}$$

That is to say, if estimated of E{κ} and VAR{κ} are known, the parameters 'a' and 'b' can be derived. Consequently, E{κ|K} and VAR{κ|K} can be computed. Because each entity of the reference population has its own estimates of the expected collision frequency, and the mean and the variance of κ is useful in the EB procedure, Hauer (1997) proposed two methods, 'the method of sample moments' and 'the multivariate regression method', to estimate E{κ} and VAR{κ}. These two methods are grounded on two common equations.

$$\mathrm{E}\{\mathrm{K}\} = \mathrm{E}\{\kappa\} \tag{2.13}$$

$$\mathrm{VAR}\{\mathrm{K}\} = \mathrm{E}\{\kappa\} + \mathrm{VAR}\{\kappa\} \tag{2.14}$$

That is to say, the expected number of collisions in the reference population equals to the expected value of the κ in the reference population, while the variance of the number of collisions in the reference population equals to the sum of the expected value of the κ and the variance of the κ in the reference population.

The sample mean and the sample variance of the method of sample moments defined as follows:

$$\overline{K} = \sum Kn(K)/n \tag{2.15}$$

$$s^2 = \sum(K - \overline{K})^2 n(K)/n \tag{2.16}$$

Where n= the number of entities in the reference population

n(K)=the number of collisions recorded at the entity n during a certain period

$\overline{K}$ approaches E{K} and s^2 approaches VAR{K} with the increase of the number of reference entities. If $\overline{K}$ and s^2 are replaced by E{K} and VAR{K} respectively, the updated equations can be expressed by the following forms:

$$\mathrm{E}\{\kappa\} = \mathrm{E}\{\mathrm{K}\} = \overline{K} \tag{2.17}$$

$$\mathrm{VAR}\{\kappa\} = s^2 - \overline{K} \tag{2.18}$$

Compared to the approach of sample moments, Hauer (1997) concluded that the multivariate regression approach has two main advantages.

1. It is possible that an appropriate reference population cannot be found when estimates of the safety of entities of interest are continuous or numerous in nature, but the multivariate regression method does not require a sizeable reference population for any specific combination of characteristics, and it can account for the changes in the factors that not only are measured but also are vague.
2. Regression is able to estimate a sequence of values $\kappa_1, \kappa_2, \kappa_3, \ldots, \kappa_y$ for year 1 to year y in the before period for each sites of interest without the effect of the RTM, and these estimates in the before period for each treated site are the launching pad for predicting the safety in the imagined after period had the treatment not been applied. Thus, the estimates of E{κ} and VAR{κ} for a reference population calculated from this method have a more precise match to the characteristics of the treated entities.

Thus, the multivariate regression method is more commonly accepted for road safety. This method used multivariate statistical regression analysis to estimate E{κ} and VAR{κ}, and the formulas are given below:

$$\mathrm{E}\{\kappa\} = \alpha \times X1^{\beta 1} \times X2^{\beta 2} \times X3^{\beta 3} \times \ldots \tag{2.19}$$

$$\mathrm{VAR}\{\kappa\} = \frac{[\mathrm{E}\{\kappa\}]^2}{b} \tag{2.20}$$

Where 'α' is a constant, $\beta 1$ to $\beta 3$ are the parameters of the independent variables X1 to X3, and 'b' is the parameter performed earlier which associated with the Gamma distribution. The independent variables used in this equation include specified traits such as traffic flow, width of lanes, number of lanes, etc. more details of the regression model will be discussed in the next section. It is noted that the parameter 'b' is typically estimated by the maximum likelihood method during the process of fitting a multivariate regression model to collision data (Hauer, 1997).

2.3.3.1 Comments and summary

Three methods of before-after studies were introduced in the sections above. Compared to conventional before-after methods which provide overestimated results of the safety benefits of the treatment, the empirical Bayes before-after procedure not only removes the bias, but also produces more precise results. It has advantages especially when a sizeable and suitable reference population does not exist. In this case, the EB method is able to predict the value of the mean and the variance (Hauer, 1997; Rimiller, 2001). However, the EB approach also has its own limitations. Assumptions about the probability distribution of collision occurrences are enforced. Furthermore, it is complicated to implement (Shen, 2007).

2.3.4 Safety performance function

The EB approach is able to help prevent the RTM bias that comes from the non-random selection of treated entities by estimating the number of collisions in the after period with no treatment. This prediction is based on the information from both the entities with treatment and the reference population. In the EB method, the expected number of crashes at reference sites with similar characteristics to the treated sites is predicted from a regression model that is calibrated by the data with similar traits as the treated sites, which is also known as the safety performance function. It is one of the fundamental features to predict the expected collision frequency for the location after the treatment, evaluate the anticipated safety change of a safety treatment (Hauer, 1997; Persaud et al., 2012), and estimate the safety performance of an entity in relation to others (Rodegerdts et al., 2010). Thus, it is required as a critical part of the EB procedure.

Generally, a SPF is a simple multivariate model developed based on multivariate regression analysis, which links the crash occurrence of a site to its characteristics such as traffic and geometric traits. For predicting the safety effects of an implemented construction, a critical issue is that the data used for

calibrating the SPFs should reproduce the characteristics of the entity prior to the treatment as closely as possible (Persaud et al., 2012). To ensure that the intersections in the reference group used to calibrate the SPF have a proper fit, only intersections that have similar traits to the treated entities over the years before installing safety improvement should be selected. In other words, a reference population is the pivotal part to establish the multivariate model for the EB procedure. It can be considered as a sample that represents a significant number of entities so as to provide referential information for evaluating the safety change.

There are two levels of SPFs in the literature. One demonstrates crash occurrence as a function of traffic volume. Another level of SPFs, which is referred to as the full SPFs, expresses crashes as a function of both traffic volumes and other external factors.

The integrity of the multivariate regression model is based on choosing a proper model form and estimating parameters of the equation. There are several statistical regression models to describe the relationship between the number of collisions and the traffic volume. Maximum likelihood is applied on a wide range of the estimation of the unknown parameters in these models.

To begin with, a likelihood function with an identified probability distribution is necessary to conduct the maximum likelihood estimation. Then, it will be used to combine the information of the observations. That is to say, first the covariate values are fitted in the function, and then the probability of the number of collisions is a function of the unknown parameters, and it is called the likelihood function. The process of estimating parameters is the process of making the likelihood function achieve the largest value.

Hauer (1997) provided a simple model function on a road section using data in the reference population:

$$\mathrm{E}\{\kappa_{i,y}\} = d_i \alpha_y F_{i,y}^{\beta} \tag{2.21}$$

Where $E\{\kappa_{i,y}\}$ = the mean of the expected number of collision in year y for all intersections in the imagined reference population of entity 'i'

d_i = the length of this road section

α_y = a parameter for year y

$F_{i,y}$= the traffic flow for road section 'i' in year y

β = a parameter deciding how $\kappa_{i,y}$ changes with the traffic flow for road section 'i' in year y

Although the example given is for a road section, the model forms for other types of road safety analysis are similar.

Poisson regression model is usually used on the road safety study (El-Basyouny and Sayed, 2009). The probability of an entity 'i' having K crashes in a certain period is defined mathematically as:

$$P\left(\mathrm{K}_{i,y}\right) = \frac{\kappa_{i,y}^{K_{i,y}} \exp\left(-\kappa_{i,y}\right)}{\mathrm{K}_{i,y}!} \tag{2.22}$$

Where $P\left(K_{i,y}\right)$ = probability of entity i having K crashes in the year y; therefore $P\left(\mathrm{K}_{i,y}\right) \subseteq [0,1]$

$K_{i,y}$ = number of collisions for entity 'i' in the year y

$\kappa_{i,y}$ = expected number of collisions for entity 'i' in the year y

If we assume that there are R entities in the reference population, and for each entity, collision counts are collected for Y years in the before period and Z years had the treatment has been implemented, the probability can be re-expressed as:

$$P\left(\{\mathrm{K}_{i,y}\}\right) = \prod_{i=1}^{R} \prod_{y=1}^{Y+Z} \frac{\kappa_{i,y}^{K_{i,y}} \exp\left(-\kappa_{i,y}\right)}{\mathrm{K}_{i,y}!} \tag{2.23}$$

In this function, total R x (Y+Z) parameters are included. To make the function look simple, the relationship between the number of collisions and variables can be described as:

$$ln\left(\kappa_{i,y}\right) = \beta X_i \text{ or } \kappa_{i,y} = \exp\left(\beta X_i\right) \tag{2.24}$$

Where β = a vector of regression parameters

X_i = a vector of explanatory variables

There is an assumption that the changes of κ regarding the changes in traffic flow, environmental factors, and driver demography, etc., in order to account for the κ's change from year to year for each entity. Thus, the change in $\kappa_{i,y}$ is defined by the following equation:

$$\frac{\kappa_{i,y}}{\kappa_{i,1}} = \mathrm{C}_{i,y} \tag{2.25}$$

Eq. 2.25 intensely reduces the number of unidentified parameter s in the likelihood function by making all $\kappa_{i,y}$ as a function of $\kappa_{i,1}$. Recall that the $\kappa_{1,1}$, $\kappa_{2,1}$, $\kappa_{3,1}$ to $\kappa_{R,1}$ are gamma distributed, the natural logarithm of the likelihood function for the Poisson regression model is shown as:

$$\ln(L) = \sum_{i=1}^{R}\left(\left[\sum_{y=1}^{Y+Z} \mathrm{K}_{i,y} \times \ln\left(\mathrm{C}_{i,y}\right)\right] + b \times \ln\left(b/E\{\kappa_{i,1}\}\right) - \left(\sum_{y=1}^{Y+Z} \mathrm{K}_{i,y} + b\right) \times \ln\left(b/E\{\kappa_{i,1}\} + \sum_{y=1}^{Y+Z} \mathrm{C}_{i,y}\right) + \ln(b) + \ln(b+1) + \cdots + \ln\left(b + \sum_{y=1}^{Y+Z} \mathrm{K}_{i,y} - 1\right)\right) \tag{2.26}$$

Normally, the variance of the collision data is greater than their mean, and this phenomenon is called over-dispersion. However, Poisson regression is based on the assumption that the variance of the crash data equals to the mean of them. The parameter 'β' in the Poisson model can be misestimated without accounting for the over-dispersion.

Instead, the negative binomial distribution is an appropriate way to handle over-dispersion crash data. Hence, negative binomial regression model has been accepted as a substitute to the Poisson regression model and widely applied to analyze crash data (Lord and Persaud, 2000). In addition, a common statistical software used to calibrate the safety performance models in the previous studies is the Generalized Linear Interactive Modeling (GLIM) with the assumption of negative binomial error structure (Hauer, 1997; Hadayeghi et al., 2010).

For an entity 'i', the anticipated number of crashes is defined mathematically as:

$$\lambda_i = \exp\left(\beta V_i + \varepsilon_i\right) \tag{2.27}$$

Where $\exp(\varepsilon_i)$ = a gamma distributed error

The negative binomial distribution is expressed as:

$$f\left(N_{i,y}, P\{K_{i,y}\}, \alpha\right) = \frac{(N_{i,y}+\alpha-1)!}{(N_{i,y})!(\alpha-1)!} P(K_{i,y})^{\alpha}[1 - P\left(K_{i,y}\right)]^{N_{i,y}} \tag{2.28}$$

Where α = the over-dispersion parameter

$P\{K_{i,y}\}$= probability of entity 'i' having K crashes in the year y; it is assumed to follow the gamma distribution (Lord, 2006).

$N_{i,y}$=number of crashes of entity 'i' is likely to experience in the year y; N_i= 0, 1, 2…

The mean and the variance of the expected number of crashes for entity 'i' in the year y are given by:

$$E\left(N_{i,y}\right) = \frac{\alpha(1-P\{K_{i,y}\})}{P\{K_{i,y}\}} \tag{2.29}$$

$$VAR\left(N_{i,y}\right) = E\left(N_{i,y}\right) + \frac{[E\left(N_{i,y}\right)]^2}{\alpha} \tag{2.30}$$

The larger the α is, the more dispersed the distribution becomes. On the contrary, if α equals to 0 here, the $VAR(N_i)$ equals to the $E(N_i)$. Consequently, the negative binomial regression model will be the same as the Poisson regression model.

The likelihood function is given by:

$$L(N_{i,y}) = \prod_{i=1}^{n} \frac{(N_{i,y}+\alpha-1)!}{(N_{i,y})!(\alpha-1)!} P(K_{i,y})^{\alpha}[1 - P(K_{i,y})]^{N_{i,y}} \quad (2.31)$$

2.3.4.1 Safety performance function for Intersections

The following review consists of examples selected from prior studies.

- Unsignalized intersections:
  - Using the 1993 to 1995 data on four-leg unsignalized intersections in British Columbia, Sayed (1999) developed the following SPF to predict number of collisions at intersections.

    Number of collisions for three years = $1.5406 \times (\frac{\text{AADTmajor}}{1000})^{0.4489} \times (\frac{\text{AADTminor}}{1000})^{0.6475}$

  - Based on data on 125 rural unsignalized intersections in Minnesota over the period of 1985 to 1987, Bonneson and McCoy (1993) created the following function.

    Number of collisions per year = $0.000379 \times (\text{AADTmajor})^{0.256} \times (\text{AADTminor})^{0.831}$

- Signalized interesections:
  - For rural signalized intersection, Bonneson et al. (1993) also developed an equation:

    Number of collisions per year = $0.00703 \times (\text{AADTmajor})^{0.51} \times (\text{AADTminor})^{0.29}$

  - Persaud and Nguyen (1998) developed the following functions for different crash severity types using data for four-leg signalized intersections in Ontario.
    - For property damage only crashes

      Number of collisions per year = $0.000169 \times (\text{AADT})^{1.00}$

    - For severe crashes

      Number of collisions per year = $0.000422 \times (\text{AADT})^{0.863}$

- Roundabouts:
  - The *National Cooperative Highway Research Program (NCHRP) Report 672: Roundabouts: An Informational Guide*, released in 2010, which is administered by the Transportation Research Board (TRB) in cooperation with the U.S. Department of Transportation and the Federal Highway Administration (FHWA), provides a state-of-the-art synthesis of analytical

methods for predicting and evaluating the operational and safety effects of roundabouts. It records intersection-level safety performance models developed by Transportation Research Board (2010) to predict the expected total crashes and injury crashes occurred at intersections, using the data for roundabouts in the United States. The general equation form is shown as:

$$\text{Number of crashes per year} = a \times (\text{AADT})^{b} \tag{2.32}$$

This equation is provided for crashes occurring on roundabouts with different number of approaches, different circulating lanes, different AADTs and different crash severity types. Table 2-2 and 2-3 give the parameter values for each model.

Table 2-2 Intersection-level safety performance models for total crashes

	Model for Predicting the Expected Total Crash Frequency per Year by Number of Approaches		
Circ. Lanes	**3 Legs**	**4 Legs**	**5 Legs**
1	$0.0011(AADT)^{0.7490}$ 4,000 to 31,000 AADT	$0.0023(AADT)^{0.7490}$ 4,000 to 37,000 AADT	$0.0049(AADT)^{0.7490}$ 4,000 to 18,000 AADT
2	$0.0018(AADT)^{0.7490}$ 3,000 to 20,000 AADT	$0.0038(AADT)^{0.7490}$ 2,000 to 35,000 AADT	$0.0073(AADT)^{0.7490}$ 2,000 to 52,000 AADT
3 or 4[1]	Not Available	$0.0126(AADT)^{0.7490}$ 25,000 to 59,000 AADT	Not Available
	Dispersion parameter: k = 0.90		

Reprinted from Rodegerdts et al. (2010), p. 5-23

Table 2-3 Intersection-level safety performance models for injury crashes

	Model for Predicting the Expected KAB Injury Crash Frequency per Year by Number of Approaches		
Circ. Lanes	**3 Legs**	**4 Legs**	**5 Legs**
1 or 2	$0.0008(AADT)^{0.5923}$ 3,000 to 31,000 AADT	$0.0013(AADT)^{0.5923}$ 2,000 to 37,000 AADT	$0.0029(AADT)^{0.5923}$ 2,000 to 52,000 AADT
3 or 4[1]	Not Available	$0.0119(AADT)^{0.5923}$ 25,000 to 59,000 AADT	Not Available
	Dispersion parameter: k = 0.946		

Reprinted from Rodegerdts et al. (2010), p. 5-23

The number of circulating lanes and legs, the AADT range for the calibration data, and the type of crash severity are shown in the tables above. For each type of crashes, the value of parameter 'a' and parameter 'b' can be found according to validity ranges.

2.3.5 Examples of before-after study on the safety effect of converting intersections to roundabouts

Observational before-after studies provide an important way of understanding the safety effect of entities, such as drivers, road sections, and intersections.

Since the roundabout is an effective alternative to intersections with conventional control types (e.g., signalized intersections and stop-controlled intersections), the safety performance of roundabouts has been studied and documented in a number of previous studies involving a wide range of intersection locations and traffic conditions during the last several decades.

Various studies have been done to discover whether the conversion from conventional intersections with traffic light or stop sign controls to roundabouts causes a decrease in the likelihood of vehicle collisions (Gross et al, 2013; Hauer, 1997; Hauer et al., 1988; Jensen, 2013; Kim and Choi, 2013; Persaud et al., 2001; Robinson et al., 2000; Rodegerdts et al., 2010; Shadpour, 2012). If the answer is positive, then the unknown is the extent to which this alteration influences society regarding the changes in the types of collisions (i.e., fatal, injury, and property damage only collisions).

Most studies noted that roundabouts are a safer intersection type than other intersections with conventional control types. Significant reductions in vehicle collisions and injuries were found in the process of converting intersections from stop signs or signalized intersections to roundabouts. Some typical studies are summarized in Table 2-4. For each study, the authors, the year of publication, the study area, the conversion type, the method, the crash severity type, and the effect of the conversion were recorded.

Table 2-4 Summary of studies of converting intersections to roundabouts

Authors	Year	Country	Conversion	Method	Crash type	Change in the number of crashes
Richardson	1982	Australia	Stop or Give Way sign controls(in one case is police control) to roundabouts	Naïve before-after	PDO	-32%
					Fatal	-74%

Authors	Year	Country	Conversion	Method	Crash type	Change in the number of crashes
Tudge	1990	Australia	n/a	Before-after, control for trends	PDO	-40%
					Injury	-45%
					Fatal	-63%
Schoon and van Minnen	1994	Netherlands	Traffic signals or stop signs to roundabouts	Naïve before-after	Total	-47%
					Injury	-71%
					Severe injury*	-81%
Flannery et al.	1998	United States	Stop-controlled to single-lane roundabouts	Naïve before-after	Total	↓**
Retting et al.	2001	United States	20 intersections from stop sign and 4 for traffic signal control to roundabouts	Empirical Bayes	Total	-38%
					Injury	-76%
Persaud et al.	2001	United States	19 intersections from stop sign and 4 for traffic signal control to roundabouts	Empirical Bayes	Total	-40%
					Injury	-80%
			Signalized, urban		Total	-35%
					Injury	-74%
			Stop controlled, urban, multilane		Total	-5%
			Stop controlled, urban, single lane		Total	-72%
					Injury	-88%
			Stop controlled, rural, single lane		Total	-58%
					Injury	-82%
Jensen	2013	Denmark	n/a	Before-after, control for RTM	Total	-27%
					Fatal	-87%
					Injury	-60%

Note:

*Severe injury results in hospital admissions

** The analysis was limited in scope, but overall the entities experienced a reduction in collision rates

A notable fact is that some studies conducted the before-after study on conversions with different previous control types, and some of them mixed all types of prior control together. However, the estimated variable parameters for a SPF based on a certain previous control type can be relatively

different from those for a SPF based on all types of previous control, so the studies of safety effect for each previous control type can lead to more precise results (Persaud et al., 2012).

It is also noteworthy that many studies targeted the impacts on road safety of converting intersections to roundabouts in Australia (Richardson, 1982; Tudge, 1990), the United States (Flannery et al., 1998; Persaud et al., 2001; Retting et al., 2001), as well as in some European countries (Jensen, 2013). To date, although roundabouts become a popular alternative intersection type in Canada, very limited before-after studies of Canadian roundabouts have been reported in the literature. The current study addresses the need for studying safety effects of roundabouts in Canada.

Chapter 3 Data and Methods

This chapter describes the methods used to determine the relative risk of roundabouts in the Region of Waterloo compared with similar intersections with conventional control types. The analysis is based on the weather and collision records from the years 2002 to 2015. A matched-pair approach is adopted to calculate the relative risk of both roundabouts and conventional intersections in adverse weather. An Empirical Bayes approach is then utilized to evaluate the safety effects of converting from conventional intersections to modern roundabouts.

Section 1 of this chapter describes the characteristics and the traffic safety pattern of the study area, and the historical weather conditions throughout the study period.

Section 2 quantifies precipitation-related crash risks for both roundabouts and signalized intersections, including a description of weather data and collision data sources, and a detailed explanation of the analytical approach.

Section 3 estimates the safety implications of converting from signalized intersections to roundabouts in the Region of Waterloo, including a detailed explanation of the analytical approach.

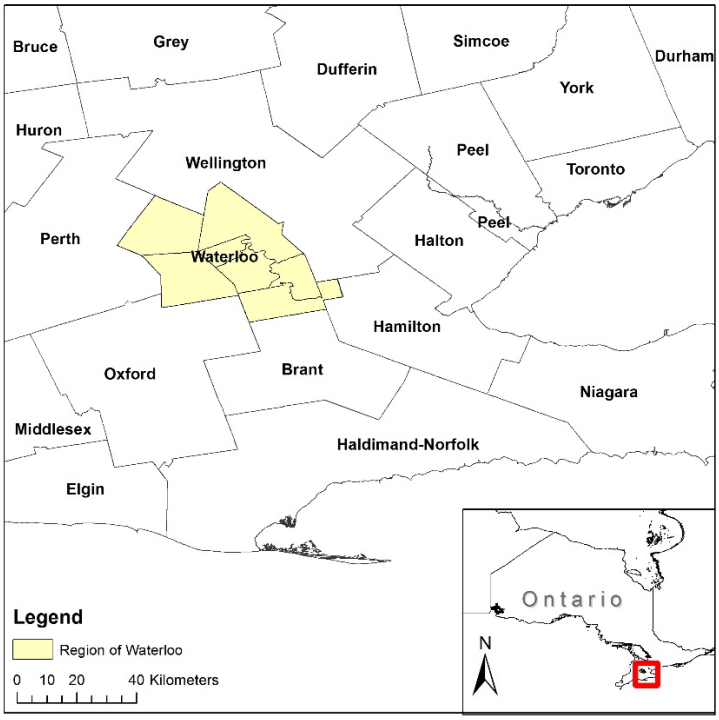
3.1 Study area

The first part of this section is to describe the general characteristics of the Region of Waterloo, followed by the historical traffic patterns and weather and climate conditions. Because the Region of Waterloo has among the densest distribution of roundabouts in Canada, and a significant number of collisions occur annually, it was selected as the study area for this research.

3.1.1 General characteristics

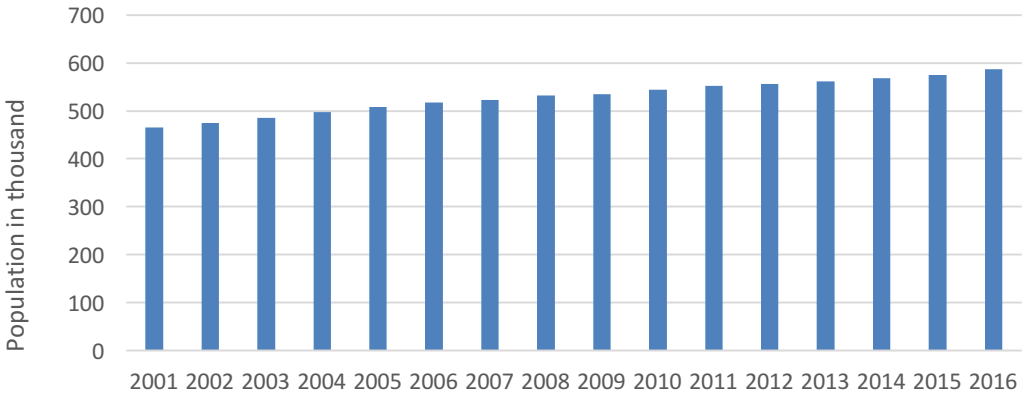
As one of the fastest growing regions in Ontario, the Region of Waterloo (Figure 3-1) is located in southwestern Ontario, approximately 100 kilometres southwest of Toronto. The Region of Waterloo covers an area of approximately 1369 square kilometers, consisting of three cities (City of Waterloo, City of Kitchener, and City of Cambridge), and four rural townships (Township of North Dumfries, Township of Wellesley, Township of Wilmot, and Township of Woolwich) with an estimated total population of around 510,000 (Statistics Canada, 2011b). Over the past 15 years from 2001 to 2016, the Region of Waterloo's population has grown an average of 1.56 percent per year (Figure 3-2). Modal shares are

similar between cities and townships in the Region, with around 90 percent of trips relying on motorized vehicles, vehicles according to data from Statistics Canada in 2011 (Table 3-1).



Data source: Region of Waterloo (2016), Statistics Canada (2011a)

Figure 3-1 Region of Waterloo



Data source: Region of Waterloo, Planning, Development and Legislative Services (n.d.)

Figure 3-2 Trend in population of the Region of Waterloo, 2001-2016

Table 3-1 The proportion of commuters to work by mode of transport, Region of Waterloo

					Modal share				
Name	Population*	% of CMA population*	Land area (km^2)*	Population density (per km^2)*	Vehicle	Transit	Bike	Walk	Collision count*
Cambridge	126748	25%	113	1121.66	90.8%	4.5%	0.6%	3.2%	1553
Kitchener	219153	43%	136.79	1602.11	87.4%	6.6%	0.9%	4.3%	2617
Waterloo	98780	19%	64.02	1542.96	85.5%	5.4%	2.1%	5.8%	1194
North Dumfries	9334	2%	187.44	49.80	94.2%	1.8%	0.0%	3.5%	138
Wellesley	10713	2%	277.79	38.57	89.1%	0.5%	1.1%	6.8%	61
Wilmot	19223	4%	263.72	72.89	92.0%	0.8%	1.4%	4.5%	155
Woolwich	23145	5%	326.17	70.96	90.2%	1.0%	2.6%	5.3%	313
Waterloo region	507096	100%	1368.93	370.43	88.3%	5.2%	1.1%	4.4%	6031

Data source: Statistics Canada (2011b)
*Data year: 2011

As shown in Table 3-1, modal shares are similar, varying from 85.5 and 87.4 percent in the cities of Waterloo and Kitchener, which are the top two densest areas in the region, to 94.2 percent in the rural township of North Dumfries. Overall, of those who commuted to work, vehicles, including car, truck and van, is the most commonly used mode of transportation (over 90 percent) in the Region of Waterloo.

3.1.2 Traffic conditions

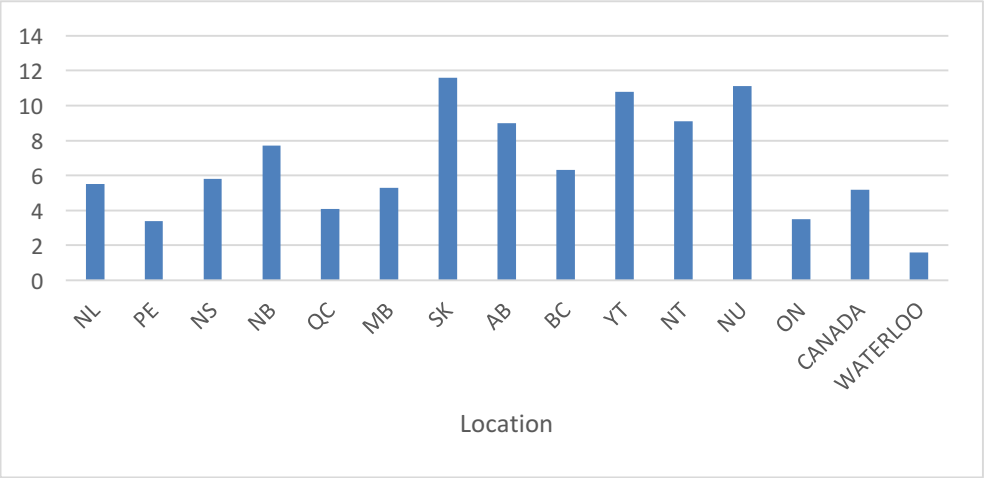
In the Region of Waterloo, traffic operation and traffic safety are controlled by the Transportation Administration of the Region of Waterloo. It is not surprising that road safety is a priority for the Region of Waterloo government.

The public transportation in the Region of Waterloo is provided by Grand River Transit with dozens of different routes, which could reduce residents' dependencies on cars. Furthermore, light rail transit between the City of Kitchener and the City of Waterloo is under construction and is expected to open soon. The Region of Waterloo also has an airport called the Region of Waterloo International Airport, which, according to data released by Statistics Canada (2010), has the 20th highest aircraft movements in Canada.

Table 3-2 Road traffic safety in the Region of Waterloo, 2005-2014

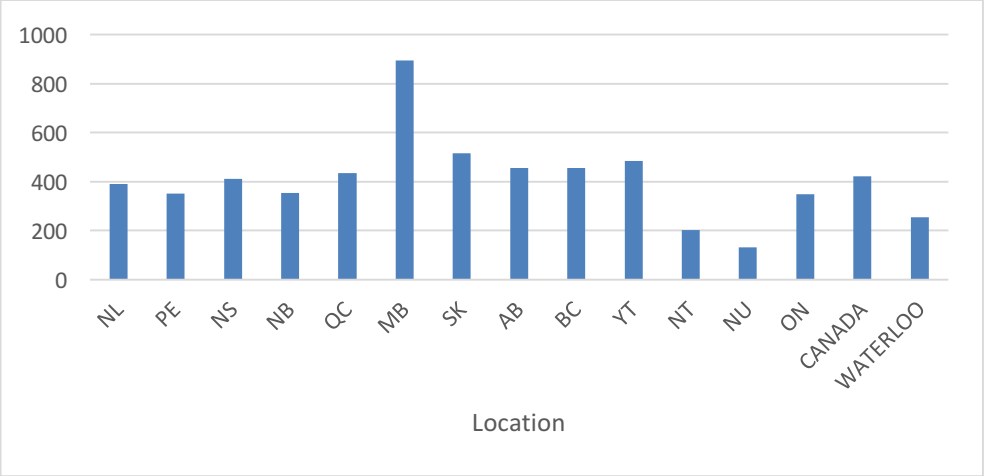
Year	Fatal collisions	Injury collisions	Property damage only collisions	Total collisions	Estimated population	Fatal collisions per 100,000 Pop.
2005	12	1460	4276	5748	507900	2.4
2006	9	1398	4281	5688	517400	1.7
2007	5	1355	4620	5980	523200	1.0
2008	11	1359	4453	5823	532100	2.1
2009	9	1196	4342	5547	535300	1.7
2010	8	1341	4460	5809	544000	1.5
2011	15	1379	4637	6031	551500	2.7
2012	10	1350	4435	5795	556200	1.8
2013	10	1433	4832	6275	561800	1.8
2014	9	1441	5012	6462	567900	1.6
Data source: Region of Waterloo (2014a)						

For almost 20 years, the Region of Waterloo has measured road traffic safety by recording the number of fatal, injury, and PDO collisions, and computing the number of collisions per 1000 population (Region of Waterloo, 2014a). As Table 3-2 shows, from 2005 to 2014, the Region of Waterloo had an average of approximately 5900 total reported collisions, including 10 fatal collisions and 1400 injury collisions, each year. In the Region of Waterloo, the fatality rate for every 100,000 population in 2005 was 2.4, while it was 1.6 in 2014. The actual number of fatalities for 2005 and 2014 are 12 and 9 respectively. There are some fluctuation during the period from 2005 to 2014, but no clear trend. Comparing the statistics of fatal and injury collision records of the Region of Waterloo in 2014 to those at provincial level, it is clear to see the Region of Waterloo has a lower fatality and injury rate than the provincial average (Figure 3-3 and 3-4). Since Ontario has a strong record of road safety, and was consistently ranked in the top two among all North American jurisdictions from 1999 to 2013 (Ministry of Transportation, 2013), it is clear that the Region of Waterloo has a good overall record of road safety. The possible reasons might be the improvements the region has made and the progresses of the driver's behavior.



Data source: Region of Waterloo (2014a)

Figure 3-3 Fatalities rate per 100,000 population

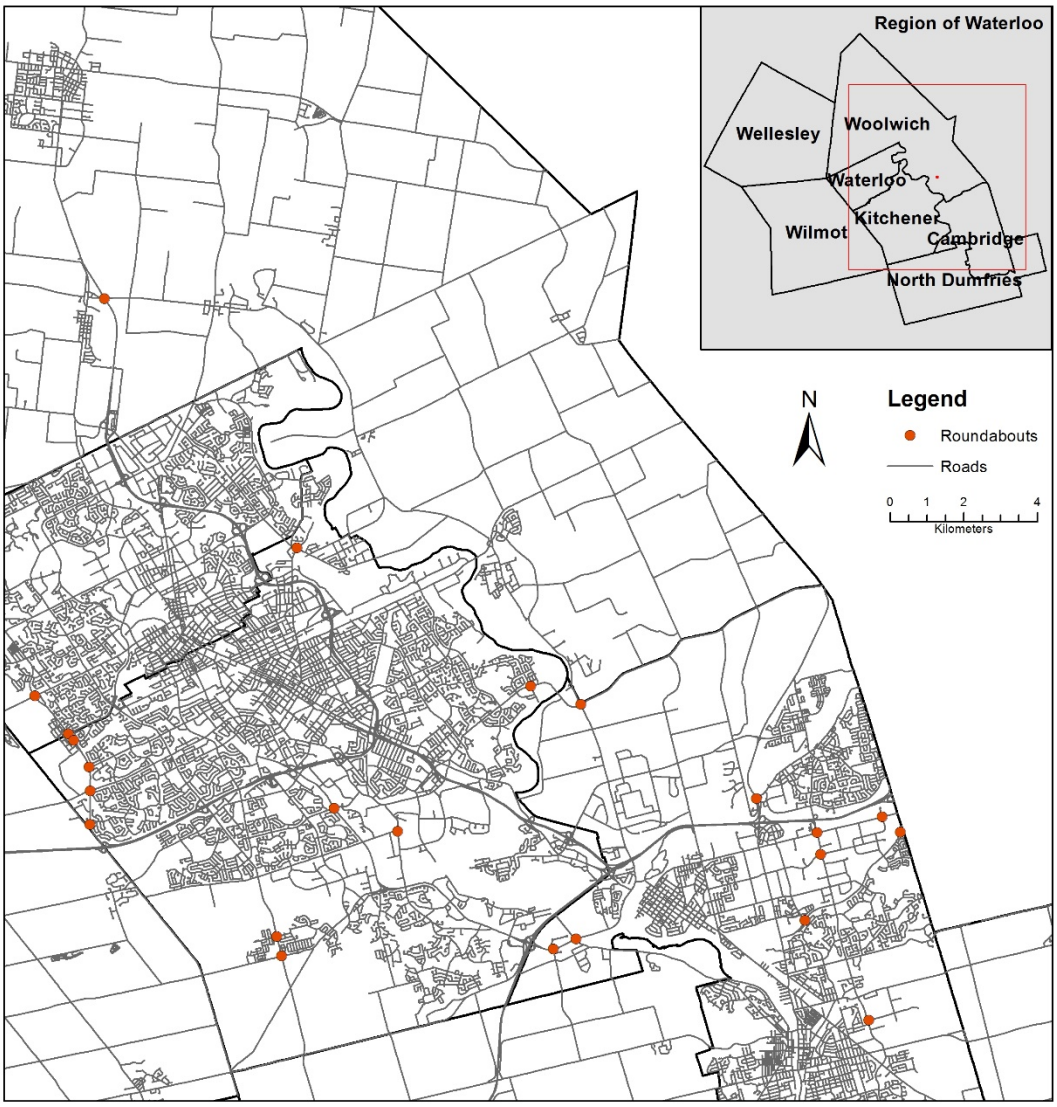


Data source: Region of Waterloo (2014a)

Figure 3-4 Injuries rate per 100,000 population

The transportation network of Waterloo Region consists of about 700 kilometers of roads, 160 bridges and 480 traffic signals (Region of Waterloo, 2014a). Since 2004, the year when the Region of Waterloo's first roundabout was opened at the intersection of Ira Needles Boulevard and Erb Street, roundabouts have been a significant part of intersection landscape in the region. As of January 2017, the Region of Waterloo has 30 roundabouts (Appendix A). However, the data provided by the Transportation Administration in the Region of Waterloo only have 23 roundabouts, since some new roundabouts were installed in 2016, and data for these roundabouts are not available. Figure 3-5 illustrates the location of

roundabouts used in the analysis. Noted that the roundabout installed at the intersection of Arthur Street and Sawmill Road is located in the township of Woolwich, but it is managed by the City of Waterloo. In order to help the public become familiar with roundabouts, the Region of Waterloo adopted a variety of methods, such as cartoons, maps, brochures, training videos, and presentations, to share background information on roundabouts, and information on how to pass through a roundabout as a motorist, cyclist, or pedestrian (Region of Waterloo, n.d.).



Data source: Region of Waterloo (2016)

Figure 3-5 Distribution of roundabouts in the analysis (N=23)

3.1.3 Collisions at roundabouts

Collision data for roundabouts in the study area were compiled from the Transportation Administration of the Region of Waterloo and the Region of Waterloo annual collision reports. As shown in Table 3-3, over the period from 2005 to 2015, the Region of Waterloo saw an increase in the number of collisions occurring at roundabouts. As the number of roundabouts increased in the Region, so did the traffic volume passing through them. It is concluded in some previous research and it stands to reason that there is a positive correlation between the traffic volume and the occurrence of collisions (Lord and Persaud, 2000; Persaud, 2001).Thus, it is not surprising that there are increases in the numbers of total, fatal and injury, and PDO collisions (Table 3-4). In addition, the rates of collisions, regardless of the collision type, generally go down at first and then go up, as drivers become accustomed to this form of intersection control.

Table 3-3 Number of collisions and collision rates at roundabouts in the Region of Waterloo, 2005-2015

Year	Total collisions	Total rate*	Casualty (fatal and injury) collisions	Casualty (fatal and injury) collisions rate	Property damage only	Property damage only rate
2005	34	1.83	4	0.22	17	0.91
2006	45	1.62	2	0.07	28	1.01
2007	81	1.67	10	0.21	36	0.74
2008	112	1.63	5	0.07	42	0.61
2009	87	1.00	10	0.11	34	0.39
2010	146	1.45	14	0.14	80	0.79
2011	230	1.96	23	0.20	142	1.21
2012	264	2.02	27	0.21	234	1.79
2013	322	2.10	32	0.21	275	1.79
2014	402	2.44	44	0.27	347	2.11
2015	473	n/a**	45	n/a	418	n/a
2005-2014		1.77		0.17		1.14
2005-2015	2196		216		1653	

*Crashes per 1 million entering vehicles (MEV)
** Total AADT is not available for 2015, so the rates cannot be calculated

Table 3-4 Characteristics of collisions occurring at roundabouts in the Region of Waterloo, 2005-2015

Characteristics of collision**	%***
Season of year	
Spring (Mar – May)	21.9
Summer (Jun – Aug)	22.7
Autumn (Sep – Nov)	31.4
Winter (Dec – Feb)	24.0
Day of week	
Monday	13.8
Tuesday	15.7
Wednesday	14.2
Thursday	16.9
Friday	17.9
Saturday	13.3
Sunday	8.4
Time of day	
0:00-5:59 (Late night)	2.4
6:00-9:59 (Morning rush hour)	18.9
10:00-14:59 (Midday)	29.8
15:00-18:59 (Afternoon rush hour)	37.9
19:00-23:59 (Evening)	11.0
Weather condition*	
Rain	11.4
Snow	6.5
Frozen precipitation	0.5
Visibility limitation	0.7
Road surface condition*	
Wet	20.5
Snow, slash, or ice	9.6

Characteristics of collision**	%***
Light condition*	
Daylight	80.5
Dawn/dusk	4.1
Darkness	15.3
Initial impact type*	
Angle	30.9
Rear-end	24.5
Sideswipe	18.6
Turning movement	14.9
Classification of collision*	
Fatal	0.0
Non-fatal injury	9.8
PDO	75.3

*Due to the incompleteness of the data, the percentage of these five characteristics of collision were based on the existing data.
** Since the opening dates of two roundabouts (Geo_ID: 21805 and 15587) are in December 2015 and September 2016 respectively, no collisions have occurred at these two roundabouts by the end of 2015. Therefore, they are excluded from the analysis.
*** It means the percentage of collisions at roundabouts in the Region of Waterloo

Table 3-4 demonstrates the characteristics of the collisions which occurred at 23 roundabouts in the Region of Waterloo from 2005 to 2015. In the Region of Waterloo, for each season consisting of a three-month period, the distribution of the number of collisions is fairly even. Autumn has the highest number of collisions with more than 30 percent of total, while spring has the lowest. This may be linked to the opening dates of new roundabouts, since winter sees the highest number of collisions at signalized intersections. Most of the roundabouts in the Region of Waterloo opened in late summer or autumn (between August to November), so the public may be not familiar enough with the new roundabout and still on a learning curve to adapt to the change during the time in which the new roundabout just opened. In terms of day of week, Friday records the highest crash counts, while weekends have lower counts. Results also indicate that the lowest proportion of collisions occurred on Sunday. This is likely from the travel behaviour of the public. People have fewer work trips on weekends than weekdays. In terms of

day-of-the-week, the afternoon rush hour accounts for the highest number of collisions in a day, most likely due to the heavy commuter travel.

Precipitation was occurring for almost 20 percent of total collisions. This pattern is also confirmed by road surface condition: almost 20 percent of collisions occurred when road surface is wet. Most collisions occurred during daylight condition, probably because daytime has higher commuting traffic volume.

Initial impact types of angle and sideswipe account for almost half of collisions. This may be because all the traffic moves the same way around the roundabout, which reduces the possibility of head-on collisions. Over-three quarters of all collisions at roundabouts are PDO collisions, and non-fatal injury collisions account for 10 percent of collisions. It is worth noting that a large amount of the severity of collisions are non-reportable, thus fatal, injury and PDO collisions do not add up to total collisions.

3.1.4 Historical weather and climate

In terms of weather and climate, the Region of Waterloo can be an appropriate study area for this study because it has a humid continental climate and a reasonably complete observed historical weather records at the weather station since 1970 (Region of Waterloo, 2014b). In addition, it also has detailed collision data.

The Region of Waterloo has a local weather station situated at the Region of Waterloo international airport. Although the weather station was moved slightly within the airport and been renamed three times, it provides valuable historical weather data for the Region of Waterloo. All the analysis in this section is based on data acquired from these weather stations (Table 3-5).

Table 3-5 Weather stations and weather data summary for the Region of Waterloo

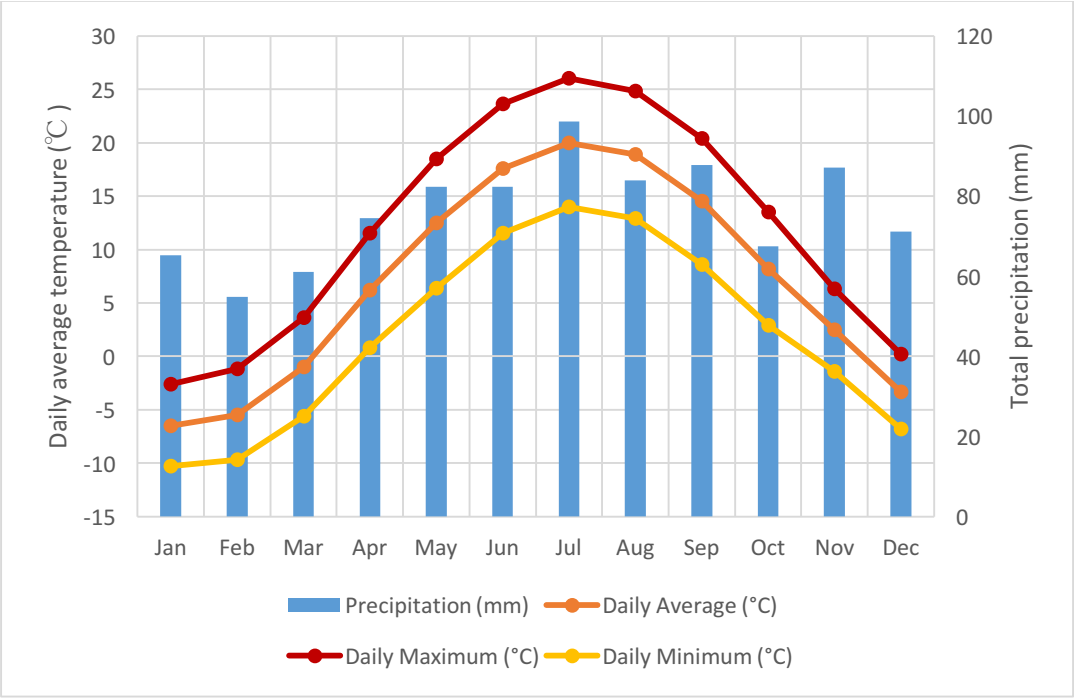
	KITCHENER/ WATERLOO*	REGION OF WATERLOO INT'L AIRPORT*	WATERLOO WELLINGTON 2 ONTARIO*	WATERLOO WELLINGTON A ONTARIO*
Climate station ID	6144239	6149388	6149389	6149387
Latitude	43°27'39.000" N	43°27'32.000" N	43°27'00.000" N	43°27'00.000" N
Longitude	80°22'43.000" W	80°22'39.000" W	80°23'00.000" W	80°23'00.000" W
Elevation	321.6 m	321.3 m	313.6 m	317 m
Overall**	Start: 2010-04-18	Start: 2002-10-03	Start: 2003-12-01	Start: 1970-03-01
	End: 2017-03-02	End: 2010-04-17	End: 2017-03-01	End: 2002-10-31
Rain/snow**	n/a	Start: 2004-11-01	Start: 2003-12-01	Start: 1970-03-01
	n/a	End: 2004-11-30	End: 2017-03-01	End: 2002-10-31

	KITCHENER/ WATERLOO*	REGION OF WATERLOO INT'L AIRPORT*	WATERLOO WELLINGTON 2 ONTARIO*	WATERLOO WELLINGTON A ONTARIO*
Precipitation**	Start: 2010-04-18	Start: 2002-10-03	Start: 2003-12-01	Start: 1970-03-01
	End: 2017-03-02	End: 2010-04-17	End: 2017-03-01	End: 2002-10-31
Temperature**	Start: 2010-04-18	Start: 2002-10-03	n/a	Start: 1970-03-01
	End: 2017-03-02	End: 2010-04-17	n/a	End: 2002-10-31

Data source: Government of Canada (2017)
*Data available from the stations that are listed more left in the table have higher priority than data available from the stations listed more right in the table.
**Data may be incomplete within some ranges listed.

3.1.4.1 Climate normal from 1981 to 2010

The Region of Waterloo has a humid continental climate, with a clear seasonal temperature pattern as Figure 3-6 illustrates. According to the Canadian Climate Normals 1981-2010 Station Data, typically, temperature in the Region of Waterloo varies from -6.5℃in January to 20.0℃in July.



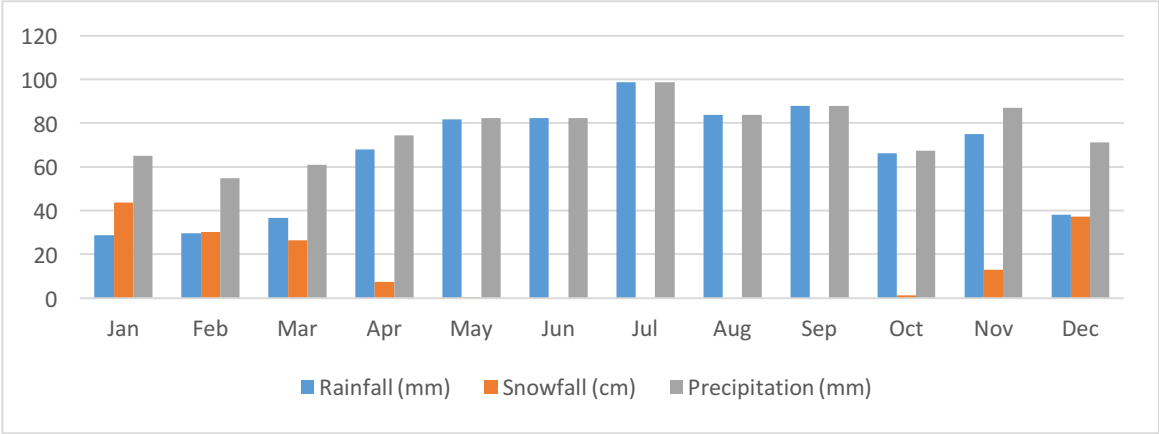
Data source: Government of Canada (2017)

Figure 3-6 Average monthly maximum, mean, and minimum temperature and total precipitation, 1981-2010

In the Region of Waterloo, average annual number of days with rainfall, snowfall, and precipitation from 1981 to 2010 is 118.7, 62.2, and 166.2, respectively (Table 3-6). Almost a third of precipitation days are snow days. Approximately 777 mm rainfall, 160 cm snowfall and 916 mm precipitation is observed per year. In general, rainfall and precipitation can occur through the year but snowfall has a distinct seasonal pattern which mostly occur from late autumn to mid spring (Figure 3-7).

Table 3-6 Climate summary for the Region of Waterloo, 1981 - 2010

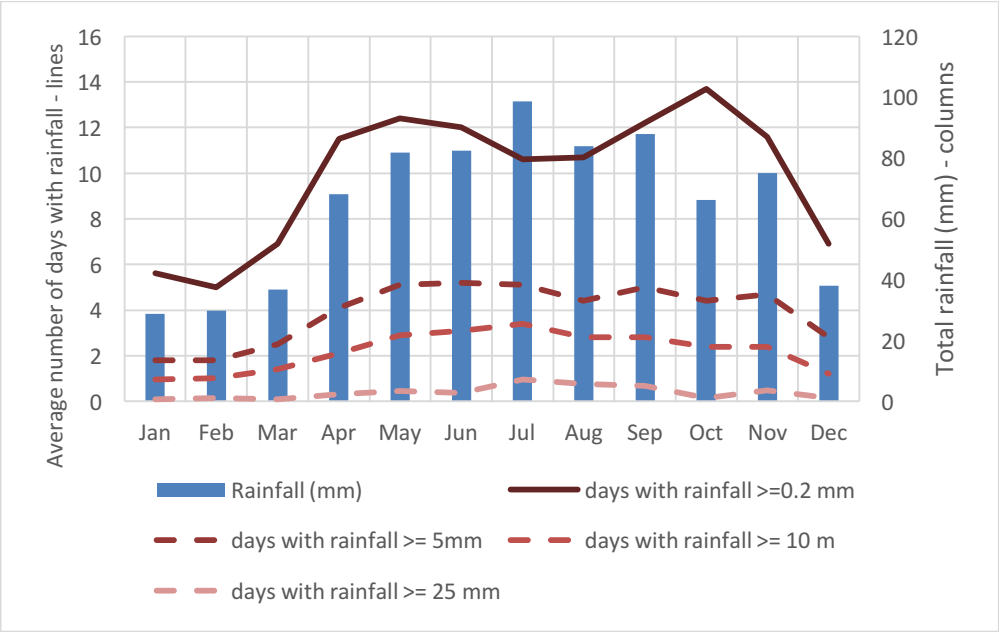
Average daily max temp.	12.0 °c
Average daily mean temp.	7.0°c
Average daily min temp.	2.0°c
Average daily mean temp., January	-6.5°c
Average daily mean temp., July	20.0°c
Average annual # rainfall days*	118.7
Average annual # snowfall days*	62.2
Average annual # precipitation days*	166.2
Average annual rainfall	776.8 mm
Average annual snowfall	159.8 cm
Average annual precipitation	916.3 mm
*0.2 millimetres precipitation is the minimum threshold used by Environment Canada to define a day with rainfall, snowfall or precipitation Data source: Government of Canada, the Canadian Climate Normals 1981-2010 Station Data (2017)	



Data source: Government of Canada (2017)

Figure 3-7 Mean monthly total rainfall, snowfall and precipitation, 1981-2010

In terms of precipitation, the distribution of precipitation through the year is relatively even. Rainfall is quite common during relative warm seasons. As shown in Figure 3-8, July accounted for both the highest number of rainfall days and the greatest rainfall accumulation. Months in the winter season normally receive less rainfall but greater winter precipitation as snowfall.



Data source: Government of Canada (2017)

Figure 3-8 Mean monthly total rainfall and the number of rain days, 2005-2015

3.1.4.2 Study period, 2005-2015

A study period from 2005 to 2015 was selected to produce the rainfall-related crash risk analysis for roundabout safety. Table 3-7 summarizes the missing days of the weather data over the study period. Generally, the completeness of data is acceptable. In terms of the temperature, this period is slightly warmer than the climate normals from 1981 to 2010 for the Region of Waterloo as Table 3-8 indicates. Compared to long term averages from 1981 to 2010, annual days with rainfall, snowfall and precipitation for study period from 2005 to 2015 are less than average.

Table 3-7 Missing days of the weather data, 2005-2015

Year	Total count of days	Missing days			
		Max Temp	Min Temp	Mean Temp	Total Precipitation
2005	365	0	0	0	0
2006	365	0	0	0	18
2007	365	1	0	1	23
2008	366	3	1	3	12
2009	365	1	0	1	5
2010	365	16	10	18	9
2011	365	17	14	17	15
2012	366	4	3	4	13
2013	365	7	3	7	12
2014	365	19	15	21	24
2015	365	10	9	10	13
2005-2015	4017	78	55	82	144
Missing %		2%	1%	2%	4%

Table 3-8 Climate normal for the Region of Waterloo, 2005-2015

	Daily average (°C)	Total rainfall (mm)	Total precipitation (mm)	Annual number of rain days	Annual number of snow days	Annual number of precipitation days
2005	7.0	553.5	804.8	75	59	146
2006	8.1	692.0	927.5	78	35	135
2007	7.1	224.0*	464.0*	67*	57*	144*
2008	6.6	673.0	973.5	110	59	207
2009	6.6	631.0	852.5	98	40	173
2010	8.0	534.9	730.7	78	38	120
2011	7.6	689.5	922.6	92	49	142
2012	9.0	494.2	655.5	79	34	133
2013	6.9	710.2	913.7	86	63	146
2014	5.6	598.7	734.3	83	58	130
2015	7.0	495.5	636.6	73	47	112
2005-2015	7.2	607.3	815.2	85.2	48.2	144.4
1981-2010	7.0	776.8	916.3	119.1	62.3	166.2
*Due to the incompleteness of the data, the values for 2007 are based on available data.						

3.2 Relative risk analysis

This section intends to quantify precipitation-related crash risks for both roundabouts and signalized intersections. A variety of methods have been used in past studies to quantify precipitation-related crash risks, including a matched-pair approach (Andrey et al., 2003), Poisson and negative binomial regressions (Eisenberg and Warner, 2005), and a least squares method. This research adopted a matched-pair approach, which is a common approach for temporal comparison. The matched-pair approach was also adopted in many prior studies (Andrey, 1989; Andrey et al., 2003; Andrey and Yagar, 1993; Hambly, 2011; Hambly et al., 2013; Suggett, 1999).

The general steps taken for analyzing relative crash risks are demonstrated in Figure 3-9.

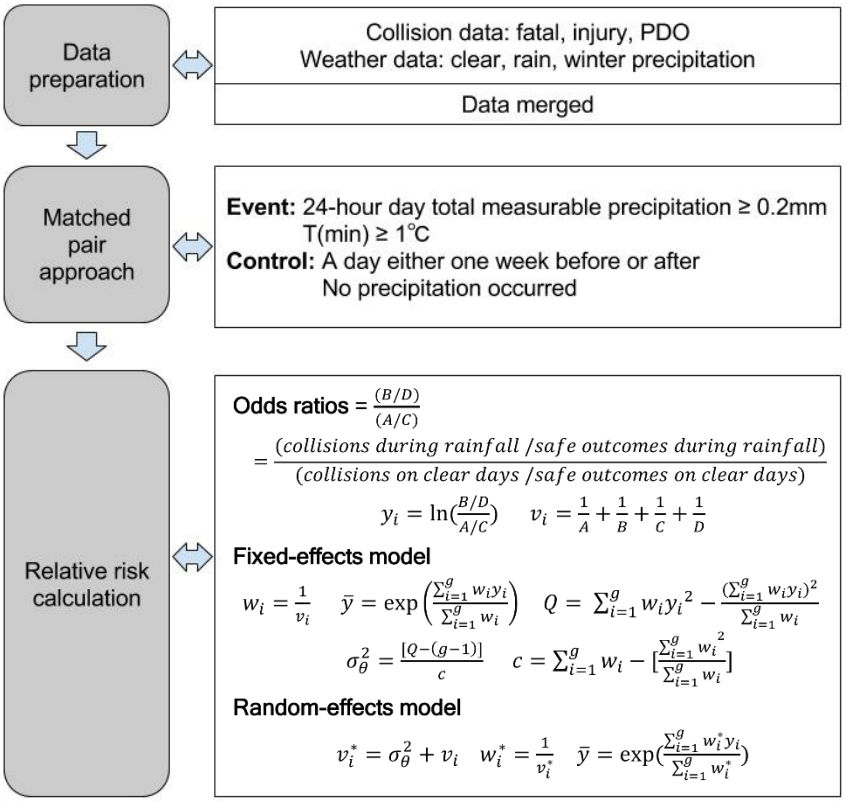


Figure 3-9 Steps taken in analyzing relative crash risks

3.2.1 Data

The first step in the analysis procedure is to obtain the required data. The analysis of rainfall-related crash risk is built on the incorporation of two main datasets: collision data and weather data.

3.2.1.1 Collision data

Collision data at roundabouts and comparable signalized intersections are provided by Transportation Administration of the Region of Waterloo from the year 2005 to 2015, the most recent period for which complete collision data are available. The first roundabout in the Region of Waterloo opened in 2004. It should be noted that some of the older data before 2010 do not include as many details as the new data after 2010 due to the different collision record systems used by the Transportation division in the Region. The lack of data in some fields may cause some difficulties in the analysis, which will be discussed as appropriate.

In order to compare the effect of inclement weather on intersection safety, collision data include all reportable vehicle collisions that occurred at or near roundabouts and intersections with traffic signal control but share a similar set of traits (traffic volume and geometric elements) to these roundabouts in the Region of Waterloo from 2005 to 2015. During the study period, the Region of Waterloo reported 2,196 and 3,337 collisions respectively at roundabouts and signalized intersections which are similar in traffic volume and other characteristics to roundabouts (Table 3-9).

Table 3-9 Summary of collisions at roundabouts and signalized intersections, 2005-2015

Severity type	Roundabouts (N=23*)	Signalized intersections (N=22**)
Total collisions***	2196	4021
Fatal collisions	0	4
% of fatal collisions	0.0%	0.1%
Injury collisions	216	959
% of injury collisions	9.8%	23.8%
PDO collisions	1653	2126
% of PDO collisions	75.3%	52.9%

*Since the opening dates of two roundabouts (GEO_ID 21805 and 15587) are in December 2015 and September 2016 respectively, there are no collisions occurred at these two roundabouts by the end of 2015. Therefore, they are excluded from the analysis.
** Nine roundabouts are converted from signalized intersections during the study period. In the analysis, 22 signalized intersections with 11 years data and nine signalized intersections with incomplete data are included.
***A large amount of the severity of collisions are non-reportable, thus fatal, injury and PDO collisions do not add up to total collisions.

In the dataset, the following collision elements were included:

- Collision location
- Date and time which containing day of the week
- Classification of collision severity (e.g., fatal, injury, or property damage only)
- Initial impact type of collision (e.g., approaching, rear end, and sideswipe)
- Impact location

- Environment condition, light condition, and road surface condition
- Vehicle type, and vehicle damage
- Apparent driver action, pedestrian action
- Driver/pedestrian condition
- Sequence of events

3.2.1.2 Historical Weather Data

In addition to collision data, weather data acquired from a local weather station was required for the events and controls define process in the matching period. For this study, the closest weather station to the study area having complete daily precipitation and different kinds of temperature data available from 2005 to 2015 is the Region of Waterloo international airport weather station.

Relative risk analysis in this study is based on daily weather data, because six-hourly total precipitation is not available at the Region of Waterloo international airport weather station. Historical daily weather data for each year from 2005 to 2015, which was measured at the Region of Waterloo international airport weather station, were obtained from the Environment and Natural Resources historical data of the Government of Canada. It includes basic information as precipitation details, temperature (e.g., daily mean temperature, maximum daily temperature, and minimum daily temperature) and some other characteristics, from which one can infer daily weather conditions. However, it is worth noting that this station was renamed from the Region of Waterloo International Airport to Kitchener/Waterloo with slightly different in location in 2010.

A challenge of the analysis is to match the observed weather conditions measured at the weather station with environmental conditions recorded on collision reports. Weather could be different from season to season, day to day, hour to hour, even minute to minute (Gutro, 2005). Compared with temperature, precipitation is subject to higher uncertainty because of the larger temporal and spatial variation. Issues that were considered include the temporal dissimilarity in weather conditions which were recorded on collision reports and recorded at the weather station. Weather conditions recorded on collision reports are documented by the police officer, and largely depend on their interpretation at the time the collision occurred, whereas weather records at the weather station used for this study were recorded at the daily level. In addition, since the location of the weather station is fixed, and the location where a collision occurred can be anywhere throughout the city, there is the potential for dissimilar weather conditions.

Furthermore, collision records also do not have records on air temperature and precipitation intensity. Therefore, weather conditions recorded on collision reports were only used to verify the representativeness of the data from observing weather station for the Region of Waterloo.

As mentioned in prior paragraphs, collision records from the Region also offer some information about the environmental conditions at an individual collision, including weather (clear, rain, snow, and other types), light condition (daylight, dawn/dusk, and darkness), road surface condition (dry, wet, snow, slash, or ice). It is noteworthy that Andrey and Olley (1990) stated that the agreement between the weather observed at hourly level at a local weather station and recorded on the collision reports can almost reach 85 percent. Similarly, as shown in Table 3-10, there are more than 80 percent of weather recorded on the spot and at the weather station for collisions are matched, which is reasonably consistent with the Andrey and Olley's finding.

Table 3-10 Weather condition comparison between the weather station and collision reports for the Region of Waterloo, 2005-2015

	Rainfall is observed at the weather station	Rainfall is not observed at the weather station
Rainfall is recorded on the collision report	342	356
Rainfall is not recorded on the collision report	657	4178
Matched % = (342+4178)/(356+342+4178+657) x 100% = 81.7%		

3.2.2 Matched-pair approach

This study adopts a matched-pair approach to estimate the collision risk associated with precipitation at roundabouts in the Region of Waterloo. The method involves matching the collision data with observed weather data and reasonably controls for the effect of time-dependent variables (e.g., seasonality, day of week, time of day, and traffic volume) by assuming that travel patterns are similar from one week to the next (Hambly, 2011).

Collisions are compared between events and controls. For instance, in the matching process, a rainy Sunday (event) would be matched only to another Sunday on which no precipitation occurred (control), either one week before or after this rainy Sunday. Therefore, most travel patterns in all respects are soundly controlled.

The temporal period of the events and controls has a large range, from hourly to six-hourly to daily to monthly. In this study, because the six-hour period's weather data obtained from Environment Canada do not possess the value of the total precipitation, an event is defined as a 24-hour climatological day with precipitation, and a control is a day on which the weather is clear.

The matched-pair approach effectively controls external factors in all aspects of event-control pairs (e.g., day of week, study area, etc.) except the precipitation. Accordingly, the safety effect of the precipitation on roundabouts and signalized intersections is isolated from that of other factors. It should be noted that traffic volume is an extra variable that needs to be controlled, and which could affect the exposure to collisions. As far as possible to control the potential differences in traffic volume between a pair of observations, an event is matched with a day either one week before or after (Andrey, 2010; Hambly, 2011; Hambly et al., 2013). However, the only potential problem not fully solved is that the precipitation condition may result in decrease in travel, so the difference in traffic volume between days with precipitation and normal dry days may exist and cause relatively conservative estimates (Hambly, 2011).

Historical weather data used for this study only include temperature (daily mean temperature, maximum daily temperature, and minimum daily temperature), precipitation details and some other factors, but no information for the detailed weather type. The only approach that can be taken to determine events and controls is to use existing data and criteria to infer precipitation condition.

Several selection criteria for event and control scenarios were utilized in prior studies (Andrey et al., 2003). In this study, precipitation events are categorized into two types defined as follows:

Rainfall is identified as total precipitation of no less than 0.2 millimetres in a 24-hour day, and the minimum daily temperature equal to or higher than one degree Celsius. Snowfall is identified as total precipitation of more than zero in a 24-hour day, and a daily mean temperature below zero degree Celsius.

In terms of the amount of rainfall, 0.2 millimetres precipitation is the minimum threshold used by Environment Canada to measure precipitation and define a precipitation day (Environment Canada, 2016). In general, with regard to temperature, most precipitation is shown as snow when temperature is less than zero degree Celsius. With the increase of temperature, the chance of snow and other frozen precipitation will drop sharply. Once the air temperature is above zero degree Celsius, more precipitation falls as rain. However, when temperature is between zero degree Celsius and two degrees Celsius, the fraction of snow to rain and the air temperature show a linear relationship (Interdisciplinary Centre on

Climate Change & University of Waterloo, 2015). Kienzle (2008) mentioned that temperature of the atmospheric layers is the primary factor to indicate whether precipitation falls as snow or rain, but not the only factor. Other meteorological conditions like air mass movement, cloud type, and humidity also affect the results (Kienzle, 2008). In order to eliminate the chance of snow and other frozen precipitation occurring when the temperature just greater than zero degree Celsius, one degree Celsius is selected as the cut off temperature value in this study. Hambly (2011) also established the threshold as one degree Celsius after checking the historical daily climate record for days in which both rain and snow were quantified in Toronto and Vancouver.

However, it should be noted that this threshold also inevitably excluded some real rainy days from rainfall events. Actually, the definitional standard for temperature has a substantial influence on the Region of Waterloo, because the region may have a great number of days with measured rains but without reaching the standard of the one degree Celsius minimum daily temperature. As shown in Table 3-11, in the Region of Waterloo, 1588 days (around 26 percent of all days) were defined as rain days according to the precipitation criteria, but only 919 days meet the criteria for rainfall event in this study. Almost 42 percent of all rain days are disqualified from the analysis, and it will lead to conservative evaluation results because the number of rain days included in the analysis is less. In comparison to the result from Hambly's (2011) research (about 20 percent and less than 10 percent of all rain days are removed for Toronto and Vancouver respectively), more data are excluded from the analysis, which may cause more conservative outcomes. In order to avoid confusion, the words "rain days" and "rainfall" are used to refer to liquid rain days (i.e., daily minimum temperature is no less than one degree Celsius) in the following chapters, unless otherwise noted.

Table 3-11 Rain days and liquid rain days in the Region of Waterloo, 2005-2015

	All rain days		Liquid rain days(>=1)	
Rainfall amount (mm)	# days	Total mm	# days	Total mm
0.2-4.9	1073	1555.2	555	831.2
5-9.9	239	1693.7	146	1045.1
10-19.9	183	2511.9	135	1856.9
>=20	93	2854.9	83	2563.3
Total	1588	8615.7	919	6296.5

The procedure for identifying event/control day pairs is to start with control days with zero precipitation, and then look for precipitation event days exactly one week prior to or after the control day. The matching procedure was completed in Excel. All the events were checked sequentially to make sure each of them has a corresponding control. Once a control was found a week prior to the event, it will be removed from the control group temporarily since every control only can be matched once in the matching process. After finishing all the matches in the first phase, an attempt was made to pair unmatched events to a control one week later. Eventually, remaining events and controls that could not be matched were also removed from the study.

Since traffic exposure is most likely affected by holidays (Andrey et al., 2003), all statutory holidays (New Year's Day, Easter, Victoria Day, Canada Day, Labour Day, Thanksgiving, Remembrance Day, Christmas, and Boxing Day) and weekends associated with holidays were excluded during the analysis (Appendix B). In this process, roughly 20 percent of pairs were removed from the analysis.

The distribution of the matched pairs by month in the Region of Waterloo, presented in Table 3-12, indicates that there is a seasonal variation that reflects the observed seasonal distribution of rainfall, with almost 90 percent of rain days falling within the period from April to November and approximately 95 percent of matched pair also happening in the same period. It is not surprising that there are many fewer matched pairs in the winter months, because most days cannot meet the temperature requirements for liquid rainfall.

Table 3-12 Seasonal distribution of event-control pairs, 2005-2015

Month	% of rain days*	% of matched pairs
Jan	3.8%	1.6%
Feb	0.6%	0.2%
Mar	3.5%	1.8%
Apr	19.7%	7.2%
May	32.8%	12.0%
Jun	42.1%	17.2%
Jul	40.5%	13.1%
Aug	34.3%	12.2%
Sep	40.6%	14.2%
Oct	37.5%	13.1%

Month	% of rain days*	% of matched pairs
Nov	13.0%	5.7%
Dec	4.7%	1.6%
Count	919 days	557 pairs
*rain days here refer to all annual days with ≥ 0.2 mm liquid rainfall		

3.2.3 Relative risk calculation

After the matching procedure, the relative risk of a collision is estimated as the total number of collisions occurring during events divided by the total number of collisions occurring on the control days (Andrey et al., 2003). It should be noted that the relative risk of a collision is not the same as the absolute risk of a collision. Since traffic volume is not accessible throughout the whole study area, absolute collision rates are not available. However, because adverse weather would influence people's travel mode, and less traffic would to be expected on the roads, the minor difference in traffic volume between adverse weather and normal weather would lead to a more conservative result produced by relative precipitation-related risk, compared with absolute precipitation-related risk.

There is a method using odds ratios for estimating darkness-related collision risk (Johansson et al., 2009). In this study, precipitation-related collision risk is calculated based on Johansson et al.'s (2009) odds ratios approach, which represents ratios of the probability of a type of thing happening during one condition to the probability of this happening during another condition. For example, an odds ratio of rainfall-related collision risk is calculated as the probability of a collision during rain compared to the chance of a collision occurring during clear weather conditions.

For each matched pair, an odds ratio is computed as shown below:

$$Odds\ Ratio = \frac{(collisions\ during\ an\ event/safe\ outcomes\ during\ an\ event)}{(collisions\ during\ a\ control/safe\ outcomes\ during\ a\ control)} \tag{3.1}$$

In this equation, whether safe outcomes during an event or during a control presents the number of trips where no collision occurred. Relative to the number of trips where a collision occurred, the number of safe outcomes is unavailable but far greater. Thus safe outcomes can be estimated as an arbitrary enormous number. Referring to Hambly's research in 2011, in this study, 1000000 is selected.

After having all odds ratio for single matched pair, the relative risk of roundabouts and conventional intersections can be estimated via combining all individual odds ratio by the fixed-effects model or the random-effects model.

The step details of relative risk estimation followed by Johansson et al.'s (2009) research is given below.

Assuming the number of collisions during a control is A, the number of collisions during an event is B, safe outcomes during a control is C, and safe outcomes during an event is D. The logarithm of the odds ratio (y_i) and the variance (v_i) are calculated as:

$$y_i = \ln \frac{B/D}{A/C} \tag{3.2}$$

$$v_i = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} + \frac{1}{D} \tag{3.3}$$

For each matched pair in the fixed-effects model, the statistical weight (w_i) is inversely proportional to the variance (v_i).

$$w_i = \frac{1}{v_i} \tag{3.4}$$

The weighted mean effect based on a set of g estimates is calculated below. In this equation, w_i is the statistical weight of each matched pair and y_i is the logarithm of each estimate of risk.

$$\bar{y} = \exp\left(\frac{\sum_{i=1}^{g} w_i y_i}{\sum_{i=1}^{g} w_i}\right) \tag{3.5}$$

There is an assumption of the fixed-effects model that the difference in risk estimates is purely random, which means it is only caused by sampling variation. The validity of the variation assumption can be verified statistically as:

$$Q = \sum_{i=1}^{g} w_i {y_i}^2 - \frac{(\sum_{i=1}^{g} w_i y_i)^2}{\sum_{i=1}^{g} w_i} \tag{3.6}$$

If the result is statistically significant, which shows that systematic variation in effects is found, a random-effects model will be preferred. In order to obtain a more precise result, a variance component that reflects the amount of systematic variation in estimate of risk is added to the statistical weight of each matched pair in a random-effects model.

In this study, the Q test statistics is statistically significant for rainfall event-control pairs in the Region of Waterloo, so the random-effects model is used.

$$\sigma_\theta^2 = \frac{[Q-(g-1)]}{c} \tag{3.7}$$

In this equation, Q is the test statistic, g is the number of event-control pairs, and c is an estimator as follows:

$$c = \sum_{i=1}^{g} w_i - [\frac{\sum_{i=1}^{g} {w_i}^2}{\sum_{i=1}^{g} w_i}] \tag{3.8}$$

Now, the new variance of each event-control pair and the new statistical weight in the random-effects model are calculated as:

$${v_i}^* = \sigma_\theta^2 + v_i \tag{3.9}$$

$${w_i}^* = \frac{1}{{v_i}^*} \tag{3.10}$$

And a new weighted mean estimate on a set of estimates becomes:

$$\bar{y} = \exp(\frac{\sum_{i=1}^{g} {w_i}^* y_i}{\sum_{i=1}^{g} {w_i}^*}) \tag{3.11}$$

The standard error of the risk estimate becomes:

$$SE = \frac{1}{\sqrt{\sum_{i=1}^{g} {w_i}^*}} \tag{3.12}$$

A 95% confidence interval is calculated by applying the standard error on the weighted mean estimate of effect. Then, the upper and lower confidence boundaries can be calculated by anti-logging the value of 95% confidence interval.

$$95\%\ confidence\ interval = risk\ estimate\ \pm 1.96 \times SE \tag{3.13}$$

$$95\%\ C.I. = \exp[\left(\frac{\sum_{i=1}^{g} {w_i}^* y_i}{\sum_{i=1}^{g} {w_i}^*}\right) \pm 1.96 \times (\frac{1}{\sqrt{\sum_{i=1}^{g} {w_i}^*}})] \tag{3.14}$$

3.3 Safety effect of the conversion

In order to have a better understanding, the general steps taken for analyzing safety effect of the conversion are demonstrated in Figure 3-10.

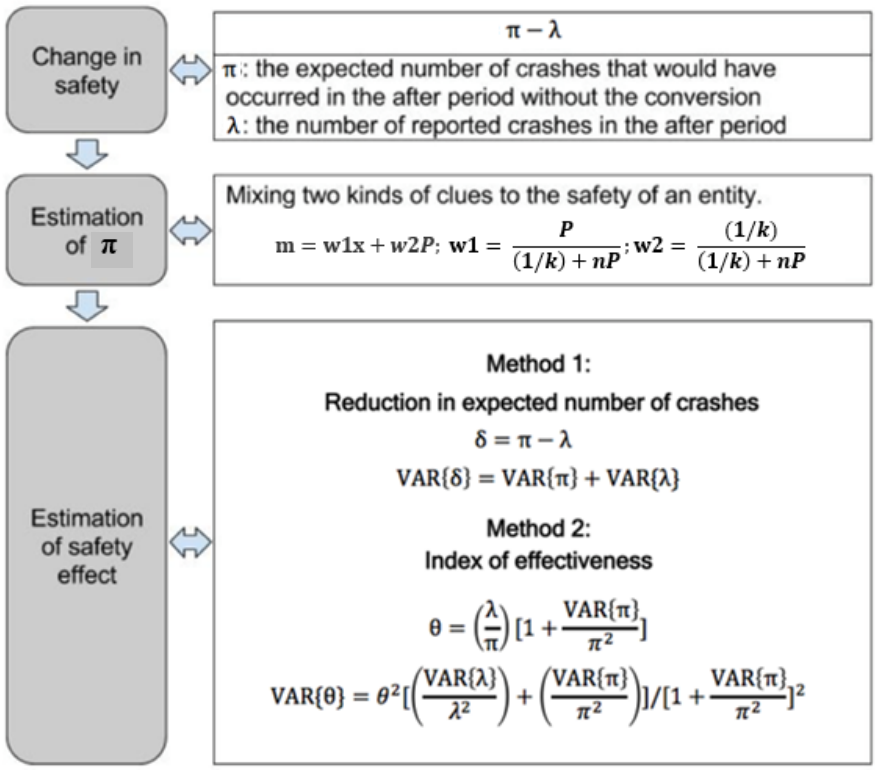


Figure 3-10 Steps taken in analyzing safety effect of the conversion

3.3.1 Data

The data used to evaluate the safety effect of roundabouts were obtained from the Transportation Administration of the Region of Waterloo for treated entities and reference population in the Region of Waterloo. This section describes the data extraction and manipulation process as well as the data summary. The major objective of this part is to quantify the safety effects of converting a signalized intersection to a roundabout using the EB method.

3.3.1.1 Summary statistics of data for treated entities

Data of treated intersections for the Region of Waterloo in Ontario, Canada are selected for study. There are 14 intersections that were converted to roundabouts from 2006 to 2016. Of the 14 intersections reviewed in this analysis, nine were previously signal-controlled, and five were stop-controlled. All the roundabouts are double circulation lane design.

For the analysis of the treatment of the "conversion from signalized intersections to roundabouts", four intersections are excluded from the analysis because the roundabouts are too new (opened in late 2015 and 2016) and data are not available.

For each intersection, collision data are collected from the Transportation Administration of the Region of Waterloo for both before conversion period and after conversion period. Although construction dates of the transformations are not available, based on the opening dates and collision information during the before period, the construction period for each roundabout studied is estimated. In addition, in order to have finer data, the estimated construction period and the opening month are excluded from analysis. The reform from an intersection to a roundabout have different construction periods, so the lengths of the before and after periods varied are consistent with available collision data, but all periods are longer than 15 months.

The collision records contain detailed information about each collision such as collision location, AADT, date and time, environment condition, light condition, road surface condition, injury severity level, vehicle type, initial impact type, vehicle damage, and sequence of events, etc.

Since crash information is gathered from crash reports, some minor variations in definitions of collisions at intersections are expected but are not expected to essentially influence the consequences. In this study, the severity of collisions is reclassified into two types: total and casualty. Total collisions represent all reported severity of injuries ranging from minimum to severe, while casualty collisions count both injury and fatal collisions.

Finally, for the treatment of "conversion from signalized intersections to roundabouts", the Region of Waterloo has five intersections with available collision data (Appendix C), which were converted to roundabouts with four-legged and double-lane circulating way between 2006 and 2013.

The different crash severity types considered in the analysis are:

1. Total collisions
2. Casualty collisions (Fatal and injury collisions)

And the different environment condition types considered in the analysis are:

1. Total
2. Precipitation

Precipitation form is determined by the temperature profile of the atmosphere (Hambly, 2011). It falls in liquid form such as rainfall, if the temperature is well above zero degree Celsius near and at the surface of the earth, whereas it falls in frozen form such as snowfall, if the temperature is well below zero degree Celsius. The analysis based only on rainfall conditions was conducted for consistency. However, given the small sample size of the rainfall (42 total collisions and 6 injury collisions in the before period, and 54 total collisions and 2 injury collisions in the after period at combined five roundabouts), it is not surprising that it cannot yield a good estimate. Thus, the sample size is extended to all precipitation, in this case, including rainfall, snowfall and frozen precipitation.

Table 3-13 and Table 3-14 provide details of treated signalized intersections in all environment conditions and rain/snow conditions respectively. In addition, Table 3-15 demonstrates the summary statistics for the study intersections.

Table 3-13 Details of treated intersections which were previously signal-controlled with four legs and double lanes in all environment conditions (N=5)

STREET_1	STREET_2	MUN	Year opened	Phase				Crash count			
				AADT		Months		Before		After	
				Before	After	Before	After	All	Injury	All	Injury
SAWMILL RD	ARTHUR ST	WOO	2006	27691	25244	48	84	48	19	127	10
HOMER WATSON BLVD	Block Line Rd	KIT	2011	34822	36062	72	36	65	12	232	24
LANCASTER ST/Carisbrook Dr	BRIDGE ST	KIT	2009	24936	24929	72	60	48	14	46	7
FOUNTAIN ST	DICKIE SETTLEMENT RD/Conestoga College Access	CAM	2010	15289	18951	72	48	26	5	56	3
HESPELER RD	Beaverdale Rd/Queen St	CAM	2013	29399	34822	60	15	41	9	80	6
Combined Roundabouts (N=5)				26427	28001	324	243	228	59	541	50
Note: WOO = Waterloo, KIT = Kitchener, CAM = Cambridge											

Table 3-14 Details of treated intersections which were previously signal-controlled with four legs and double lanes in precipitation conditions (N=5)

STREET_1	STREET_2	MUN	Year opened	Phase				Crash count			
				AADT		Months		Before		After	
				Before	After	Before	After	All	Injury	All	Injury
SAWMILL RD	ARTHUR ST	WOO	2006	27691	25244	48	84	9	1	12	1
HOMER WATSON BLVD	Block Line Rd	KIT	2011	34822	36062	72	36	21	3	27	1
LANCASTER ST/Carisbrook Dr	BRIDGE ST	KIT	2009	24936	24929	72	60	11	2	12	2
FOUNTAIN ST	DICKIE SETTLEMENT RD/Conestoga College Access	CAM	2010	15289	18951	72	48	10	1	4	0
HESPELER RD	Beaverdale Rd/Queen St	CAM	2013	29399	34822	60	15	6	2	16	0
Combined Roundabouts (N=5)				26427	28001	324	243	57	9	71	4
Note: WOO = Waterloo, KIT = Kitchener, CAM = Cambridge											

Table 3-15 Summary of treated intersections (N=5)

Environment conditions	Period	All severity				Fatal + Injury severity			
		Max	Min	Mean	Sum	Max	Min	Mean	Sum
Total	Before	65	26	45.6	228	19	5	11.8	59
	After	232	46	108.2	541	24	3	10.0	50
Precipitation	Before	21	6	11.4	57	3	1	1.8	9
	After	27	4	14.2	71	2	0	0.8	4
		Max		Min		Mean		Sum	
AADT	Before	34822		15289		26427		132136	
	After	36062		18951		28001		140007	
Number of months	Before	72		48		64.8		324	
	After	84		15		48.6		243	

In terms of environmental conditions, the mean number of crashes before and after are 45.6 and 108.2 and the mean numbers of injury crashes are 11.8 and 10 per roundabout for the before and after period respectively. In terms of rain or snow conditions, the mean numbers of crashes are 11.4 and 14.2 and the

mean numbers of injury crashes are 1.8 and 0.8 per roundabout for the before and after period respectively.

3.3.1.2 Summary statistics of data for reference population

As shown in Table 3-16, the percentage changes for 5 converted roundabouts estimated by the Naïve before-after method are larger than them of the EB method. The Naïve before-after approach magnifies the effects of the conversion, because crash rates could be affected by the RTM or any changes in other external factors. That is to say, the number of collisions at an entity before the treatment may be not a good estimate for forecasting the anticipated number of collisions that would occur at this entity in the after period had treatment not been implemented.

Table 3-16 Comparison between the Naïve before-after study and EB method

GEO_ID	Naïve Before-after Study		EB Before-after Study	
	Percentage reduction for total collisions	STD	Percentage reduction for total collisions	STD
2711	-49%	21%	-21%	20%
10941	-593%	126%	-506%	82%
13116	-12%	24%	-7%	21%
16327	-205%	79%	-171%	60%
19457	-611%	215%	-447%	98%

In order to appropriately account for the RTM bias while normalizing for dissimilarities in traffic volume between the periods before and after the conversion, the safety performance of roundabouts will be estimated by using historical collision records at treated intersections along with the collision data at intersections with similar traits (similar in terms of traffic volume, number of lanes, and number of legs).

After comparing the configuration of treated intersections and other nearby intersections via Google Maps and having several on-site investigations, 25 intersections in the Region of Waterloo were matched. Of the 25 intersections, 20 are signalized intersections that have similar characteristics to treated roundabouts (For relative risk analysis, there are 22 signalized intersections. For, safety effect of the conversion, two three-legs signalized intersections are removed from the dataset, so there are 20 signalized intersections), and they are compiled as the reference population for the treated intersections in the Region of Waterloo (Appendix D).

The collision data at signalized intersections in the reference group used for the calibration process were also obtained from the Waterloo Region, including similar information to treated intersections such as collision location, date and time, environment condition, light condition, road surface condition, injury severity level, vehicle type, initial impact type, vehicle damage, and sequence of events, etc. The data consisted of 13 years of crash counts from 2002 to 2014. Table 3-17 provides the summary statistics of these data used in calibrating SPFs.

Table 3-17 Details of the data set used to calibrate the regression model (N=20)

			All severity				Fatal + Injury severity			
	Environment conditions	Jurisdiction	Max	Min	Mean	Sum	Max	Min	Mean	Sum
Collisions	Total	Total	51	0	13.3	3468	14	0	3.3	858
		Waterloo	21	0	8.6	559	6	0	1.9	122
		Kitchener	51	0	14.8	1543	14	0	3.9	403
		Cambridge	37	0	15.0	1366	13	0	3.7	333
	Precipitation	Total	13	0	3.0	792	4	0	0.7	171
		Waterloo	11	0	2.2	144	3	0	0.4	29
		Kitchener	10	0	3.4	351	4	0	0.8	80
		Cambridge	13	0	3.3	297	4	0	0.7	62
Traffic Volume	Jurisdiction	# of intersections	# of years	AADT						
				Max	Min	Mean				
	Total	20	13	78190	5724	34214.4				
	Waterloo	5	13	47014	12439	29800.3				
	Kitchener	8	13	69288	5724	32999.5				
	Cambridge	7	13	78190	16525	38755.8				

Of the 20 signalized intersections in the reference group, five are located in the City of Waterloo, eight in the City of Kitchener, and seven in the City of Cambridge. The mean numbers of crashes are 13.3 and 3.0 and the mean numbers of injury crashes are 3.3 and 0.7 per roundabout for the total and rain/snow environment conditions over the 13-years study period respectively.

3.3.2 Empirical Bayes approach

As mentioned in literature review, the EB procedure can be used to estimate the change in the expected crash frequency of converting an intersection to a roundabout and provide a measureable tool for

designers and city planners (Hauer, 1997; Hauer et al., 2002; Persaud et al., 2010). The procedure has some notable advantages. First, it appropriately accounts for RTM bias. Second, it increases the level of certainty when the safety effect is estimated. Third, it solves the problem of the volume differences between the before and after period by using crash rates to do the normalization (Hauer, 1997).

3.3.2.1 Calibrated safety performance functions

In the EB approach, the calibrated SPF is able to account for the RTM and the difference between traffic volumes (Hauer, 1997; Persaud et al., 2012). It also can be combined with the observed crash frequencies to predict a refined expected crash frequency for a treated site.

In this study, a SPF model at intersection level can be used to estimate the expected average number of collisions each year of the before period would have at intersections that share similar traffic volumes and other features to a treated roundabout being analyzed which was converted from an existing signalized intersection. In addition, the SPF allows the evaluation of the safety performance of an existing roundabout relative to that of other intersections with similar characters.

A variety of models with different parameter values are discussed in the literature review. According to prior studies, two types of safety performance models are most commonly used for the estimation of anticipated number of collisions at signalized intersections (Bonneson et al., 1993; Persaud and Nguyen, 1998; Persaud et al., 2001; Persaud et al., 2012).

Level 1:

$$\text{\# of crashes per year} = \alpha \times (total\ entering\ AADT)^{\beta} \tag{3.15}$$

Level 2:

$$\text{\# of crashes per year} = \alpha \times (total\ entering\ AADT)^{\beta 1} \times (minor\ road\ proportion\ of\ AADT)^{\beta 2} \tag{3.16}$$

In general, Level 2 model is preferable if entering AADTs are available for each approach. However, due to the lack of existing data, entering AADTs were only available for the intersection as a whole not for each approach. Although the second model can produce better estimates, in this research, the model to predict the annual number of expected crashes for signalized intersections was of the following form:

$$\text{Number of crashes per year} = \alpha \times (total\ entering\ AADT)^{\beta}$$

Where AADT is the annual average daily traffic, and ‘α’ and ‘β’ are two parameters need to be estimated.

The local safety performance model is recalibrated and the value of these two parameters are estimated using data in the reference group that are able to represent treated sites, including dependent variables as AADT of each signal-controlled intersection, total number of crashes and the number of casualty crashes for each year of the year 2002 to 2014.

It should be noted that because estimated variable parameters for a SPF based on a certain crash type can be relatively different from those for a SPF based on all types of crashes, SPFs had better apply to each individual evaluated crash type (Persaud et al., 2012). Thus, SPFs are developed for two types of crash severity (total, casualty) in two conditions (total and rain/snow). Following suggestions of previous works by Hauer (1997), the statistical software for generalized linear modeling, R, was used for estimating the parameter 'α' and 'β' for all crashes and injury crashes in the equations. Since a log-link function is used, the outputs of parameters are given in the form of ln(α) and 'β'.

Table 3-18, Table 3-19 and Table 3-20 list parameter estimates with their standard errors, over-dispersion parameters, R-squared values, and P-values for total collision models, casualty collision models, and total collisions during rainy or snowy days.

Table 3-18 SPF's parameters for 4-legged signalized intersections based on Total entering AADT and total collisions

Model form: # of crashes per year = α x (total entering AADT) $^{\beta}$							
Year	Ln (α)	Standard error	β	Standard error	k	R^2	P
2002	-12.631	2.86	1.436	0.28	1.95	0.60	6.19E-05
2003	-11.949	1.93	1.374	0.19	2.10	0.75	7.68E-07
2004	-10.959	2.09	1.280	0.20	3.21	0.69	5.59E-06
2005	-9.313	3.00	1.102	0.29	4.45	0.45	1.24E-03
2006	-8.024	1.90	1.003	0.18	5.72	0.62	3.36E-05
2007	-5.541	2.79	0.781	0.27	10.02	0.32	9.88E-03
2008	-8.013	2.76	1.023	0.27	6.24	0.44	1.38E-03
2009	-7.551	2.07	0.974	0.20	6.62	0.57	1.25E-04
2010	-13.934	1.88	1.591	0.18	2.84	0.81	6.29E-08
2011	-11.350	2.22	1.343	0.22	3.62	0.68	6.87E-06
2012	-11.903	2.34	1.388	0.23	3.65	0.68	8.13E-06

Year	Ln (α)	Standard error	β	Standard error	k	R^2	P
2013	-12.743	2.19	1.476	0.21	3.92	0.73	1.53E-06
2014	-14.350	2.92	1.627	0.28	4.02	0.65	1.70E-05
Average			1.260		4.49		

Table 3-19 SPF's parameters for 4-legged signalized intersections based on Total entering AADT and casualty collisions

Model form: # of crashes per year = α x (total entering AADT) $^{\beta}$							
Year	Ln (α)	Standard error	β	Standard error	k	R^2	P
2002	-10.348	2.18	1.113	0.21	3.04	0.61	5.06E-05
2003	-7.267	1.35	0.811	0.13	5.34	0.68	6.98E-06
2004	-8.821	2.29	0.967	0.22	5.08	0.52	3.54E-04
2005	-7.380	2.27	0.823	0.22	7.19	0.44	1.42E-03
2006	-5.677	2.30	0.661	0.22	11.39	0.33	7.93E-03
2007	-3.520	3.27	0.468	0.32	24.80	0.11	1.59E-01
2008	-9.178	3.95	1.009	0.39	6.40	0.27	1.78E-02
2009	-6.608	2.57	0.770	0.25	10.21	0.35	6.20E-03
2010	-6.338	2.86	0.749	0.28	12.05	0.29	1.42E-02
2011	-11.148	2.67	1.199	0.26	4.50	0.55	1.99E-04
2012	-6.350	3.99	0.726	0.38	12.65	0.17	7.52E-02
2013	-10.816	3.89	1.177	0.37	6.15	0.36	5.57E-03
2014	-12.490	3.39	1.320	0.33	5.92	0.48	7.51E-04
Average			0.910		8.82		

Table 3-20 SPF's parameters for 4-legged signalized intersections in precipitation condition based on Total entering AADT and total collisions

Model form: # of crashes per year = α x (total entering AADT) $^{\beta}$							
Year	Ln (α)	Standard error	β	Standard error	k	R^2	P
2002	-8.820	2.19	0.958	0.21	3.97	0.53	2.66E-04
2003	-6.137	2.32	0.697	0.22	7.03	0.35	6.00E-03
2004	-7.672	2.33	0.852	0.23	6.28	0.44	1.35E-03
2005	-7.608	2.41	0.820	0.23	7.24	0.41	2.36E-03
2006	-6.232	3.12	0.713	0.30	10.03	0.24	2.91E-02
2007	-6.419	2.64	0.743	0.26	10.91	0.32	9.52E-03
2008	-7.091	3.34	0.827	0.33	9.31	0.26	2.10E-02
2009	-6.967	2.97	0.787	0.29	9.79	0.30	1.33E-02
2010	-9.458	3.48	1.044	0.34	6.41	0.35	6.16E-03
2011	-9.425	2.31	1.041	0.22	5.91	0.55	1.96E-04
2012	-9.630	2.98	1.033	0.29	6.44	0.42	2.08E-03
2013	-4.388	2.76	0.553	0.27	27.40	0.19	5.16E-02
2014	-5.536	3.21	0.649	0.31	22.86	0.20	4.95E-02
Average			0.824		10.28		

Because the standard errors of ln(α)s and βs are reasonably small, the statistical significances of them are recognized. Following Hauer's (1997) study, the value of over-dispersion parameter (k) indicates the relative accuracy of models. Recently, in the before-after studies, it is preferred as a better measurement of the goodness of fit than the conventional R-squared measure. k is calculated as $\frac{(P)^2}{VAR\{P\}}$, where P represents the expected annual counts of collisions that would happened at intersections with similar characteristics to treated sites. The greater the value of k, the smaller the variance and the better the goodness of fit. Generally, R-squared values are satisfactory for total collisions. For casualty collisions and total collisions during days with precipitation, although R-squared values are relatively lower, they are still tolerable. As shown in the model calibration results for total collisions, all p-values are much less than the common significance level of 0.05, which indicates that it is statistically significant. In other two conditions, most p-values are still much less than 0.05. In a word, the results from Table 3-18 to 3-20

suggest that the goodness of estimation values shown for models are reasonable. The only one notable exceptions are the model for casualty collision taken place in rain or snow, which the number of observed collisions is too small, so it is excluded from the study.

3.3.3 Empirical Bayes analysis

In general, the change in safety measurement for a given crash-severity type at a selected intersection is calculated by

$$\pi - \lambda, \tag{3.17}$$

where π is the anticipated number of collisions which would have taken place at the treated intersection in the after period but the conversion had not been implemented and λ is the actual number of collisions recorded in the collision reports during the after period (Persaud and Nguyen, 1998; Persaud et al., 2011; Pesaud et al., 2010; Persaud et al., 2012; Retting et al., 2001).

It is worth noting that the count of crashes in the period before the treatment is not a good estimate of π because of the changes in traffic volume, in safety that may be caused by RTM, and in other temporal factors (Persaud et al., 2001). Most conventional methods, such as the naïve before-after method and the comparison-group method, use only the collision counts to estimate the safety performance. Unlike them, instead, the EB procedure estimates π using both historical collision information of this treated entity and the expected number of collisions at similar conventional intersections that share a similar set of characteristics. More specifically, the procedure predicts π by combining the estimates of the expected annual number of crashes ($E\{\kappa i,y\}$) that would have occurred at an intersection similar to a treated site and the count of the observed crashes (K) during the before period (Hauer, 1997).

The step details of the EB analysis followed by Hauer's (1997) research is given below. This procedure estimates $E\{\kappa i,y\}$ from the process of regression calibration in the previous section, and obtain K directly from the collision data. The estimation of the anticipated annual number of crashes ($E\{\kappa|K\}$) at a treated entity in the before period takes the following form

$$E\{\kappa|K\} = \alpha E\{\kappa\} + (1-\alpha)K\,, \tag{3.18}$$

where the weight α is related to the mean and variance are estimated as

$$\alpha = \frac{1}{1+r\frac{VAR\{\kappa\}}{E\{\kappa\}}}\,, \tag{3.19}$$

where r is ratio of the number of year to which K refers to the number of years to which κ refers.

If κi,y represents the anticipated number of collisions per year for site 'i' in year 'y', it should not be assumed that the κ keeps the same value over time (Hauer, 1997). Therefore, a rule is expected as:

$$\frac{\kappa_{i,y}}{\kappa_{i,1}} = C_{i,y} \tag{3.20}$$

Actually, the fundamental assumption of this rule is that the change in the covariates over time is able to effectively reflect the change of the κ of a treated site. Then, the expected number of collisions of the treated site 'i' in year 'y', which can be expressed as κi,y, is estimated as:

$$\hat{\kappa}_{i,1} = \frac{\hat{b}+\sum_{y=1}^{Y} \mathrm{K}_{i,y}}{\frac{\hat{b}}{\hat{E}\{\kappa_{i,1}\}}+\sum_{y=1}^{Y} \hat{\mathrm{C}}_{i,y}} \tag{3.21}$$

and

$$VAR\{\hat{\kappa}_{i,1}\} = \frac{\hat{b}+\sum_{y=1}^{Y} \mathrm{K}_{i,y}}{\left(\frac{\hat{b}}{\hat{E}\{\kappa_{i,1}\}}+\sum_{y=1}^{Y} \hat{\mathrm{C}}_{i,y}\right)^2} = \frac{\hat{\kappa}_{i,1}}{\left(\frac{\hat{b}}{\hat{E}\{\kappa_{i,1}\}}+\sum_{y=1}^{Y} \hat{\mathrm{C}}_{i,y}\right)^2}. \tag{3.22}$$

As mentioned in the section of literature review, $b = \frac{(\mathrm{E}\{\kappa\})^2}{\mathrm{VAR}\{\kappa\}}$. In addition, $\widehat{\ }$ means that the value under is an estimate value.

Following the assumption above, an equation can be written as:

$$\frac{\hat{\kappa}_{i,y}}{\hat{\kappa}_{i,1}} = \hat{C}_{i,y} \text{ and } \widehat{VAR}\{\hat{\kappa}_{i,y}\} = \hat{\mathrm{C}}_{i,y}{}^2 \times \widehat{VAR}\{\hat{\kappa}_{i,1}\} \tag{3.23}$$

A similar approach can be implemented for the years in the after period (if the treatment is applied on year Y, years after can be expressed as Y+1, Y+2, Y+3…). That is to say, for y which is greater than Y,

$$\frac{\hat{\kappa}_{i,y}}{\hat{\kappa}_{i,1}} = \hat{C}_{i,y} \text{ and } \widehat{VAR}\{\hat{\kappa}_{i,y}\} = \hat{\mathrm{C}}_{i,y}{}^2 \times \widehat{VAR}\{\hat{\kappa}_{i,1}\} \tag{3.24}$$

Table 3-21 summarizes values calculated from the equations demonstrated above for each entity per year in three conditions. Finally, an estimate of π, the anticipated number of collisions that would have occurred after the conversion but without the treatment, at each entity was obtained.

Table 3-21 Computation of values for total collisions, casualty collisions, and total collisions during days with precipitation

		Total crashes							Fatal and injury crahes							Total crashes during rainfall or snowfall						
2711																						
YEAR	**AADT**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**
2002	25477	18	6.93	1.00			10.40	1.47	8	2.57	1.00			3.94	0.84	2	2.46	1.00			2.23	0.62
2003	25987	15	7.53	1.09			11.31	1.60	4	2.67	1.04			4.08	0.87	3	2.58	1.05			2.34	0.65
2004	29357	6	9.08	1.31			13.64	1.93	2	3.10	1.20			4.74	1.01	2	2.98	1.21			2.70	0.75
2005	29944	9	7.77	1.12	48.00	4.52	11.66	1.65	5	3.02	1.17	19.00	4.41	4.62	0.98	2	2.32	0.94	9.00	4.20	2.10	0.58
2006																						
2007	23095	17	10.02	1.45			15.05	2.13	3	3.25	1.26			4.97	1.06	2	2.86	1.16			2.59	0.72
2008	21833	16	9.06	1.31			13.60	1.92	1	2.47	0.96			3.78	0.80	2	3.23	1.31			2.93	0.81
2009	25562	7	10.32	1.49			15.50	2.19	1	3.33	1.29			5.10	1.09	0	2.79	1.13			2.52	0.70
2010	24090	26	8.33	1.20			12.51	1.77	2	3.38	1.31			5.18	1.10	2	2.92	1.18			2.64	0.73
2011	28204	22	11.16	1.61			16.76	2.37	1	3.11	1.21			4.76	1.01	2	3.45	1.40			3.13	0.87
2012	28345	20	10.22	1.47			15.34	2.17	2	2.99	1.16			4.57	0.97	3	2.62	1.06			2.37	0.66
2013	25578	19	9.32	1.35			14.00	1.98	0	3.10	1.20			4.74	1.01	1	3.41	1.38			3.09	0.86
							π	**σ{π}**						**π**	**σ{π}**						**π**	**σ{π}**
							102.76	14.54						33.10	7.05						19.28	5.35
10941																						
YEAR	**AADT**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**
2005	35143	10	9.26	1.00			7.81	0.94	2	3.44	1.00			2.17	0.50	3	2.64	1.00			2.52	0.47
2006	35846	5	12.10	1.31			10.20	1.22	1	3.51	1.02			2.21	0.50	2	3.46	1.31			3.30	0.62
2007	36563	12	14.34	1.55			12.09	1.45	0	4.03	1.17			2.54	0.58	5	4.02	1.52			3.83	0.72
2008	31650	13	13.24	1.43			11.16	1.34	2	3.59	1.04			2.26	0.52	4	4.39	1.66			4.19	0.79
2009	34690	9	13.90	1.50			11.71	1.41	3	4.22	1.22			2.66	0.61	4	3.54	1.34			3.38	0.64
2010	35037	16	15.12	1.63	65.00	8.42	12.74	1.53	4	4.48	1.30	12.00	6.76	2.82	0.64	3	4.31	1.63	21.00	8.47	4.11	0.77
2011																						
2012	37495	53	15.06	1.63			12.69	1.52	3	3.66	1.06			2.31	0.53	6	3.50	1.32			3.34	0.63
2013	35084	72	14.86	1.60			12.52	1.50	8	4.49	1.30			2.83	0.65	9	4.06	1.54			3.87	0.73
2014	35606	107	14.85	1.60			12.51	1.50	13	3.84	1.11			2.42	0.55	12	3.54	1.34			3.37	0.63
							π	**σ{π}**						**π**	**σ{π}**						**π**	**σ{π}**
							37.73	4.53						7.55	1.72						10.58	1.99
13116																						
YEAR	**AADT**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**
2003	28413	4	8.51	1.00			8.16	1.15	1	2.87	1.00			2.51	0.57	0	2.75	1.00			2.14	0.50
2004	25679	10	7.65	0.90			7.34	1.04	3	2.72	0.95			2.39	0.54	2	2.66	0.97			2.06	0.49
2005	26193	6	6.70	0.79			6.43	0.91	2	2.70	0.94			2.37	0.54	4	2.08	0.75			1.61	0.38
2006	26717	8	9.01	1.06			8.64	1.22	3	2.89	1.01			2.53	0.58	3	2.81	1.02			2.18	0.51
2007	21096	14	9.34	1.10			8.95	1.26	3	3.11	1.09			2.73	0.62	2	2.67	0.97			2.08	0.49
2008	21518	6	8.92	1.05	48.00	5.89	8.56	1.21	2	2.43	0.85	14.00	5.83	2.13	0.48	0	3.19	1.16	11.00	5.87	2.48	0.58
2009																						
2010	23086	9	7.79	0.91			7.47	1.06	0	3.28	1.14			2.87	0.65	0	2.79	1.01			2.17	0.51
2011	24581	9	9.28	1.09			8.90	1.26	2	2.64	0.92			2.31	0.53	5	2.99	1.09			2.33	0.55
2012	24827	13	8.50	1.00			8.15	1.15	2	2.71	0.95			2.38	0.54	4	2.28	0.83			1.78	0.42
2013	27266	10	10.24	1.20			9.82	1.39	2	3.34	1.16			2.92	0.66	0	3.53	1.28			2.75	0.65
2014	24887	5	8.29	0.97			7.95	1.12	1	2.39	0.83			2.09	0.48	3	2.80	1.02			2.18	0.51
							π	**σ{π}**						**π**	**σ{π}**						**π**	**σ{π}**
							42.29	5.97						12.58	2.86						11.20	2.64
16327																						
YEAR	**AADT**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**
2004	15691	0	4.07	1.00			3.36	0.62	0	1.69	1.00			1.00	0.32	0	1.75	1.00			1.63	0.40
2005	16234	7	3.95	0.97			3.26	0.60	1	1.82	1.08			1.08	0.34	3	1.40	0.80			1.31	0.32
2006	16559	3	5.58	1.37			4.60	0.85	1	2.11	1.25			1.25	0.39	2	2.00	1.14			1.87	0.46
2007	16890	4	7.85	1.93			6.46	1.20	1	2.81	1.66			1.66	0.52	2	2.26	1.30			2.11	0.52
2008	11866	6	4.86	1.19			4.00	0.74	1	1.33	0.79			0.79	0.25	1	1.95	1.12			1.82	0.45
2009	14491	6	5.94	1.46	26.00	7.91	4.89	0.91	1	2.15	1.27	5.00	7.05	1.28	0.40	2	1.78	1.02	10.00	6.38	1.66	0.41
2010																						
2011	14782	12	4.68	1.15			3.86	0.71	0	1.43	0.85			0.85	0.27	1	1.76	1.01			1.65	0.41
2012	14930	11	4.20	1.03			3.46	0.64	2	1.88	1.11			1.11	0.35	1	1.35	0.77			1.26	0.31
2013	24685	22	8.85	2.17			7.29	1.35	1	2.97	1.76			1.76	0.55	2	3.34	1.92			3.12	0.77
2014	21407	11	6.49	1.59			5.35	0.99	0	1.96	1.16			1.16	0.37	0	2.54	1.46			2.38	0.59
							π	**σ{π}**						**π**	**σ{π}**						**π**	**σ{π}**
							19.95	3.69						4.89	1.54						8.41	2.08
19457																						
YEAR	**AADT**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**	**Ki,y**	**E(κi,y)**	**Ĉi,y**	**∑Ki,y**	**ΣĈi,y**	**κi,y**	**σ{κi,y}**
2008	25360	16	10.55	1.00			7.70	1.12	3	2.87	1.00			1.87	0.48	0	3.66	1.00			2.12	0.54
2009	29956	6	12.05	1.14			8.79	1.28	1	3.77	1.31			2.45	0.62	2	3.16	0.86			1.83	0.47
2010	30256	5	11.98	1.13			8.74	1.27	1	4.01	1.40			2.61	0.67	1	3.70	1.01			2.14	0.55
2011	30559	5	12.43	1.18			9.07	1.32	2	3.42	1.19			2.23	0.57	1	3.75	1.03			2.17	0.56
2012	30865	9	11.50	1.09	41.00	5.54	8.39	1.22	2	3.18	1.11	9.00	6.01	2.07	0.53	2	2.86	0.78	6.00	4.68	1.66	0.42
2013	31781	17	12.84	0.30			2.34	0.34	0	4.00	0.35			0.65	0.17	3	3.84	0.26			0.56	0.14
2014	37862	63	16.41	1.55			11.98	1.74	6	4.16	1.45			2.71	0.69	13	3.68	1.01			2.13	0.54
							π	**σ{π}**						**π**	**σ{π}**						**π**	**σ{π}**
							14.32	2.08						3.36	0.86						2.69	0.69

After that, the estimates of π and VAR{ π} are summed over all converted intersections and compared with the actual count of crashes occurred at these roundabouts during the after period. Based on an assumption that the variance of λ follows Poisson distribution, it was given by Var (λ) = λ.

There are two ways to estimate safety effect: 'reduction in expected number of crashes' and 'index of effectiveness' (Hauer, 1997).

The first method, the reduction in anticipated number of crashes (δ), represents the dissimilarity between the sums of the κi and Ki over all converted intersections in the after period, which is given by $\delta=\pi-\lambda$, where $\pi=\sum \kappa i$ and $\lambda=\sum Ki$.

The second method, index of effectiveness, can be estimated as $\theta = \lambda/\pi$, and the standard deviation of θ is calculated by

$$\sigma(\theta)=\sqrt{\theta^2\{[Var(\lambda)/\lambda^2] + [Var(\pi)/\pi^2]\}/[1+Var(\pi)/\pi^2]^2} \quad (3.25)$$

The θ is about equal to the ratio of the total number of crashes occurring at all sites in a treatment group after conversion to the anticipated total number that the conversion had not taken place. The treatment is effective if θ is less than 1. Conversely, it is risky if θ is greater than 1. The percent change of the expected collision can be expressed as 100(1- θ).

Chapter 4 Results

4.1 Collisions characteristics

Table 4-1 examines collision characteristics and provides additional insight into the rainfall-related crash risk in section 4.2. The percentage of collisions occurred at roundabouts and signalized intersections in all collisions and those during rainfall are categorized by the characteristics of collisions. Be aware that the values in the table refer to collisions that occurred during the whole study period from 2005 to 2015, not just those occurred in matched pairs.

Table 4-1 Weather conditions as identified in collision reports, 2005-2015

Characteristics of collision	Roundabouts (N=23*)		Signalized intersections (N=22)	
	All collisions (%)	Raining (%)	All collisions (%)	Raining (%)
Season of year				
Spring (Mar – May)	21.9	15.5	21.4	18.2
Summer (Jun – Aug)	22.7	35.9	21.4	38.3
Autumn (Sep – Nov)	31.4	44.8	27.4	41.0
Winter (Dec – Feb)	24.0	3.8	29.7	2.5
Day of week				
Monday	13.8	10.0	14.9	13.0
Tuesday	15.7	16.2	16.0	14.8
Wednesday	14.2	18.6	15.7	16.9
Thursday	16.9	20.0	16.7	19.0
Friday	17.9	16.6	16.9	15.2
Saturday	13.3	12.4	11.7	12.7
Sunday	8.4	6.2	8.0	8.2
Time of day				
0:00-5:59 (Late night)	2.4	0.7	2.4	2.2
6:00-9:59 (Morning rush hour)	18.9	17.6	15.3	14.7
10:00-14:59 (Midday)	29.8	31.4	23.4	23.9
15:00-18:59 (Afternoon rush hour)	37.9	38.3	29.3	30.5
19:00-23:59 (Evening)	11.0	12.1	10.8	12.1

Characteristics of collision	Roundabouts (N=23*)		Signalized intersections (N=22)	
	All collisions (%)	Raining (%)	All collisions (%)	Raining (%)
Weather condition*				
Rain	11.4	-	13.8	-
Snow	6.5	-	8.6	-
Frozen precipitation	0.5	-	0.3	-
Visibility limitation	0.7	-	0.5	-
Road surface condition*				
Wet	20.5	34.1	26.2	48.4
Snow, slash, or ice	9.6	0.0	11.9	0.0
Light condition*				
Daylight	80.5	84.5	75.5	80.1
Dawn/dusk	4.1	5.2	5.3	4.6
Darkness	15.3	10.3	19.2	15.3
Initial impact type*				
Angle	30.9	36.9	5.0	3.9
Rear-end	24.5	23.4	52.6	56.2
Sideswipe	18.6	17.9	10.1	7.2
Turning movement	14.9	14.1	26.2	26.5
Classification of collision*				
Fatal	0.0	0.0	0.1	0.0
Non-fatal injury	9.8	10.0	23.8	25.4
PDO	75.3	81.7	52.9	49.3

*Due to the incompleteness of the data, the percentage of these five characteristics of collision were based on the existing data

*Since the opening dates of two roundabouts (GEO_ID 21805 and 15587) are in December 2015 and September 2016 respectively, there are no collisions occurred at these two roundabouts by the end of 2015. Therefore, they are excluded from the analysis.

The seasonal pattern of the collision distribution over the rainy days is somewhat different from the study period for both roundabouts and signalized intersections. Summer and autumn all see a significant increase in the percentages of collision incidence (from 22.7 to 35.9 in summer and from 31.4 to 44.8 in

autumn at roundabouts, and from 21.4 to 38.3 in summer and from 27.4 to 41.0 in autumn at signalized intersections) at both junctions. This is as expected, because summer and autumn have the highest probabilities of rain in Waterloo Region. Conversely, there is a substantial decrease in these percentages in winter (from 24.0 to 3.8 at roundabouts, and from 29.7 to 2.5 at signalized intersections). It is not surprising because of the rare chance of rain. More crashes occur on Tuesday, Wednesday and Thursday, but fewer crashes occur on Monday, Friday, Saturday and Sunday at roundabouts. Comparatively, except for Monday, Tuesday and Friday, others have a higher frequency of collisions at signal-controlled intersections. Time of day distributions are similar between two conditions at both junctions, with fewer collisions occurring during late night and morning rush hours and more collisions occurring from the midday to evening during rainfall.

Given that this table refers to collisions that occurred during the whole study period from 2005 to 2015, as would be expected that, regardless of intersection type, substantially more collisions on wet roads would occur during days with rainfall, whereas the frequency of collisions on roads with snow, slash, or ice would be almost zero. Compared to other weather types, wet road appears more likely during days with rainfall. Rainfall is associated with a slightly increased percentage of crashes in daytime. This is likely indicative of the selection of the travel time. Fewer collisions occurred during darkness at both roundabouts and signalized intersections. Rainfall contributes to more angle collisions at roundabouts, but marginally less rear-end, sideswipe, and turning movement collisions. At signalized intersections, rear-end and turning movement collisions occur at a slightly higher incidence, but angle and sideswipe collisions are decrease during rainfall. All in all, the severity of collisions is similar among three classes for both junctions, but the only exception is that the percentage of PDO collisions during rainfall is higher than that over the whole period at roundabouts but lower during the eleven-year period at signalized intersections.

4.2 Rainfall-related crash risk, 2005-2015

In this section, estimates of the relative crash risks at roundabouts during rainfall in the Region of Waterloo in the period from 2005 to 2015 are presented, along with a comparison to those of 22 nearby signalized intersections. They are produced by a matched-pair research design using historical weather and collisions data obtained from the Environment and Natural Resources historical data of Government of Canada and the Transportation Administration of the Region of Waterloo respectively. In addition, these estimates are discovered for different rainfall intensities, crash severities, and seasons. The analysis is based on the daily level, because six-hourly data are not available.

Recall that 'events', 'rainfall', and 'rain days' all exactly refer to a subgroup of liquid rain with the total precipitation measured no less than 0.2 millimetres in a 24-hour day, and the minimum daily temperature is equal to or higher than one degree Celsius. Thus, all snowfall and winter precipitation are removed.

Altogether, 557 matched pairs (128 pairs that include holidays have been excluded) are produced for the Region of Waterloo study in the matching process (4017 days from 2005 to 2015). They account for 14% of days during the analysis period, and approximately 29 percent and 26 percent of all collisions are included in the pairs at roundabouts and signalized intersections respectively. Table 4-2 demonstrates the sample size for crash risks, including total crashes, casualty crashes (fatal and injury crashes), and PDO crashes.

Table 4-2 Collisions sample size, collision counts, and matched pair results summary, 2005-2015

Severity type	Total for all days	Rainfall days		Matched events collisions		Matched controls collisions		Matched pairs
		Sum	% of total	Sum	% of total	Sum	% of total	% of total
Roundabouts (N=23*)								
Total* **	2196	524	23.9%	329	15.0%	306	13.9%	28.9%
Casualty	216	59	27.3%	39	18.1%	33	15.3%	33.3%
PDO	1653	387	23.4%	243	14.7%	233	14.1%	28.8%
Signalized intersections (N=22)**								
Total* **	4021	958	23.8%	601	14.9%	457	11.4%	26.3%
Casualty	963	243	25.2%	152	15.8%	110	11.4%	27.2%
PDO	2126	472	22.2%	302	14.2%	241	11.3%	25.5%

*Since the opening dates of two roundabouts (GEO_ID 21805 and 15587) are in December 2015 and September 2016 respectively, there are no collisions occurred at these two roundabouts by the end of 2015. Therefore, after excluding these two roundabouts, there are total 21 roundabouts with available collision data in the analysis.

** Nine roundabouts are converted from signalized intersections during the study period. In the analysis, 22 signalized intersections with 11 years' data and nine signalized intersections with incomplete data are included.

**A large amount of the severity of collisions are non-reportable, thus Casualty and PDO do not add up to Total.

The reader is reminded that the relative risk ratios demonstrate the probability of a type of thing happening during one condition to the probability of this happening during another condition. In this study, it indicates the extent to which collision rates are higher (or lower) in rainfall compared to good weather conditions at both roundabouts and signalized intersections. If the risk ratio is greater than 1, the collision risks are higher during rainfall. If it is less than 1, the risks are lower during rainfall. The rates of collisions are the same in rainfall and clear conditions if the ratio is exactly equal to 1.

Results of the rainfall-related collision risk analysis for roundabouts and signalized intersections in the Region of Waterloo for all types of collision severities at daily level are provided in Table 4-3. The estimates of daily relative risk of collisions during rainfall is between 0.90 and 1.17 at roundabouts and between 1.07 and 1.36 at signalized intersections at a 95 percent confidence level. The results indicate that in the case of roundabouts, there is no evidence of a statistically significant increase in crashes on days with rainfall. For signalized intersections, there is evidence of such an increase in crash risk from 7 to 36 percent. This compares reasonably well with previous studies conducted by Andrey et al. (2013a), where rainfall accounts for generally 13 percent increase for total collisions occurred on roads at eight combined Canadian cities at daily level. The relative risk estimated at signalized intersections is 1.21(Table 4-4), which is slightly higher than the estimates predicted by Andrey et al. (2013a). However, it should be noted that, in the analysis produced by Andrey et al. (2013a), rainfall is measured as the precipitation amount is at least 0.4 mm per day. In addition, the analysis is based on collisions on roads. The current analysis enlarged the measurement standard for a rainfall event from 0.4 mm to 0.2 mm precipitation. Also, intersections are widely accepted as the most dangerous locations in the road network, because they have the high potential for conflict. It is not surprising that risk increase is likely to be somewhat higher at intersections than on roads.

Furthermore, at a 95 percent confidence level, the estimates of relative risk for casualty and PDO collisions in rainfall days are between 0.86 and 1.19 and between 0.88 and 1.16 at roundabouts and between 0.94 and 1.27 and between 0.97 and 1.28 at signalized intersections, indicating that there are no statistically significant increases in crashes on days with rainfall for these types of collisions at these forms of intersections.

Table 4-3 Summary of relative risk estimates, 2005-2015 (95% confidence intervals)

Severity Type	Roundabouts	Signalized intersections
Total crashes	0.90-1.17	1.07-1.36
Casualty crashes (Fatal + injury)	0.86-1.19	0.94-1.27
PDO crashes	0.88-1.16	0.97-1.28

Andrey et al. (2013a) also provided results of the safety analysis for rainfall-related risks at six-hourly study period. For injury collisions in Toronto, the result indicating that the estimate rainfall-related collision risk is 1.30, which means that the collision rates are around 30 percent higher over six-hourly event periods relative to six-hourly control periods. Comparatively, there are no statistically significant increases in fatal and injury collisions at signalized intersections on days with rainfall in the Region of Waterloo. The reason might be more percent of dry hours that would affect and dilute the estimates of the risk during a 24-hour period than a six-hour analysis period, so the estimate of relative risk based on daily data is likely to be lower than the estimate calculated over six-hourly study period. In addition, the differences that Andrey et al. (2013a) examined rainfall as the precipitation amount is at least 0.4 mm per day and the analysis is for injury collisions may also associated with a lower estimate.

4.2.1 Breakdown of rainfall-related crash risk by rainfall intensity

Complete daily precipitation information at daily level is included in the historical weather data acquired from Environment Canada. Based on Hambly's (2011) research, the daily rainfall intensity can be generally classified into four categories: very light rain (0.2 to 4.9 mm), light rain (5.0 to 9.9 mm), moderate rain (10.0 to 19.9 mm), and heavy rain (≥ 20.0 mm).

Table 4-4 demonstrates matched event-control pairs, event collisions, and control collisions with different rainfall intensity levels and crash severity types at both roundabouts and signalized intersections, along with the relative risk and its 95 percent confidence interval.

Table 4-4 Summary of relative risk estimates with different rainfall intensities, 2005-2015 (95% confidence intervals)

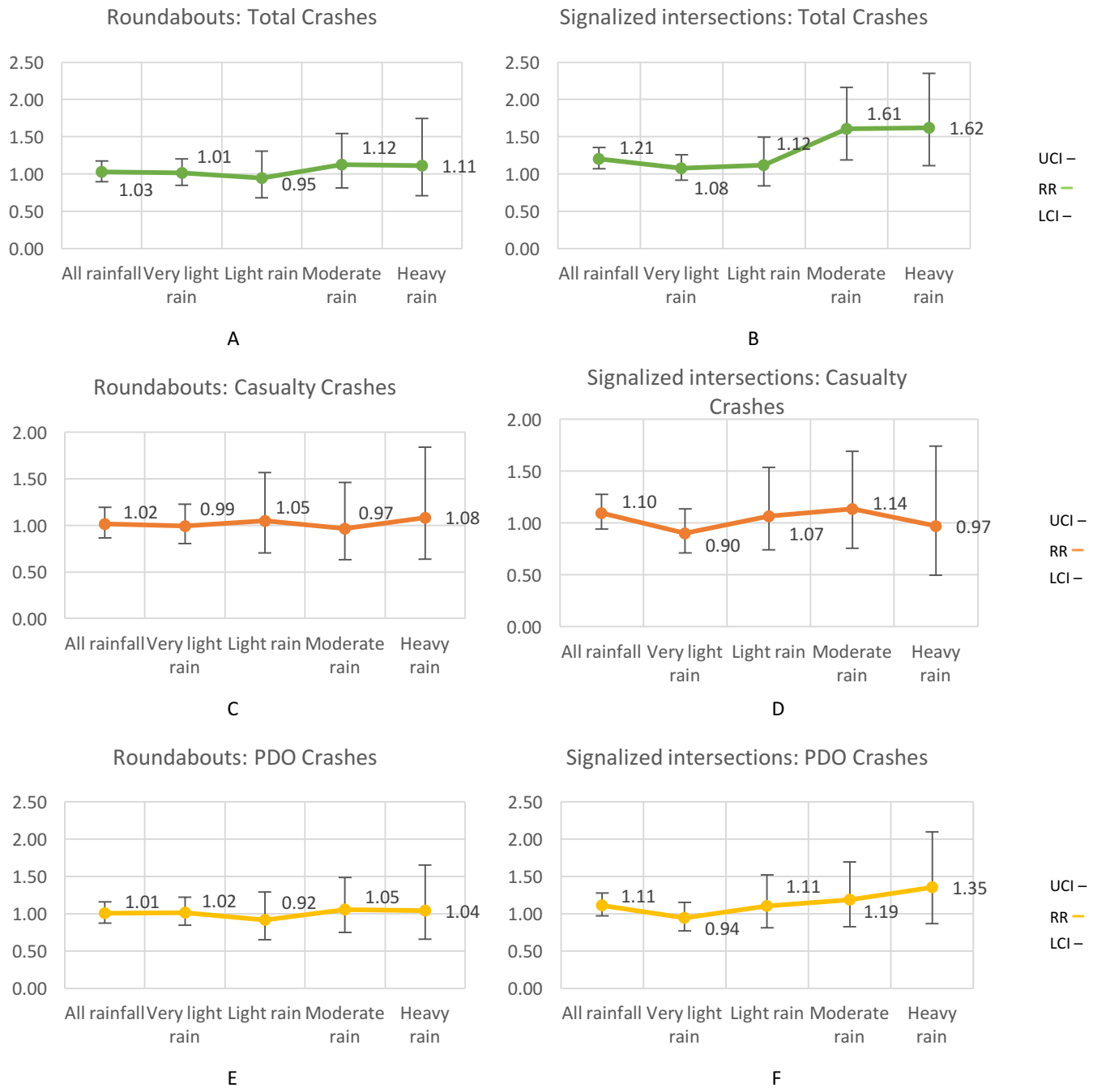
Daily rainfall intensity	Event-control pairs	Event crashes	Control crashes	Total crashes	Event crashes	Control crashes	Casualty crashes (Fatal + injury)	Event crashes	Control crashes	PDO crashes
Roundabouts										
All rainfall	557	329	306	1.03 (0.90-1.17)	39	33	1.02 (0.86-1.19)	243	233	1.01 (0.88-1.16)
0.2 to 4.9 mm (very light)	323	185	178	1.01 (0.85-1.20)	19	20	0.99 (0.80-1.23)	141	134	1.02 (0.85-1.22)
5.0 to 9.9 mm (light)	87	55	57	0.95 (0.68-1.31)	8	6	1.04 (0.69-1.55)	39	44	0.92 (0.65-1.29)
10.0 to 19.9 mm (moderate)	93	64	50	1.12 (0.82-1.55)	9	7	1.03 (0.70-1.53)	43	36	1.05 (0.75-1.48)
≥ 20.0 mm (heavy)	54	25	21	1.11 (0.71-1.75)	3	0	1.09 (0.65-1.85)	20	19	1.04 (0.66-1.65)
Signalized intersections										
All rainfall	557	601	457	1.21 (1.07-1.36)	152	110	1.10 (0.94-1.27)	302	241	1.11 (0.97-1.28)
0.2 to 4.9 mm (very light)	323	313	277	1.08 (0.92-1.26)	81	67	1.06 (0.87-1.29)	157	142	1.06 (0.88-1.27)
5.0 to 9.9 mm (light)	87	102	89	1.12 (0.84-1.50)	21	20	1.02 (0.70-1.49)	55	50	1.06 (0.76-1.47)
10.0 to 19.9 mm (moderate)	93	111	53	1.61 (1.19-2.16)	30	14	1.24 (0.86-1.79)	53	30	1.25 (0.89-1.76)
≥ 20.0 mm (heavy)	54	75	38	1.62 (1.11-2.35)	20	9	1.25 (0.77-2.02)	37	19	1.36 (0.88-2.11)

On the whole, rainfall has no evident effects on roundabout safety, but the risk of total collisions is 7 percent to 36 percent higher at signalized intersections during rainfall at a 95 percent confidence level. Consistent with previous studies, risk increases as precipitation amount increases for collisions at signalized intersections. As shown in Figure 4-1, no statistically significant increases in all crash severities on days with very light rain or light rain. However, the moderate and heavy rain normally see increases in relative risk estimates at signalized intersections. Comparatively, the estimates of the

increases of the severe crash risks are generally less than those of total crashes. They are might be interpreted as that the increased rainfall intensities are coupled with the reduction in visibility and road surface friction (Andrey, 2010). Hence, once the traffic light turns yellow or red, the friction between tire and pavement is lower during rainfall, so the chance of rear-end collisions will increase at signalized intersections. But, drivers tend to be more careful when the weather condition is more hazardous, which leads to some extent of the reduction of crash severity (Hogema, 1996). Given the small sample size of some certain conditions, it should be noted that only the estimates for total collisions at signalized intersections for all rainfall, moderate and heavy rainfall are statistically significant, and there is no evidence of a statistically significant increase in others.

Roundabouts have lower risk estimates for moderate and heavy rainfall than signalized intersections, but are not statistically significant and no patterns can be found at roundabouts. The reason might be that the roundabouts effectively reduce vehicle speed as drivers approaching the entry lane and navigating the intersection (Robinson et al., 2000; Rodegerdts et al., 2010). Generally, the absolute speed of conflicting flows is lower for roundabouts than for signal-controlled intersections (Robinson et al., 2000). Thus, drivers have more time to react to potential conflicts so that the likelihood of a collision decreases, and the relative low speed is able to reduce the severity of a collision. For roundabouts, it appears that they are less affected than signal-controlled intersections under the effect of rainfall, but it is not statistically significant because of the small sample size. The changes of the estimates of the relative risks during days with rainfall are generally less than those of signalized intersections for all types of severity.

It should be noted that the count of collisions for some conditions is insufficient for obtaining robust estimates. This is particularly the case for casualty crashes, and days with large precipitation accumulation. For them, the 95 percent confidence intervals are much greater than 0.1, which indicates that the confidence intervals for the point estimates are relatively broad (Figure 4-1).



Note: UCI = upper confidence interval, LCI = lower confidence interval

Figure 4-1 Daily relative risk estimates with different rainfall intensities, 2005-2015 (95 percent confidence interval)

4.2.2 Breakdown of rainfall-related crash risk by season

In order to explore the seasonal pattern of the rainfall-related crash risk, the estimates of spring, summer, autumn and winter are developed. Table 4-5 shows matched event-control pairs, event collisions, and control collisions in different seasons and crash severity types at roundabouts and signalized intersections, along with the relative risk and its 95 percent confidence interval.

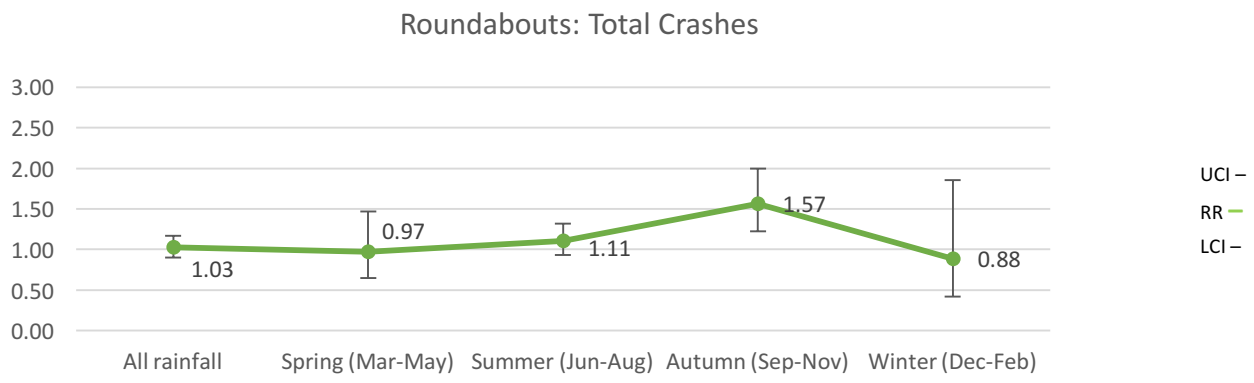
Table 4-5 Summary of relative risk estimates in different seasons, 2005-2015 (95% confidence intervals)

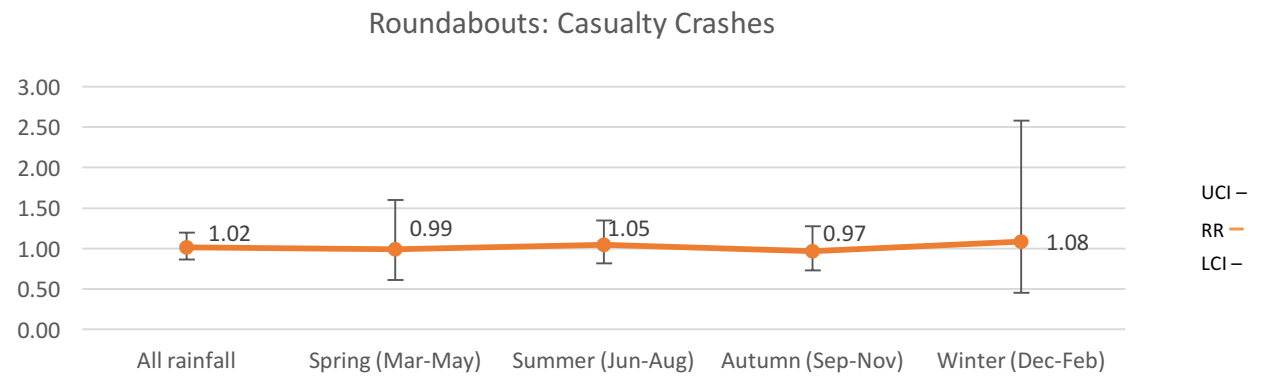
Daily rainfall intensity	Event-control pairs	Event crashes	Control crashes	Total crashes	Event crashes	Control crashes	Casualty crashes (Fatal + injury)	Event crashes	Control crashes	PDO crashes
Roundabouts										
All rainfall	557	329	306	1.03 (0.9-1.17)	39	33	1.02 (0.86-1.19)	243	233	1.01 (0.88-1.16)
Spring (Mar-May)	117	61	68	0.97 (0.65-1.47)	6	4	0.99 (0.62-1.60)	51	52	1.02 (0.67-1.56)
Summer (Jun-Aug)	237	121	98	1.11 (0.93-1.32)	17	9	1.05 (0.82-1.34)	87	77	1.03 (0.83-1.29)
Autumn (Sep-Nov)	184	134	126	1.57 (1.23-2.00)	14	19	0.97 (0.73-1.28)	96	91	1.02 (0.80-1.29)
Winter (Dec-Feb)	19	13	14	0.88 (0.42-1.86)	2	1	1.08 (0.46-2.58)	9	13	0.81 (0.38-1.73)
Signalized intersections										
All rainfall	557	601	457	1.21 (1.07-1.36)	152	110	1.1 (0.94-1.27)	302	241	1.11 (0.97-1.28)
Spring (Mar-May)	117	106	93	0.80 (0.55-1.14)	35	25	0.90 (0.58-1.41)	49	46	0.94 (0.62-1.43)
Summer (Jun-Aug)	237	236	188	1.25 (1.05-1.49)	57	45	1.07 (0.84-1.34)	109	90	1.11 (0.98-1.25)
Autumn (Sep-Nov)	184	241	163	1.31 (1.07-1.60)	57	37	1.14 (0.88-1.48)	132	98	1.19 (1.05-1.34)
Winter (Dec-Feb)	19	18	13	1.29 (0.65-2.54)	3	3	0.97 (0.42-2.26)	12	7	1.35 (0.64-2.84)

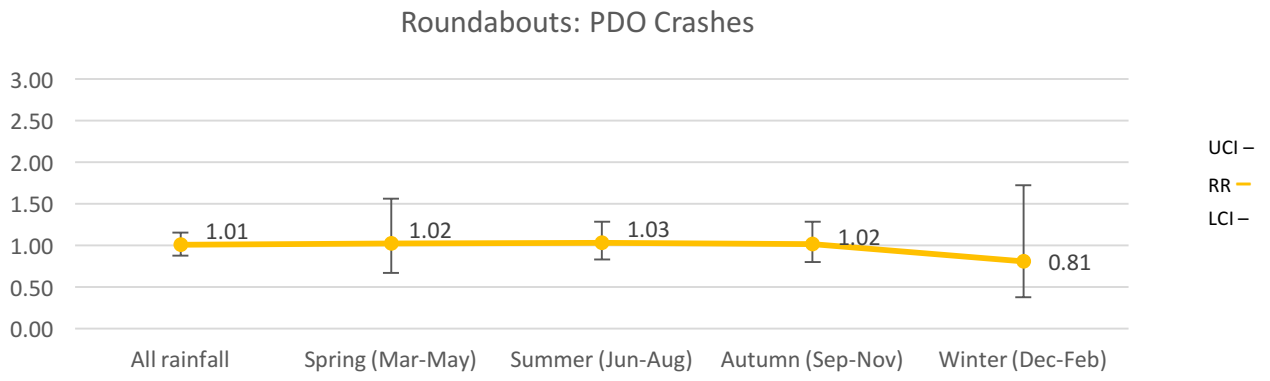
At a 95 percent confidence level, there is a significant increase in relative risk in autumn at both roundabouts and signalized intersections, and in summer only at signal-controlled intersections. Autumn will likely encounter a 57 percent higher risk at roundabouts, while a 31 percent on at signalized intersections. Summer will likely encounter a 25 percent higher risk at signalized intersections. However, it is unclear whether there is any elevation or reduction of relative risk in other cases. The reason might be that the count of collisions for some seasons are very limited.

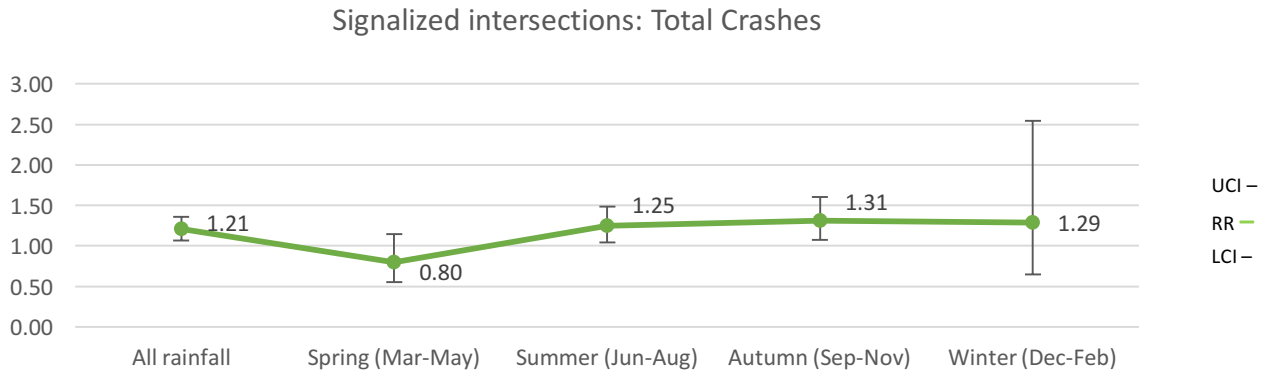
Generally, for both of them, autumn has the highest collision risk estimates, followed closely by summer and winter at roundabouts and signal-controlled intersections respectively (Figure 4-2). Conversely, there is a slight decrease in risk estimates during spring. The estimates of relative risk in winter for these two kinds of intersections are opposite, indicating that the collision risks are higher during rainfall in winter at signalized intersections, whereas they are lower at roundabouts. However, the estimates for all of them, except for summer at signalized intersection and autumn at both intersections, are not statistically significant.

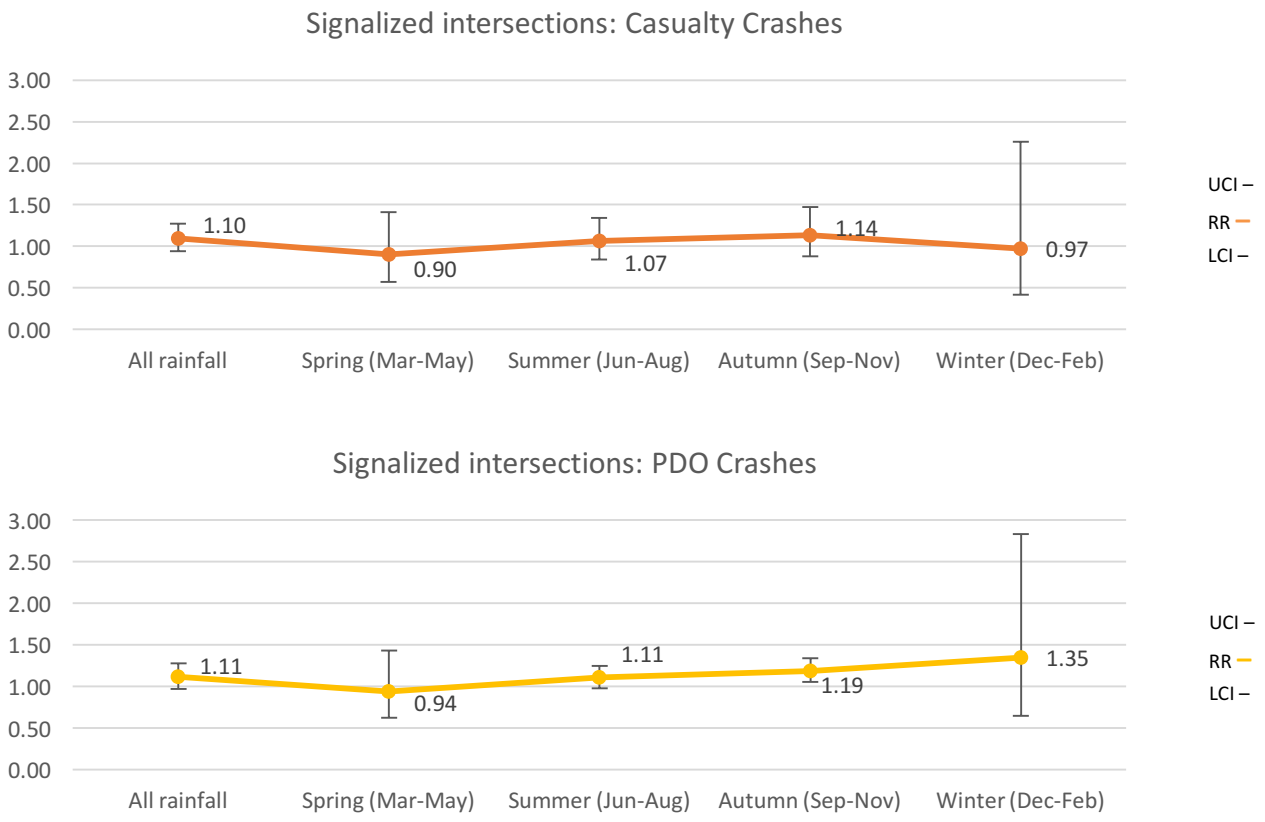
Compared to the results for total collisions, the change in relative risk is not obvious for casualty collisions at both junctions. For PDO crashes, the relative risk of roundabouts has no significant changes, but a slightly higher risk in autumn at signal-controlled intersections is evident.




Roundabouts: Casualty Crashes
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1.02
0.99
1.05
0.97
1.08
All rainfall
Spring (Mar-May)
Summer (Jun-Aug)
Autumn (Sep-Nov)
Winter (Dec-Feb)
UCI –
RR
LCI –


Roundabouts: PDO Crashes
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1.01
1.02
1.03
1.02
0.81
All rainfall
Spring (Mar-May)
Summer (Jun-Aug)
Autumn (Sep-Nov)
Winter (Dec-Feb)
UCI –
RR
LCI –


Signalized intersections: Total Crashes
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1.21
0.80
1.25
1.31
1.29
All rainfall
Spring (Mar-May)
Summer (Jun-Aug)
Autumn (Sep-Nov)
Winter (Dec-Feb)
UCI –
RR
LCI –



Note: UCI = upper confidence interval, LCI = lower confidence interval

Figure 4-2 Daily relative risk estimates in different seasons, 2005-2015 (95 percent confidence interval)

4.3 Safety effect of the conversion

Recall that the second objective for this thesis is to model the overall safety effect of converting signalized intersections to roundabouts, the EB procedure is used to estimate the change in collision frequency expected with a roundabout's implementation at an existing signalized intersection without the RTM bias. Two crash severity types and two environmental conditions are considered in this study.

For the five conversions in the Region of Waterloo, Table 4-6 illustrates the actual count of crashes in the after period, the variance of λ, the estimate of π, and the variance of π in three conditions. To recap, these conditions applied in this study are: total collisions overall, fatal and injury collisions overall, and total collisions during precipitation. GEO_IDs are the ID numbers to which the roundabouts refer, and the name can be found in Table 4-7 later.

Table 4-6 Empirical Bayes estimates for the conversions in the Region of Waterloo

GEO_ID	Total collisions				Casualty collisions (Fatal + Injury)				Total collisions during days with precipitation			
	After period count		EB estimate		After period count		EB estimate		After period count		EB estimate	
	λ	VAR(λ)	π	VAR(π)	λ	VAR(λ)	π	VAR(π)	λ	VAR(λ)	π	VAR(π)
2711	127	127	102.8	211.4	10	10	33.1	49.7	12	12	19.3	28.7
10941	232	232	37.7	20.5	24	24	7.6	3.0	27	27	10.6	4.0
13116	46	46	42.3	35.7	7	7	12.6	8.2	12	12	11.2	7.0
16327	56	56	20.0	13.6	3	3	4.9	2.4	4	4	8.4	4.3
19457	80	80	14.3	4.3	6	6	3.4	0.7	16	16	2.7	0.5
Total	541	541	217.1	285.6	50	50	61.5	64.0	71	71	52.2	44.4

'Reduction in expected number of crashes' and 'index of effectiveness' are two ways for estimating the safety effect. Table 4-7 summarizes the estimated collision change in these two measures of safety effects and Figure 4-3 shows the percentage change for each roundabouts because of the differences between various roundabout settings. They also include the results for five combined roundabouts.

Table 4-7 Estimates of safety effect on treated entities estimated by EB approach for all conditions

Condition	GEO_ID	STREET_1	STREET_2	Reduction	SD	Percentage reduction (%)	SD (%)
Total	2711	Sawmill Rd	Arthur St	-24.2	18.4	-21.2	19.8
	10941	Homer Watson Blvd	Block Line Rd	-194.3	15.9	-506.2	81.7
	13116	Lancaster St /Carisbrook Dr	Bridge St	-3.7	9.0	-6.6	21.3
	16327	Fountain St	Dickie Settlement Rd	-36.1	8.3	-171.4	59.9
	19457	Hespeler Rd	Beaverdale Rd/Queen St	-65.7	9.2	-447.1	98.3
	Total			-324.0	28.8	-147.8	21.9
	Total *			-129.7	24.0	-70.9	18.2

Condition	GEO_ID	STREET_1	STREET_2	Reduction	SD	Percentage reduction (%)	SD (%)
Casualty (Fatal + Injury)	2711	Sawmill Rd	Arthur St	23.1	7.7	71.1	10.5
	10941	Homer Watson Blvd	Block Line Rd	-16.5	5.2	-202.0	87.9
	13116	Lancaster St /Carisbrook Dr	Bridge St	5.6	3.9	47.1	22.2
	16327	Fountain St	Dickie Settlement Rd	1.9	2.3	44.1	33.4
	19457	Hespeler Rd	Beaverdale Rd/Queen St	-2.6	2.6	-67.7	75.8
	Total			11.5	10.7	20.0	15.1
	Total *			27.9	9.3	52.8	11.3
Total collisions during Precipitation	2711	Sawmill Rd	Arthur St	7.3	6.4	42.2	21.5
	10941	Homer Watson Blvd	Block Line Rd	-16.4	5.6	-146.4	64.1
	13116	Lancaster St /Carisbrook Dr	Bridge St	-0.8	4.4	-1.5	35.8
	16327	Fountain St	Dickie Settlement Rd	4.4	2.9	55.2	23.6
	19457	Hespeler Rd	Beaverdale Rd/Queen St	-13.3	4.1	-458.7	187.5
	Total			-18.8	10.7	-33.9	23.0
	Total *			-2.4	9.2	-3.4	21.7

*** Roundabout 10941 (Homer Watson Blvd/Block Line Rd) is excluded in Total* as an outlier, because the observational number of collisions at this roundabout is distant from other observations.**
Note: negative sign means an increase in collisions

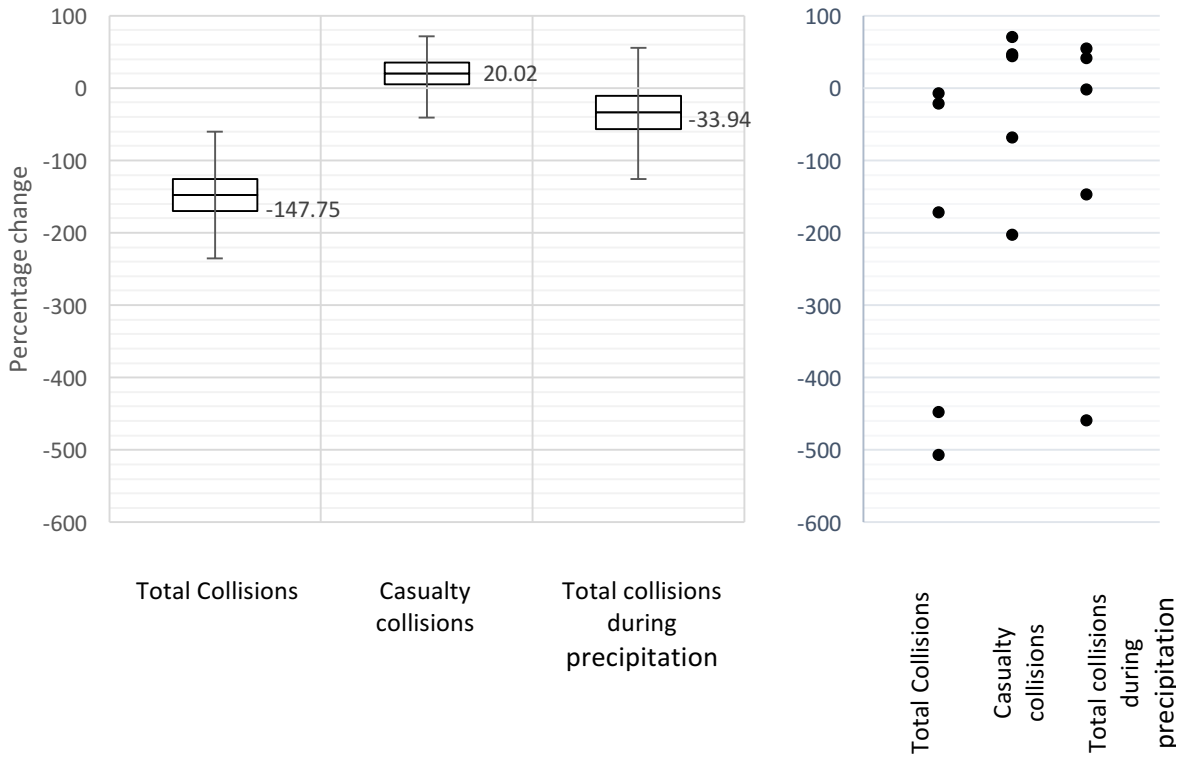


Figure 4-3 Percentage change for roundabouts in all conditions

For the table on the left, the line inside the box indicates the effectiveness of the treatment for combined five roundabouts, and the central rectangle denotes the values of one standard deviation of the percentage reduction. In all cases but one, the whiskers above and below the rectangle represent the values of the minimum and maximum. Once an outlier, which is 150 percent of the interval of the box or more above the top of the box or below the bottom of the box, is present, the whisker on the proper side will be replaced by the inner fence, a line that is 1.5 times of the interval of the rectangle far from the edge of the box. For the table on the right side, the points illustrate the distribution of percentage change for individual roundabouts in three different conditions.

The results indicate that, in the Region of Waterloo, after a signalized intersection is converted to a modern roundabout, there will be an increase in total collisions. Generally, a highly significant 148 percent increase for all crash severities is estimated. These effects are not in agreement with many other research results that roundabouts normally lead to a reduction in collisions (Flannery et al., 1998; Jensen, 2013; Persaud et al., 2012; Retting et al., 2001), but are consistent with the result of a recent Waterloo Region report, which shows that collisions generally increased by about 35 percent at intersections that

were replaced by roundabouts (Region of Waterloo, n.d.). In terms of casualty collisions, three out of five roundabouts see a substantial reduction, but others have a great increase. One is the roundabout at Homer Watson Boulevard and Block Line road, which is the most dangerous intersection in the region in 2016. Another is the roundabout at Hespeler Road, Beaverdale Road and Queen Street, which just opened in 2013 and has a learning curve. Although the small samples make it difficult to measure the conversion effects on casualty collisions, overall, based on combined roundabouts, the procedure estimates that the conversion brings about a 20 percent reduction with a standard deviation of 15 percent. In other words, roundabouts are expected to become safer regarding severe collisions, which is consistent with the finding of previous analysis, but at a lower magnitude than found previously (Jensen, 2013; Pesaud et al., 2001; Schoon and Van Minnen, 1994). The decrease in collisions can be primarily explained by two factors, the reduction of the navigating speed and the elimination of some certain types of conflicts between vehicles, such as high-angle and rear-end collisions. During days with precipitation, the effect of conversion is unclear. Risk increases at three roundabouts and decreases at two roundabouts. Based on the number of collisions at all roundabouts, the results suggest a 34 percent increase in total collisions.

It should be pointed out that the roundabout located at Homer Watson Boulevard and Block Line road has an extremely high collision count compared to other roundabouts. According to a news from *The Record*, a daily newspaper in the Region of Waterloo, it ranks as the regional most dangerous intersection (Outhit, 2017). As shown in Figure 4-3, the percentage changes at Homer Waterson Boulevard and Block Line Rd are outliers, which are distant from other observations for all conditions. If this intersection is excluded from the analysis, the new results show a 71 percent increase, 52 percent decrease, and 3 percent decrease for total collisions, injury collisions, and total collisions in rainy or snowy days respectively.

The following shows the safety effect of the conversion over time, after the roundabout has been installed. Most roundabouts in the Region of Waterloo are relatively new, so the data are limited and the results should be regarded as indicative. Five roundabouts have 7, 5, 4, 3 and 2 years' data individually. Based on available data, the results indicate that there are some fluctuations over the beginning period, then the changes generally level off for total and severe collision (Figure 4-4a and b). This is most likely explained by the learning curve. Drivers and other road users need time to adapt to the change, not only the alteration of the intersection form (e.g., it takes time for a driver who is not familiar to roundabouts to learn how to navigate them), but also the variation of environment (e.g., it takes time for a driver who drives through a junction every day to adjust to the same location but with a different design). For fatal and injury collision, the percentage reduction of collisions increases slightly after a few years. In terms of

days with precipitation, it is difficult to estimate, because the trend is not obvious (Figure 4-4c). This might be attributed to the small number of the collisions in these kinds of weather.

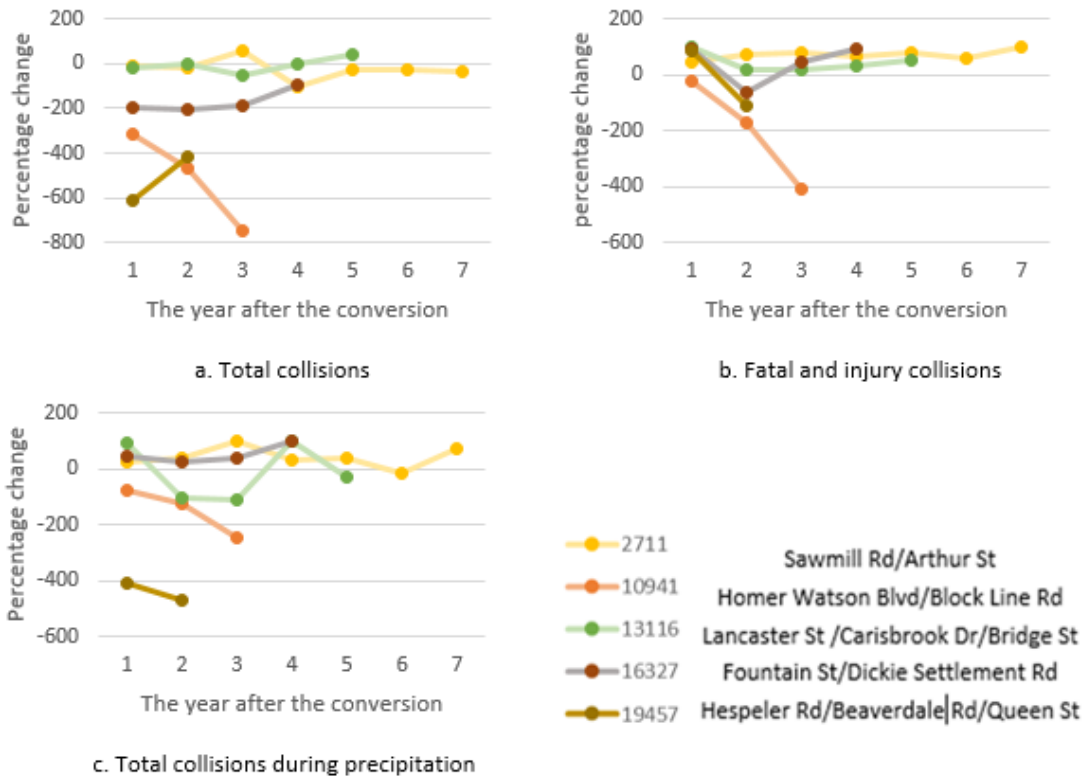


Figure 4-4 Time series of the safety effect on roundabouts for all conditions

Chapter 5 Conclusion and discussion

5.1 Summary of data and methods

To contribute to road safety, addressing questions from not only an operation perspective, but also from a weather hazards perspective, this thesis has two objectives. The first objective is to estimate the relative risk of collisions during rainfall compared to normal clear weather conditions for both roundabouts and signalized intersections in the Region of Waterloo during 2005 to 2015. The second objective is to evaluate the safety effects after roundabouts are installed at intersections previously controlled by traffic signals.

The method used to predict rainfall-related crash risks is based on the commonly used matched-pair approach. This procedure organizes the collision data into two groups: events and control. Hence, the effect of time-dependent variables is effectively controlled. In order to conduct the analysis, historical collision data and daily climate records over an eleven-year study period from 2005 to 2015 were used. Date of collision has been considered to estimate the effect of seasonal variation on collisions. The empirical results are documented for different types of collision (total collisions, fatal and injury collisions, and PDO collisions), different intensities of rainfall (total, very light, light, moderate, and heavy), and different seasons (spring, summer, autumn, and winter).

The method used to estimate the safety effect of the conversion is based on the empirical Bayes before-after study developed by Hauer in 1997, which is accepted as one of the most well-known and effective ways to address the RTM problem and account for the changes in external factors which can affect the safety, while evaluating the safety effects of a treatment. Historical crash information from five treated sites located in the Region of Waterloo and data from 20 signalized intersections with similar set of traits in a reference group were used to complete the analysis. Based on the information from the reference sites which is able to represent the treated entities, SPF which reflects the relationship between traffic volume and the occurrence of the particular collision types are recalibrated to estimate the number of collisions that would be anticipated at these intersections. In terms of roundabouts converted from signalized intersections, the safety performance can be predicted as a weighted average of the SPF's estimates and the actual count of collisions at treated sites. This study tracks collision information through the second initial months after the new roundabout has been applied, attempting to see how the number of collisions change along with time. Many reasons may contribute to the change, such as the development of the understanding to roundabouts, and the installation of additional countermeasures.

5.2 Conclusion

The key results of the first objective include:

- There is no evidence of a statistically significant increase in crashes on days with rainfall relative to 'good' weather conditions for roundabouts, whereas there is evidence of an increase in collision risks for signalized intersections.
- Overall, the relative risk at signalized intersection on days with rainfall is 1.21, indicating that crash rates are 21 percent higher on rain days than on clear control days. At a 95 percent confidence interval, the relative risk of collisions is 7 percent to 36 percent higher during rainy days relative to clear days, which is reasonably consistent with previous studies.
- There are no statistically significant increases in crashes on days with rainfall for casualty and PDO collisions at roundabouts and signalized intersections.

In terms of the relative risk estimates with different rainfall intensities, the analysis shows the following:

- The escalation of relative risk as rainfall intensifies at signalized intersections is clear, as found in previous research for road network or segments.
- It is remarkable that there is an insignificant change in relative risk at roundabouts for rainfall intensity and all severity types. Compared with results concluded at signalized intersections, the change of risk estimates as rainfall intensifies at roundabouts are not statistically significant. No typical correlations between the rainfall intensity and the relative collision risk can be found at roundabouts.
- At signalized intersections, no statistically significant increases in all crash severities were observed on days with very light rain or light rain, but significant increases were found for moderate and heavy rain for total collisions.
- For both roundabouts and signalized intersections, the estimates of the increases of the severe crash risks are generally less than those of total crashes, but they are not statistically significant. The reason might be that drivers tend to be more careful when the weather condition is more hazardous, which leads to some extent of the reduction of crash severity.
- It appears that roundabouts are less affected than signal-controlled intersections under the effect of rainfall, but it is not statistically significant because of the small sample size. For roundabouts,

the changes of the estimates of the relative risks during days with rainfall are generally less than those of signalized intersections for all types of severity.

In terms of the relative risk estimates in different seasons, the analysis shows the following:

- The risk is significantly higher for rainfall in autumn at both roundabouts and signalized intersections. Autumn will likely encounter a 57 percent higher risk at roundabouts, while a 31 percent on at signalized intersections. The reason might be the high probabilities of rain in autumn.
- For signalized intersections, significant increases were found for total collisions in summer, and total collisions and PDO collisions in autumn.
- In general, compared to the changes in relative risk for total collisions, those for collisions involving causality or PDO is typically less, regardless of the season. However, it is not statistically significant.

The key results of the second objective include:

- In the Region of Waterloo, roundabouts are experiencing increases in total collisions and total collisions during days with precipitation. The increase for combined roundabouts is approximately 148 percent and 34 percent for these two conditions, which are not in agreement with the findings concluded by previous studies that roundabouts generally lead to a reduction in the chance of collisions, but are consistent with the results of a recent report in the Region of Waterloo (Region of Waterloo, n.d.).
- Roundabout installation is shown as an effective safety prevention for severe collisions. Results show that there is an almost 20 percent reduction, which is generally consistent with the results of other studies.
- Looking at the percentage change of the safety effect, it appears that there are some fluctuations in the initial period after conversion and then the changes generally level off for total and severe collision. However, no obvious trends have been found for total collisions during days with precipitation.
- Roundabout safety performance, to some extent may be related to the surrounding environment of the roundabout and drivers' familiarity. However, a firm conclusion cannot be made, because each location of roundabouts has its own site-specific condition, and other factors may also have

impacts on collision risks. For roundabouts with relatively more years' data, the safety tends to be better with time.

Generally, this thesis predicts the relative risk of collisions during days with rainfall compared to days with clear weather for both roundabouts and signalized intersections, and estimates the safety effect of the conversion in the Region of Waterloo. The new findings for roundabouts in this study may contribute to future roundabout studies since the implications of inclement weather for roundabout safety have not been completely considered and more existing intersections may be converted to roundabouts.

5.3 Discussion

Traffic safety is a complex field because various factors, including human, environmental, and vehicle factors are associated with outcomes. This thesis is attempt to have a better understanding of the safety performance of roundabouts in relation to weather and the conversion process. The practical implication of it, overall, is connected with intersection safety, and more specifically, roundabout safety.

It is important for traffic engineers to select the type of control to install at an intersection, because it can have significant safety or efficiency implications for a traffic network. The trade-offs between design, operation and safety when planning a new roundabout should be considered carefully. There are different reasons for choosing roundabouts, such as cost savings on maintenance, relieving congestion, pursuing environmentally friendly designs, reducing collisions, and controlling speed (Gross, 2000). However, the most important reason why these circular intersections are implemented is quite simple: safety.

It is widely recognized in the intersection safety research that, in comparison to traffic signals, a roundabout is a safer design for an intersection. It eliminates some dangerous maneuvers and hence associated crashes are eliminated. The geometric design forces drivers to slow down while navigating a roundabout, so that they have more time to adjust their behavior to react to surroundings. Accordingly, we expect both the number and also the severity of collisions to be reduced because of the lower travel speeds and reduced opportunities for serious conflicts.

The results seen here align with previous studies showing that roundabouts experience fewer severe collisions than signalized intersections. However, the results in this thesis indicate that the installation of a roundabout at an existing signalized intersection will lead to a substantially elevated number of collision, which contradicts findings in studies conducted in other countries, but is in agreement with the findings concluded by the Region of Waterloo and another research conducted for roundabouts in Arizona by the

National Transportation Center at the University of Maryland (Mamlouk and Souliman, 2016). It verifies that roundabout safety can be context-specific, being tied to geographical locations to some extent.

Unlike drivers in the UK or other countries with numerous roundabouts, who are very familiar with the concept of roundabouts as an intersection type, a large proportion of people in Canada are still novice users.

Roundabouts have been a source of some debate in the Region of Waterloo since the first one was opened to the public. As reported by some in local media, driving through a roundabout is a confusing experience for a substantial number of residents. More than thirty stories related to roundabouts were published in *The Record*, a daily newspaper published in the Region of Waterloo, this year. A substantial number of them are critical of roundabouts, focusing primarily on the ability of users to adapt to roundabouts. Undoubtedly, roundabouts require a learning curve. It takes time for road users to fully understand how to properly use roundabouts. More education may hasten this process. Therefore, it is crucial for governments and transportation authorities to continue to educate drivers and other road users, such as pedestrians and cyclists, to learn how to properly use roundabouts.

As a supplement to the analysis conducted for the thesis, the author recently engaged in the University of Waterloo survey of Region of Waterloo residents by adding questions related to traffic safety in Waterloo Region, including questions ask how safe the respondents feel at roundabouts compared to intersections with traffic lights. The feedback received from the survey indicates that a large number of people in the region do not think that roundabouts are safer than signalized intersections, which is not in agreement with the majority of the findings in scientific literature, but is consistent with the results of this thesis. The government chooses and promotes roundabouts because the literature indicates they are better, but why the public do not think so? This may be explained as the fact that roundabouts experience more collisions than the period that the conversions had not been installed in the Region of Waterloo. Why do roundabouts have more collisions? This may be explained as the lack of adequate education on how to use roundabouts or just the learning curve. Also, some drivers are still going too fast through roundabouts without signaling properly.

It is worth noting that the roundabout at Homer Watson Boulevard and Block Line Road, opened in 2011, is unique because of the extremely high number of collisions at this location. It ranked as the most dangerous intersection in the region in 2016. The count of collisions has continued to grow, from 51 in 2011, to 53 in 2012, 72 in 2013, 107 in 2014, and 119 in 2015. It would have been difficult to foresee this situation, since the total number of collision at that intersection before the installation of the roundabout

was about 10 per year. The trend of injury collisions also goes up. What may be less apparent is that a variety of countermeasures have been applied to attempt to advance the safety performance, such as changing speed limits and installing signs (Outhit, 2017), but no obvious improvement has been observed. From the perspective of human behavior, it might be explained by the lack of the understanding of how to use roundabouts properly or by the fact that there is a high school (St. Mary's High School) nearby this troubled roundabout. Comparatively, teenagers may be more vulnerable at roundabouts because they may not as well-prepared as adults for any dangers that may befall them. Thus, roundabouts may pose a problem for high school students. In addition, some drivers do not signal when they leaving the roundabouts and also do not yield to pedestrians at exiting lanes. Failing to yield the right of way accounts for more than 50 percent of collisions at this roundabout. From the perspective of the roundabout design, it can be interpreted as that the roundabout attracts more traffic. As the overall volume of traffic increases, so does the number of conflicts between pedestrians or cyclists and vehicles. There are residential areas, a high school, and a few bus stops around this roundabout. It can be expected that heavy pedestrian and cyclist volume could conflict with high traffic volume.

The findings of numerous research suggest that roundabouts should be encouraged as an effective alternative to conventional intersections, to improve safety and efficiency. However, roundabouts are not appropriate at all intersections, not only because they require considerable construction areas, but also the local education regarding roundabout safety and how to use roundabouts must be strengthened. Thus, for the Region of Waterloo, while building more roundabouts, government authorities have to take bigger steps towards enhancing the public's understanding of how to use roundabouts. It is evident that the opening of new roundabouts is not the end point. More research is required on the specific problems users experience with roundabouts and the effectiveness of public education programs.

There are a couple of limitations in this research and could be addressed in further studies. The first one is the small sample size for the statistical analysis. So far there are 30 roundabouts reported on the Waterloo Region's website; however, only 23 roundabouts are included in the study because of data availability. For the rainfall-related risk analysis, condition requirements further reduced the sample size. For evaluating the change in safety performance between traffic signals and roundabouts, only five roundabouts could be used for the analysis. In addition, the chance of injury being incurred are relatively small for all type of intersections, especially for roundabouts, the latter because of the lower design speed at roundabouts. Thus, the amount of data for some specific severity types or in some specific conditions is too small to ensure enough power to extrapolate the statistical results to the overall population. Since the

small sample size is not able to meet the significance level, in future research there is a need to consider extending the study area to improve the sample size and make a cross-region comparison possible.

The second limitation is about the temporal unit of the analysis. The relative risk analysis can be produced at different temporal levels, hourly, six-hourly and daily. This thesis is based on daily weather data, because six-hourly weather data obtained from Environment Canada do not provide accumulations of precipitation at finer temporal scales. However, the risk estimates at daily level is based on event days were potentially most hour were dry. In other words, the risk estimates are diluted. When the temporal scale of analysis is finer, the risk estimates increase and are more reflective of the added risk during inclement conditions (Andrey et al., 2013a). For future research, analysis of the weather effects on roundabout safety should consider to choose a finer temporal scale as well as other weather conditions. In addition, this method is not able to account for the reductions of traffic volume that occur due to precipitation.

In some countries (e.g., the United States, and Netherlands), the difference in safety performance is shown to be greater for intersections with higher speed limits (Nambisan and Parimi, 2007; Schoon and Van Minnen, 1994). It can be interpreted as that the larger difference in speed, the greater the advantage that roundabouts will have since lower speed is associated with fewer collisions and less serious collisions. Thus, moving forward, the analysis of roundabout safety in Canada with different speed limits can be conducted.

In addition, it has usually been a controversial issue whether roundabouts affect pedestrians and cyclists' safety. Some findings suggest that roundabouts are safer for them than signalized intersections. However, New Zealand Transport Agency concludes that cyclists experience less safety at roundabouts than at traffic signals (Campbell et al., 2006). They also said the safety effect for pedestrians is not obvious at roundabouts. Furthermore, Persaud et al. (2001) recommends that roundabouts may not be suitable for the intersection with high volume of both vehicle and bicycle. It can be linked to the increase of the exposure to conflicts. Thus, intersections with high volumes of vehicles and pedestrians may also not be a proper location for roundabouts. In future studies, there is a need to evaluate the safety of vulnerable road users at roundabouts and how the conversion is connected to the pedestrians and cyclists' safety. This may, indeed, provide insights that help us to understand problematic roundabouts such as the one at Homer Watson Boulevard and Block Line Road.

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Appendix A Current roundabouts in the Region of Waterloo, 2017

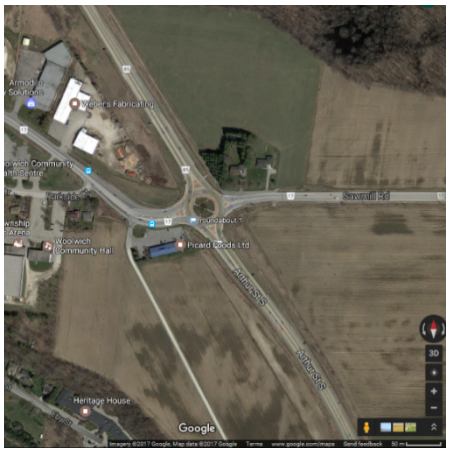
	Name	Jurisdiction	Year Opened
1	Arthur St @ Sawmill Rd	Woolwich	2006
2	Westmount Rd @ Laurelwood Dr	Waterloo	2014
3	Ira Needles Blvd @ University Ave	Waterloo	2007
4	Ira Needles Blvd @ Erb St	Waterloo	2004
5	Ira Needles Boulevard @ Thorndale Drive	Waterloo	2016
6	Erb Street and Costco Lane @ Waterloo Landfill Lane Gate One	Waterloo	2016
7	Erb Street and Platinum Drive @ Waterloo Landfill Lane Gate Two	Waterloo	2016
8	Ira Needles Blvd @ Boardwalk Access	Kitchener	2010
9	Ira Needles Blvd @ Victoria St	Kitchener	2007
10	Ira Needles Blvd @ Highland Rd	Kitchener	2007
11	Ira Needles Blvd @ Highview Dr	Kitchener	2004
12	Bridge St @ Lancaster St	Kitchener	2009
13	Fairway Rd @ Zeller Dr	Kitchener	2012
14	Homer Watson Blvd @ Block Line Rd	Kitchener	2011
15	Fischer-Hallman Rd @ Seabrook Dr	Kitchener	2007
16	Fischer-Hallman Rd @ Huron Rd	Kitchener	2007
17	Bleams Road @ Manitou Drive	Kitchener	2015
18	Fountain St @ Kossuth Rd	Cambridge	2011
19	Fountain St @ Dickie Settlement Rd	Cambridge	2010
20	Fountain St @ Blair Rd	Cambridge	2006
21	Can-Amera Pkwy @ Conestoga Blvd	Cambridge	2006
22	Pinebush Rd @ Thompson Dr	Cambridge	2009
23	Can-Amera Pkwy @ Townline Rd	Cambridge	2004
24	Hespeler Rd @ Queen St W	Cambridge	2013
25	Franklin Boulevard @ Clyde Road	Cambridge	2016
26	Franklin Boulevard @ Bishop Street	Cambridge	2016
27	Franklin Boulevard @ Main Street	Cambridge	2016
28	Franklin Boulevard @ Pinebush Road	Cambridge	2016
29	Franklin Boulevard @ Savage Drive	Cambridge	2015
30	Franklin Boulevard @ Sheldon Drive	Cambridge	2016
Data source: Region of Waterloo (2017)			

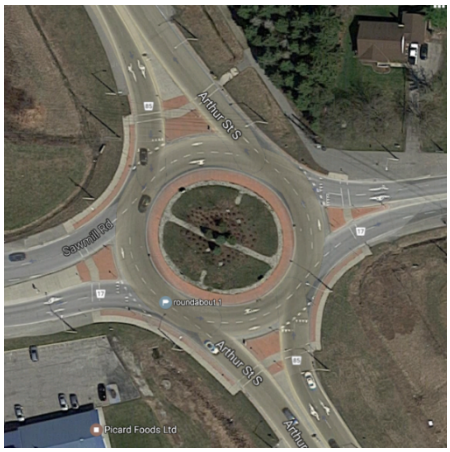
Appendix B Excluded holidays from analysis, 2005-2015

Year	Holiday								
	New Year's Day	Easter weekend (Fri-Mon)	Victoria day (Fri-Mon)	Canada day	Civic day (Fri-Mon)	Labour day (Fri-Mon)	Thanksgiving Day (Fri-Mon)	Remembrance Day	Christmas (Dec 24-26 and the closest weekend)
2005	Dec 31-Jan 3	Mar 25-28	May 20-23	Jun 30 - Jul 3	Jul 29 - Aug 1	Sep 2-5	Oct 7-10	Nov 11	Dec 23-26
2006	Dec 31-Jan 2	Apr 14-17	May 19-22	Jun 30 - Jul 3	Aug 4-7	Sep 1-4	Oct 6-9	Nov 11	Dec 23-26
2007	Dec 31-Jan 1	Apr 6-9	May 18-21	Jun 29 - Jul 2	Aug 3-6	Aug 31 - Sep 3	Oct 5-8	Nov 11	Dec 22-26
2008	Dec 30-Jan 1	Mar 21-24	May 16-19	Jun 28 – Jul 1	Aug 1-4	Aug 29-Sep 1	Oct 10-13	Nov 11	Dec 24- 28
2009	Dec 31-Jan 1	Apr 10-13	May 15-18	Jul 1	Jul 31-Aug 3	Spe 4-7	Oct 9-12	Nov 11	Dec 24- 27
2010	Dec 31-Jan 3	Apr 2-5	May 21-24	Jun 30-Jul 1	Jul 30-Aug 2	Spe 3-6	Oct 8-11	Nov 11	Dec 24-26
2011	Dec 31-Jan 3	Apr 22-25	May 20-23	Jun 30 - Jul 3	Jul 29 - Aug 1	Sep 2-5	Oct 7-10	Nov 11	Dec 23-26
2012	Dec 30-Jan 2	Apr 6-9	May 18-21	Jun 29 - Jul 2	Aug 3-6	Aug 31 - Sep 3	Oct 5-8	Nov 11	Dec 22-26
2013	Dec 30-Jan 1	Mar 29-Apr 1	May 17-20	Jun 28 – Jul 1	Aug 2-5	Aug 30-Sep 2	Oct 11-14	Nov 11	Dec 24-26
2014	Dec 31-Jan 1	Apr 18-21	May 16-19	Jun 28 – Jul 1	Aug 1-4	Aug 29-Sep 1	Oct 10-13	Nov 11	Dec 24- 28
2015	Dec 31-Jan 1	Apr 3-6	May 15-18	Jul 1	Jul 31-Aug 3	Spe 4-7	Oct 9-12	Nov 11	Dec 24- 27

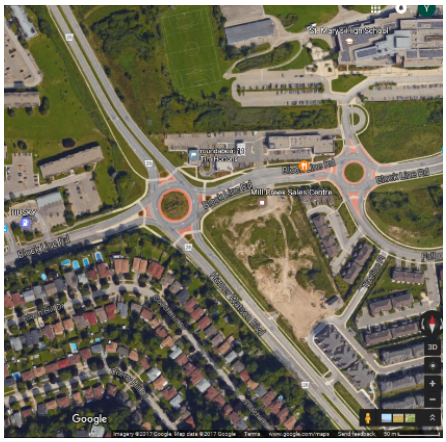
Appendix C Screenshots of five converted roundabouts via Google Maps

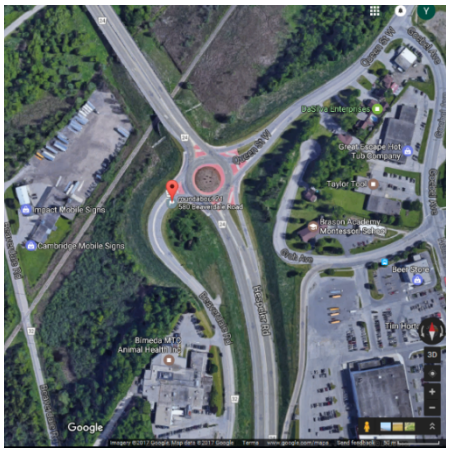
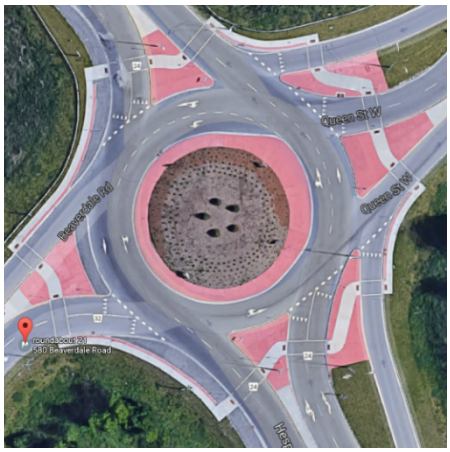
GEO_ID	STREET_1	STREET_2
2711	Sawmill Rd	Arthur St





10941	Homer Watson Blvd	Block Line Rd



GEO_ID	STREET_1	STREET_2
13116	Lancaster St /Carisbrook Dr	Bridge St
		
16327	Fountain St	Dickie Settlement Rd
		
19457	Hespeler Rd	Beaverdale Rd/Queen St
		

Appendix D 4-legged signalized intersections in the reference group

GEO_ID	STREET_1	STREET_2	MUN
15020	TOWNLINE RD	PINEBUSH RD/Cty Rd 32(Lake Rd)	CAM
15355	HESPELER RD	EAGLE ST/PINEBUSH RD	CAM
16210	FOUNTAIN ST	MAPLE GROVE RD	CAM
18701	HESPELER RD	MAPLE GROVE RD/Fisher Mills Rd	CAM
20363	HESPELER RD	BISHOP ST	CAM
27986	FRANKLIN BLVD	CAN-AMERA PKWY	CAM
28255	HESPELER RD	CAN-AMERA/YMCA (250 Hespeler Rd)	CAM
6110	HIGHLAND RD	FISCHER-HALLMAN RD	KIT
9755	BLEAMS RD	FISCHER-HALLMAN RD	KIT
11768	OTTAWA ST	HOMER WATSON BLVD	KIT
12387	BRIDGEPORT RD (Riverbend Dr)	LANCASTER ST	KIT
20632	VICTORIA ST	FISCHER-HALLMAN RD	KIT
21985	HOMER WATSON BLVD	BLEAMS RD	KIT
22283	FAIRWAY RD	RIVER RD/River Rd	KIT
22407	FAIRWAY RD	LACKNER BLVD/Fairway Cres	KIT
2929	SAWMILL RD	NORTHFIELD DR	WAT
8449	ERB ST	FISCHER-HALLMAN RD	WAT
8967	BRIDGE ST	UNIVERSITY AVE/University Ave	WAT
20586	UNIVERSITY AVE	FISCHER-HALLMAN RD	WAT
29535	WESTMOUNT RD	BEARINGER RD/Bearinger Rd	WAT
Note: WAT = Waterloo, KIT = Kitchener, CAM = Cambridge Data source: Transportation Administration of the Region of Waterloo			

Appendix E Summary of collisions with different action types, 2005-2015

Action types	Roundabouts				Signalized intersection			
	Total*	Fatal	Injury	PDO	Total*	Fatal	Injury	PDO
Number of collisions								
2 vehicle actions	1982	0	178	1495	3806	3	892	2007
1 vehicle action	213	0	38	157	214	1	66	119
2 vehicle + pedestrian actions	1	0	0	1	1	0	0	1
1 vehicle + pedestrian actions	15	0	14	1	42	1	40	1
No action reported	1	0	0	1	1	0	1	0
Percentage of collisions								
2 vehicle actions	90.3%	0.0%	8.1%	68.1%	94.7%	0.1%	22.2%	49.9%
1 vehicle action	9.7%	0.0%	1.7%	7.1%	5.3%	0.0%	1.6%	3.0%
2 vehicle + pedestrian actions	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
1 vehicle + pedestrian actions	0.7%	0.0%	0.6%	0.0%	1.0%	0.0%	1.0%	0.0%
No action reported	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

*A large amount of the severity of collisions are non-reportable, thus fatal, injury and PDO collisions do not add up to total collisions.