A Surrogate Safety Assessment of Scrambled Phase Intersections

by

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Abstract

Since traffic safety is a significant concern for policymakers and researchers, multiple studies have been conducted to address this issue and create a safer environment for all road users, especially pedestrians. One of the approaches to achieving this is installing scramble phases at intersections with high volumes of vulnerable road users. This research evaluated the safety impact of installing the scramble phase at the two intersections in Edmonton, Canada, over three periods. The first observation was made before the installation of the scramble phase, followed by observations immediately after the installation, and finally, after six months of installation. The research utilized two approaches to evaluate the safety impact of the scramble phase installation. The first approach was to observe the frequency of right-turn-on-red violations. The second approach involved investigating the frequency of serious conflicts before and after the installation using three safety indicators, namely, Time to Collision (TTC), Time Difference to Point of Intersection (TDPI), and Distance between Stop Position and Pedestrian (DSPP). The number of breaches before and after the installation was counted manually to evaluate the frequency of right-turn-on-red violations. The results showed a decrease in the total number of right-turn-on-red violations after the implementation during the six months. However, there was a slight increase in violations during the pedestrian phase at one intersection after six months. The research used conflict detection and automatic indicator calculations to assess the frequency of serious conflicts. The results showed a 65% decrease in all three safety indicators immediately after the installation of the scramble phase at the Calgary trail intersection. Furthermore, after six months, there were no incidents of DSPP and TDPI at this intersection. At one of the study intersections, there was also a reduction in serious conflicts, although it was less than 50% immediately after the installation. However, this improvement increased to 80% for all indicators after six months. Reduced severe conflicts and total right-turn-on-red violations indicate that installing the scramble phase positively impacted intersection safety.

*To my dear parents, **Maryam** and **Hossein**,*

*and my beloved sisters, **Mahboobeh** and **Maliheh**,*

for being an amazing source of inspiration to me

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List of Acronyms

BA	Before and After study
CI	Crash Index
CIF	Criticality Index Function
CNN	Convolutional Neural Network
CPI	Crash Potential Index
DRAC	Deceleration Rate to Avoid a Crash
DSPP	Distance between Stop Position and Pedestrian
DSS	Difference of Space Distance, and Stopping Distance
CSV	Comma-Separated Values
LTC	Line To Crosswalk
MTC	Margin to collision
MUTCD	Manual on Uniform Traffic Control Devices
PET	Post Encroachment Time
PI	Point of Intersection
PICUD	Potential Index for Collision with Urgent Deceleration
PSD	Proportion of Stopping Distance
RTOR	Right-turn-on-red
SDLP	Standard Deviation of Lateral Position
StrongSORT	Strong Simple Online and Real-time Tracking
TCT	Traffic Conflict Technique
TDPI	Time Difference to the Point of Intersection
TET	Time Exposed Time to collision
TIT	Integrated Time-to-collision
TTC	Time To Collision
UD	Unsafe Density
VRU	Vulnerable Road User
WHO	World Health Organization
YOLOv5	You Only Look Once Version 5

1

Introduction

1.1 Background

The challenges posed by a rapidly expanding global population and finite resource availability have emphasized the need to maintain a cleaner and more habitable world. The escalating volume of vehicles constitutes a critical factor in various transportation-related issues, such as air and noise pollution, climate change, and road safety, which pose a significant risk to global well-being. As such, policymakers are advocating for the promotion of non-motorized modes of transportation.

Walking is one of the sustainable non-motorized modes of transportation, which not only results in less air pollution, energy consumption, and traffic congestion but also increases people's activity, which undoubtedly has positive impacts on social health. Research has shown that walking 10,000 steps daily can be associated with lower mortality risk and incidences of cardiovascular disease and cancer. Taking steps at a faster pace may lead to even more significant risk reduction, emphasizing the importance of moderate to vigorous physical activity for maintaining good health [1].

Although walking confers numerous benefits, the safety of pedestrians remains imperilled by motorized vehicles. Pedestrian injury can culminate in disastrous and financially onerous harm, comprising 11% of all road user fatalities. In Canada, injuries are the primary cause of mortality for individuals under 45 years of age and the fourth most pervasive cause of death across all age groups. The malign consequences of pedestrian injury equate to nearly 4000 hospitalizations annually in Canada [2].

According to the World Health Organization (WHO), approximately 1.3 million people die yearly from road collisions [3]. In Canada, in 2020, 266 pedestrians died because of collisions, comprising 15.2 % of the total fatalities [4]. Therefore, pedestrian safety has long been a topic of interest for researchers and practitioners, focusing on evaluating pedestrian behaviour and developing viable ways to improve their safety. Serious pedestrian collisions can cause debilitating physical injuries that can have a long-term impact on the victims, potentially leading to disability.

Aside from physical injuries, pedestrian accidents can result in emotional distress, such as anxiety, sadness, and post-traumatic stress disorder. These psychological illnesses can significantly impact an individual's quality of life, impairing their ability to function in daily activities. Additionally, pedestrian collisions can have significant financial consequences for people and society, including medical expenses, lost income due to time away from work, and ongoing rehabilitation and treatment costs. Given that most traffic accidents occur at or close to intersections [5], mitigating collisions at these points could considerably reduce the overall number of accidents, thereby promoting safer roadways. Consequently, it is imperative to investigate viable methods to enhance pedestrian safety at intersections.

Minimizing pedestrians' conflicts with motorized road users can be achieved by implementing a scramble phase, a type of signal timing at intersections for pedestrians first adopted in the 1950s in Denver, Colorado [6]. For an intersection with a scramble phase, vehicles in all directions must stop during the pedestrian crossing phase. Pedestrians then can safely cross conventionally or diagonally without the interference of turning vehicles. The implementation of the scramble phase has benefits beyond safety as it also promotes equity. This is achieved by reducing the interaction between pedestrians and vehicles, creating a safer environment for Vulnerable Road Users (VRUs). The diagonal crossing provided by the scramble phase is more comfortable and convenient for impaired, children, and elderly individuals, compared to the conventional method that involves interactions with parallel or turning vehicles. In addition, it promotes a safer environment for individuals who cannot afford to purchase a vehicle and rely on walking as their primary mode of transportation.

Many studies have evaluated the impact of installing exclusive phases at intersections on road safety. However, implementing an exclusive phase for pedestrians can increase cycle lengths and decrease vehicle and pedestrians' green time, increasing delays for all road users. Referring to [7], a long wait would reduce pedestrian compliance, thus negatively affecting the intersection's safety. Consequently, it remains unclear whether the scramble phase effectively enhances intersection safety, necessitating a more protracted monitoring period to evaluate its impact thoroughly.

1.2 Research Motivation

Assessing the effectiveness of a safety countermeasure, such as implementing a scramble phase based on collision data, poses two significant challenges. Firstly, a considerable amount of data is required to conduct a collision analysis; however, collecting this information is challenging due to the infrequent and random occurrence of collisions [8], [9]. Secondly, not all collisions are reported, and the likelihood of recording a collision depends on its severity and the type of road users involved [10], [11]. This issue can lead to underreporting collisions involving vulnerable road users, thus potentially skewing the overall safety assessment.

Traffic conflict and traffic conflict techniques (TCT) are frequently utilized as surrogate measures of safety [12]. A traffic conflict arises when road users take evasive action to prevent a collision, as in the case of two vehicles or a vehicle and a pedestrian sharing a collision course [13]. Transportation engineers utilize the TCT to identify and analyze potential roadway hazards or conflicts. This technique involves observing and documenting incidents of road user interactions, such as near-misses or conflicts, between various types of road users, including vehicles, cyclists, and pedestrians, at specific locations or along particular routes.

Typically, TCT comprises several steps, including the selection of an observation location, identification of potential conflict points and road user types, recording of interactions, analysis of the collected data, and provision of recommendations for improvement, such as the enhancement of signage, alteration of traffic signals, or installation of additional pedestrian crossings. By utilizing the TCT to identify and analyze potential conflicts, transportation professionals can make well-informed decisions to improve road safety and mitigate the risk of accidents.

A study focusing on traffic conflicts at three locations in Sweden indicates that the scramble phase is effective in small towns with a limited number of pedestrians [14]. In a project by Bechtel et al. [7], a before-and-after (BA) study was conducted to evaluate the safety benefits of the scramble phase and analyze pedestrian-vehicle interactions, including pedestrian violations. The results confirmed a statistically significant decrease in pedestrian-vehicle conflicts and increased pedestrian violations. Ismail et al.[15], investigated the impact of implementing a scramble phase in Chinatown, Oakland, California, using a BA automated analysis of pedestrian-vehicle conflicts. Their study reported a reduction in the spatial density of conflicts and a shift away from the pedestrian crosswalk locations. Abrams et al. [16] found that pedestrian non-compliance could easily nullify the advantages of a scramble phase.

This study evaluates the safety impact of implementing a scramble phase at two intersections in Edmonton: Whyte Avenue and Calgary Trail, and Whyte Avenue and Gateway Boulevard. The investigation is conducted in two periods, immediately after implementation and six months later, to comprehensively understand the scramble phase's effectiveness. The analysis is divided into two parts. In the first part, right-turn-on-red violations are analyzed. The second part examines the frequency of serious conflicts before and after the implementation based on three indicators, two of which were recently introduced and designed explicitly for pedestrian-vehicle conflicts.

1.3 Research Objective

The primary objective of this study is to investigate the safety impact of implementing a scramble phase at two intersections in Edmonton. Two following secondary objectives have been pursued to fulfil this aim.

Violations of right-turn-on-red can heighten the danger of accidents and harm involving pedestrians. When drivers disregard the 'no right turn on red' rule, they may turn into crosswalks while pedestrians are crossing, creating a potential collision situation. Moreover, pedestrians can be more challenging for drivers to spot while making a right-turn-on-red, especially if they emerge from behind parked cars or other obstacles. As a result, violating this rule can jeopardize the safety of pedestrians and undermine their well-being. Observing the frequency of right-turn-on-red violations after scramble phase installation makes it feasible to obtain a more profound understanding of the effectiveness of intersection safety measures, especially regarding pedestrian safety.

The second sub-objective of this study entails an automatic analysis of traffic conflicts. These offer valuable insights into intersection safety. By recording and analyzing instances of near-crash or crash-relevant between different road users, transportation professionals can identify potential safety concerns and implement appropriate measures to address them. For instance, if a particular intersection witnesses a high frequency of conflicts involving pedestrians, transportation professionals may consider additional pedestrian crossings, enhancing signage, or modifying traffic signals to reduce the risk of accidents and injuries. Similarly, if conflicts involving vehicles are identified, transportation professionals may consider implementing traffic-calming measures or altering road design to improve the safety of all road users. As such, analyzing traffic conflicts represents a critical approach to identifying and resolving safety issues at intersections, thereby enhancing the safety of the entire transportation network. By leveraging conflict identification, traffic conflict indicator calculation, and analysis of results before and after installation, this study aims to assess the impact of scramble phase implementation on intersection safety, with a specific focus on pedestrian safety.

1.4 Thesis Structure

This thesis consists of six chapters. The first chapter deals with pinpointing the importance of intersection safety, focusing on pedestrians. The second chapter is divided into two sections, presenting a comprehensive review of the current literature relevant to this research topic. The first section of the second chapter reviews the studies on the safety impact of the installation of the exclusive phase, while the second section explores surrogate safety indicators that have been introduced to date. The third chapter elaborates on the collected data and study area. Chapters four and five discuss the introduction, methodology, and results of several right-turn-on-red violations and calculated surrogate safety measures. The final chapter offers conclusions and recommendations that can be drawn from this study.

2

Literature Review

In this chapter, previous studies are into two distinct subsections: the safety impact of the scramble phase and surrogate safety indicators. The first subsection expounds upon earlier research concerning the safety impact of the installation of the scramble phase. The second subsection deals with surrogate safety indicators utilized to assess the traffic safety of intersections and roadways.

2.1 Safety Impact of Scramble Phase

Evaluating the safety impact of implementing the scramble phase at intersections is a popular research topic. In one study, Garder [14] investigated the efficacy of an exclusive pedestrian phase at three intersections. His investigation indicated that installing a scramble phase could yield positive outcomes in a small town.

However, due to the high frequency of jaywalking in Stockholm, he concluded that installing a scramble phase would be ineffective. Similarly, Abrams et al. [16] conducted a study which confirmed the safety benefits of implementing a scramble phase. Nevertheless, they also cautioned that low pedestrian compliance levels might negate the positive safety effects. Bechtel et al. [7] conducted a BA assessment by implementing the scramble phase at a signalized intersection in Oakland, California. The authors manually recorded the number of pedestrians and vehicle-pedestrian conflicts to develop linear models for conflict rates and violations. Their findings revealed a significant decrease in vehicle-pedestrian conflicts after the implementation. However, the number of pedestrian violations showed a dramatic increase. This escalation in pedestrian violations resulted from the illegal crossing of pedestrians on the “safe side” of the intersection, which means crossing parallel to the direction of the vehicle movement. Despite this, the study found that installing the scramble phase positively impacted the collision numbers at the intersection.

Similarly, Kattan et al. [6] conducted a safety evaluation of the scramble phase at an intersection in Calgary, Canada. They discovered results that were similar to those of the earlier discussed study. Their research employed two Poisson regression models to simulate the frequency of conflicts and violations. Following the execution of the scramble operation, they observed a significant reduction in the frequency of pedestrian-vehicle conflicts. However, there was a considerable upsurge in the frequency of pedestrians breaching regulations. Upon closer inspection, it was revealed that roughly 13% of all violations were ‘safe side’ crossings, where the crossing aligned with the vehicle’s movement. Additionally, 2% of the breaches were “unsafe side” crossings. In comparison, nearly 40% of the violations occurred during the initial 2 to 3 seconds of the “Don’t Walk” phase. However, pedestrians could still safely traverse the intersection within the designated pedestrian period.

Moreover, in Connecticut, Zhang et al. [17] conducted a study to estimate the severity of vehicle interaction and pedestrian crash counts at 42 intersections in four cities. They used non-linear mixed models to predict the outcomes at intersections with concurrent and exclusive phases. The study found that pedestrians crossing during the scramble phase experienced less severe interactions than those crossing concurrent intersections. Additionally, the researchers discovered that although the total number of pedestrian collisions was lower at intersections with concurrent phases, the number of severe collisions was higher in such intersections. Consequently, the study suggested that it would be beneficial to install a scramble phase at intersections where pedestrians are more likely to comply.

2.2 Surrogate Safety Indicators

The first chapter highlights that because collisions are rare and random, and because only the most severe ones are typically reported, it is not reasonable to use collision data as a basis for assessing the effectiveness of safety measures. Therefore, surrogate safety measures have been applied to evaluate the safety level of highways and intersections. Studying traffic safety based on conflict analysis is one of the surrogate measures of safety.

In traffic safety, a conflict arises when two or more individuals on the road, such as drivers, pedestrians, or bicyclists, are in danger of colliding with one another or an object in their surroundings. The severity and frequency of conflicts can be used as a surrogate measure of safety. By analyzing these factors, researchers can estimate the potential risk of collisions occurring on a specific route or intersection. In one study, Heinrich [18] came up with the idea that proposed a hierarchical arrangement of events that ranged from fatal accidents to near-misses (conflicts). According to his theory, there were numerous minor incidents and near-misses for every major injury or fatal accident. By recording these lower-severity events and keeping the hierarchy intact, it may be possible to draw inferences about the incidence of severe top-level events.

Conflict indicators determine how close two road users are to colliding. In his thesis, Ismail [19] mentioned these indicators have several advantages, one of which is that calculated incidences involving conflict indicators are more prevalent than actual collisions. Furthermore, because conflict indicators are quantifiable, they may be measured objectively, reducing some subjectivity involved with observer-based conflict indicators. They also quantify the intensity of traffic disputes and have been utilized in various studies to assess safety, allowing for cross-comparisons and study validation. Based on Mahmud et al. [20], safety indicators can be categorized into four main groups: temporal indicators, distance-based indicators, deceleration-based indicators, and other indicators.

One of the most popular temporal safety indicators is Time-to-Collision (TTC). TTC is a parameter that indicates the temporal closeness to a probable collision assuming the concerned road users maintain their current speeds and trajectories. This variable is computed continuously and can only be determined while the road users are on a collision course. If the road users continue to follow a collision course, this continuous variable could be computed [21], [22]. Various studies evaluate the validation of TTC, one of which [23] sought to verify TTC-based indicators, which divided the findings for VRUs and motor vehicles. Another study [24] focused on pedestrians. In addition, [25] and [26] included VRUs in their analyses. However, VRUs were only involved in a small proportion of the conflicts studied. While utilizing diverse methodologies to assess this correlation, all four studies showed a high correlation between critical events and accidents. Another temporal indicator is Post Encroachment Time (PET), which calculates the time elapsed between when the first road user departs from the second user's path and when the second user reconnects with the first user's path [27]. Some research has explored the validity of PET. Some of these investigations, such as those by [28], [29], and [30], have found a correlation between collisions and conflicts. However, a study by [24] discovered no correlation between conflicts and collisions. There are other temporal indicators such as Time Exposed Time-to-collision (TET) [31], Time Integrated Time-to-collision (TIT) [31], Crash Index (CI) [32] etc.

One distance-based indicator introduced by Iida et al. [33] is the Potential Index for Collision with Urgent Deceleration (PICUD), which assesses the likelihood of a collision between two successive vehicles if the lead vehicle abruptly applies its brake, particularly during lane changes. Two parameters must be predetermined for calculating the PICUD: reaction time and deceleration rate. In their study, Uno et al. [34] assumed a deceleration rate of 3.3 m/s^2 and a reaction time of 1.0 seconds. Another safety indicator is Proportion of Stopping Distance (PSD). Allen et al. [27] developed the PSD measurement to compare the remaining distance to a probable collision point to the minimum allowable stopping distance. It is calculated by dividing the remaining distance by the shortest possible stopping distance. Other distance-based indicators are Margin to collision (MTC) [35], Unsafe Density (UD) [36], Difference of Space Distance, and Stopping Distance (DSS) [37].

Deceleration Rate to Avoid a Crash (DRAC) is a deceleration-based safety indicator that includes potential collision speed differentials and deceleration. [38]. It divides the speed differential between a following and a leading vehicle by their closing time. While DRAC is useful for traffic flow[39]–[42], some analysts claim that it does not reliably predict potential traffic conflicts since it does not take into account individual vehicle braking performance over time under various road and traffic conditions[43]–[45]. As a result, to account for required deceleration rates and individual vehicle braking capabilities, a modified safety signal is required. Other deceleration-based indicators are Crash Potential Index (CPI)[46], Criticality Index Function (CIF) [47] etc.

Aron et al.[48] first proposed the J-value as a safety indicator categorized under “Other indicators”. This indicator aggregates the risk of vehicles in a platoon. The criteria for this indicator are derived from individual vehicle data, such as speed and the time interval between two successive vehicles [49]. Other indicators are Jerks [50] and Standard Deviation of Lateral Position (SDLP) [51] etc.

In addition to the conventional indicators mentioned above, two novel indicators attracted the author’s attention. These indicators, which only consider pedestrian-vehicle conflicts, are Time Difference to the Point of Intersection (TDPI) and Distance between Stop Position and Pedestrian (DSPP). To the best of the author’s knowledge, a minimal number of studies implement and focus on these two indicators. A brief review of what has work been done is provided here.

According to Wu [52], one possible conflict location between vehicles and people is the point of intersection (PI) along their trajectories. In normal circumstances, there should be a difference in the timestamps of vehicles’ and pedestrians' arrival at the PI. A collision happens if the timestamps are identical. As such, TDPI was developed as a conflict indication. TDPI is the time it takes for a pedestrian and a vehicle to collide at a certain point on their respective paths. Unlike TTC, TDPI has no assumption about the drivers' speed; the threshold for this indicator is the driver reaction time, which is 2.5 seconds. In an imaginary situation, a driver might come to a complete stop before the point of intersection. If the distance between the stopped vehicle and the pedestrian crossing the intersection is very short, it should be considered a serious conflict. However, TDPI would result in a large value, thus failing to reflect this imaginary situation as a serious conflict. To address this shortcoming, DSPP is introduced [52]. When a vehicle comes to a complete stop before hitting a pedestrian, the distance between the vehicle and the pedestrian is defined as the DSPP. According to the Manual on Uniform Traffic Control Devices (MUTCD) [53], vehicles must stop before the yield or stop line to ensure a safe distance for pedestrians. At a controlled intersection, the distance between the yield or stop line to crosswalk (LTC) should be at least 1.2 m ahead of the nearest crosswalk line. Therefore, the threshold for DSPP is 1.2 m.

3

Data Description

3.1 Study Area

The two intersections evaluated in this study are located on 104 and 103 Streets, i.e., Calgary Trail and Gateway Boulevard, respectively, and 82nd Avenue, i.e., Whyte Avenue, Edmonton, Alberta, Canada. Figure 1 shows the 82 (Whyte) Avenue corridor with the two study intersections.

The selection of these two intersections is based on their location in a heavily pedestrianized area, with numerous commercial busniess and their proximity to the University of Alberta contribute to the already crowded surroundings. Additionally, both Calgary Trail and Gateway Boulevard are major arterials in Edmonton with high vehicular traffic volume, underscoring the significance of enhancing pedestrian safety in this area.

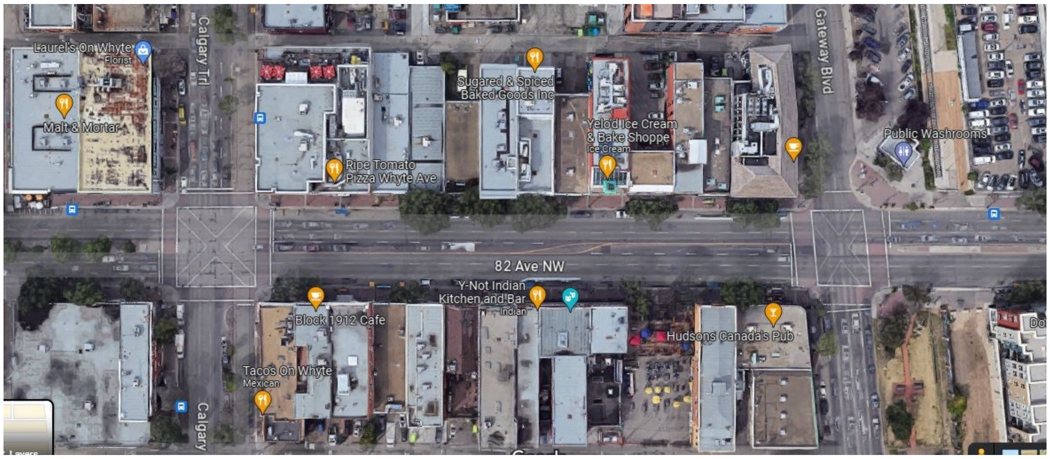

Figure 1- Map corridor

The intersection at Calgary Trail and Whyte Avenue comprises four legs, with the North and South legs running unidirectionally from North to South. On the other hand, the Gateway Boulevard and Whyte Avenue intersection also consists of four legs, but the North-South legs run one way from South to North. Both intersections are high pedestrian locations situated in a commercial and populated area. Figures 2 and 3 depict these intersections.

Figure 2- Calgary Trail & Whyte Avenue intersection

Taken from [54]

Figure 3- Gateway Boulevard & Whyte Avenue intersection

Taken from [55]

3.2 Road Users' Movement Data

Four batches of data in the form of 24-hour long videos recorded by two cameras installed at the Gateway Boulevard intersection and one camera monitoring the Calgary Trail intersection are used in the study. The first batch represents Aug. 25th and Aug. 30th in 2021 before the installation of the scramble phase. The second batch, which includes the recordings between Sep. 22nd and 27th, was collected immediately after the implementation of the scramble phase, while the third and fourth batches consist of the videos recorded around six months later, i.e., between Apr. 5th and 12th, and Apr. 22nd and 28th, respectively. Table 1 shows the summary of the period of the collected data.

The months of August and September were selected as the time period before and right after the implementation due to the high volume of summer activities and back-to-school rush, resulting in increased pedestrian traffic. Analyzing the effectiveness of the scramble phase during these months provides a better understanding of its impact on pedestrian safety. Subsequently, the month of April is selected for the evaluation of the scramble phase's impact on pedestrian safety six months after its installation.

Choosing shorter time periods for data collection, rather than continuous data collection from before the implementation of the scramble phase until six months after, is the advantage of analyzing safety based on traffic conflicts. Unlike collisions, which are rare and random, analyzing conflicts can be done within a shorter timeframe. Furthermore, collisions analysis would typically require multiple years to capture the data, which is quite reactive.

Table 1- Time period of data

Period	**Batch No.**	**Calgary Trail and 82nd Avenue**	**Gateway Boulevard and 82nd Avenue**
Before	1	25- 30 August	25-30 August
After	2	22-27 September	22-27 September
	3	6 – 12 April	5 – 11 April
	4	22-26 April	22 – 28 April

The CCTV camera installed at the Calgary Trail intersection covers all directions of the intersection; therefore, all directions are analyzed. However, at Gateway Boulevard, one of the CCTV cameras is facing south and covers Northbound (NB), Eastbound (EB), and Southbound (SB) of the intersection, while the other camera covers Westbound (WB) and NB directions. The first camera is mainly used to analyze the intersection, preventing the analyst from studying the conflicts and right turn on red violations in the WB directions. However, due to a lack of data between Apr. 5th and Apr. 11th, the second camera is used, and only WB and NB directions are analyzed.

4

Right-turn-on-red Violations

4.1 Introduction

This project aims to evaluate the safety impact of installing a scramble phase at two intersections. One key factor that can be used to assess intersection safety is the number of right-turn-on-red violations, as collisions involving turning vehicles are among the most prevalent [14]. Before the implementation of the scramble phase, drivers were permitted to turn right on red when it was safe to do so. However, after the installation of the scramble phase, turning right on red is prohibited at all times.

Right-turn-on-red violations can create conflicts between vehicles, pedestrians, and other road users, leading to serious accidents. During the pedestrian phase, when all vehicles are required to stop, unexpected right-turn-on-red violations can pose a significant threat to pedestrians crossing the intersection.

To evaluate the effectiveness of the scramble phase in reducing right-turn-on-red violations, the number of violations was counted and analyzed in this project. The analysis was conducted for three different time periods to examine any changes in right-turn-on-red violations over time.

This project aims to provide valuable insights into the safety benefits and drawbacks of implementing a scramble phase at intersections by analyzing the data on right-turn-on-red violations. The results can inform the development of evidence-based strategies to improve intersection safety and reduce the risk of accidents caused by right-turn-on-red violations.

4.2 Methodology

4.2.1 Counting Right-turn-on-red Violations

Right-turn-on-red violations were manually counted. This manual counting procedure entailed visually reviewing the videos and detecting occasions where a vehicle made an unsafe and illegal right turn despite a red light at an intersection. Every violation was documented in Excel with the incident's date, time, and details on the involved drivers. The documentation also stated whether the offence occurred during a pedestrian phase.

However, it is important to emphasize that manually counting objects can take time and potentially be subjective or inaccurate caused by human error.

Furthermore, since some right-turn violations may occur outside of the scope of the observed videos or may not be adequately apparent, manual counting may not identify all of them.

4.2.2 T-test Analysis

The t-Test is employed for comparing two sample means and assessing if there is a notable distinction between them. In the context of comparing right-turn-on-red violations between two distinct time periods, the aim is to ascertain if there has been a significant alteration in the average count of violations between them. By utilizing a t-Test, it can conclude whether the disparity in the number of violations observed is statistically significant or if it could have arisen by chance. This allows the assessment of the efficacy of any interventions or modifications made during the period between the two samples.

First, the alternative and null hypotheses are formulated as follows: The alternative hypothesis proposes a significant difference between the two periods, while the null hypothesis suggests no observable difference in the normalized count of right-turn-on-red violations between the two distinct time periods.

In order to account for the independent nature of each time period and the differing variances between them, Excel's data analysis tool employs the "t-Test: Two-Sample Assuming Unequal Variances" option. If the calculated t-value exceeds the t-critical value, the null hypothesis may be dismissed, indicating a significant difference in the number of right-turn-on-red violations between the two time periods. The data is analyzed using a two-tailed t-test with a confidence level of 90%.

4.2.3 Normalizing The Number of Right-turn-on-red Violations

Since the duration of each time period varies, i.e., the hours of the first and last days of each period are less than 24 hours due to the installation and uninstallation of the cmeras, the count is normalized by dividing it by the total number of hours and multiplying by a factor of 10 in each day to accurately demonstrate the trend of the number of right-turn-on-red violations.

The graphs depicting the results of the non-normalized count can be found in the appendix A.

4.3 Results

4.3.1 After Installation (September 2021)

To clarify, an SB violation in this study refers to a situation where a vehicle turns right onto Whyte Avenue on a red light while travelling southbound on Calgary Trail. Similarly, an EB violation occurs when a vehicle turns right onto Calgary Trail on a red light while travelling eastbound on Whyte Avenue. Figure 4 illustrate the EB and SB right turn on a diagram.

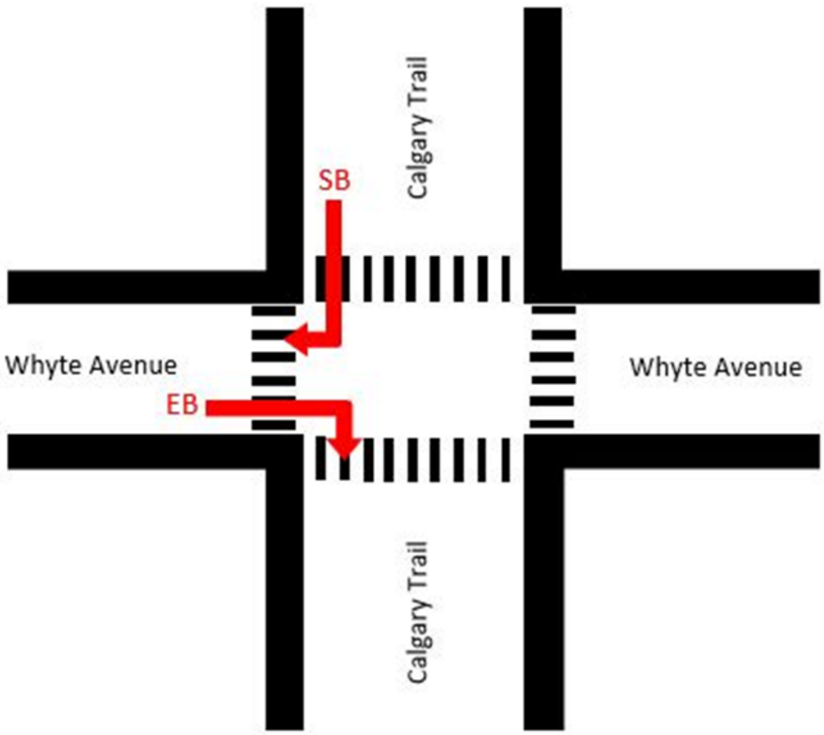

Figure 4- Directions of right-turn at Calgary Trail

At the Calgary Trail and Whyte Avenue intersection, vehicles can turn right only when travelling in the EB and SB directions. Figure 5 shows the normalized total number of right-turn-on-red violations at this intersection in each direction in September 2021, right after the implementation of the scramble phase, while Figure 6 illustrates the number of right-turn-on-red violations in the pedestrian phase only for the same period of time. As is evident in the figures, the number of EB right-turn-on-red violations was higher than SB. In addition, the number of EB violations in the pedestrian phase was also higher than the number of SB violations.

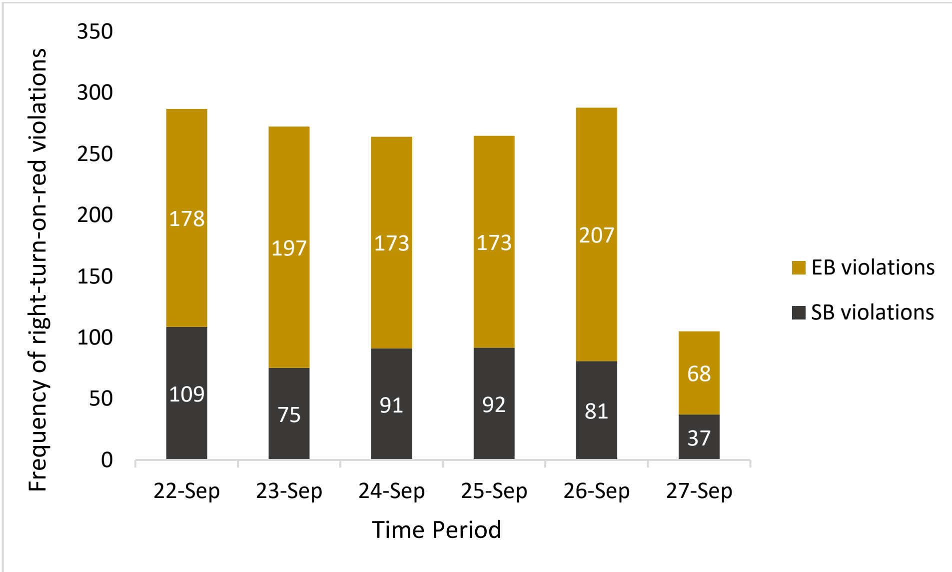

Figure 5- Normalized right turn violations at Calgary Trail & Whyte Avenue intersection between Sep. 22 - 27

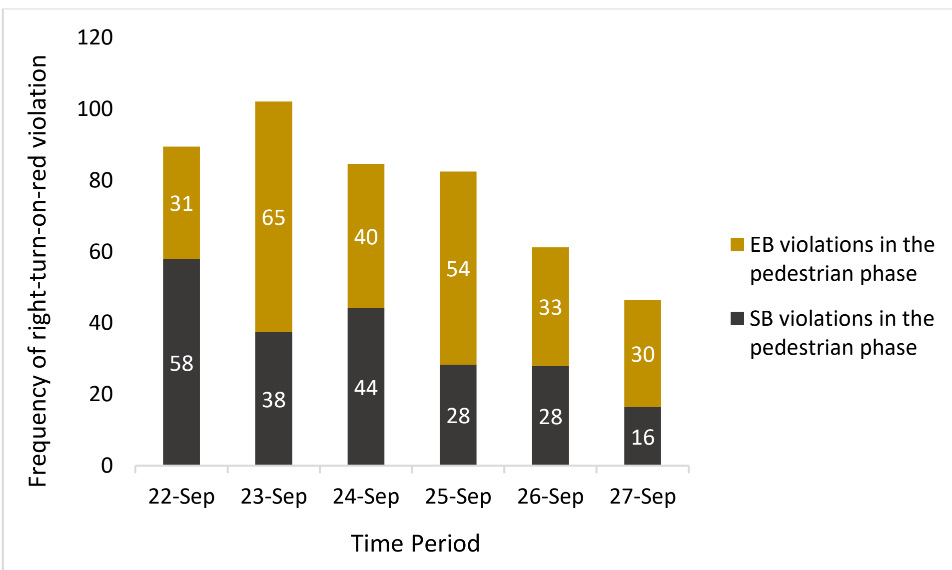

Figure 6- Normalized right turn violations in the pedestrian phase at Calgary Trail & Whyte Avenue intersection between Sep. 22 - 27

Notably, at Gateway Boulevard, an NB violation refers to a vehicle facing NB on Gateway Boulevard that turns right onto Whyte Avenue during a red light; a WB violation is a vehicle facing WB on Whyte Avenue that turns right onto Gateway Boulevard on a red light. Figure 7 illustrate the NB and WB right turn on a diagram.

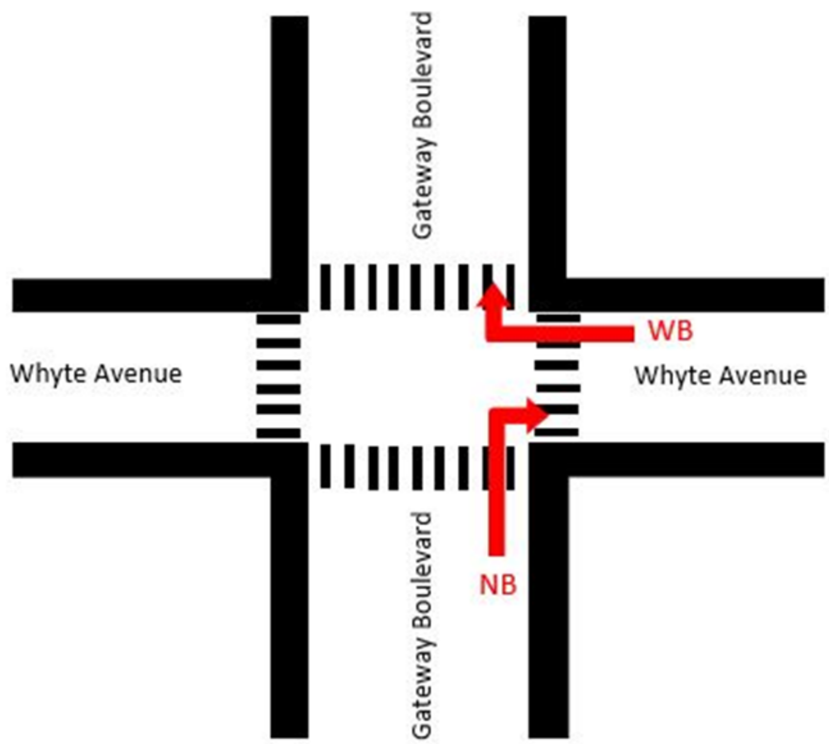

Figure 7- Directions of right-turn at Gateway Boulevard

Similarly, there are only two possible right turns for the Gateway Boulevard and Whyte Avenue intersection, i.e., WB and NB. The normalized total number of right-turn-on-red violations at this intersection in September 2021, right after the implementation of the scramble phase, is shown in Figure 8, while Figure 9 presents the right-turn-on-red violations that occurred during the pedestrian phase only. These figures illustrate that the normalized number of NB violations was significantly larger than that of WB violations. Moreover, the NB violations were higher in the pedestrian phase than in WB.

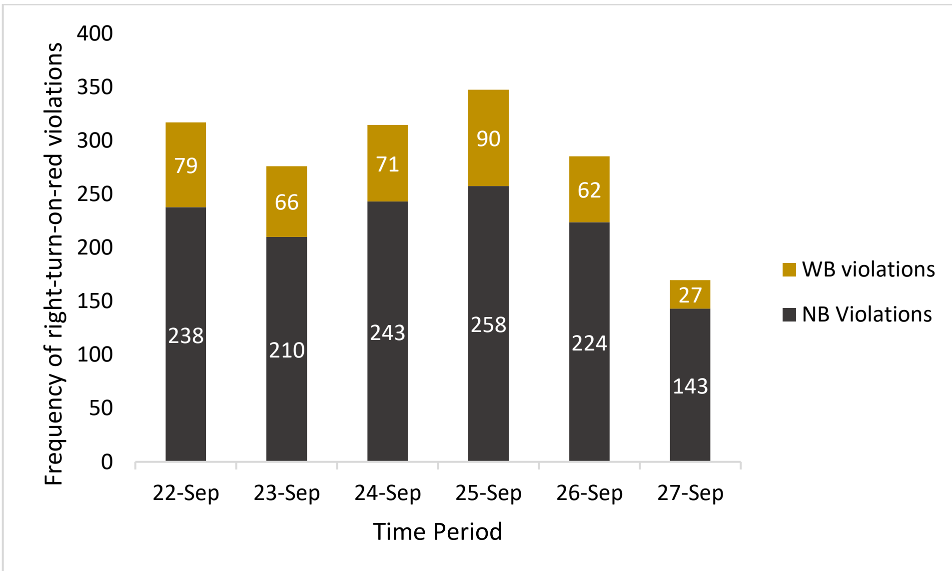

Figure 8- Normalized right turn violations at Gateway Boulevard & Whyte Avenue intersection between Sep. 22 - 27

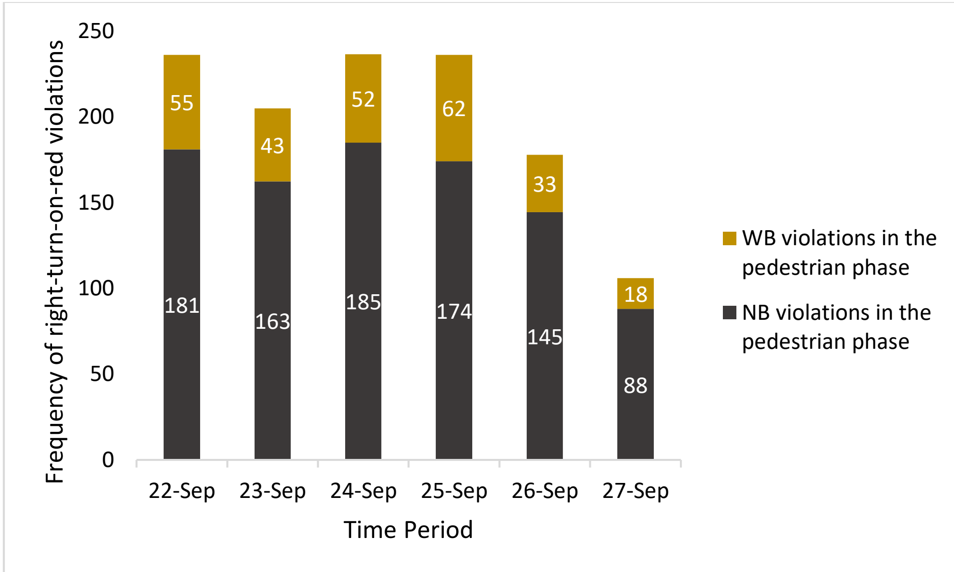

Figure 9- Normalized right turn violations in pedestrian phase at Gateway Boulevard & Whyte Avenue intersection between Sep. 22. - 27

A comparison of the results outlined in Figures 5 and 8 indicates that the normalized total number of violations at the Gateway intersection was higher than that observed at the Calgary Trail intersection.

4.3.2 After Installation (Early April 2022)

Six months after the installation, based on the analysis results conducted immediately after the installation in September, the City of Edmonton decided to install digital no-right-turn-on-red signs at both intersections. The signs were activated only during the pedestrian phase. Drivers were still permitted to turn right by yielding to other vehicles outside the pedestrian phase, similar to any regular intersection. This measure was expected to decrease the frequency of right-turn-on-red violations during the pedestrian phase. Right-turn-on-red violations were counted again at both intersections in early and late April.

Figures 10 and 11 illustrate the normalized number of right-turn-on-red violations at Calgary Trail from Apr. 6 - 12. By comparing Figures 5 and 10, it can be concluded that after six months of installation, the normalized number of right-turn-on-red violations decreased by more than 35.2%, indicating that drivers became accustomed to and respected the scramble phase. Based on Figure 11, there is no noticeable change in thenormalized number of violating vehicles in the pedestrian phase after six months.

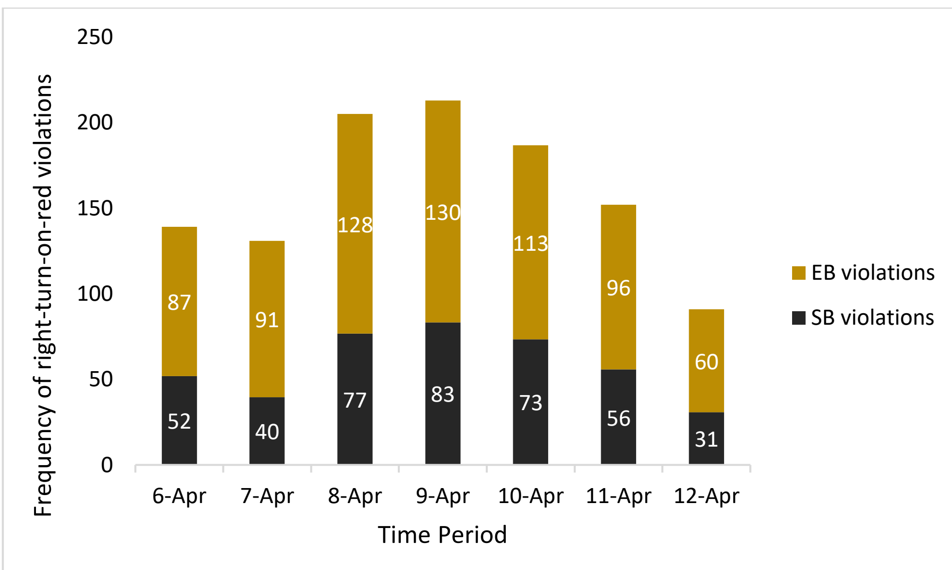

Figure 10- Normalized right turn violations at Calgary Trail & Whyte Avenue intersection between Apr. 6 - 12

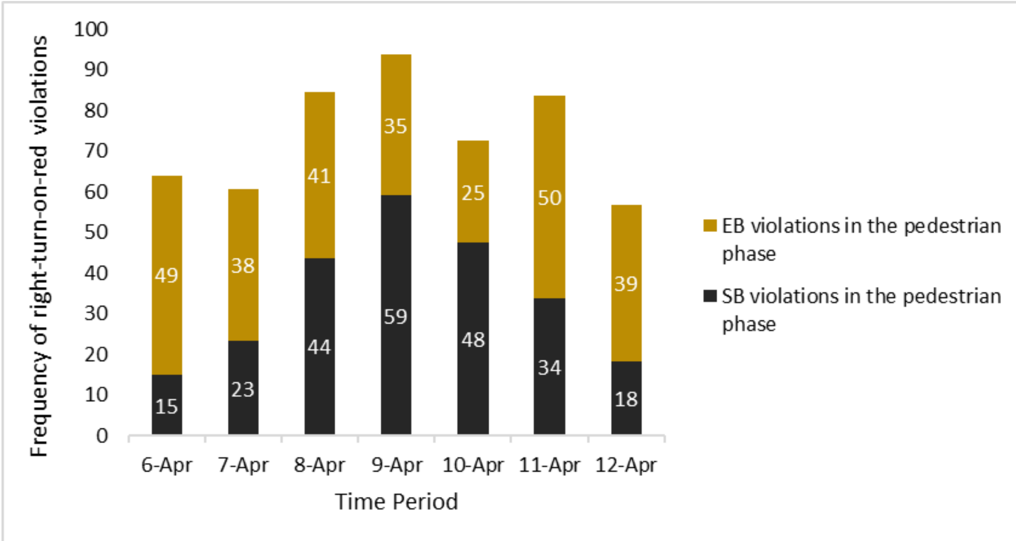

Figure 11- Normalized right turn violations during the pedestrian phase at Calgary Trail & Whyte Avenue intersection between Apr. 6 - 12

Table 2 shows the results of the t-test with 90% confidence level of the two time periods, September and Early April at Calgary Trail intersection. The mean of normalized total number of violations in September was found to be 246.93 while the mean of normalized total number in early April was 159.64. The t-value was found to be 2.63, which is greater than the t-critical value of 1.86. Therefore, the null hypothesis can be rejected, and it can be concluded with 90% confidence that there is a significant difference between the normalized total number of right-turn-on-red violations in September and early April.

Table 2- t-Test results for the the normalized total number of right-turn-on-red violations at Calgary Trail & Whyte Avenue in September & Early April

	September	**Early April**
Mean	246.93	159.64
Variance	4930.49	1944.46
Observations	6	7
Hypothesized Mean Difference	0	
df	8	
t Stat	2.63	
P(T≤ t) one-tail	0.02	
t Critical one-tail	1.40	
P(T≤ t) two-tail	0.03	
t Critical two-tail	1.86	

Table 3 shows the results of the t-Test in 90% confidence level to compare the difference of the normalized number of right-turn-on-red violations happened during the pedestrian phase at September and Early April at Calgary Trail intersection. the mean of normalized number of violations in September was 77.71 while it was 73.77 in early April. The variance for the September data was 410.74 and 193.89 for early April. The t-statistic was 0.40, and the t-critical is 1.83 which is greater than t-statistic. The p-value for a two-tailed test was 0.7, which is higher than the significance level of 0.10, indicating that there is not enough evidence to reject the null hypothesis that there is no significant difference between the mean of normalized number of right-turn-on-red violations during pedestrian phase in September and early April.

Table 3- t-Test results for the normalized number of right-turn-on-red violations during pedestrian phase at Calgary Trail & Whyte Avenue in September & Early April

	September	Early April
Mean	77.71	73.77
Variance	410.74	193.90
Observations	6	7
Hypothesized Mean Difference	0	
df	9	
t Stat	0.40	
P(T≤ t) one-tail	0.35	
t Critical one-tail	1.38	
P(T≤ t) two-tail	0.70	
t Critical two-tail	1.83	

At the Gateway Boulevard and Whyte Avenue intersection, only the number of violating vehicles in the WB direction was counted due to the unavailability of data from Apr. 5 - 11 from the camera used mainly. However, Figure 12 shows a reduction of more than 34.84% in the normalized number of violating vehicles after six months of installation in early April. Also, based on Figure 13, there is a noticeable 38.63% decline in violations during the pedestrian phase in the WB direction after six months.

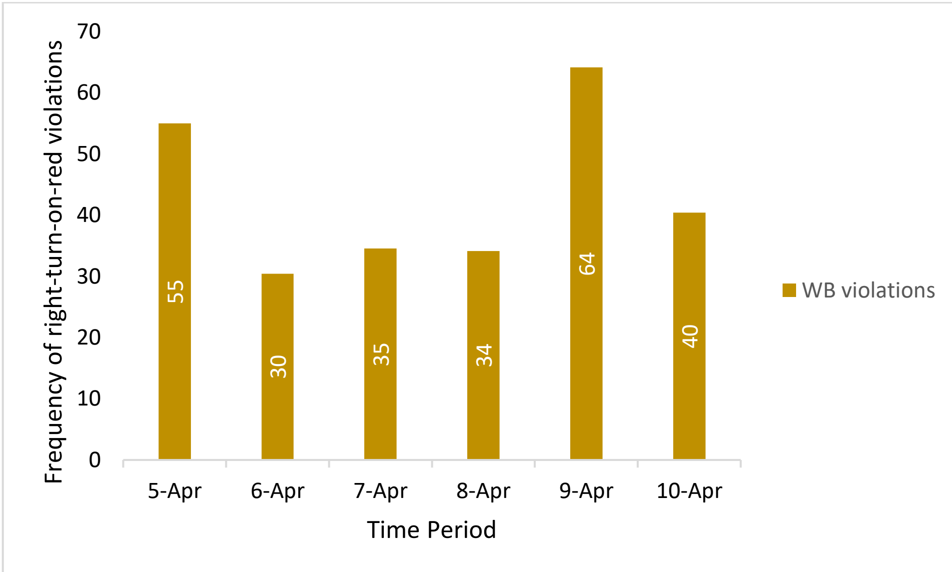

Figure 12. Normalized right turn violations at Gateway Boulevard & Whyte Avenue intersection between Apr. 5 - 10

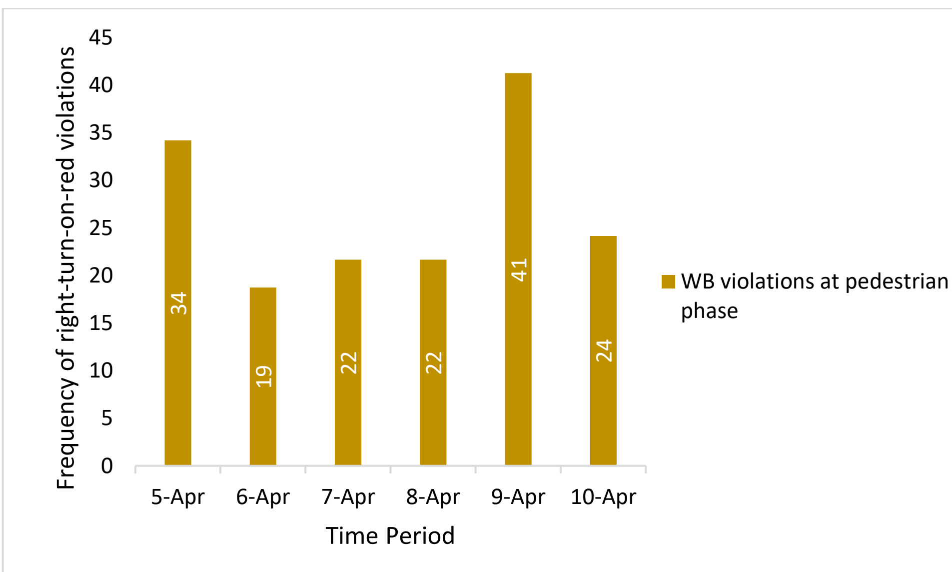

Figure 13. Normalized right turn violations in pedestrian phase at Gateway Boulevard & Whyte Avenue intersection between Apr. 5 - 10

Based on table 4, the t-Test between September and Early April at Gateway Boulevard for the normalized total number of right-turn-on-red violations with a 90% confidence level, the mean of normalized total number of violations in September (65.82) is significantly higher than that of Early April (43.13). The t-statistic value of 2.18 is greater than the t-critical value of 1.86, indicating that the null hypothesis can be rejected and there is a significant difference between the two periods in terms of the normalized number of right-turn-on-red violations. The p-value for a two-tailed test is 0.061, which is less than the alpha level of 0.1, indicating that the result is marginally significant.

Table 4- t-Test results for the normalized total number of right-turn-on-red violations at Gateway Boulevard & Whyte Avenue in September & Early April

	September	**Early April**
Mean	65.82	43.13
Variance	471.40	181.25
Observations	6	6
Hypothesized Mean Difference	0	
df	8	
t Stat	2.18	
P(T≤ t) one-tail	0.03	
t Critical one-tail	1.40	
P(T≤ t) two-tail	0.06	
t Critical two-tail	1.86	

Table 4 shows the results of the t-Test in 90% confidence level to compare the difference of the normalized number of right-turn-on-red violations during the pedestrian phase at September and Early April at Gateway Boulevard intersection. Since the calculated t-value is greater than the critical t-value (2.24> 1.86), and the p-value is less than the significance level of 0.1 (0.06< 0.1), the null hypothesis is rejected. Therefore, it can be concluded that there is a significant difference between the mean number of right-turn-on-red violations in September and Early April.

Table 5- t-Test results for the normalized number of right-turn-on-red violations during pedestrian phase at Gateway Boulevard & Whyte Avenue in September & Early April

	September	Early April
Mean	43.78	26.95
Variance	259.84	77.58
Observations	6	6
Hypothesized Mean Difference	0	
df	8	
t Stat	2.24	
P(T≤ t) one-tail	0.03	
t Critical one-tail	1.40	
P(T≤ t) two-tail	0.06	
t Critical two-tail	1.86	

4.3.3 After Installation (Late April 2022)

The last batch of data collected during seven days from Apr. 22 - 26 was analyzed for right-turn-on-red violations. Figures 14 and 15 display the results for this phase of the study. Calgary Trail has a 25.5% reduction in right-turn-on-red violations after six months in late April. The change in the normalized number of right-turn-on-red violations during the pedestrian phase after six months is insignificant.

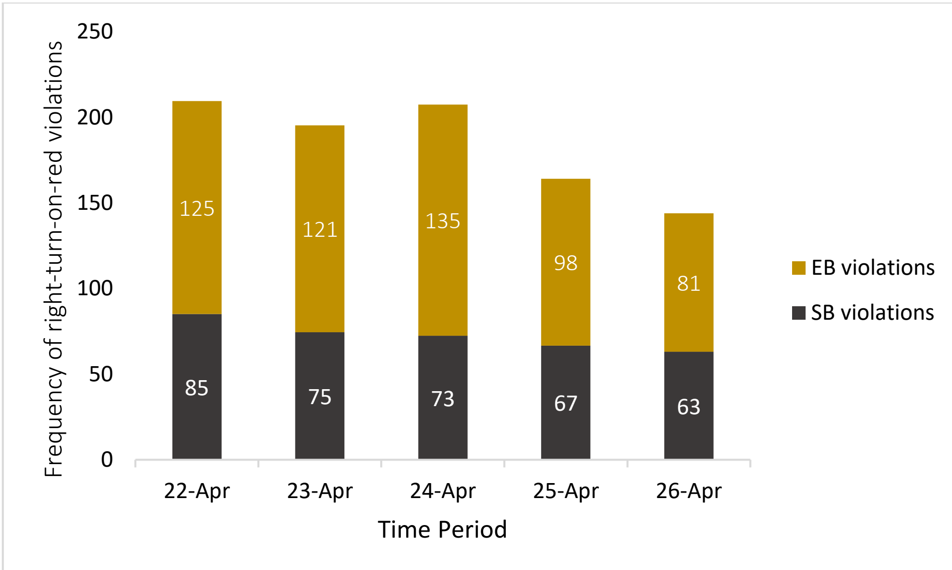

Figure 14. Normalized right turn violations at Calgary Trail & Whyte Avenue intersection between Apr. 22 - 26

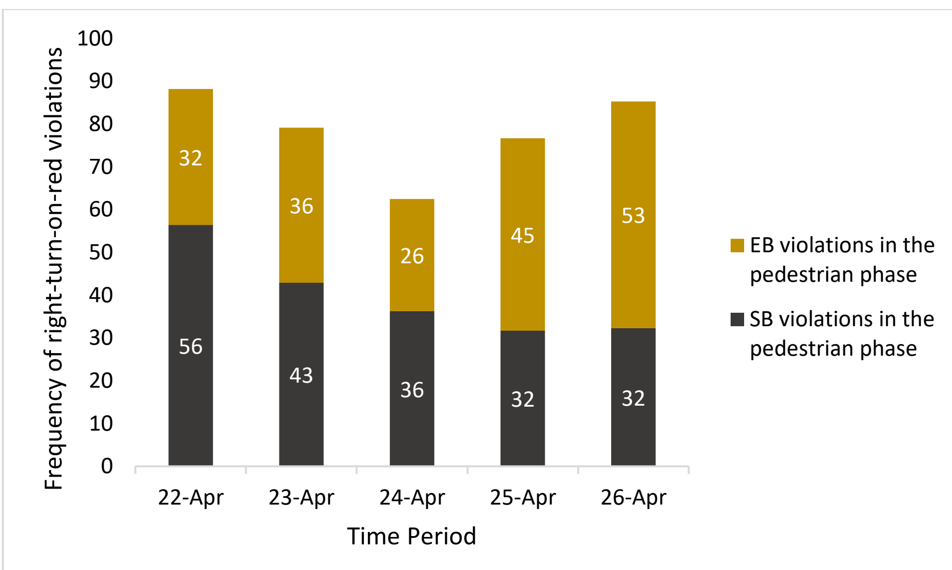

Figure 15. Normalized right turn violations in the pedestrian phase at Calgary Trail & Whyte Avenue intersection between Apr. 22 - 26

Based on the results in Table 6, the mean of normalized total number of right-turn-on-red violations at Calgary Trail intersection in September was higher than in late April, with a mean of 246.93 and 184.15 respectively. The variance in September is also higher compared to late April, with values of 4930.49 and 830.95 respectivelythe. As, Calculated t-value is greater than the one-tailed t-critical value and the two-tailed t-critical value, the null hypothesis can be rejected. Therefore, it can be concluded that there is a significant difference between the mean of normalized total number of right-turn-on-red violations in September and late April with a 90% confidence level.

Table 6- t-Test results for the normalized total number of right-turn-on-red violations at Calgary Trail & Whyte Avenue in September & Late April

	September	Late April
Mean	246.93	184.15
Variance	4930.49	830.95
Observations	6	5
Hypothesized Mean Difference	0	
df	7	
t Stat	2.00	
P(T≤ t) one-tail	0.04	
t Critical one-tail	1.41	
P(T≤ t) two-tail	0.09	
t Critical two-tail	1.89	

This table shows the results of a t-Test with a 90% confidence level comparing the normalized number of right-turn-on-red violations during pedestrian phase in September with those in late April at Calgary Trail intersection. The calculated t-statistic was -0.07, which suggests that there was no significant difference between the two time periods in terms of the number of right-turn-on-red violations. The one-tailed P-value was 0.47, which is greater than the significance level of 0.1, and the two-tailed P-value was 0.95, which is also greater than 0.1. Therefore, the null hypothesis cannot be rejected indicating no significant difference between the two time periods.

Table 7- t-Test results for normalized total number of right-turn-on-red violations during pedestrian phase at Calgary Trail & Whyte Avenue in September & Late April

	September	Late April
Mean	77.71	78.36
Variance	410.74	99.87
Observations	6	5
Hypothesized Mean Difference	0	
df	8	
t Stat	-0.07	
P(T≤ t) one-tail	0.47	
t Critical one-tail	1.40	
P(T≤ t) two-tail	0.95	
t Critical two-tail	1.86	

In late April, the average of normalized number of right turn violations dropped from 285 to 189 at Gateway Boulevard, translating to 33.68% fewer vehicles violating the red light compared with the conditions observed in September 2021. Figures 16 and 17 show the normalized number of violating vehicles each day. According to Figure 17, the normalized number of violations on red lights during the pedestrian phase, on average, decreased from 200 per day in September to 129 per day in late April.

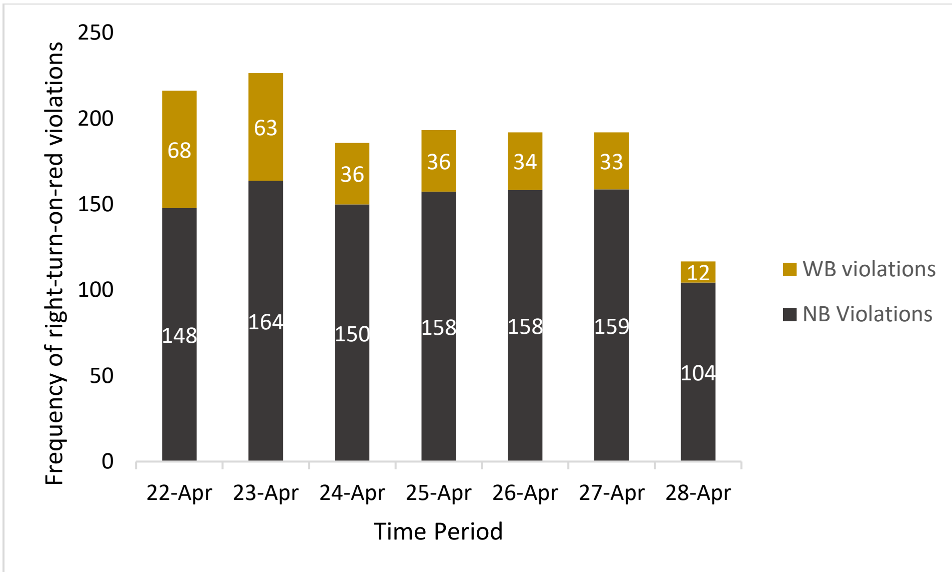

Figure 16. Normalized right turn violations at Gateway Boulevard & Whyte Avenue intersection between Apr. 22 - 28

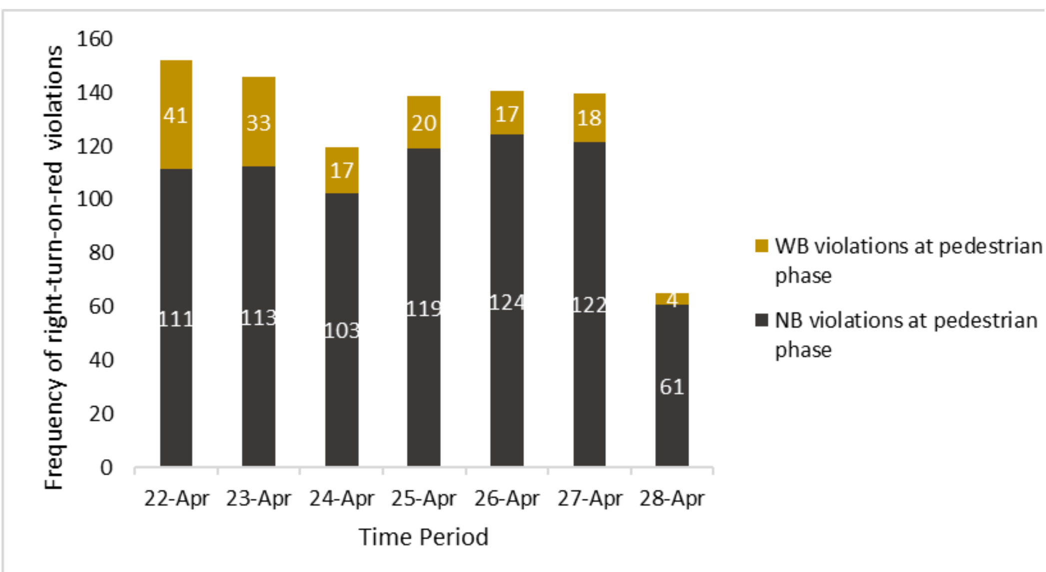

Figure 17. Normalized right turn violations in the pedestrian phase at Gateway Boulevard & Whyte Avenue intersection between Apr. 22 - 28

Table 8 presents the results of a t-Test between the normalized total number of right-turn-on-red violations in September and late April at Gateway Boulevard. The calculated t-value of 3.36 is greater than the critical t-value of 1.86, which indicates that the null hypothesis can be rejected and the difference between the two means is statistically significant.

Table 8- t-Test results for the normalized total number of right-turn-on-red violations at Gateway Boulevard & Whyte Avenue in September & Late April

	September	**Late April**
Mean	285.07	189.01
Variance	3836.33	1239.33
Observations	6	7
Hypothesized Mean Difference	0	
df	8	
t Stat	3.36	
P(T≤ t) one-tail	0.005	
t Critical one-tail	1.40	
P(T≤ t) two-tail	0.001	
t Critical two-tail	1.86	

Based on Table 9, t-Test results with a 90% confidence level, the mean of normalized number of right-turn-on-red violations during pedestrian phase in September is higher than the mean of normalized number in late April at Gateway Boulevard. The t-statistic is 2.96, which is greater than the critical value of 1.86 in the two-tail test, and the p-value is 0.02, which is less than the significance level of 0.1. Therefore, the null hypothesis can be rejected. This indicates that there was a significant difference in the mean of normalized number of violations between these two time periods, with September having a higher mean number of violations.

Table 9- t-Test results for the normalized total number of right-turn-on-red violations during pedestrian phase at Gateway Boulevard & Whyte Avenue in September & Late April

	September	Late April
Mean	199.68	128.85
Variance	2662.11	891.36
Observations	6	7
Hypothesized Mean Difference	0	
df	8	
t Stat	2.96	
P(T≤ t) one-tail	0.01	
t Critical one-tail	1.4	
P(T≤ t) two-tail	0.02	
t Critical two-tail	1.86	

4.4 Summary

Table 10 shows the average of normalized number of right-turn-on-red violations in each time period. Note that only the WB direction was analyzed in early April due to the lack of data. According to this table, the average normalized number of violating vehicles at Gateway Boulevard is higher than that on Calgary Trail. However, the declining trend could be seen at both intersections after six months, which means drivers became accustomed to the scramble phase.

Also, the statistical analysis performed using the t-Test confirmed the decreasing trend in the normalized count of right-turn-on-red violations.

Table 10. The average normalized number of total right turn violations in different time periods at each intersection

Date	The average number of total right-turn violations per day	
	Calgary Tr. & Whyte Ave.	Gateway Blvd. & Whyte Ave.
September 2021	247	285
Early April 2022	160	43
Late April 2022	184	189

Table 11 compares the normalized total violations in the pedestrian phase as a percentage of normalized total violations for both Calgary Trail and Gateway Boulevard intersections. Such a measure can appropriately represent the safety of pedestrians exposed to collisions crossing the intersection. Because the number of violations at the Gateway intersection was higher than that observed at the Calgary Trail intersection in all three time periods, those vehicles crossing Gateway were markedly more likely to violate pedestrians' right of way than those crossing Calgary Trail. Upon comparing the average percentage of violations during the pedestrian phase, it is evident that Calgary Trail experienced a slight increase from 33% to 44%, while Gateway Boulevard had a minor reduction from 69% to 68%.

Table 11. Percentage of normalized right-turn-on-red violations in the pedestrian phase

		Date	Calgary Tr. & Whyte Ave. intersection	Gateway Blvd & Whyte Ave. intersection
Before	August		Turning right on red light was permitted	
After	September 2021	22	31%	75%
		23	37%	74%
		24	32%	75%
		25	31%	68%
		26	21%	62%
		27	44%	63%
	Average		33%	69%
	Early April 2022	5	-	62%
		6	46%	62%
		7	46%	63%
		8	41%	63%
		9	44%	64%
		10	39%	60%
		11	55%	-
		12	63%	-
	Average		48 %	70%
	Late April 2022	22	42%	64%
		23	41%	64%
		24	30%	72%
		25	47%	73%
		26	59%	73%
		27	-	56%
		28	-	70%
	Average		44 %	68%

5

Automated Vehicle-Pedestrian/Vehicle-Vehicle Conflict Detection & Calculation

5.1 Introduction

Sustainable transportation aims to address the current and future needs while reducing the negative impacts associated with current vehicular-oriented transportation, such as greenhouse gas emissions. One effective approach to promoting sustainable transport is to encourage using alternative modes of transportation, such as public transit, walking, biking, or carpooling, thus reducing the number of vehicles on the road. Ensuring pedestrian safety is essential to create livable and sustainable communities. Factors that can threaten pedestrian safety include inadequate infrastructure, poorly designed or maintained roads, dangerous crossings, and distracted or impaired driving. Policies and regulations, such as enforcing speed limits and encouraging responsible road user behaviour, can be implemented to promote safe pedestrian crossings. Another effective strategy to improve intersection safety is implementing a scramble phase, which requires all vehicles to stop in all directions, allowing pedestrians to cross the intersection diagonally and conventionally with minimal risk of conflicts with vehicles. These measures can create a safer pedestrian environment, promote active transportation, and foster healthier lifestyles. Pedestrian safety research typically focuses on the conflicts between pedestrians and vehicles because collision data is infrequent and unpredictable. Moreover, evaluating collisions after they occur based on the perceptions of those involved can make it challenging to report the exact circumstances and behaviours leading up to the collision.

Using conflict data instead of collision data can provide a more comprehensive understanding of safety issues and enable researchers to predict and address potentially dangerous situations. Safety indicators such as speed, distance, and time-to-collision are used to analyze conflicts and assess the effectiveness of safety measures. By comparing the number of severe conflicts before and after implementing these measures, researchers can evaluate their impact on pedestrian safety. Prioritizing conflict data over collision data can lead to a more proactive approach to pedestrian safety and contribute to creating sustainable and livable communities.

5.2 Methodology

This section presents a detailed explanation of the research methodology utilized in the study. The approach employs advanced algorithms to track and detect road users at two intersections. A conflict detection algorithm is then implemented to identify potential conflicts during the study period at these intersections. Moreover, three safety indicators, TTC, DSPP, and TDPI, are automatically calculated during analysis and the number of serious conflicts are normalized. Additionally, an algorithm is employed to create heatmaps that illustrate the frequency of severe conflicts at the intersections.

5.2.1 Detecting and Tracking Road Users

This research employs two algorithms, namely YOLOv5 (You Only Look Once version 5) and StrongSORT (Strong Simple Online and Real-time Tracking), to detect and track road users at intersections. At intersections, it is important to detect road users accurately in the video footage. YOLOv5 is a preferred choice for this task due to its use of advanced Convolutional Neural Network (CNN) technology, resulting in high accuracy and fast detection speeds. The ability of YOLOv5 to detect multiple objects in a single frame is especially beneficial in crowded intersection scenarios where multiple objects may be present simultaneously. The detected road users are tracked across frames using StrongSORT. This algorithm incorporates labeled data, such as license plate numbers, to enhance tracking accuracy, particularly in situations where multiple objects are close together.

StrongSORT is also highly robust, capable of handling challenging conditions such as variations in lighting, background, and noise in the input data. The study used an open-source code [56] that has been slightly modified to achieve the desired outcomes.

YOLOv5 is a computer vision algorithm for detecting objects following a two-stage approach. Firstly, the algorithm divides an input image or video frame into a grid of cells and predicts a collection of bounding boxes and their corresponding object probabilities for each cell. Secondly, the algorithm uses a non-maximum suppression technique to eliminate redundant bounding boxes and select the best bounding box for each object. YOLOv5 is built on a Convolutional Neural Network (CNN) architecture [57], [58].

StrongSORT is a tracking algorithm that integrates object detection with tracking. It operates in two stages. In the first stage, the algorithm generates object proposals by matching detected objects in successive frames, and then it estimates the object's motion using a Kalman filter. In the second stage, a strong classifier based on deep learning is employed to refine the proposals generated in the first stage. The strong classifier can handle occlusions and appearance variations that challenge conventional tracking methods. The classifier is trained using online complex sample mining and re-identification techniques to improve performance [59].

Some modifications were made to the open-source code to obtain the desired results. These changes can be summarized as follows: Firstly, the output text file generated by the YOLO algorithm was modified to print object labels, such as car and person, for convenience in subsequent object implementation steps. Secondly, the left, top, right, and bottom coordinates of the bounding box were utilized, instead of the default left, top, width, and height values, to calculate the coordinates of a road user's bounding box. This change was necessary as the centre of the bounding box is needed to obtain the object coordinates, computed by taking the average of the bounding box coordinates. Finally, a two-step approach was employed to draw each road user's trajectory. First, pixel coordinates were converted to real coordinates. Second, the real coordinates were utilized to compute the trajectory, which was then drawn. The video processing was executed on the Compute Canada cloud due to the high computational requirements of this process.

5.2.2 Detecting Conflicts

All pedestrians and vehicles in each frame must be examined to detect potential collisions between pedestrians and vehicles. As each road user has its own trajectory and identification data, it is possible to determine which pairs of road users are on a collision course. First, one object is selected as a reference point for each pedestrian-vehicle or vehicle-vehicle pair to facilitate comparisons between objects. Next, the reference trajectory is subtracted from the trajectory vectors of both objects. Also, the reference point is subtracted from the point of both road users. This transforms the coordinates of the reference trajectory to the origin. In the next step, a new trajectory is also drawn from the non-reference point to the reference point, allowing for an assessment of the trajectories' parallelism and heading. The trajectories are considered parallel if their cross product is zero, and they are heading in the same direction if their dot product is positive. Due to data noise, values within an interval of 0.02 are considered acceptable for parallelism. Finally, the two road users are on a collision course if the non-reference and newly drawn trajectories are parallel and heading in the same direction. It is important to note that all identified conflicts are checked manually to ensure that there are no false positives.

5.2.3 TTC

Surrogate safety indicators can be computed following the detection of conflicts at intersections. The TTC can be determined using the speed and coordinates of each road user obtained from the YOLO output. TTC is calculated automatically using the following formula:

$$TTC = \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}{v_1 - v_2} \tag{5.1}$$

(x_1, y_1): The coordinate of the reference object

(x_2, y_2): The coordinate of the non-reference object

v_1: The speed of the reference object

v_2: The speed of the non-reference object

The result of the TTC computation is saved in a CSV file. In the final step, all TTC values are manually inspected, and any values below the threshold of 1.5 seconds [25] are classified as significant conflicts.

5.2.4 DSPP

Following the conflict detection approach described in section 5.2.2, DSPP is computed as a safety indicator exclusively focusing on vehicle-pedestrian conflicts. To remove conflicts between vehicles and other road users, YOLO results, which provide labels for each road user, are utilized to filter out pedestrian-vehicle conflicts. DSPP assumes that the vehicle stops before encountering the pedestrian. Hence the first frame in which the vehicle speed is below 1 mph (0.447 m/s) [52] is identified to calculate DSPP. Once vehicle-pedestrian conflicts are identified, DSPP can be calculated using the formula described below:

$$DSPP = \sqrt{(x_v - x_p)^2 + (y_v - y_p)^2} \tag{5.2}$$

x_v: The X-coordinate of vehicle
x_p: The X-coordinate of pedestrian
y_v: The Y-coordinate of vehicle
y_p: The Y-coordinate of pedestrian

After DSPP has been calculated for all vehicle-pedestrian conflicts and saved in a CSV file, the values are manually reviewed. DSPP values less than 1.2 meters are filtered out during this review and marked as serious conflicts.

5.2.5 TDPI

The TDPI conflict detection approach differs from the TTC and DSPP methods as it focuses solely on vehicle-pedestrian conflicts and is a temporal indicator.

Firstly, only vehicles and pedestrians are filtered, and the pedestrians are monitored. The search involves looking five seconds worth of frames into the future for each pedestrian. Their locations are stored for future comparisons to determine if the vehicle will intersect within these locations. Next, the trajectory for each vehicle is assessed to determine if it intersects with the pedestrian's future course. If they cross, that point will be considered the intersection point. The frame at which the vehicle intersects with the pedestrian trajectory ($f_{current}$) is detected, and then the number of frames it takes for the pedestrian to reach the intersection point (f_p) is calculated by moving backwards. With the frame at which the vehicle intersects the pedestrian trajectory ($f_{current}$) and the number of frames that should go back (f_p), the frames to the point of intersection of the vehicle f_v can be determined.

$$f_v = f_{current} - f_p \tag{5.3}$$

f_v: The number of frames the vehicle takes to reach the intersection point.

f_{curren}: The frame when the vehicle reaches the intersection point.

f_p: The number of frames the pedestrian takes to reach the intersection point.

After detecting conflicts between vehicles and pedestrians, TDPI could be calculated by the following formula:

$$TDPI = \frac{f_v - f_p}{f_{ps}} \tag{5.4}$$

f_{ps}: The number of frames per second

According to the YOLO output, the number of frames per second for the data in this research is 30. Once the TDPI has been computed for all identified conflicts, the results are recorded in a CSV file and reviewed manually. Conflicts with a TDPI value of less than 2.5 seconds are considered serious and filtered out.

5.2.6 Normalizing The Number of Serious Conflicts

To accurately show the trend of serious conflicts over time, the number of incidents is normalized by dividing it by the total number of hours and multiplying it by a factor of 100. This is necessary because the time periods being compared have different durations and the first and last days of each period may have fewer than 24 hours. Graphs illustrating the trend of non-normalized serious conflicts can be found in Appendix B

5.2.7 Generating Heatmaps

The process of creating heatmaps of the number of serious conflicts at the intersections involves multiple steps. It starts with defining a local coordinate system based on converting a coordinate in latitude and longitude obtained from Google Earth to UTM, where the east and north directions are measured in meters from a reference point. A plane is then defined by locating landmark points in the image and finding their meter distances in the east and north directions from a reference point using Google Earth. The z-coordinate of the plane points is assumed to be 0.

Using OpenCV functions, the matrix of intrinsic parameters is obtained from the image and plane points, followed by the rotation and translation vectors.

The rotation and translation vectors are further refined to obtain the rotation matrix, which is concatenated with the translation vector to get the matrix of extrinsic parameters.

With the matrices, a world point (lat, lon) can be converted to a local coordinate system and the corresponding pixel coordinate of a conflict can be obtained by multiplying the matrices and then normalizing by z.

The heatmap used in this program is a Gaussian heatmap, created by forming a 2D Gaussian kernel with coordinates from the kernel's center and applying 2D convolution with the Gaussian kernel and the 2D histogram of conflicts. The heat values are then normalized from 0 to 255 using OpenCV and a colormap is applied. Zero heat values are ignored to avoid a blue background. The heatmap is overlaid on the intersection image.

The colorbar of the heatmap is generated using to represent the 2D histogram in bins. The number of conflicts is normalized, and a colormap is applied to the normalized conflicts.

5.3 Results

5.3.1 TTC

This study defines serious conflicts based on TTC as a conflict in which the TTC value is less than 1.5 seconds and counts the number of severe conflicts before (from Aug. 25 - 30, 2021) and after (from Sep. 22 - 27, 2021; Apr. 6 - 12, 2022; and Apr. 22 - 26, 2022) implementing the scramble phase.

Figure 18 displays the normalized number of severe conflicts that occurred before and after the scramble phase was installed at the intersection of Calgary Trail and Whyte Avenue. The figure reveals six severe vehicle-vehicle and pedestrian-vehicle conflicts in August before the installation, which dropped to only one after the implementation. This number remained steady in both early and late April after six months.

Figures 19, 20, 21, and 22 display heatmaps based on TTC that reveal the location of non-normalized severe conflicts at the Calgary Trail intersection. The color of the heatmaps represents the frequency of the conflicts, with warmer colors indicating a higher number of incidents. Before the scramble phase was installed, three severe conflicts occurred in the southern part, three serious conflicts happened in eastern part and one conflict happened in western part of the intersection in August. After installation, only one serious conflict occured in the eastern part in September. In early and late April, only one severe conflict occured in the western and southern parts of the intersection, respectively.

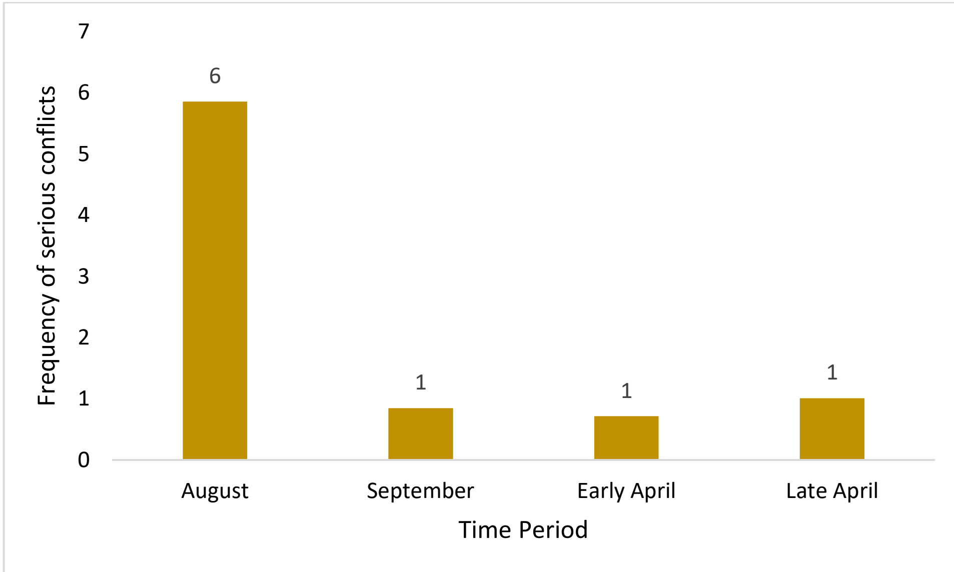

Figure 18. Normalized number of Serious Conflicts based on TTC at Calgary Trail & Whyte Avenue intersection

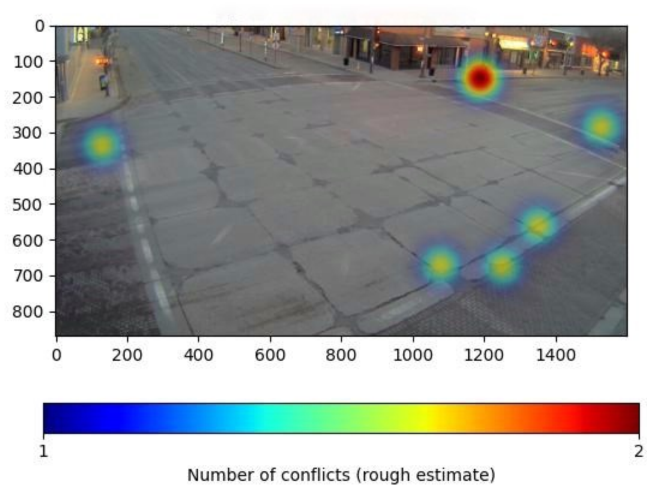

Figure 19. Heatmap of Serious Conflicts based on TTC at Calgary Trail and Whyte Avenue in August

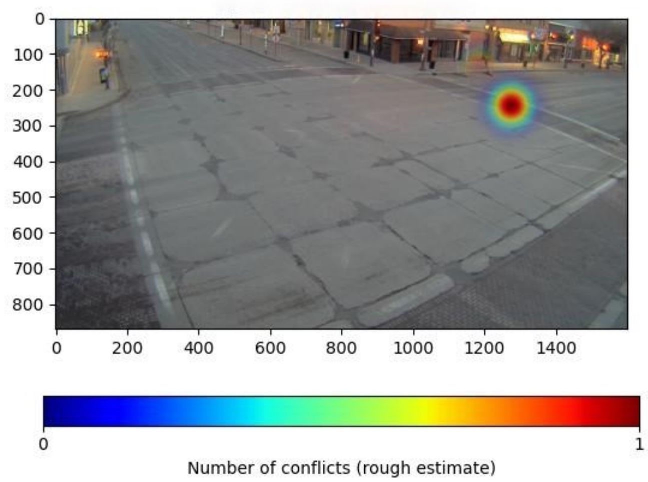

Figure 20. Heatmap of Serious Conflicts based on TTC at Calgary Trail and Whyte Avenue in September

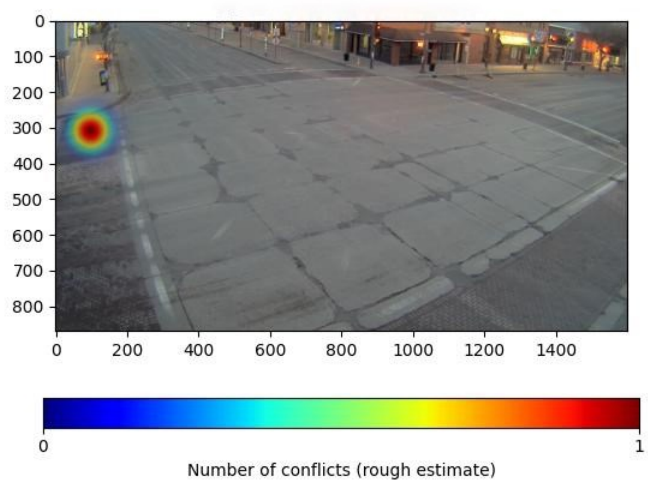

Figure 21. Heatmap of Serious Conflicts based on TTC at Calgary Trail and Whyte Avenue in Early April

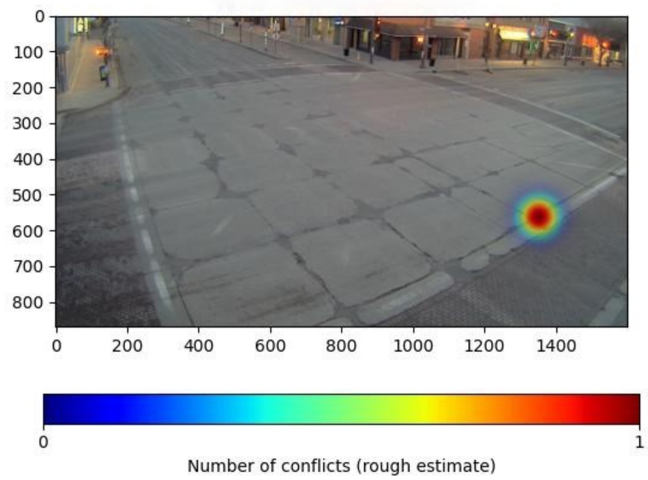

Figure 22. Heatmap of Serious Conflicts based on TTC at Calgary Trail and Whyte Avenue in Late April

At Gateway Boulevard and Whyte Avenue intersection, the TTC value for each conflict is calculated, and Figure 23 displays the normalized number of severe conflicts before and after implementing the scramble phase. The figure shows there were 10 severe conflicts before the installation, which decreased by 50% to five after the installation. The reduction in severe conflicts continued for six months, and it is evident that the number of severe conflicts based on TTC was three in early April, and it dropped to just one conflict by late April.

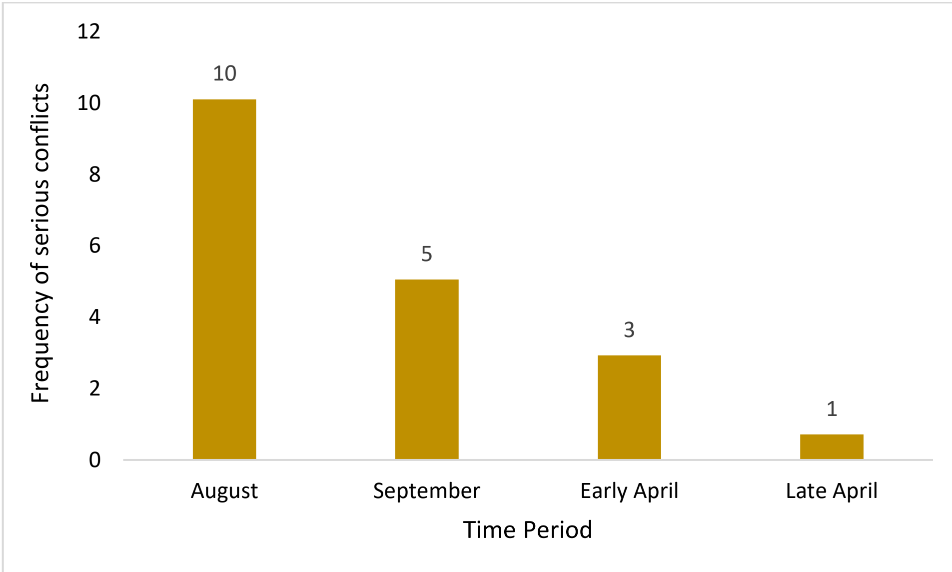

Figure 23. Normalized number of Serious Conflicts based on TTC at Gateway Boulevard & Whyte Avenue intersection

The heatmaps illustrated in Figures 24, 25, 26, and 27 exhibit the TTC-based distribution of serious conflicts transpiring at the intersection of Gateway Boulevard and Whyte Avenue. During August, the eastern portion of the intersection saw 10 severe incidents, while only two took place in the northern part. Subsequent to the installation of safety measures, the frequency of severe conflicts declined, with only five occured in the eastern sector and one occurring in the northern segment. Six months after installation, three serious conflicts occurred in the northern part, with one taking place in the western section. In Late April, only one serious conflict occurred in the northern area of the intersection.

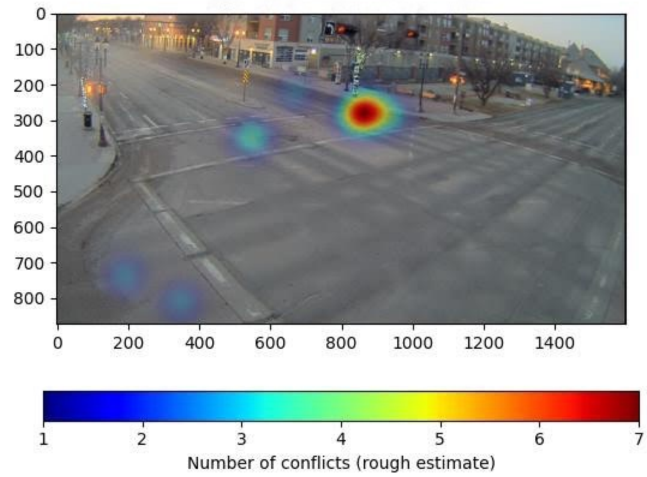

Figure 24. Heatmap of Serious Conflicts based on TTC at Gateway Boulevard and Whyte Avenue in August

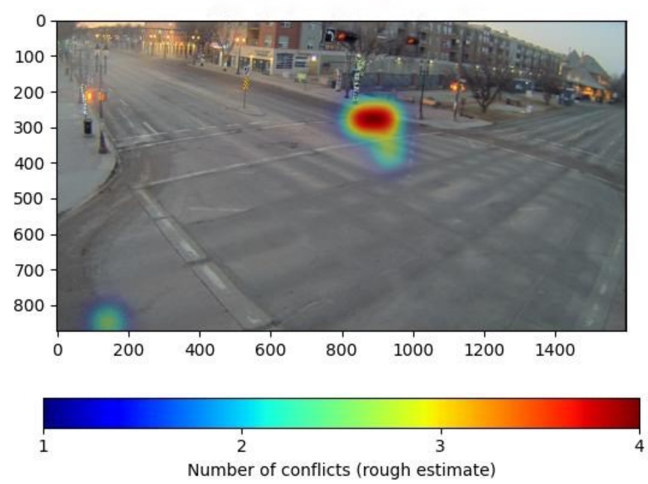

Figure 25. Heatmap of Serious Conflicts based on TTC at Gateway Boulevard and Whyte Avenue in September

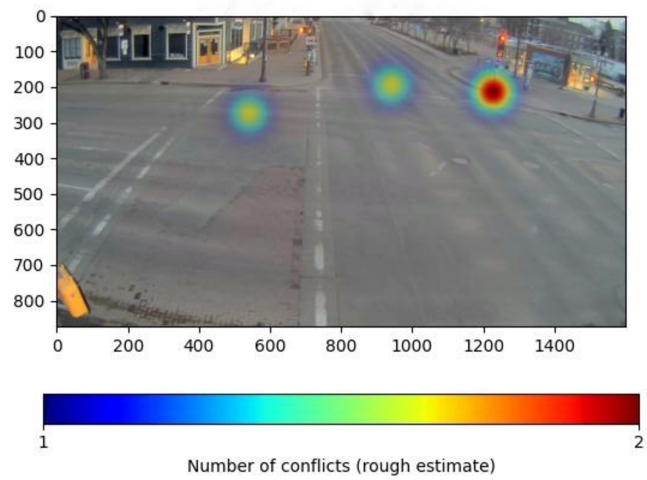

Figure 26. Heatmap of Serious Conflicts based on TTC at Gateway Boulevard and Whyte Avenue in Early April

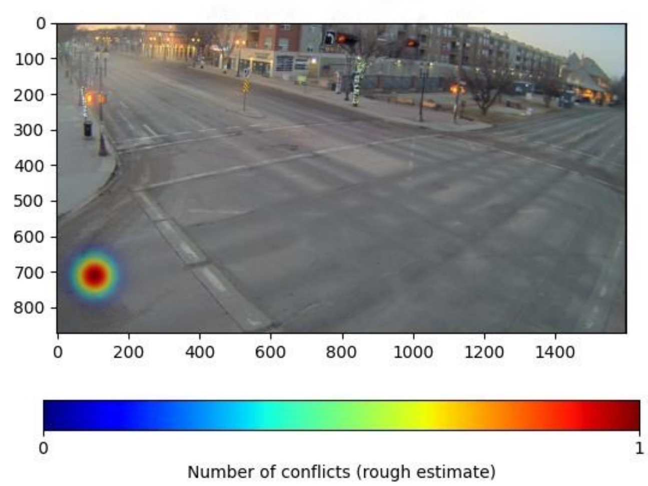

Figure 27. Heatmap of Serious Conflicts based on TTC at Gateway Boulevard and Whyte Avenue in Late April

By comparing Figures 18 and 23, it can be inferred that the normalized number of severe conflicts based on TTC was higher at the Gateway Boulevard intersection before implementing the scramble phase compared to the Calgary Trail intersection. However, six months after the installation, they had the same number of serious conflicts, as shown in late April.

Upon a comparative analysis of the heatmaps for each intersection, it was observed that the serious conflicts at the Calgary Trail intersection were scattered across multiple areas, whereas the majority of the severe incidents at the Gateway Boulevard intersection were localized in the eastern parts of the intersection.

5.3.2 TDPI

TDPI is a measure that focuses solely on collisions between pedestrians and vehicles. The TDPI value for each incident is calculated automatically, and if the value is less than 2.5 seconds, the conflict is classified as severe.

All conflicts before and after the installation at the Calgary Trail and Whyte Avenue intersection were detected and calculated. The normalized number of severe collisions based on TDPI is presented in Figure 28. As per the figure, in August, there were three severe collisions before the installation. After the installation, the number reduced to one, which remained consistent for six months until early April. However, no severe collisions between vehicles and pedestrians were detected in late April.

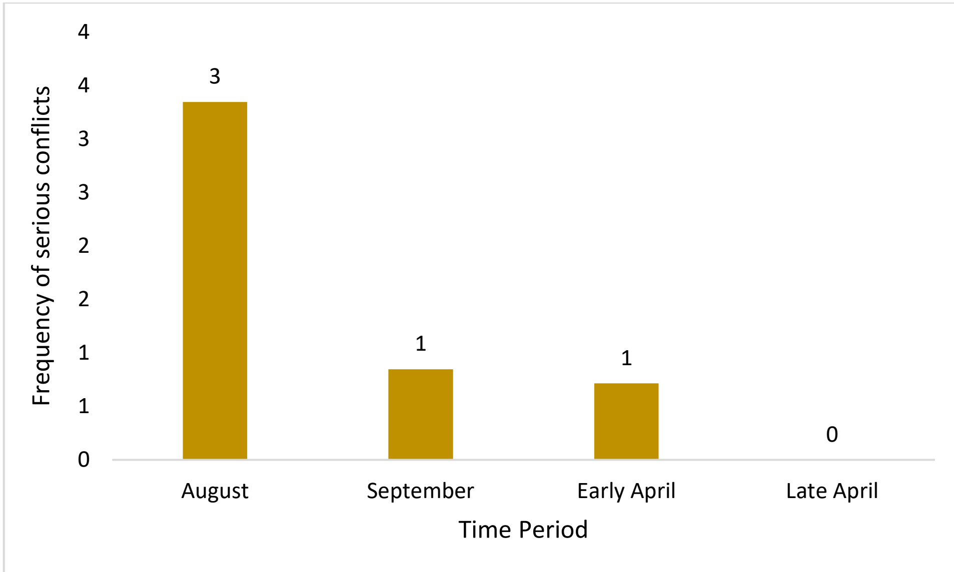

Figure 28. Normalized number of Serious Conflicts based on TDPI at Calgary Trail & Whyte Avenue intersection

The heatmaps displayed in Figures 29, 30, and 31 showcase the TDPI-based distribution of the non-normalized number of severe conflicts that took place at the Calgary Trail intersection. Prior to the installation of safety measures, two severe incidents occured in the middle of the intersection, while two occurred in the eastern sector. Following the implementation of the scramble phase in September, only one serious conflict occurred in the eastern region. In Early April, the only severe conflict took place in the southern part of the intersection.

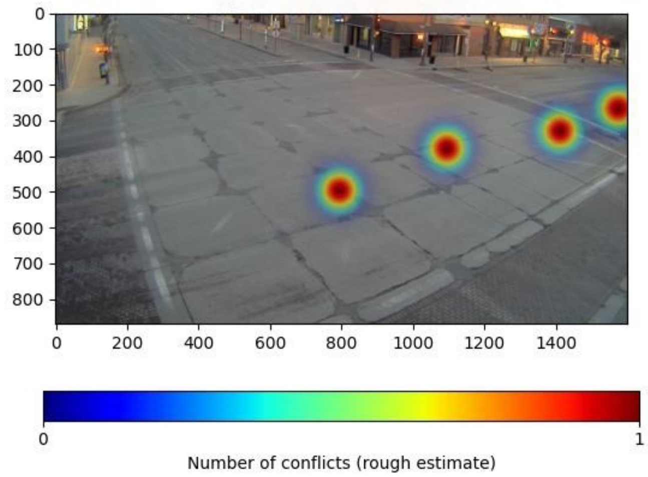

Figure 29. Heatmap of Serious Conflicts based on TDPI at Calgary Trail and Whyte Avenue in August

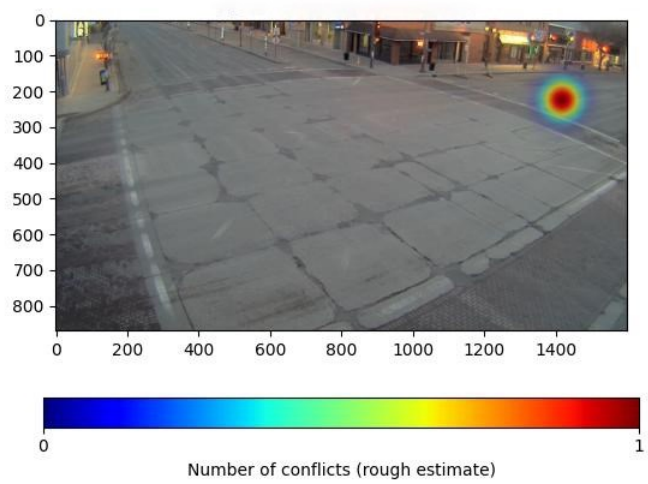

Figure 30. Heatmap of Serious Conflicts based on TDPI at Calgary Trail and Whyte Avenue in September

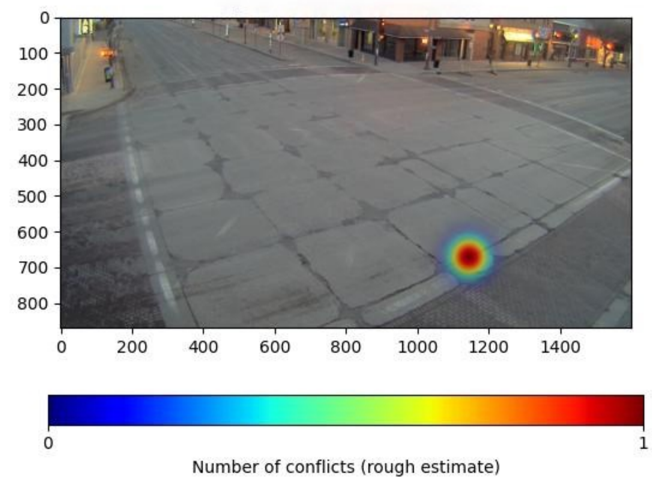

Figure 31. Heatmap of Serious Conflicts based on TDPI at Calgary Trail and Whyte Avenue in Early April

The TDPI value is calculated for each pedestrian-vehicle conflict at Gateway Boulevard, and the normalized number of severe conflicts is tallied for each time frame. Figure 32 shows eight severe conflicts between pedestrians and vehicles before the scramble phase was installed, but this number decreased by 25% to six in September after its implementation. While no severe conflicts were observed in early April, one was recorded in late April.

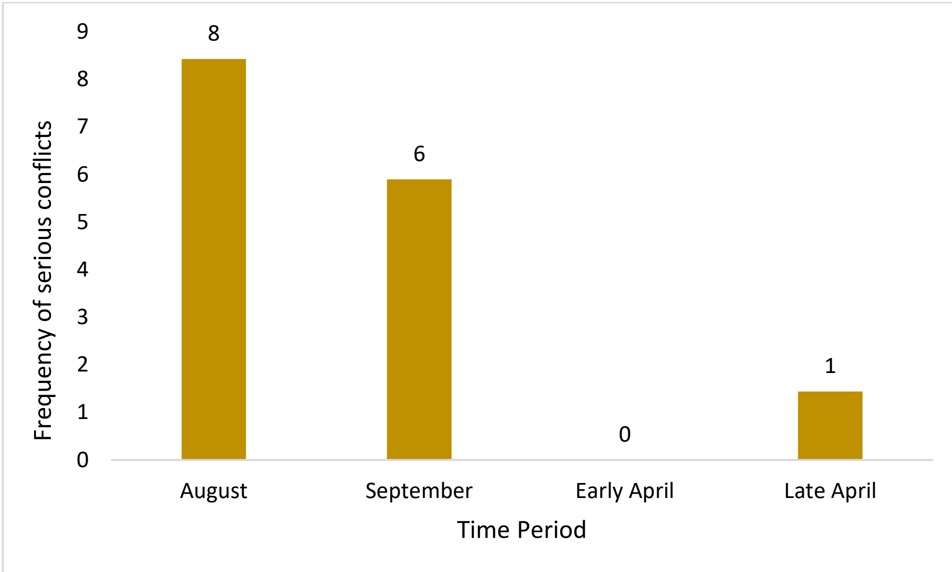

Figure 32. Normalized number of Serious Conflicts based on TDPI at Gateway Boulevard & Whyte Avenue intersection

The heatmaps illustrated in Figures 33, 34, and 35 represent the TDPI-based distribution of the normalized number of severe conflicts at the Gateway Boulevard intersection. Prior to the installation of the scramble phase, seven severe incidents took place in the eastern section of the intersection, two in the northern region, and one in the middle. Following the implementation of the safety measure in September, six severe conflicts occurred in the eastern part, while only one took place in the middle. After six months had elapsed, in Late April, one serious conflict occurred in the eastern sector and another occurred in the northern section of the intersection.

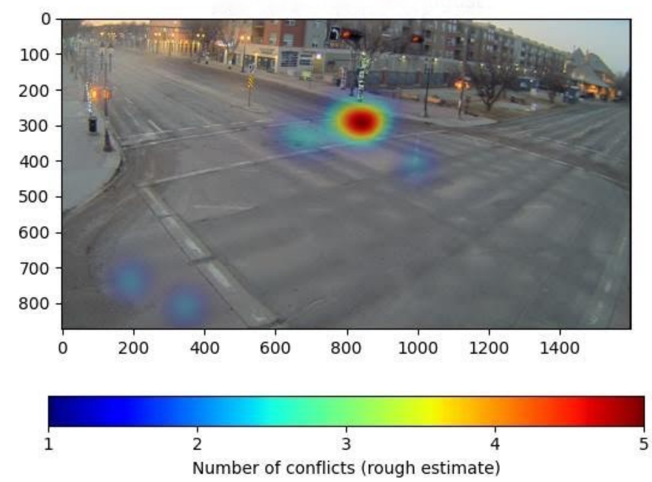

Figure 33. Heatmap of Serious Conflicts based on TDPI at Gateway Boulevard and Whyte Avenue in August

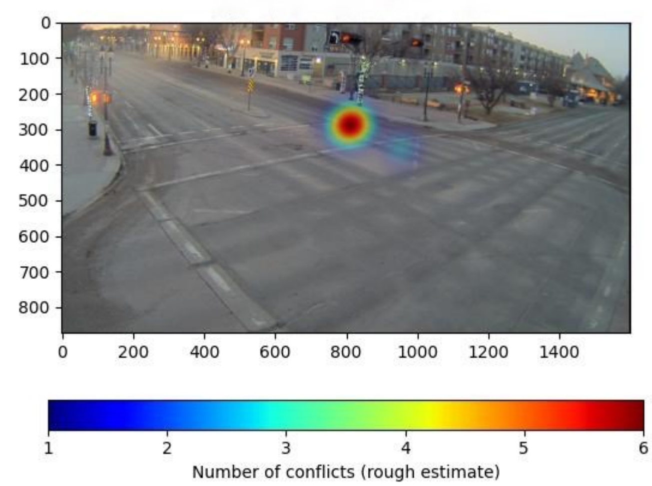

Figure 34. Heatmap of Serious Conflicts based on TDPI at Gateway Boulevard and Whyte Avenue in September

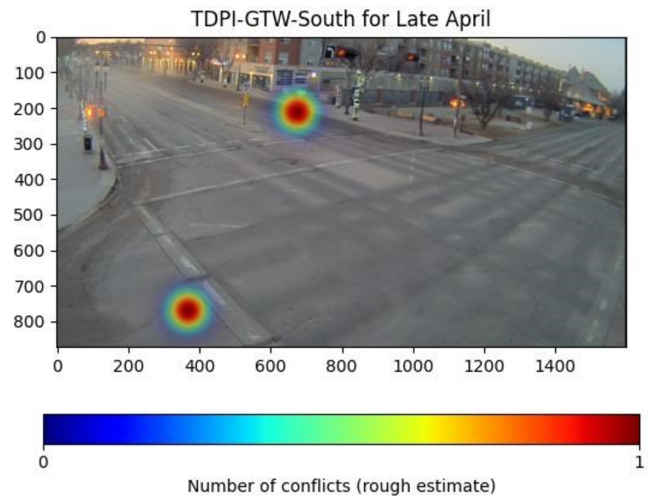

Figure 35. Heatmap of Serious Conflicts based on TDPI at Gateway Boulevard and Whyte Avenue in Late April

By comparing Figures 28 and 32, it is evident that the normalized number of severe conflicts based on TDPI was higher at Gateway Boulevard compared to Calgary Trail, both before and after the installation of the scramble phase.

The heatmaps depicting the locations of serious conflicts reveal that, at Calgary Trail intersection, such incidents took place at the eastern, middle, and southern parts of the intersection, implying that the northern and western portions are comparatively safer. Conversely, at Gateway Boulevard intersection, the majority of severe conflicts occurred in the eastern and northern regions of the intersection, signifying that these areas, particularly the eastern part, are more prone to serious conflicts than other sections.

5.3.3 DSPP

The DSPP indicator was employed to evaluate the safety impact of installing the scramble phase. Unlike TTC, this spatial indicator solely focuses on conflicts between vehicles and pedestrians, similar to TDPI. Any conflict with a DSPP value less than 1.2 m between a vehicle and pedestrian is classified as severe.

The findings of the DSPP calculations at Calgary Trail and Whyte Avenue are presented in Figure 36. Prior to the implementation of the scramble phase, there were five severe conflicts in August 2021. However, immediately after its implementation, this number decreased to two. In Early April this number reduced to 1. Subsequently, in Late April, no serious conflict based on DSPP was recorded.

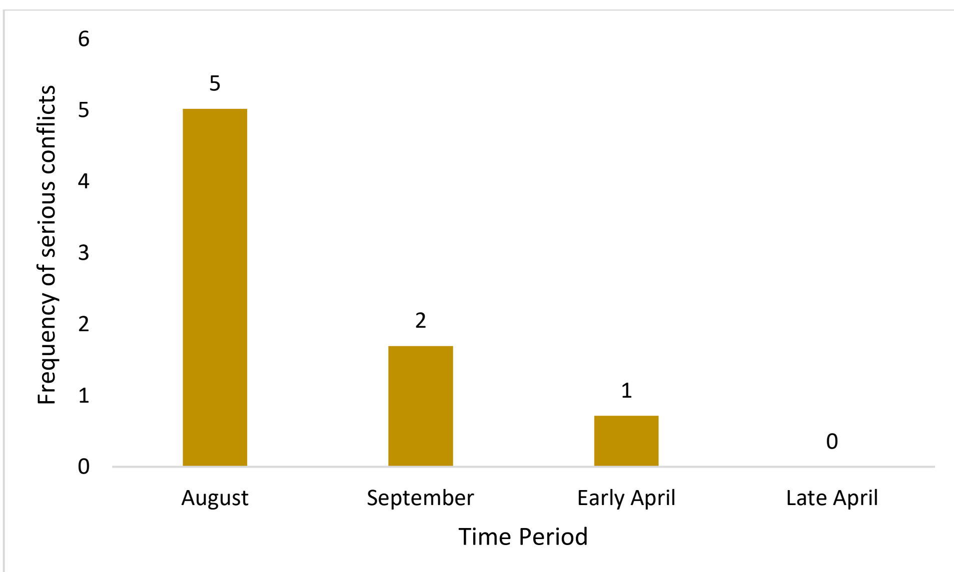

Figure 36. Normalized number of Serious Conflicts based on DSPP at Calgary Trail & Whyte Avenue intersection

Heatmaps based on DSPP at Calgary Trail intersection are displayed in Figures 37, 38, and 39. Prior to the scramble phase installation, three serious conflicts were reported in the middle of the intersection, while two and one serious incidents were observed in the eastern and southern parts, respectively. After the implementation, one serious conflict occurred in the southern and one severe conflict took place in eastern parts of the intersection in September. After six months of the installation, only one severe incident was detected in the southern part of the intersection.

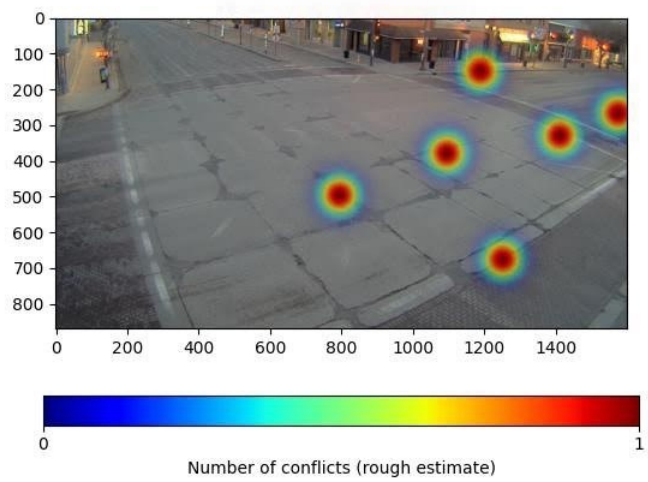

Figure 37. Heatmap of Serious Conflicts based on DSPP at Calgary Trail and Whyte Avenue in August

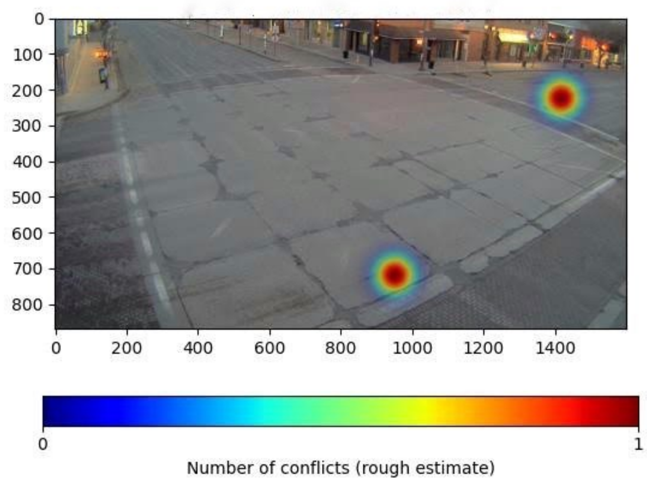

Figure 38. Heatmap of Serious Conflicts based on DSPP at Calgary Trail and Whyte Avenue in September

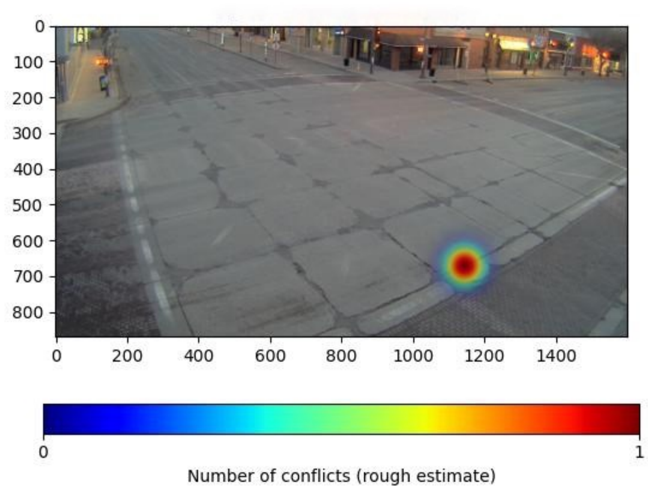

Figure 39. Heatmap of Serious Conflicts based on DSPP at Calgary Trail and Whyte Avenue in Early April

The DSPP indicator was computed for all identified pedestrian-vehicle conflicts at Gateway Boulevard and Whyte Avenue, with the related results for the normalized number of severe conflicts based on DSPP displayed in Figure 40. The figure indicates that 9 severe conflicts were identified in August before the installation, which reduced to six conflicts in September following the installation. After six months, there was a reduction of over 85% compared to the previous September, with only one serious conflicts detected in April.

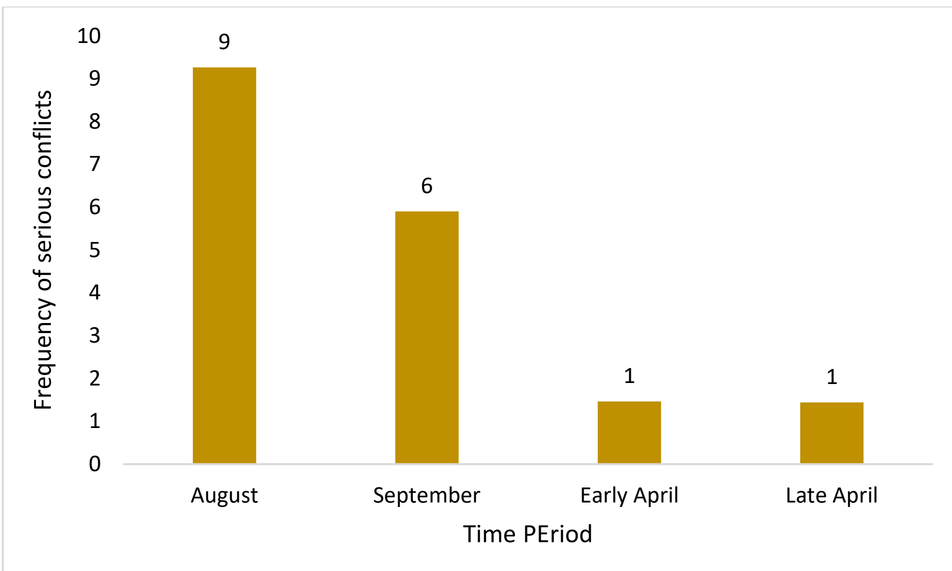

Figure 40. Serious Conflicts based on DSPP at Gateway Boulevard & Whyte Avenue intersection

The heatmaps based on DSPP at Gateway Boulevard and Whyte Avenue intersection are presented in Figures 41, 42, 43, and 44. In August, eight serious conflicts occurred in the eastern parts of the intersection, while two severe incidents took place in northern parts and one occurred in the middle of the intersection. In September, there were six severe conflicts in the eastern part, with only one serious conflict happening in the middle of the intersection. After six months, in early April, one conflict happened in the northern parts and another one in the western part of the intersection. In late April, one serious incident occurred in the eastern part, and another one in the northern part of the intersection.

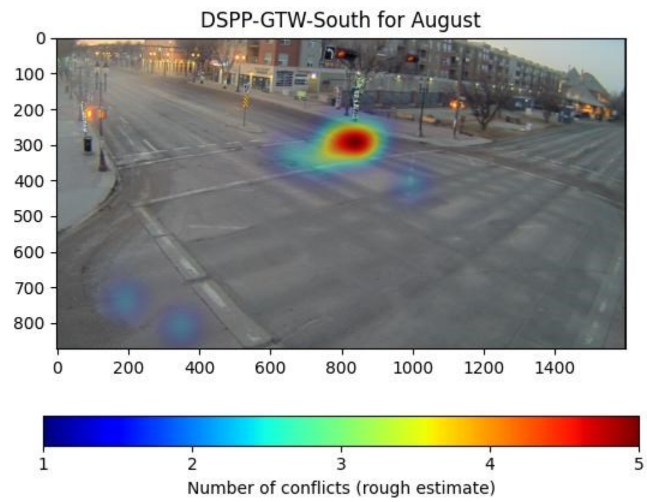

Figure 41. Heatmap of Serious Conflicts based on DSPP at Gateway Boulevard and Whyte Avenue in August

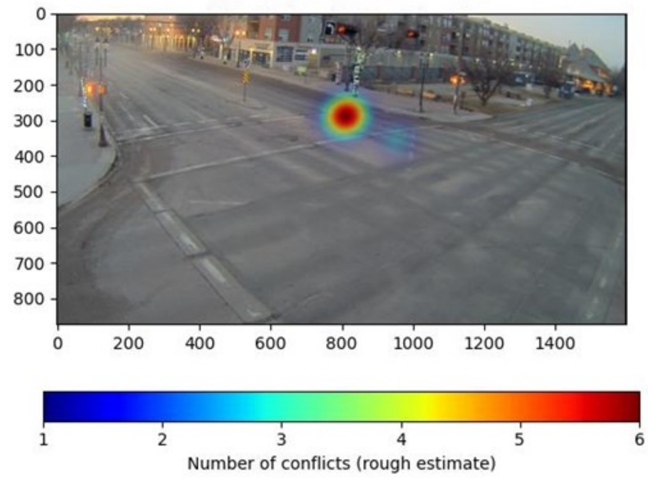

Figure 42. Heatmap of Serious Conflicts based on DSPP at Gateway Boulevard and Whyte Avenue in September

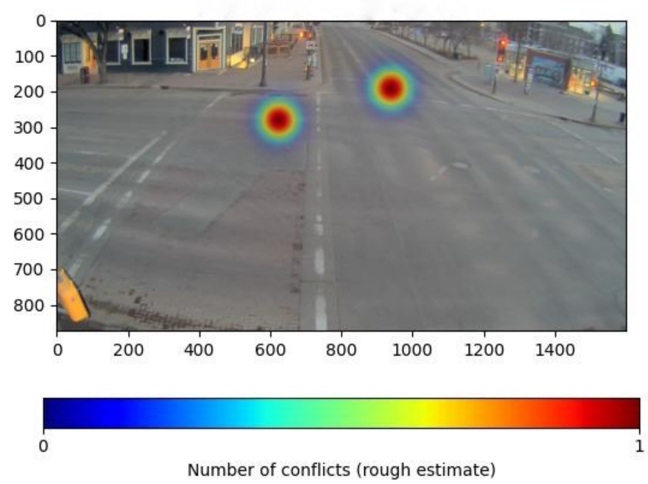

Figure 43. Heatmap of Serious Conflicts based on DSPP at Calgary Trail and Whyte Avenue in Early April

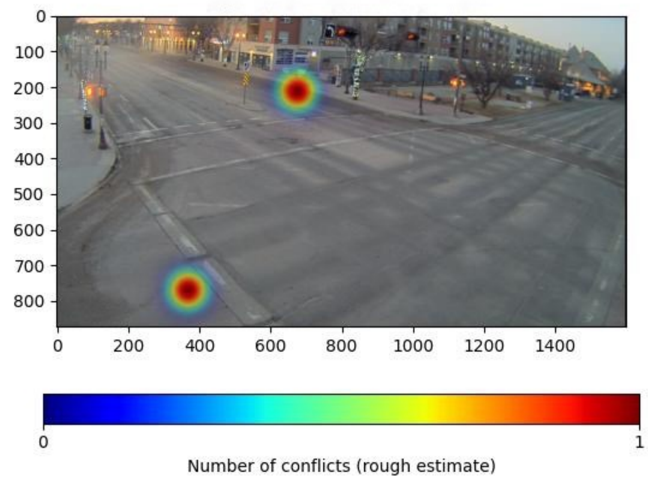

Figure 44. Heatmap of Serious Conflicts based on DSPP at Gateway Boulevard and Whyte Avenue in Late April

After comparing the DSPP results at the Calgary Trail and Gateway Boulevard intersections, it can be inferred that the normalized number of severe conflicts was reduced at both intersections after the installation of the scramble phase.

When comparing the heatmaps based on DSPP at both intersections, it is evident that the southern and eastern parts of the Calgary Trail and Whyte Avenue intersection are more prone to serious conflicts. While, the eastern parts of the Gateway Boulevard intersection are more hazardous than other areas of the intersection.

5.4 Summary

Tables 12 and 13 demonstrate a decrease in the normalized frequency of severe conflicts at both intersections after the implementation of the scramble phase, presented as a percentage reduction based on the three indicators: TTC, TDPI, and DSPPT. It is worth noting that the numbers shown in the rows labelled 'Six months later' (Tables 12 and 13) represent the normalized number of severe conflicts detected in late April. Notably, at Calgary Trail and Whyte Avenue, there was a reduction of over 60% in severe conflicts based on all three indicators merely one month after the installation. In contrast, at Gateway Boulevard, the reduction based on TTC, TDPI, and DSPP was less than or equal to 50%. Despite the significant decrease at the Calgary Trail intersection, amounting to 100% after six months in late April, according to TDPI and DSPP, the reduction was only 87.5% and 88.8%, respectively, at Gateway Boulevard.

The heatmaps based on all three indicators show that the eastern and southern parts of Calgary Trail intersection are the regions were serious conflicts were more likely to occur. Meanwhile, at the Gateway Boulevard intersection, the majority of serious conflicts occurred in the eastern and northern part.

As a result of the varying number of days and hours in the first and last days of each time period, the count of serious conflicts at both intersections was normalized by dividing them by the hour of each day. This normalization process has been documented in the appendix B, and the results demonstrate a clear downward trend in the count of serious conflicts.

Table 12. Reduction percentage of normalized number of serious conflicts at Calgary Trail and Whyte Avenue intersection

	TTC	TDPI	DSPP
One month later	83.3 %	66.6 %	60 %
Six months later	83.3 %	100 %	100 %

Table 13. Reduction percentage of normalized number of serious conflicts at Gateway Boulevard and Whyte Avenue intersection

	TTC	TDPI	DSPP
One month later	50 %	25 %	33.3 %
Six months later	90 %	87.5 %	88.8 %

6

Conclusion

6.1 Conclusion

In line with this study's objective, which aims to investigate the safety impact of implementing a scramble phase at two Edmonton intersections on Whyte Avenue, at Calgary Trail and Gateway Boulevard, respectively, two sub-objectives were introduced. The first sub-objective entailed examining the frequency of right-turn-on-red violations immediately after the implementation of the scramble phase and six months later. The findings discussed in Chapter 4 reveal that the frequency of right-turn violations at the Gateway Boulevard intersection is higher than that at the Calgary Trail intersection during both time periods (September and Late April), but a reduction trend is noticeable at both intersections. Specifically, the average number of violations at the Calgary Trail intersection in September was 512 per day, which experienced a 28.5% reduction after six months, reaching an average of 366.6 per day. Similarly, at the Gateway Boulevard intersection, there was a 34.5% reduction in the average frequency of right-turn violations from 586.16 in September to 383.57 in Late April.

Regarding the frequency of right-turn violations in the pedestrian phase, the average percentage of right-turn-on-red violations in the pedestrian phase of total violations was calculated. The results indicate that although the total frequency of violations reduced during the six months at the Calgary Trail intersection, the percentage of violations in the pedestrian phase slightly increased from 30.8% to 41.1%. Conversely, a slight reduction from 70.1% to 68.5% during the six months was observed at Gateway Boulevard. It means that despite the decrease in violations at both intersections after six months, the slight increase at Calgary Trail and the reduction at Gateway Boulevard indicate that pedestrians are still at a high risk of collision with violating vehicles.

The second sub-objective of this study focused on conflict analysis. As outlined in Chapter 5, three safety indicators, i.e., TTC, TDPI, and DSPP, were programmed to be automatically calculated for detected conflicts. Also, heatmaps were generated to show the the locations that had more serious conflicts at both intersection. The results demonstrate that at the Calgary Trail intersection, a reduction of over 65% based on all three safety indicators was observed immediately after the installation of the scramble phase. Furthermore, after six months, a 100% reduction was noted for DSPP and TDPI at this intersection.

Similarly, serious conflicts based on these indicators were reduced at the Gateway Boulevard intersection, albeit to a lesser extent, of less than 50% immediately after the installation. However, this number increased to 80% for all indicators after six months. The mentioned reduction trend suggests that implementing the scramble phase reduced the number of serious conflicts at both intersections.

In conclusion, while serious conflicts decreased at both intersections after the implementation, the increasing number of right turn-on-red violations in the pedestrian phase suggests that the number of crash-relevant or low-risk incidents has not decreased. This raises concerns regarding pedestrian safety, as low-risk collisions could still threaten pedestrians.

6.2 Limitations and Future Work

It is essential to acknowledge the limitations of any study to provide a fair and accurate assessment of its findings. In this study, missing data for the early April at Gateway Boulevard intersection may have limited the accuracy of the results, as only WB and NB directions data were available. Additionally, the limited duration of data collection, which was only immediately and six months after the implementation of the scramble phase, may not fully capture the longer-term effects of the intervention. Furthermore, the study focused on a limited set of safety indicators, which could have been expanded to provide a more comprehensive analysis. Therefore, future studies may benefit from considering and calculating additional safety indicators to compare results and better understand the frequency of serious conflicts. Additionally, a longer-term study evaluating pedestrian behaviour would provide a more complete picture of the effects of the scramble phase on safety. In order to enhance compliance with the no right-turn-on-red (RTOR) rule for vehicles, additional measures could be implemented alongside the digital RTOR sign that the City of Edmonton introduced in April. Examples of such measures include implementing a sign that alert drivers to the scramble phase or using distinct coloration for lane markings at intersections with scramble phases to differentiate them from other signalized intersections.

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Appendix A

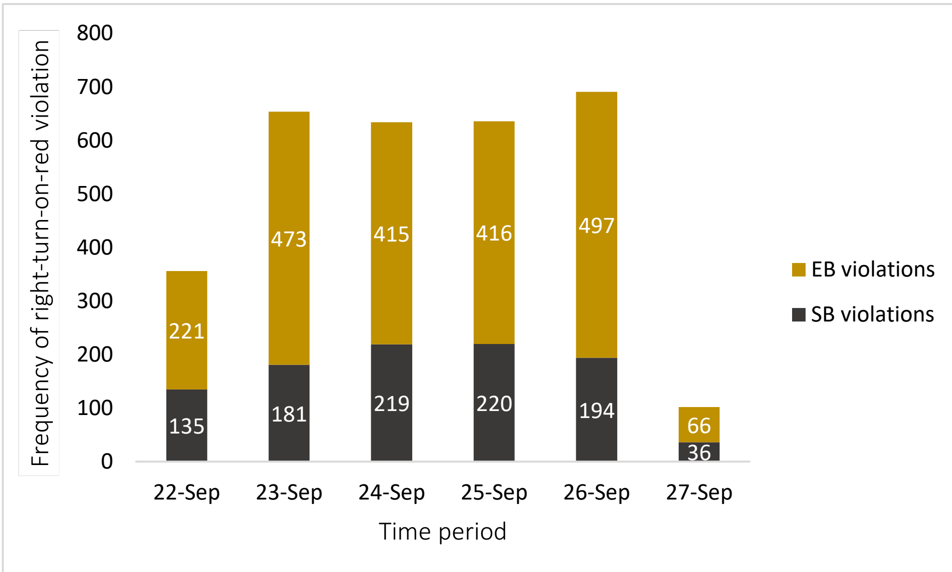

Figure 45- Right turn violations at Calgary Trail & Whyte Avenue intersection between Sep. 22 - 27

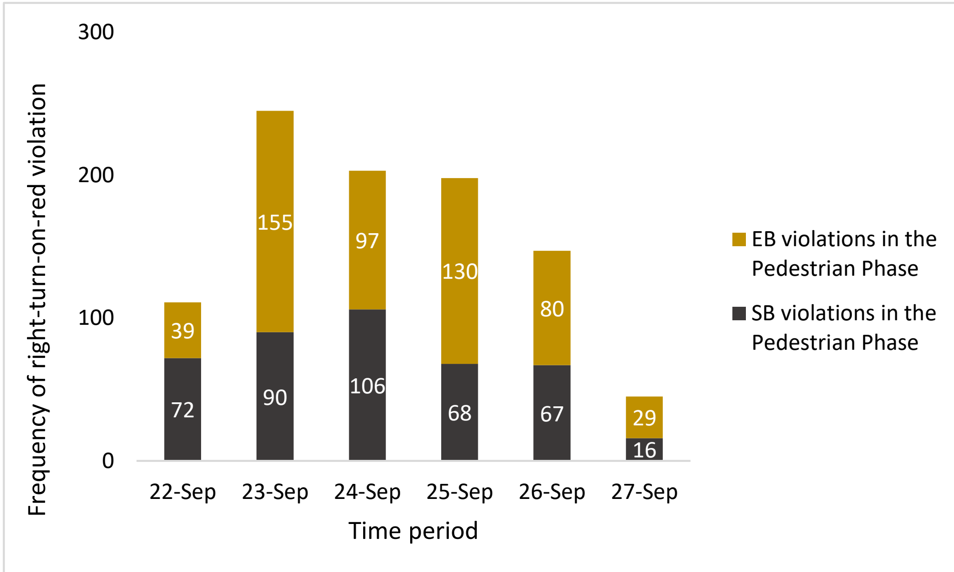

Figure 46- Right turn violations in the pedestrian phase at Calgary Trail & Whyte Avenue intersection between Sep. 22 - 27

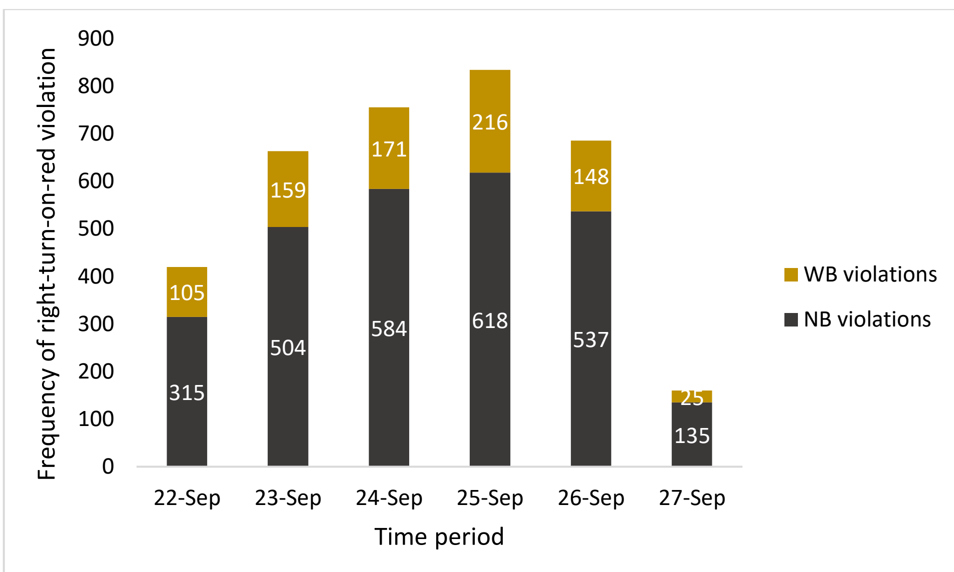

Figure 47- Right turn violations at Gateway Boulevard & Whyte Avenue intersection between Sep. 22 - 27

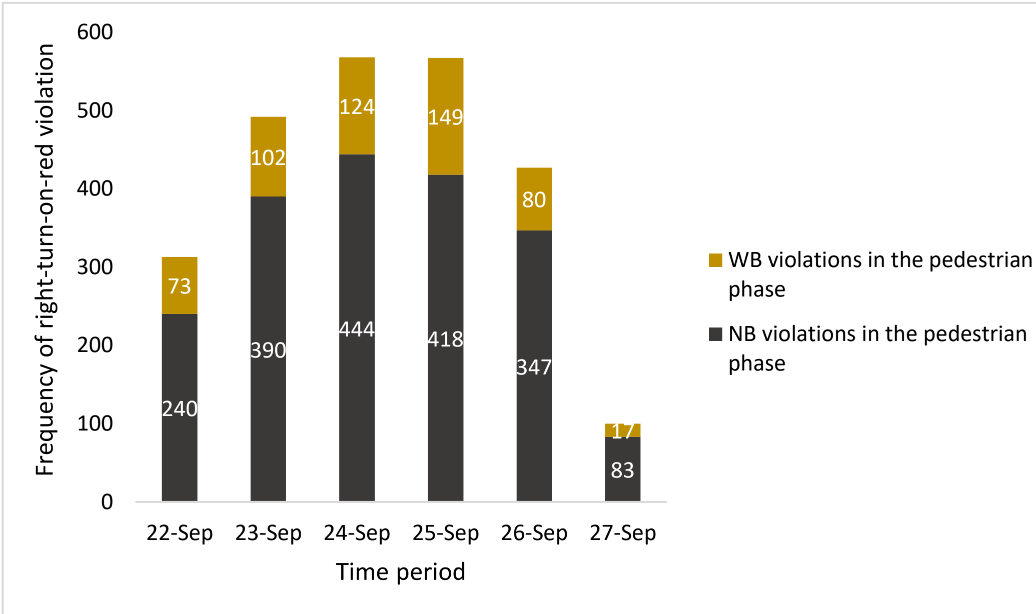

Figure 48- Right turn violations in the pedestrian phase at Gateway Boulevard & Whyte Avenue intersection between Sep. 22 - 27

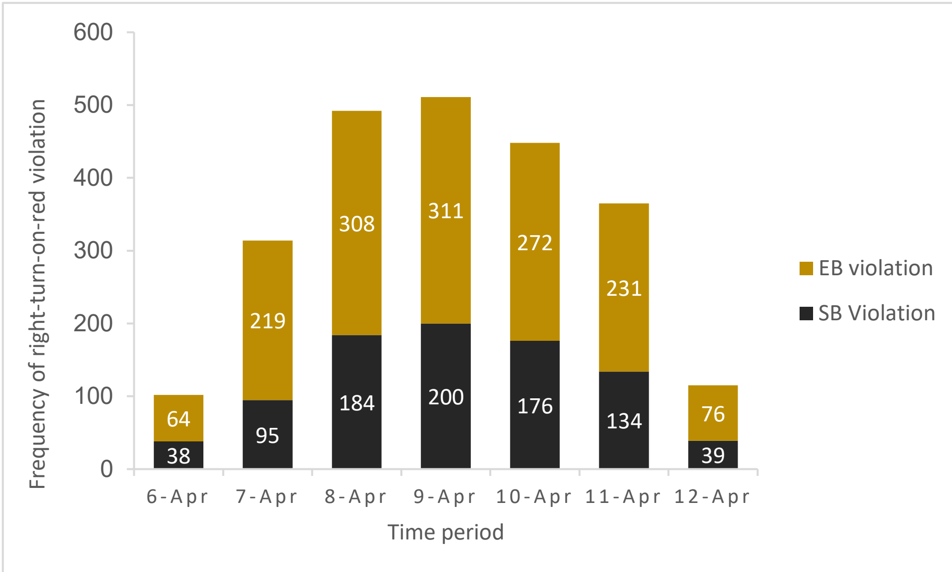

Figure 49- Right turn violations at Calgary Trail & Whyte Avenue intersection between Apr. 6 - 12

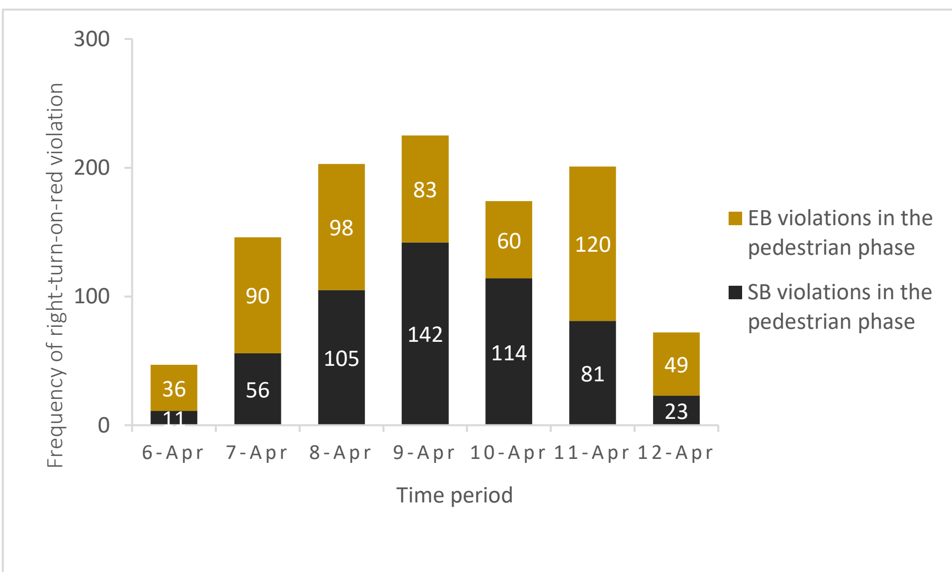

Figure 50- Right turn violations in the pedestrian phase at Calgary Trail & Whyte Avenue intersection between Apr. 6 - 12

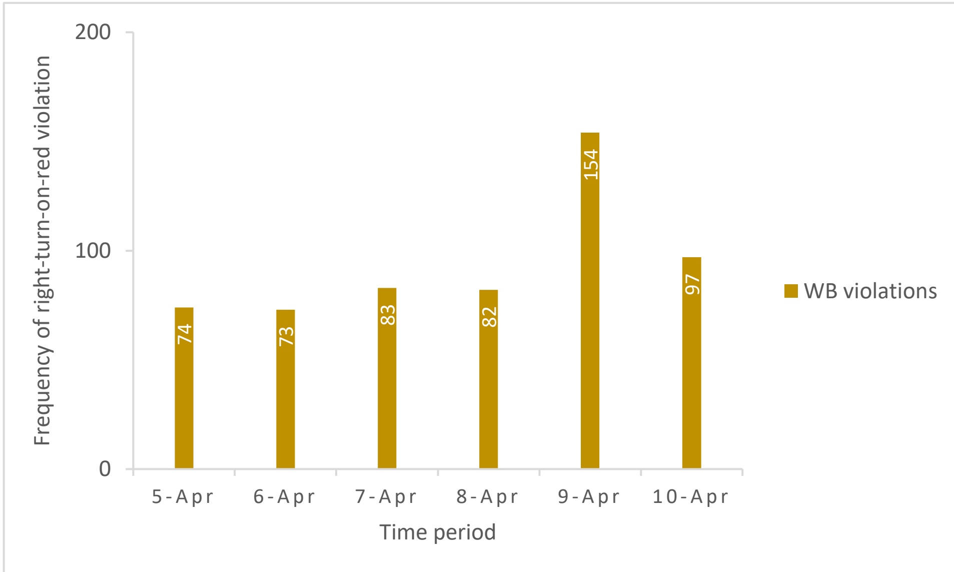

Figure 51- Right turn violations at Gateway Boulevard & Whyte Avenue intersection between Apr. 5 - 10

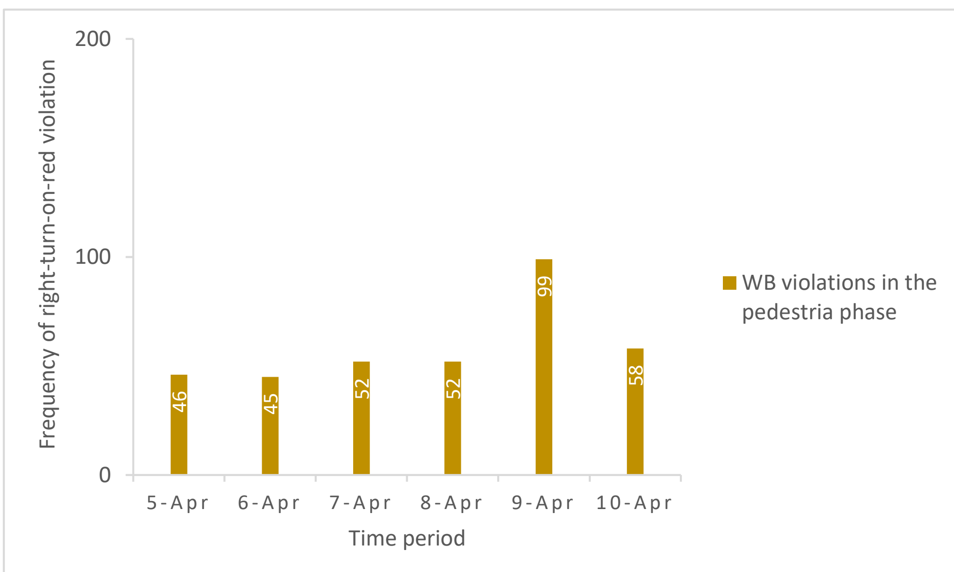

Figure 52- Right turn violations in the pedestrian phase at Gateway Boulevard & Whyte Avenue intersection between Apr. 5 - 10

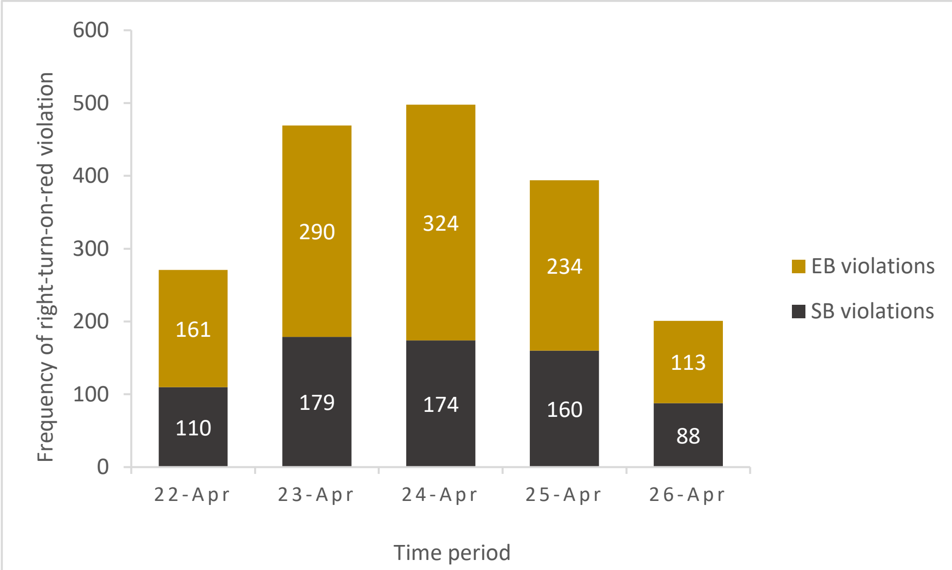

Figure 53- Right turn violations at Calgary Trail & Whyte Avenue intersection between Apr. 22- 26

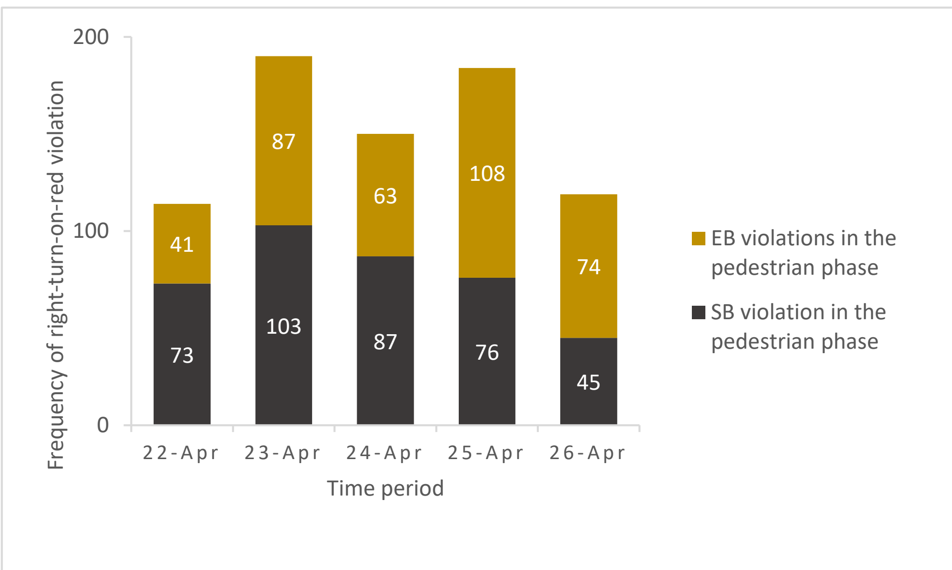

Figure 54- Right turn violations in the pedestrian phase at Calgary Trail & Whyte Avenue intersection between Apr. 22 - 26

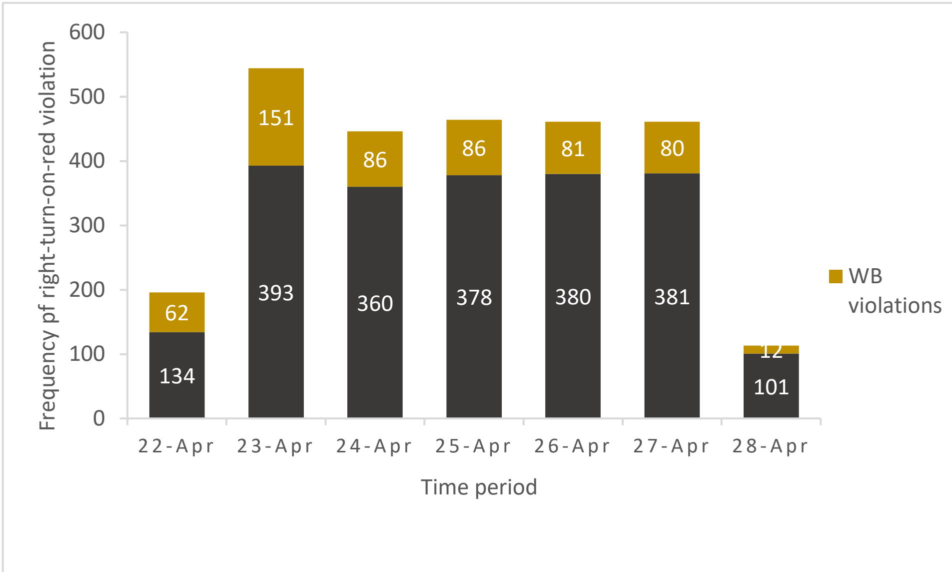

Figure 55- Right turn violations at Gateway Boulevard & Whyte Avenue intersection between Apr. 22- 28

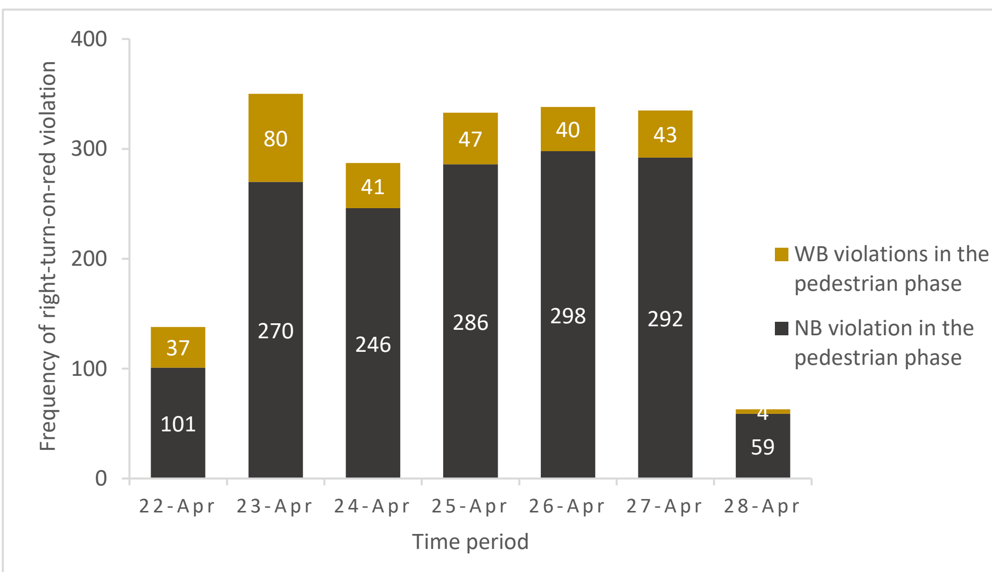

Figure 56- Right turn violations in the pedestrian phase at Gateway Boulevard & Whyte Avenue intersection between Apr. 22 - 28

Appendix B

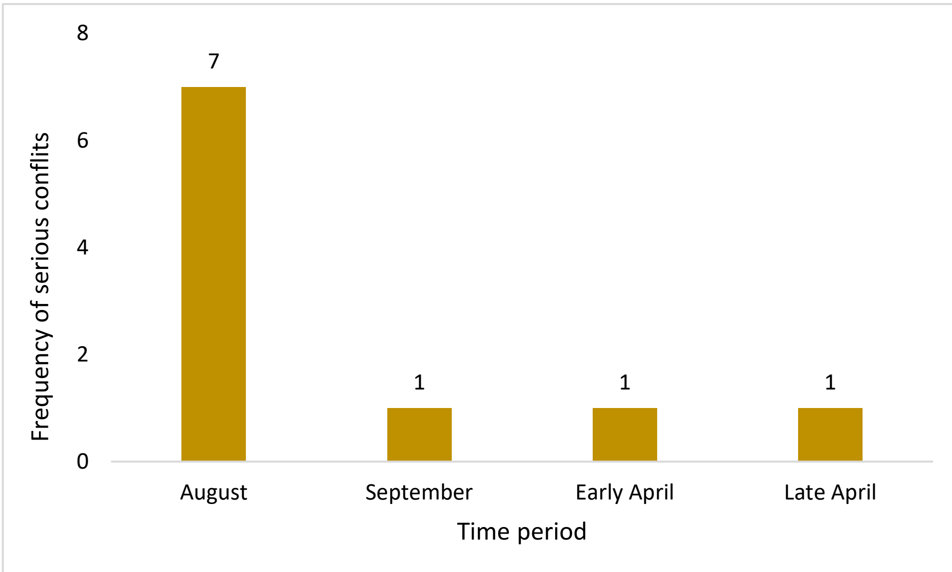

Figure 57- Serious Conflicts based on TTC at Calgary Trail & Whyte Avenue intersection

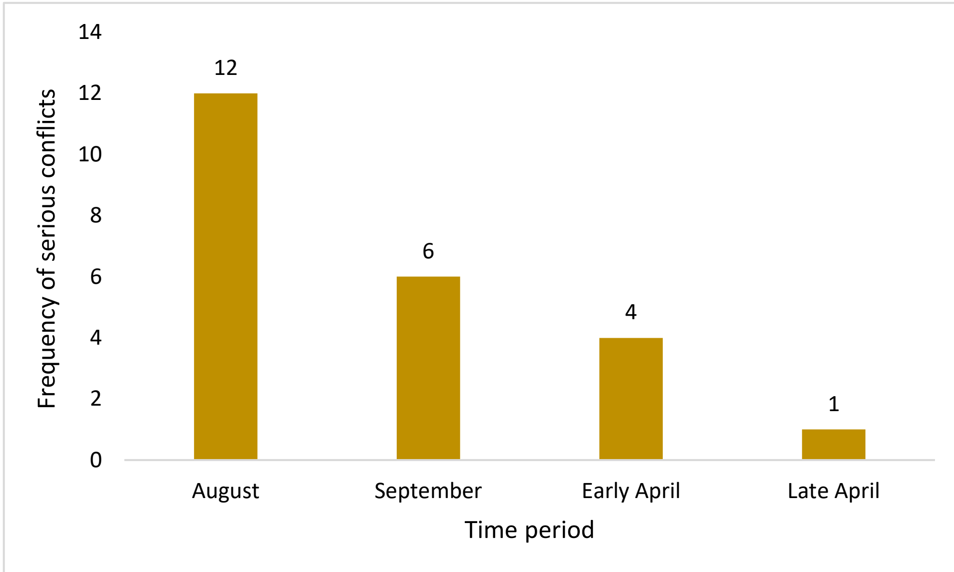

Figure 58- Serious Conflicts based on TTC at Gateway Boulevard & Whyte Avenue intersection

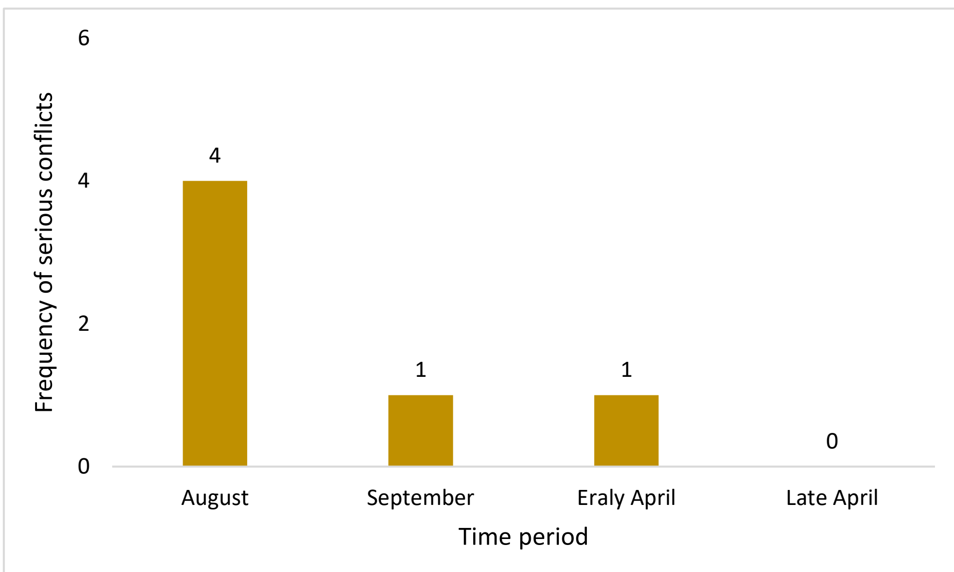

Figure 59- Serious Conflicts based on TDPI Calgary Trail & Whyte Avenue intersection

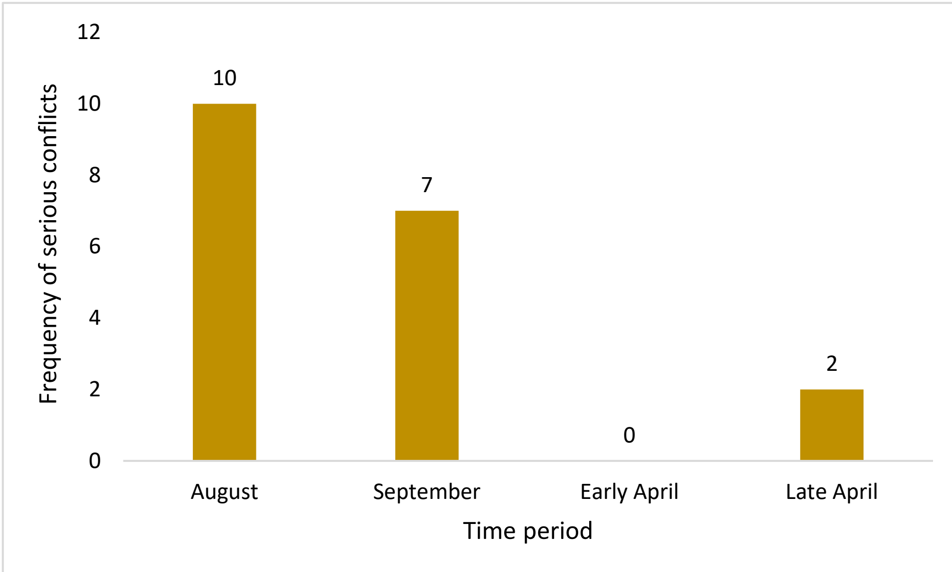

Figure 60- Serious Conflicts based on TDPI at Gateway Boulevard & Whyte Avenue intersection

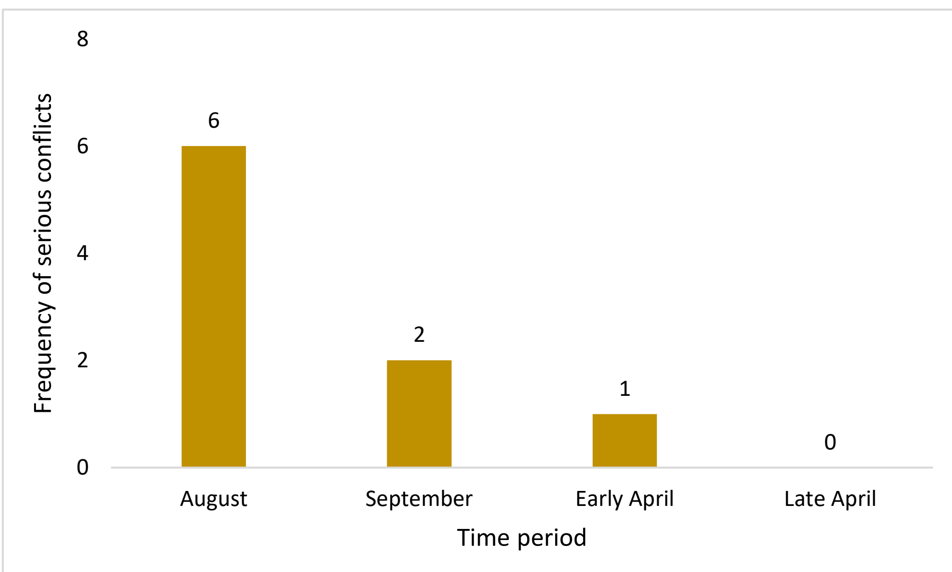

Figure 61- Serious Conflicts based on DSPP at Calgary Trail & Whyte Avenue intersection

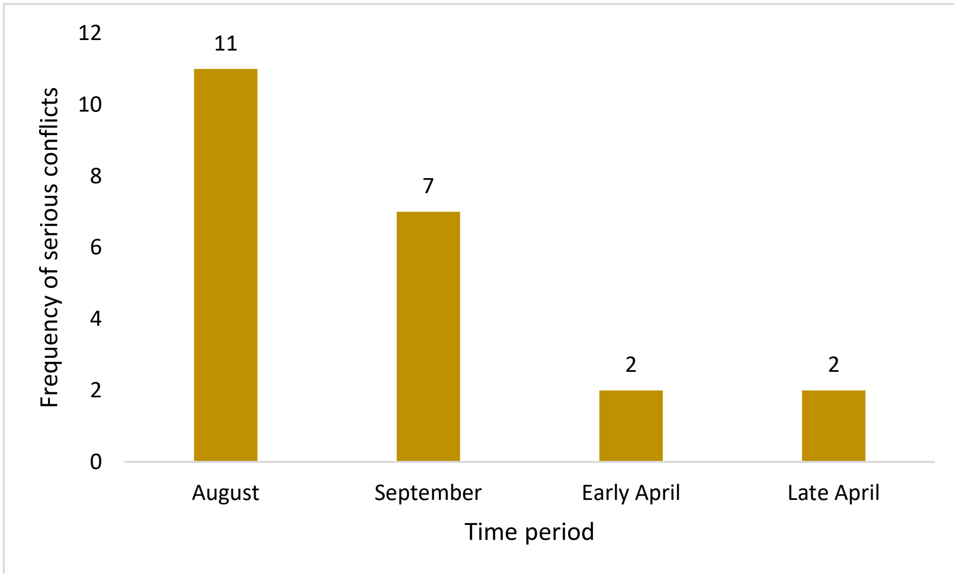

Figure 62- Serious Conflicts based on DSPP at Gateway Boulevard & Whyte Avenue intersection