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SAFETY ANALYSIS OF ROUNDABOUT CONVERSIONS BASED ON VIDEO OBSERVATIONS

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SAFETY ANALYSIS OF ROUNDABOUT CONVERSIONS BASED ON VIDEO OBSERVATIONS

présenté par : WOODALL-KALFAIAN Stephen

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DEDICATION

To my parents, who have done so much for me,

To my friends and family,

To the memory of my Aunt Ruth who left us this May.

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RÉSUMÉ

Les carrefours giratoires prennent de plus en plus de place dans le réseau routier Nord-Américain, remplaçant les intersections à géométrie plus standard pour accroître la sécurité et l'efficacité. La réduction à la fois des vitesses, mais aussi du nombre et de la sévérité des collisions, tout en conservant un débit de véhicules efficace, sont tous des avantages qui ont justifié l'introduction des carrefours giratoires dans les réseaux routiers en Amérique du Nord.

Le développement des nouvelles technologies utilisées dans l'ingénierie des transports a engendré de meilleures capacités analytiques dans le domaine de l'analyse de la sécurité routière. Le domaine de la vision par ordinateur, qui a émergé au cours des années 1970, a permis aux analyses d'être basées sur des données vidéo plutôt que sur des données d'accidents, dont l'utilisation est courante depuis que les études d'analyse de sécurité routière ont débuté.

Ce projet de recherche vise à utiliser l'efficacité accrue de l'analyse de données vidéo automatisée afin d'étudier deux sites de conversion en carrefour giratoire suivant une méthode « Avant-Après ». Les sites sont tous deux basés en Amérique du Nord (l'un à New York City, l'autre à Gatineau, au Québec). L'analyse de sécurité liée aux conversions en carrefour giratoire utilise des mesures substitutives d'analyse ; c'est-à-dire des méthodes visant à remplacer l'utilisation des données d'accidents en offrant une manière plus proactive d'évaluer la sécurité.

La méthodologie développée pour l'évaluation de la conversion des carrefours giratoires dans le cadre de cette étude repose sur plusieurs méthodes d'analyse qui sont complémentaires. L'objectif de la méthodologie est d'analyser la conversion en carrefour giratoire à plus grande échelle avant d'ajouter une analyse plus microscopique du comportement des usagers de la route. Premièrement, une analyse préliminaire des points de conflit permet de comparer les deux conceptions d'intersection différentes en termes de « points chauds » dangereux potentiels pour les usagers de la route. Dans une deuxième analyse nécessitant l'utilisation des outils logiciels (tvaLib et Traffic Intelligence) pour détecter et analyser les trajectoires des usagers de la route, deux indicateurs bien connus de sécurité sont utilisés : la vitesse et le temps à la collision (TTC).

À cette seconde analyse s'ajoute l'étude comparative des conversions en carrefour giratoire et consiste à déterminer les mouvements comparables entre les deux configurations d'intersection, en utilisant à la fois les attributs géométriques des intersections et l'analyse préliminaire des points de

conflit. La méthode d'analyse par mouvement nécessite alors la collecte de paires d'usagers de la route pour l'ensemble des mouvements comparables pour les deux configurations d'intersection.

Toutes ces méthodes visent à comparer les performances du carrefour giratoire transformé comparativement à l'intersection qu'il remplace, en termes de comportement des usagers de la route et de danger pour la sécurité des usagers. Les résultats sont contrastés ; tandis que la conversion du carrefour giratoire à New York a montré une amélioration en termes de ralentissement de la vitesse des usagers de la route, il y avait peu de changement dans les valeurs TTC médianes pour les paires d'usagers impliquées dans chacune des intersections. L'analyse par mouvement a montré une diminution globale du nombre de paires d’usagers sur l’ensemble des mouvements étudiés, bien que les résultats ne soient pas concluants dû à des problèmes de suivi des véhicules entre origines et destinations. Les résultats pour le site Jean-Proulx à Gatineau n'ont pas été concluants pour les différentes analyses, en raison du dysfonctionnement des caméras et des disparités dans le comptage des véhicules.

ABSTRACT

Roundabouts in North America have been increasing in importance in recent years, as they replace intersections for increased safety and efficiency. The reduction in speeds as well as in the number and severity of collisions while conserving efficient vehicle flow are all advantages that have justified the introduction of roundabouts into recent road designs in North America.

New technologies used in transportation engineering have allowed for better analytical capabilities in the field of traffic safety analysis. The field of computer vision, which has emerged during the seventies, has enabled analysis to be based on video data rather than accident data, the use of which has been standard since road safety analysis studies began post-Second World War.

This research project aims to use the capabilities and increased efficiency of automated video data analysis in order to analyse two roundabout conversion sites following a "before-after" method – the sites are both based in North America (one in New York City, the other in Gatineau, Quebec). Safety analysis related to the roundabout conversions uses surrogate measures of safety, i.e. analysis methods aiming to replace accident data by offering a more proactive way of evaluating safety.

The methodology developed for the roundabout conversion evaluation in the context of this research study is based on several, complementary methods of analysis. The objective of the methodology is to analyse the roundabout conversion on a larger scale before adding a more microscopic analysis of road user behaviour. Firstly, a preliminary conflict point analysis helps compare the two different intersection designs in terms of potential hazardous "hotspots" for road users. In a second analysis requiring the use of the software tools (tvaLib and Traffic Intelligence) used to detect and analyse road user trajectories, two well-known safety indicators are used: speed and time-to-collision (TTC) distributions.

A further part of the second analysis method adds to the comparative analysis of the roundabout conversions, and consists of determining the comparable movements between the two intersection configurations, using both the geometrical attributes of the intersections and the preliminary conflict point analysis. The movement analysis method then requires the collection of road user pairs in the set of comparable movements for both intersection configurations.

All of these methods aim to compare the performance of the converted roundabout as opposed to the intersection it replaces, in terms of road user behaviour and safety hazard. The results are contrasted; while the roundabout conversion in New York City showed an improvement in terms of slowing road user speeds, there was little change in the median TTC values for user pairs involved in both intersections. Movement analysis showed a decrease in user pairs for the different conflicting movements, yet the results remain inconclusive due to tracking problems. The results for the Jean-Proulx site in Gatineau were also inconclusive, for all analyses, due to camera malfunction and disparities in vehicle counts.

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LIST OF SYMBOLS AND ABBREVIATIONS

TCT	Traffic Conflict Technique
OD	Origin-Destination
TTC	Time-to-Collision
MA	Movement Analysis
SSM	Surrogate Safety Measures
NCHRP	National Cooperative Highway Research Program
FHWA	Federal Highway Administration
ICTCT	International Co-operation on Theories and Concepts in Traffic Safety

GLOSSARY

Alignment: According to the definition proposed by St-Aubin (St-Aubin, 2016), an alignment is "a spline or series of points in space defining the centre line of a lane".

Approach: Segment of a road leading to an intersection or other type of road infrastructure.

Circulatory Roadway: "The circulatory roadway is the curved path used by vehicles to travel in a counter clockwise fashion along the central island." (NCHRP Report 672, FHWA, 2010)

Collision Course: Situations in which two or more road users are predicted to collide (using a motion prediction method) in the absence of a reaction.

Conflict Point: A conflict point is the physical point in space created by two (or more) conflicting vehicle paths, and therefore where a collision between vehicles may occur. The geometrical characteristics of the conflicting paths, such as their direction and angle can result in three different types of conflict points: converging, diverging and crossing conflict points.

Conflicting Flow: Traffic flow of road users already engaged in a roundabout entering the merging zone, thus opposing users entering the roundabout via an approach.

Exposure: "A measure of spatial or temporal duration in the traffic system in relation to the number of dynamic system objects, road users, vehicles, etc" (Archer, 2004). Exposure to collision relates to any pre-cursor situation in which a collision can take place.

Homography: "A mathematical coordinate transformation between two planes, which projects a point from an image space plane to a world space plane." (St-Aubin, 2016)

Interaction: The situations in which two road users exist "simultaneously and closely in space" (St-Aubin, 2015) (Saunier et. al, 2010).

Merging Zone: As defined by St-Aubin in his thesis, a merging zone represents "a roundabout sub-segment where merging action takes place between approaching and conflicting flows". (St-Aubin, 2016)

Motion-Prediction Method: A method of predicting road users' expected positions (and thus expected trajectories) using an algorithm relying road users' previous positions.

Movement: Vehicle trajectory within an intersection defined by both an origin (the road user's entry point) and a destination (the road user's exit point).

Occlusion: An occlusion occurs when an observed object is partially (or completely) obstructed from view by an object that is physically situated between the observer (here the camera) and the observed object (in this case, a road user).

Road User: A person or object (automated or otherwise) using the road for transportation purposes. Types of road users include vehicles, pedestrians, cyclists, buses, lorries, etc.

Time-to-Collision: The time remaining for two vehicles to collide should their trajectories remain the same, supposing evasive action does not take place.

Traffic Conflict: In transportation engineering, a traffic conflict is an "event involving two or more moving vehicles approaching each other in a traffic flow situation in such a way that a traffic collision would ensue unless at least one of the vehicles performs an emergency manoeuvre". (Amundsen, F. & Hydén, C., 1977)

Traffic Event: Period of time during which one or more road users passes through a given road section.

Trajectory: A series of positions as a function of time which define the movement of an object. The objects, in the context of this thesis, are road users.

User pair: "A pair of road users coexisting within a finite distance over a finite common time interval" (St-Aubin, 2016).

LIST OF APPENDICES

CHAPTER 1 INTRODUCTION

1.1 Research Problem

Roundabouts are gradually taking a place of importance in North American road networks, as an efficient and safe alternative to most types of intersections. This relatively recent type of design initially appeared in the 1960s following changes in the British Highway Code—users engaged in traffic circles previously had to yield to oncoming traffic. One of the main objectives of roundabouts being to improve both safety (by reducing the number of accidents and their severity) and traffic flow, many research studies have tackled the topic of road safety in roundabouts and their effect on the behaviour of road users.

With the emergence of cars as a popular and effective way of travelling, road safety became a concern of great proportion. Studies relating to road safety initially started by presenting accident data as a means of measuring dangerousness (for evaluation of both infrastructures and driving behaviour). However, accidents are also rare events, which makes both sample size and the data collection process an issue when analysing road user behaviour. Furthermore, accident data such as reports collected at the scene by police and ambulance officials do not necessarily contain all the information required for analysis by traffic engineers, as the purpose of such reports is of a different nature.

While fatal and injury accidents are the most undesirable events and only happen rarely, data pertaining to the most common types of dangerous road events (fender-benders, traffic conflicts) is even more challenging to collect as reports are not always available, or even exist in the first place.

As traffic engineers have taken to analysing road safety, various methods have been developed for traffic safety analysis, relying on accidents, non-crash events (such as traffic conflicts) and other safety related events and behaviours. Collecting safety-related events using more or less automated video analysis is a recent practice (starting in the mid-2000s) which has relied on information technology developments and new computer vision technologies for the processing and treatment of video data.

With the relatively recent introduction of roundabouts in North America, questions have surfaced regarding their effectiveness and safety in North American driving environments, as roundabouts are still a relatively unknown facility to many road users. As such, there are few before-after studies of roundabout conversions and other conversions to newer designs such as displaced left-turn or diverging diamond interchanges. There are even fewer studies at the microscopic level based on direct observation of road user pairs and behaviour. Studies are generally done at site level based on crash data, which is more readily available.

1.2 Research Objectives

As was mentioned above, crash data is not always an available or reliable resource in terms of safety analysis for road users at intersections or roundabouts, as information about driver behaviour or accident causes can be unavailable or lacking sufficient accuracy for analysis. Furthermore, comparing designs of very different natures and different *modi operandi* also constitutes a challenge; the default universally recognised method of analysing a roundabout conversion in terms of safety for road users is based on crash data comparison at the site-level.

This thesis presents a before-after analysis of two intersections subsequently transformed into roundabouts. The first intersection is in the borough of the Bronx, New York City (NYC), in the State of New York in the United States, while the second is situated in Gatineau, in the province of Quebec in Canada.

The focus of this thesis follows a series of projects undertaken by a research team conducting a large-scale, three-year research project on roundabout safety in Quebec, Canada, from 2011 to 2014, with overall results showing an inconclusive impact of roundabouts compared to signalized intersections (Saunier et al., 2015). With extra video data being available both before and after roundabout conversion for the NYC and Gatineau sites, this research project constitutes a follow up study, focusing on before-after analysis with the sole use of video data.

This research project aims to develop and apply a method using safety measures based on non-crash events called surrogate measures of safety to evaluate the safety of a converted roundabout compared to the previous geometric configuration and type of control. The main research questions leading to the analysis conducted and described in the following chapters are the following: do roundabouts constitute a safer form of intersection control than other types of standard intersections? What indicators can be used to show a change in the safety of the infrastructure? How is the safety improvement manifested, if any?

The proposed methodology is then applied to both case studies in order to firstly determine its potential in terms of before-after analysis, but also in terms of evaluating safety improvement (or lack thereof) for both sites.

1.3 Methodological approach

While the development of new road safety analysis techniques has been at the forefront of research in the field of road safety, methods to compare two very different infrastructures in terms of geometry is far from an easy task, as roundabouts and conventional intersections function in very different ways. Such an exercise presents added difficulties due to the lack of common characteristics of the various layouts, such as roundabouts or even diverging diamond interchanges – as seen in the works of Bared et. al (2005).

As mentioned previously, this thesis focuses on two specific cases, that of the installation of a roundabout to replace the 3-way intersection connecting Intervale Avenue with Dawson Street, in the Bronx, NYC, as well as the intersection of Jean-Proux Avenue and St-Joseph Boulevard in Gatineau. A specific methodology was developed to compare the two designs for each case study, relying on three distinct types of analysis:

1. an analysis of the conflict points aimed at pinpointing the points of possible conflicts (and their corresponding types) according to vehicle movements;
2. a safety analysis using the surrogate measures of safety Time-to-Collision (TTC) and speed a) at the site level and b) for the different movements (by origin-destination, referred to as OD).

The three analysis methods are complementary components of the overall safety analysis. Conflict point analysis provides an overview of the different *a priori* “hotspots” within the intersection and roundabout where road users may encounter conflict situations. The addition of TTC and speed distributions of all the road users involved in the intersections and converted roundabouts provides another dimension to the safety analysis through the actual observation of road user pairs and behaviour within the given infrastructures. Finally, after the site-level analysis of speed and TTC distributions, these are analysed by movement on a more microscopic level.

1.4 Thesis structure

This thesis comprises several sections. Chapter 2 presents a review of literature pertaining to the various fields covered by this research project, emphasizing previous research in roundabout safety and conflict analysis.

The methodology for the road safety analysis used in this research project is presented in the third Chapter 3 of this thesis. It presents both complementary analysis methods, as well as the video analysis tools.

Chapter 4 examines two case studies where the proposed methodology has been applied to compare safety in a before-after context; sections 4.1 and 4.2 follow the same structure. First, the initial intersection and its roundabout replacement are presented along with their defining characteristics. Conflict points are then drawn and examined as preliminary safety analysis. A full set of results extracted from the use of automated video analysis software for road user behaviour and road safety analysis is presented, with a highlight being made concerning road user speeds and TTCs. Movement analysis is then conducted to examine the safety of road users for OD pairs within the intersection. Finally, validation of the movement analysis and conclusions concerning the road safety effects of both infrastructures are made.

In the last chapter, an overview of the results for both case studies is presented and evaluated. Conclusions are then drawn on the overall road safety effects of roundabout implementation using the results obtained during Chapter 4, along with limitations of the methodology used during the project - recommendations are then made for future work on the topic of road safety involving roundabouts and analysis using computer vision.

CHAPTER 2 LITERATURE REVIEW

Improvements in road safety analysis techniques have been at the forefront of new research, with accident data and surrogate measures of safety (often using video analysis) being the two major categories of methods used to analyse road user behaviour and safety. The main theme explored in this project relates to the use of surrogate safety methods using video analysis at converted roundabouts, but it is pertinent in the exploration of previous work to mention related research in which roundabout safety and video analysis tools have been used and evaluated.

2.1 Safety Analysis Methods

Road safety has been a concern of many researchers for over 70 years, as the automobile industry started booming, post-Second World War. The first research attempts into traffic engineering related to road safety came in the 1950's and 1960's (Hagenzieker et. al, 2013, St-Aubin, 2016). As attempts to develop models and analysis methods to evaluate traffic safety increased, the 1970's and 1980's saw the development of Traffic Conflict Techniques (TCT) (Asmussen, 1984)[1]. This section firstly presents an introduction to road safety, followed by a section covering the background related to road safety studies and the limitations of accident data. This leads to an overview of existing TCTs – both in terms of concept and application – before Section 2.1.3 presents surrogate measures of safety for road safety analysis.

2.1.1 An Introduction to Road Safety

Most people (if not all) are, at some stage, a road user, whether that be as a motorist (car/lorry/bus driver) or passenger, a cyclist, or as a pedestrian. Road users, combined with the different infrastructures they use (roads, intersections, highways, etc.) and vehicles constitute the traffic system. Road safety analysis encompasses the means and methods used to evaluate the risk of –

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[1] It is worth noting, in the context of traffic conflict studies, that the ICTCT (initially the International Co-operation on Traffic Conflict Techniques, then rebranded as the International Co-Operation on Theories and Concepts in Traffic Safety) was founded in 1977 by a collaboration of researchers working on developing methods and setting baselines for the analysis of traffic conflicts for safety diagnosis. (ICTCT, 2016)

and prevent – accidents (the result of road users colliding) within a road system. As is illustrated in Figure 2.1, several types of accidents exist (ranging from accidents showing only vehicle physical damage to accidents of increased severity, with severe injuries or even fatalities to vehicle drivers and/or passengers). The severity of a collision is the "measure of the total amount of damage done to property and bodily harm done to individuals in the event of a collision" (St-Aubin, 2016).

Assessing road safety is traditionally based on collision risk, which should represent both the frequency, or probability, of an accident, and its severity. Basic measures are the overall number of collisions, collision rate (i.e. the number of collisions per unit of exposure[2]), and collision severity. As every road has a different traffic flow, the number of traffic accidents varies over a given period of time (whether that be a year or several years) and accident rates (usually expressed as a number of accidents per unit of exposure) are one way to compare them.

Traffic accidents are rare, but are also random events, as the number of accidents for a given period and intersection or road section varies, even with unchanged traffic conditions. It may therefore be necessary to collect data over a long period of time, without witnessing any change in road conditions or infrastructure, to collect a large enough set of accidents for statistical inference.

Another limitation to accident data derives from accident logs and reporting. Accident records are initially recorded by the police and emergency services, as opposed to traffic engineering. Traffic engineers are concerned with infrastructure, as well as road user behaviour (to some extent), while the collected accident data shows more use by police services in assigning responsibility. This entails that the information available on these reports is often of limited use to traffic engineers, and limits their effectiveness for use in safety analysis. Furthermore, not all accidents are reported, with the level of reporting usually depending on the severity of the accident: accidents involving injuries and fatalities are usually always reported on, while low-severity, i.e. property damage only, accidents are more often omitted (Imperialou, & Quddus, 2017).

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[2] Exposure is a measure of spatial or temporal duration in the traffic system in relation to the number of dynamic system objects, road users, vehicles, etc. (Archer, 2004)

2.1.2 Conflicts and the Traffic Conflict Techniques

Understanding and analysing road safety analysis requires the basic comprehension of various traffic events, and what they represent – in both a conceptual and a practical sense. An illustration of various traffic events with respect to accidents is illustrated in the literature by Figure 2.1 (Laureshyn, 2016):

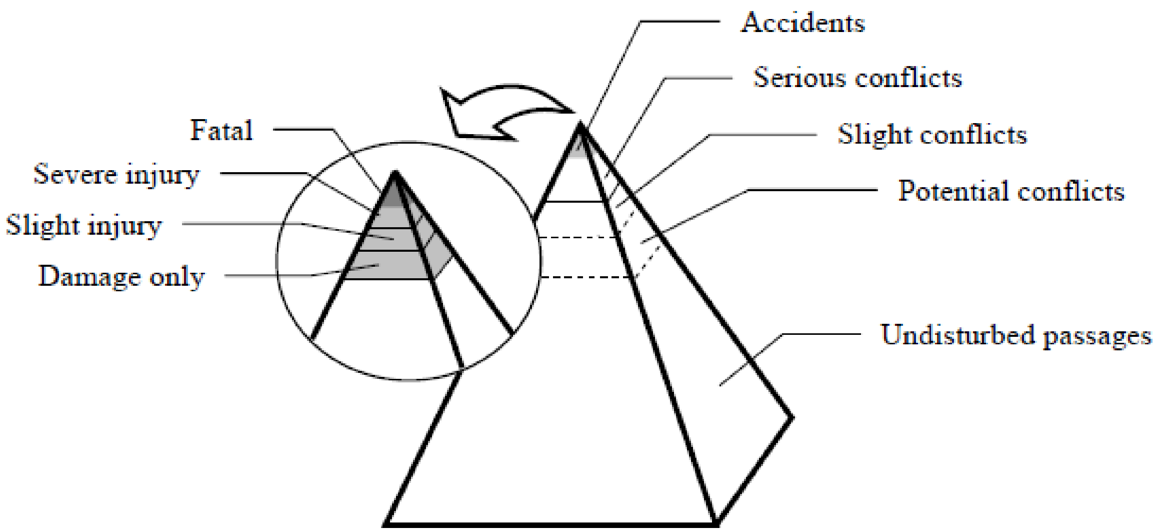

Figure 2.1 Traffic Safety Pyramid Model – (from (Laureshyn, 2016), who adapted from Hydén, 1987)

As shown by the pyramid in Figure 2.1, most traffic events are qualified as undisturbed passages, i.e. the absence of any (conscious) interactions between road users. A much lower proportion of road events are qualified as conflicts, whether these are categorised as serious, slight or potential conflicts. At the top of the pyramid (i.e. the rarest type of road event), is the accident, with the various severity levels shown to the left of the diagram.

The idea of conflict analysis was first developed by researchers at General Motors in the late sixties, as an alternative method of observing the potential for accidents (Perkins & Harris, 1967). The proposed method of evaluation for GM's method was based on the definition of five types of conflicts (1- Left-turn conflicts, 2- Weave conflict, 3- Cross-traffic conflict, 4- Red-light violation conflict, 5- Rear-end conflict) and used two observers for collection of conflict data within different intersections, with approximately 2.5 h of data collected for each approach leg (Glennon & Thorson, 1975). The term "conflict" was defined by GM in 1967 as being "either an evasive action of a driver or a traffic violation". Evasive action situations were then measured by either brake lights turning on or lane changes occurring in the presence of an "impending accident situation".

TCTs and their application to traffic safety studies became popular through the 1970's, with Swedish researcher Christer Hydén being one of the first to develop the technique. The Swedish TCT relies on conflicting speed and the Time-to-Accident (TA) concept (1996), which itself is a measure at a specific instant of the Time-to-Collision (TTC) indicator developed by Hayward (1971). In its general definition, TTC is defined as the time remaining before two road users would collide, if their movements remain unchanged. TA is a measure of the TTC at the instant a road user initiates the first evasive action (and conflicting speed is measured at the same instant).

While the definitions of most traffic events can seem simple to comprehend, proposing a definition of a traffic conflict has attracted several researchers in the field of traffic safety. During the first ICTCT meeting in 1977, the following definition was proposed and remains the most commonly used: "An observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged". (Amundsen & Hyden, 1977).

Laureshyn shows that there are two schools of thought when it comes to characterising traffic conflicts: one considers a conflict to precede evasive action, whereas the other supports the idea that evasive action precedes conflicts (2016). The common ground that all definitions of traffic conflicts have is the existence of a collision course, which implies an evasive action if there is no collision.

The traffic conflict definition to be retained for this thesis is close to the one proposed by Amundsen and Hyden (1977), and integrates the notion of road users needing to undertake evasive action to avoid a collision. It is formulated as follows: "an observable traffic event involving two or more vehicles approaching each other in space and time in such a way that there is a risk of collision unless at least one of the vehicles resorts to evasive action".

While traffic conflicts are real, observed situations, a clear distinction must be made from conflict points, which are defined by road user movements. Conflict points within an intersection are determined with the sole use of the intersection geometry. Ideal vehicle trajectories are drawn for each movement in the intersection, and conflict points are determined as being the intersections of the trajectories. The Federal Highway Administration (FHWA)'s guide (2004) illustrates that there are three types of conflict points: merging, diverging and crossing conflict points. These are defined by the angle and direction at which two road users would collide should their trajectories correspond to the ones drawn in the conflict point diagram.

2.1.3 Surrogate Measures of Safety

Historically, studies relating to road safety analysis have relied extensively on the collection and use of accident data, with the presented limitations. Collision-based safety analysis methods are limited in terms of understanding road user behaviour and other factors leading to accidents (Tarko et al., 2009).

Surrogate measures of safety (SSM) are a relatively new concept, with the TCTs constituting an early method to obtain surrogate measures of safety. The general idea behind using surrogate measures of safety is to use a more “proactive” approach, through studies involving field observations. To collect detailed information about collision processes and factors, it is cost-effective method for researchers to administer their own data collection. Thus, through direct observation of traffic events, using all observations (including undisturbed passages of road users), a road safety diagnosis can be made more quickly, without the need to wait for the occurrence of a collision. Tarko et. al indicate that surrogate measures of safety should be based on observable non-crash events which can be physically and logically related to accidents (2009).

Laureshyn et al. used the concept of TTC as an indicator for proximity between road users, and between a traffic event and a collision and applied it to video analysis (2010). Whilst this concept dates to the 1970s (Hayward, 1971) during the development of TCTs, it is still in active use, including in driver assistance technology for example. The works of St-Aubin et. al used the algorithm developed by Laureshyn to compute TTC in a case study of safety at highway ramps in the Montreal area (2013).

The surrogate measures of safety to be used in this research project are chosen due to their widespread use in road safety studies.

2.2 Roundabout Safety Studies in North America and Before-after Studies

It has been shown in major studies that roundabouts offer a significant improvement in road safety. The National Cooperative Highway Research Program (NCHRP) Report 572 reports a diminishing number and severity of crashes (especially higher-severity crashes) (FHWA, 2007). NCHRP Report 672 demonstrates a reduction in the number of conflict points in roundabouts and reports lower observed absolute and relative speeds, citing these as contributing towards safety improvement compared to stop-controlled intersections (FHWA, 2010).

While the CMF (Crash Modification Factor) is mainly used in studies involving accident data, past studies have shown a correlation to conflicts in roundabout safety studies. In a study including 53 intersections in the Toronto area (the data covered a three-year period), Shahdah et. al (2014) ran simulations to evaluate the relationship between the number of simulations run and the calibrated crash-conflict relationship and the CMF. The Wiedermann-74 car-following model was used in VISSIM, and the safety indicator used was TTC. The results showed a strong link between simulated traffic conflicts to real-life observed crashes, and that surrogate safety measures based on simulated conflicts can be used to estimate CMFs. In a study analysing the CMFs for converted roundabouts in the state of Oregon, Dixon & Zheng (2014) documented several past studies in which CMFs were used. While the variation in CMFs was significant between the studies and was also sensitive to traffic volumes in the intersections, the CMFs were globally reduced after roundabout conversion (CMF values varying between 0.13 and 1.03). It was also shown that the type of initial intersection (prior to roundabout conversion) was a likely influence on crash reductions. As a reference, the CMF from the Highway Safety Manual for conversions from stop-controlled intersections to single-lane roundabouts is 0.42 (meaning the number of collisions would drop by 58 % after conversion) (Persaud et. al, 2001). NCHRP Report 572 (2007) showed that the CMF for conversions of signalised intersections into modern roundabouts was 0.33 (in a suburban setting, for a one- or two-lane intersection). In an urban setting the CMF was of 0.99 for all crash severities (the findings were that it could increase, decrease or remain the same). Overall, for all environments and settings (one- or two-lane intersections) and all types of severities, the CMF for the conversion of signalised intersections into modern roundabouts was evaluated to be 0.52, pointing to an increase in safety for roundabout conversion.

Persaud & Lyon suggested that, after studying the accidents linked to roundabout implementation using the Empirical Bayes method, the conversion from intersection to roundabout was beneficial, and showed a reduction in injury and property damage crashes (2007). Retting et al, using the Empirical Bayes method in a before-after analysis, underlined a 90 % drop in the number of accidents causing fatalities and serious injuries and a reduction in excess of 70 % in the number of injury crashes overall (2001). Hyden & Varhelyi (2000), Senk & Ambros (2011), as well as Daniels et. al (2012) reached similar conclusions using regression models, thus validating the overall expected safety improvement from roundabout conversion.

In a report by Saunier et. al closely related to this research project, a database of approximately 100 roundabout sites (including 20 sites evaluated using video data) in Quebec was analysed, to evaluate road user safety and behaviour relating to this relatively recent type of infrastructure in Quebec (2015). The research report made use of accident data, video analysis and a survey for pedestrians in its overall evaluation of roundabout safety. Safety indicators were used in the context of video analysis, such as speeds, vehicle gaps and TTC. The analysis of speeds and TTC was inconclusive, yet answers to one of the survey questions pointed toward a generally good understanding of the way roundabouts operate. Accident frequency analysis in terms of the different roundabouts did not yield any conclusive results either. The overall conclusion in the report mentioned previously shows that larger roundabouts (i.e. roundabouts with more than one lane and over significant width) tend to show a poorer safety performance after their conversion from a standard intersection.

Roundabouts are different in nature to standard intersections and constitute a relatively new concept in North American environments. However, other non-standard types of intersections exist in North America, and while documentation on these is limited, it is relevant in the context of this project to study other work on the topic. While non-standard intersections come in many forms, and are detailed in some of the literature, there are few before-after studies relating to non-standard intersections. However, the work of Bared et. al explores the comparison between standard intersections and diverging-diamond interchanges, where lanes switch sides in the intersection (2005). The main safety finding of before-after studies of Diverging Diamond Interchanges was a significant speed reduction from vehicles crossing the interchange compared to vehicles crossing the initial intersection.

2.3 Video Analysis Tools for Traffic Analysis

Intelligent transport systems provide increasingly accurate methods for data collection and processing, for example, through computer vision, which allows automated video-based road user detection and tracking. In the context of road safety studies, data collection has often been a limiting factor in their efficient analysis, due to the required long times of observation, but more importantly due to the limited ability to collect data at a microscopic level with sufficient accuracy.

Multiple video analysis tools have been developed in the field of traffic analysis, one of the first being the AUTOSCOPE project, a video detection system developed in Minnesota by Michalopoulos et. al (1990), another being a feature-based vehicle tracking system as presented by Beymer et. al (1997). Since then, several tools for traffic safety analysis have been developed for safety evaluation. Extracting surrogate measures of safety has been one of the motivators behind the application of computer vision technology to transportation, with applications to road safety at intersections (Saunier & Sayed, 2006), as well as pedestrian-vehicle interactions at crosswalks (Ismail et. al, 2009), and cyclist safety at cycling facilities (Zangenehpour et. al, 2015).

Sakshaug et. al studied cyclist safety in roundabouts using video analysis, and found that cyclists were more prone to be involved in serious conflicts when integrated to traffic as opposed to roundabouts in which cycle paths were kept separate from traffic (2010). Video recording and automatic detection tools were used in the analysis, though conflict recordings were analysed manually.

Several studies of roundabouts have been undertaken using video analysis. Russell et. al (2012), along with the KDOT (Kansas Department of Transportation) analysed the performance of roundabouts using video data obtained by placing a camera on site. Traffic flow was then extracted from the data and subsequent roundabout simulations were conducted using SIDRA, a computer evaluation software, which enables comparison between modern roundabouts and various types of intersections. Some systems have been used for video analysis at roundabouts, such as VeTRA (Vehicle Tracking for Roundabout Analysis) in the works of Mussone et. al (2011). The use of this software requires pre-elaboration of the geometric model of the roundabout studied, on top of the camera calibration work, and produces Entry/Exit count matrices, trajectories, speed profiles as well as flow classification. A more manual and qualitative approach was sometimes preferred, as shown in the study by Krivda (2013) where the analysis of roundabouts in the Czech Republic was conducted using manual analysis providing a detailed classification for every road user entering the roundabout to monitor conflict types and severity.

As presented in recent work (St-Aubin et al., 2015), in which speed, gap and TTC were the main variables evaluated to show roundabout safety performance, width of the apron and the number of exit lanes had a significant impact on driving speeds whereas the ratio of approaching and conflicting flows (coming from inside the roundabout) was found to be significantly correlated with TTC.

The video analysis tool (tvaLib) developed as part of roundabout-related research and used in this study was developed by St-Aubin, and presented in detail in previous work (St-Aubin et al., 2015, St-Aubin, 2016). It is a shared source tool which analyses driver behaviour and safety based on the vehicle detection and tracking algorithm available in the open source Traffic Intelligence project (Jackson et al., 2013).

Traffic Intelligence implements a feature-based algorithm for tracking all road users. This enables the extraction of road user trajectories from the raw video data by first detecting and tracking pixels from one frame to the next, and recording these as feature trajectories. A road user therefore has several feature trajectories, which are grouped according to their motion over several frames.

The output of the trajectory collection enables several standard measures to be performed, based on the physical characteristics of these trajectories. As such, vehicle speeds, lane changes, basic traffic counts and other measurements of road user behaviour can be determined. tvaLib is a tool built on top of Traffic Intelligence, and constitutes a platform for surrogate safety analysis. tvaLib (and, by extension, Traffic Intelligence) is used throughout this research project to conduct all elements of video data analysis.

CHAPTER 3 METHODOLOGY

The overall methodology for the data analysis in this research project is illustrated in Figure 3.1, and detailed in the following sections of this chapter.

3.1 Conflict Point Analysis

The first approach to the before-after analysis methodology presented in this chapter is the analysis of conflict points within a given site. The objective of such a study is to determine, prior to the use of video data collected at each site, the potential for “danger” to road users. It must be noted here that the trajectories shown in the figures are ideal prototypes of vehicle trajectories as opposed to real, observed vehicle trajectories.

As was shown in the Literature Review, three types of conflict points are described in the transportation engineering literature: converging conflict points, diverging conflict points and crossing conflict points. These different types of conflict points have varying degrees of potential severity (conflict point severity is considered here as being the severity of the potential accident that may result from a collision at that point – based on the angle between the two road users’ trajectories), with crossing conflicts considered as having a significantly higher severity than converging or diverging conflicts (FHWA, 2010).

In order to illustrate the method of determination of conflict points, the latter are presented for both 3-way intersections (“Y-intersections” and “T-intersections”) as well as standard 4-way intersections. Subsequently, the conflict points for 3-branch and 4-branch roundabouts are studied in order to highlight the change in conflict points following roundabout conversion. In the defined scenarios shown in the following sections, traffic is considered to flow in both directions for every approach.

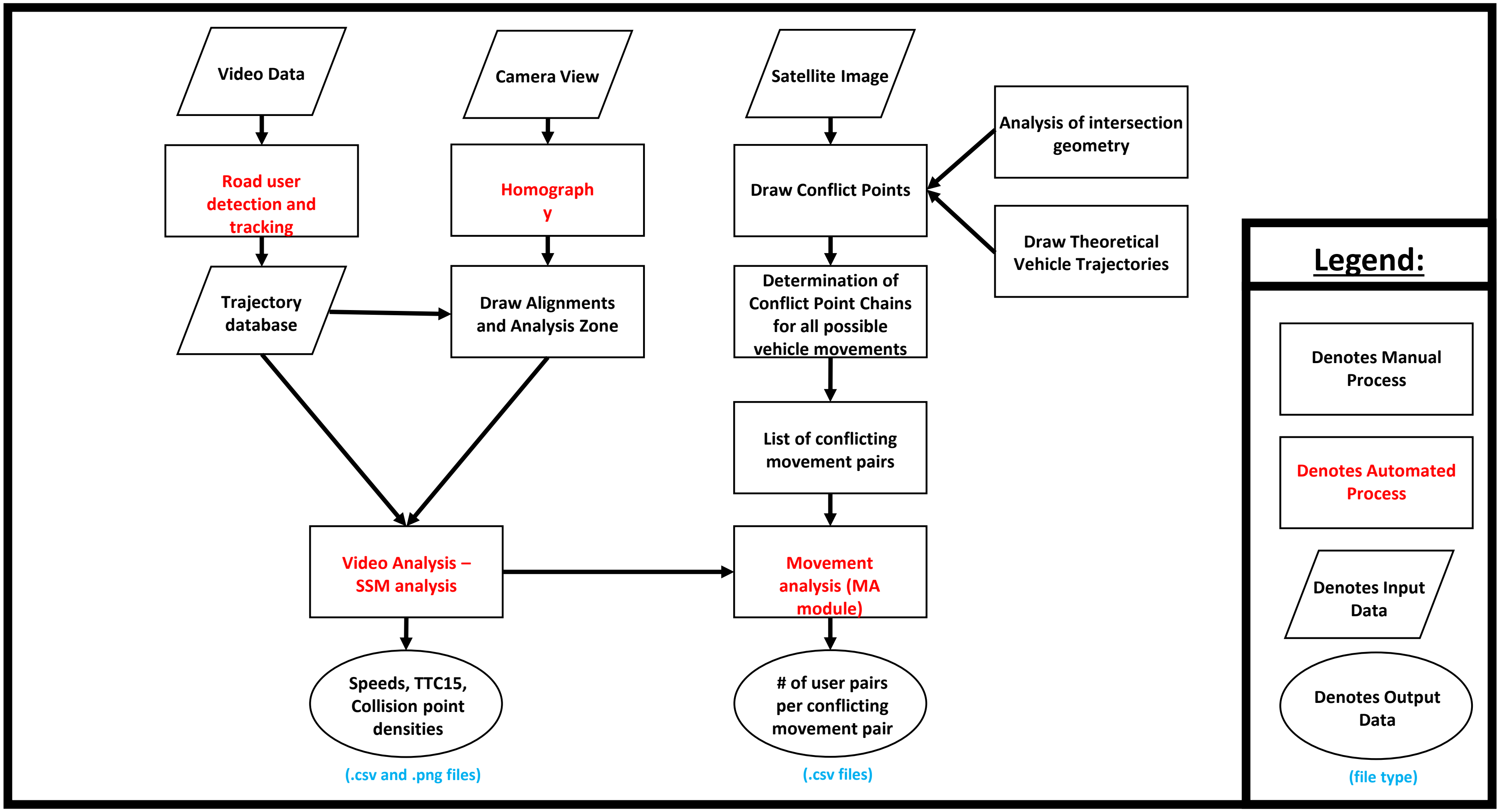

Figure 3.1: Project Methodology Flowchart

3.1.1 General Case – 3- and 4- way intersections

Figure 3.2 below illustrates the general case of a 3-way (standard "Y intersection"), including the corresponding conflict points and vehicle trajectory prototypes. All three types of conflict points (mentioned above) can be found in every intersection, and are detailed in the legend (crossing conflicts in red, converging conflicts in brown, and diverging conflicts in black).

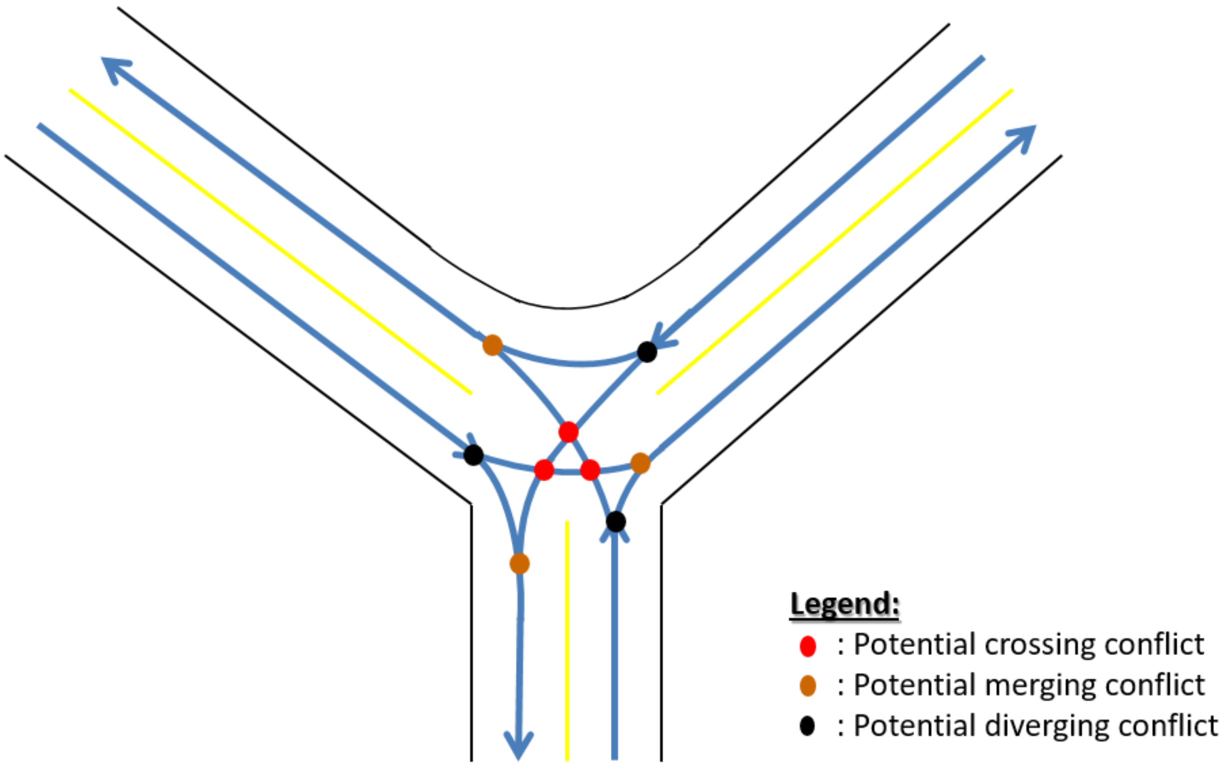

Figure 3.2: Three-way intersection ("Y intersection") with associated conflict points

Observation of the different conflict points in Figure 3.2 points to a recurring *motif*. For every trajectory (vehicle trajectories are illustrated in blue in Figure 3.2), there are two different conflict point chains. A conflict point chain is characterised as a set of conflict points potentially encountered by a road user along a given movement. For every approach in the intersection, the left-turn manoeuvre contains a chain of four conflict points, in the following order: a diverging conflict point, followed by two crossing conflict points (crossing conflicts in this situation occur only between left-turning vehicles – a geometrical exception being the "T-intersection" where one approach doesn't have a left-turn as it instead becomes a straight movement).

In the event of right-turning vehicles, a second type of conflict point chain occurs, consisting of a diverging conflict followed by a converging conflict point.

Thus, an intersection containing three approaches (regardless of “Y-intersection” or “T-intersection” geometry), comprises nine conflict points (three of each type – as illustrated in Figure 3.2 above) in total. However, geometrical attributes of intersections may vary as is the case when traffic is forbidden in one direction in one or several approaches (see Section 4.1). In those cases, both the number and the position of conflict points may vary.

Analysing standard four-way intersections follows the same logic as what has been presented for three-way intersections. However, the additional branch creates many more conflict points (mostly crossing conflict points), as is shown in Figure 3.3.

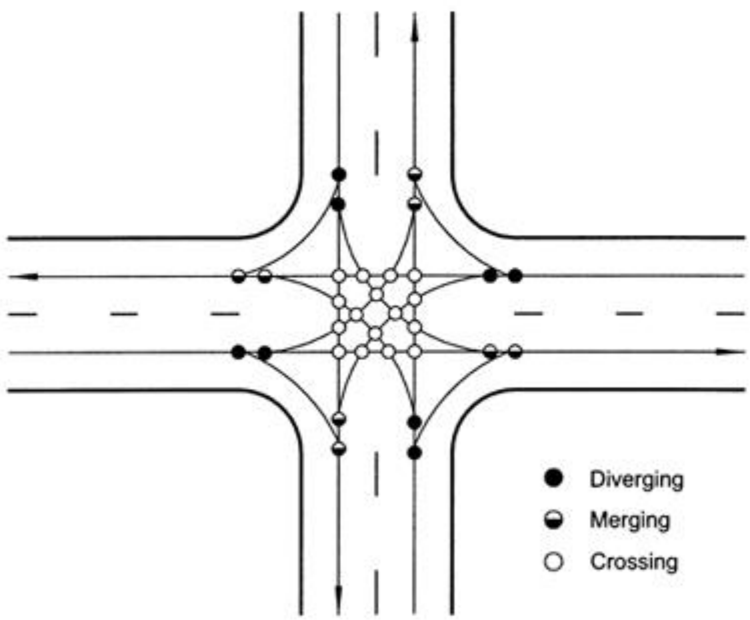

Figure 3.3: Conflict points in a four-way intersection (FHWA, August 2004)

Figure 3.3 shows a total of thirty-two conflict points, sixteen of which are crossing conflict points, with eight merging and eight diverging conflict points (two of each type in every approach). Once again, one can distinguish the conflict point chains associated with the different vehicle trajectories.

For vehicles going straight-ahead and for left-turn manoeuvres, the conflict point chains are identical: two diverging conflict points, followed by four crossing conflict points and two converging conflict points. Right-turn manoeuvres are a simple chain comprised of a diverging conflict point and a converging conflict point in that order. Given a symmetrical four-way intersection such as the one pictured in Figure 3.3, these chains apply to every single approach.

Of course, not all four-way intersections are designed with one lane and all permitted movements for all the approaches. Depending on the number of lanes in each approach, and the allowed movements for each lane, the conflict point diagrams can vary from the diagram in Figure 3.3. An example of such an occurrence is illustrated in the second case study (see Section 4.2).

3.1.2 General Case – 3-Branch Roundabout

In order to establish a before-after comparison, the evaluation of conflict points in the implemented roundabout is a necessary step in terms of comparative safety analysis once the conflict points for the initial intersection geometry have been determined.

The overall configuration of a roundabout is fundamentally different from that of a standard intersection. The conflict points in a roundabout with three branches are shown in Figure 3.4 below.

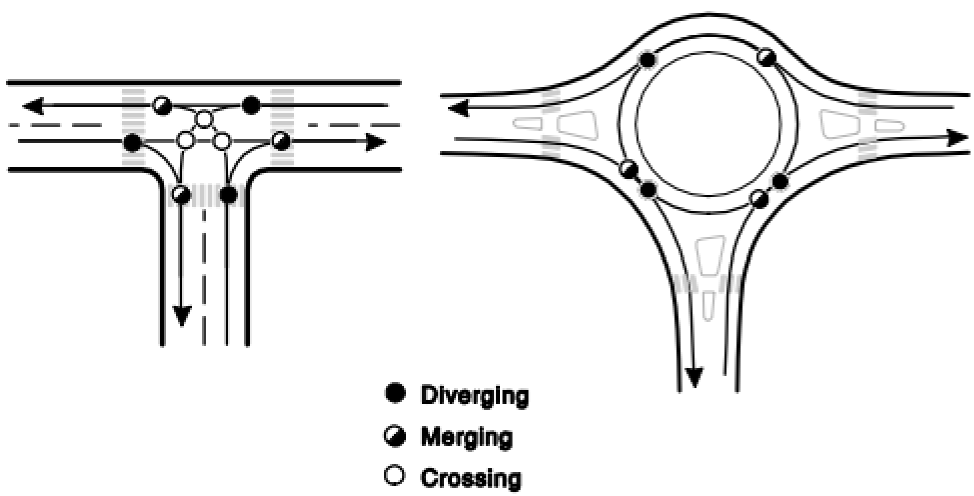

Figure 3.4: Conflict points in a 3-branch roundabout (NCHRP, Report 672, 2010)

By observing Figure 3.4, it is noticeable that both the number of conflict points as well as their severity is reduced in a three-branch roundabout as opposed to a three-way intersection. One of the main factors in this change is the fact that traffic flow within a roundabout only takes place in one direction, as opposed to the two directions in a standard intersection. This ensures elimination of crossing conflicts.

There are only six conflict points in a three-branch roundabout; the conflict point chain (defined in the previous sub-section) consists only of alternating converging and diverging conflict points. The analysis of ODs within both types of intersections in a later part of this chapter will associate the various conflict point chains to the different manoeuvres in each type of intersection or roundabout.

3.1.3 General Case – 4-branch roundabouts

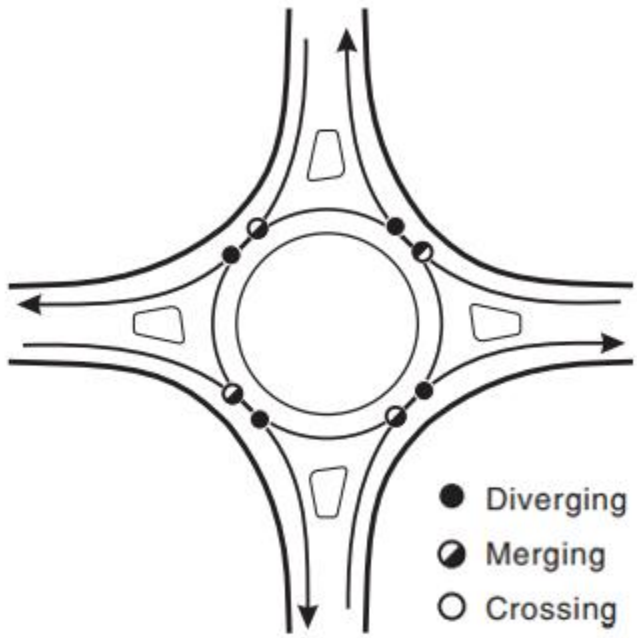

Figure 3.5: Conflict points in a four-branch roundabout (NCHRP Report 672, FHWA, 2010)

As is shown in Figure 3.5 above, there are significantly fewer conflict points in a four-branch roundabout than in a four-way intersection, with only eight conflict points as opposed to thirty-two in a standard four-way intersection (as was shown in Figure 3.3). In a perfectly symmetrical roundabout like the one shown above, one can clearly see that the conflict points are separated into four sets of two conflict points, all pairs of Merging and Diverging conflict points. This illustrates the fact that each approach of a roundabout leads to the creation of “merging zones”.

3.2 Movement Analysis

The analysis of conflict points, as described in the previous section, can give a preliminary appreciation of areas where collisions have a higher probability of occurring as well as their potential severity, for both types of intersections. As soon as a road user goes through one of these areas, he/she encounters several conflict points within a given movement, according to the type of area.

In order to evaluate the overall safety of one infrastructure as opposed to another, it is important to consider the number of conflict points a given road user encounters within an infrastructure, as a means of identifying the critical movements (i.e. the movements with increased risk of collision) within the initial intersection and, subsequently, the converted roundabout. Therefore, beyond the study of individual conflict points, movement analysis is a tool for safety analysis and understanding why safety may change after roundabout conversion.

3.2.1 Analysis of Conflict Point Chains

There are several steps to undertake for movement analysis; the first objective is to determine the number of conflict points for identified movements (a movement being defined as a manoeuvre completed between a given approach and a corresponding exit within an intersection), both pre- and post- roundabout conversion, with a view of comparing the number and types of conflict points for comparable movements.

Firstly, all possible movements within both types of infrastructures need to be defined, by OD pairs. Defining these movements requires knowledge and analysis of the intersection geometry, along with allowed directions of traffic, as well as the number of lanes. Thus, for an intersection/roundabout with three bidirectional branches, there are six (nine, including U-turns) possible vehicle movements, while there are twelve for an intersection/roundabout with four bidirectional branches. The identification of possible conflict point chains and the exposure to different conflict points for road users is used to identify the potential for dangerous situations for every OD pair within a given infrastructure – in this case, applied to both the initial intersection and converted roundabout.

To help structure the analysis, the origins/destinations for both the intersection and the roundabout can be numbered. Here, the numbering of the alignments (see illustrations and applications in Sections 4.1 and 4.2) is used to number the movements within each intersection.

Once the vehicle movements are defined (and illustrated), conflict points are extrapolated from the allowed (theoretical) vehicle movements, as per the three different types of conflict points (diverging, converging, crossing). Conflict point diagrams (as previously presented in Figure 3.2:

Three-way intersection ("Y intersection") with associated conflict points to Figure 3.5) are drawn as an aid for visual comparison.

Obtaining the different conflict point chains, as was introduced earlier, involves listing, for every OD pair within the given intersection/roundabout, the different conflict points in the order in which a road user would encounter them. The different chains can then be listed in a table, as is shown in Table 3.1 below, per the origin of a road user, for both types of infrastructures, as an example.

N.B: A roundabout's design enables a U-turn manoeuvre, something which is not always permitted in a standard intersection according to provincial or state Highway Codes. Therefore, in order to guarantee a comparison between these two very different kinds of intersections, the possible option of making a U-turn is not considered. 2.57 % of 7 115 motorists for the first case study, and 0.03% of 15 464 motorists for the second case study made U-turns at the converted roundabouts.

Table 3.1: Comparison of conflict point "chains" - 4-way intersection vs. 4-branch roundabout[3]

	Intersection	**Roundabout**
Left-Turn	Diverging (2x)-Crossing (4x)-Converging (2x)	(Converging-Diverging) (3x)
Straight Movement	Diverging (2x), Crossing (4x), Converging (2x)	(Converging-Diverging) (2x)
Right-Turn	Diverging, Converging	(Converging-Diverging) (1x)

If the studied intersection differs in any way from the general case (whether it be a three-branch or a four-branch intersection), the number and type of conflict points can differ from what is presented in Table 3.1. It is also possible that the intersections and roundabouts contain more than one lane, in which case the roundabout may contain crossing conflict points – the number of conflict points in general will increase, as will the number of possible movements.

[3] Crossing conflict points are highlighted in red due to their increased severity

The roundabout (generally) eliminates crossing conflict points, which are replaced by diverging and converging conflict points instead, due to the intrinsic geometrical characteristics of those infrastructures. The roundabout forces road users to follow the same trajectory, in one common direction, as opposed to an intersection, which allows for vehicle trajectories to cross each other, and in turn creates crossing conflict points.

Right-turn manoeuvres are identical for both infrastructures in terms of conflict point severity, with one converging and one diverging conflict point in the trajectories of right-turning road users. However, there are significant differences for straight and left-turn manoeuvres, with eight conflict points (including four crossing conflict points) involved in standard four-way intersections. Roundabouts, for straight and left-turn manoeuvres, are responsible for four and six conflict points respectively, all being of either converging or diverging types.

Applying the same logic for four-way intersections/four-branch roundabouts to three-way intersections/three-branch roundabouts, one can make similar remarks concerning expected roundabout safety.

3.2.2 Movement Analysis in the context of before-after analysis studies

While an analysis approach making use of conflict point chains can provide an indication of infrastructure dangerousness, it is solely used in this research project for two purposes: firstly, as an identification of various hotspots where road users have increased likelihood to be involved in dangerous traffic events, secondly to compare different possible vehicle movements between each type of infrastructure involved in the case studies. In short, conflict point analysis is used as a preliminary analysis prior to the other methods presented in this chapter.

As was briefly described earlier in the chapter, the aim of movement analysis is to aggregate the number of observed user pairs (defined as a pair of road users which coexist within a given, finite distance and time frame) (St-Aubin, 2016) between OD pairs existing both in the initial intersection and the converted roundabout.

Movement analysis, as defined in this research project, rests on the comparison of the number of user pairs. The latter are defined as instances during which two road users co-exist closely in space, usually within a distance where evasive action may be needed to avoid a potential collision. The goal is therefore to determine the number of user pairs, for specific ODs, defined according to the intersection geometry and conflict analysis.

Depending on the infrastructure geometry (number of lanes, allowed movements), correspondence between movements is not always exact; i.e. a given movement in one intersection setup can correspond to several movements in the corresponding converted roundabout, and vice versa. This may happen when the number of lanes (for an approach/exit for example) changes after roundabout conversion. In this case, the number of user pairs can be combined to obtain a comparison between the two different geometries.

In some cases, movements that do not exist in one intersection setup become possible after roundabout conversion, as is the case in the Intervale case study (Section 4.1). This limits the scope of the movement analysis as fewer movements can be compared. Such situations are therefore not considered in the scope of movement analysis.

As defined in earlier sections, the main method of data collection for this research project is the placement of cameras to record video data of road users. The data analysis takes place using computer vision tools which are used to detect road users based on their physical attributes, and to extract relevant information for use in road safety analysis. A specific function is developed as part of the project to allow for movement analysis and comparison between the initial intersection and the converted roundabout.

Movement analysis is prepared using the following:

1. The intersection geometry (before and after roundabout conversion) – including the alignments and their identification labels.
2. Conflict diagrams for validation of movement comparability
3. Conflict analysis and definition of comparable movements
4. Video analysis using the Traffic Intelligence and tvaLib software tools, which output speeds and TTC distributions
5. Creation of the Movement Analysis (MA) module for the tvaLib software – coded using Python 2.7.

Items 1 and 2 in this list are used conjointly: they are combined to create a list of conflict chains for every possible road user movement within the infrastructure. This list is compiled for both the initial intersection and the converted roundabout. The list of alignments is important here as it enables labelling of the origins and destinations.

The MA module is created to determine the number of observed user pairs for the movements determined with the use of the list of movements and conflict chains. The module uses a functionality included in the tvaLib library which, for every video sequence recorded for a given site, draws up a list of all the user pairs involved in the infrastructure. Once the conflicting ODs of interest are defined and entered into the code, the module iterates over the defined ODs and road users to find the number of user pairs for each movement.

The module then outputs a summary of the number of user pairs per movement, as well as the speeds for these user pairs, and the TTC values for these road users.

The overall aim, as is the case for before-after analysis in general is to then compare these values and graphs for both the initial intersection and the converted roundabout. An emphasis is placed on the three different outputs (Speed, TTC and number of user pairs) extracted using the MA module.

3.3 Analysis of Speed and TTC

With the use of computer vision software (see Section 3.4 below for details), collecting traffic data and surrogate measures of safety is made much easier. This section presents the two types of analyses which can be obtained from the use of computer vision, and contribute to the overall safety analysis.

3.3.1 Speed distribution analysis

Speed is widely defined as one of the principal factors in road safety (see Chapter 2). In terms of the surrogate safety analysis conducted during this project, road user speeds were measured and classified according to the approaches and lanes road users used, both in the initial intersection ("before" scenario) and the subsequent roundabout ("after" scenario).

Using average speed distributions allows for analysis concerning road user behaviour, but also as a measure of examining road user flow within the infrastructure. High speeds are associated with collision severity (Hauer, 2009), and are suspected to lead to higher collision probability, though significant proof of the latter remains to be properly suggested in the literature. Furthermore, large variance across users' speed distributions would suggest variable vehicle flow within the given infrastructure, which may be due to either congestion, or the presence of control signals at the intersection (such as stop signs, traffic lights, etc.).

3.3.2 TTC analysis

Introduced by Hayward et. al (1972) and initially presented in the Literature Review section (see Chapter 2), TTC is a safety indicator characterising the time left for two road users to collide, assuming they are on a collision course. TTC can be computed continuously for every user pair as long as they are on a collision course.

TTC relies on the definition of a motion prediction method, which, as defined by St-Aubin et. al, is the "ability to predict possible future positions of moving objects according to a set of consistent, context-aware, and rigorous definitions of natural motion" (2015). The chosen motion prediction method in the context of this research project is the simplest one: constant velocity. This motion prediction method entails projection of road users using constant speed and travelling along a straight path (using the initial velocity vector at every instant).

The illustration of the TTC calculation is shown in Figure 3.6.

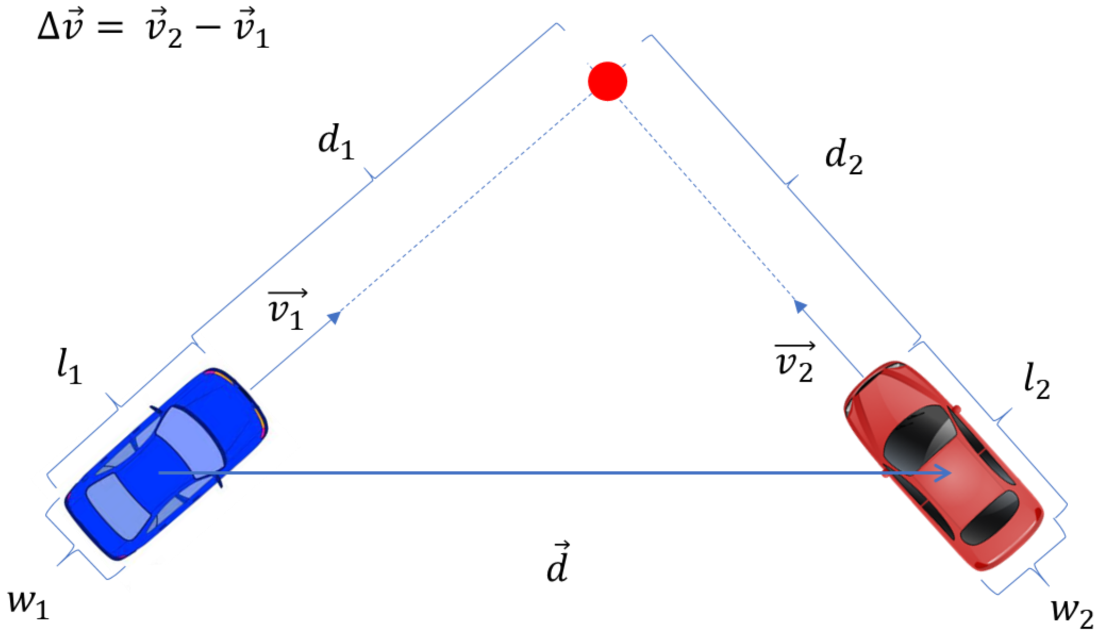

Figure 3.6: Time-To-Collision (TTC) definition

TTC, in its most common form, is calculated using the following formulae, with the assumption of constant velocity, if road users are on a collision course (Laureshyn, 2010):

For a potential side-on collision, $TTC = \frac{d_2}{v_2}\ if\ \frac{d_1}{v_1} < \frac{d_2}{v_2} < \frac{d_1+l_1+w_2}{v_1}$

$$\text{Or } TTC = \frac{d_1}{v_1}\ if\ \frac{d_2}{v_2} < \frac{d_1}{v_1} < \frac{d_2+l_2+w_1}{v_2}$$

For a potential rear-end collision: $TTC = \frac{\|\vec{d}\|-l_1}{\|\Delta\vec{v}\|}$

For a potential head-on collision: $\frac{\|\vec{d}\|}{\|\overrightarrow{v_1}+\overrightarrow{v_2}\|}$

where $\vec{d}$ represents the vector between the two interacting road user positions for which TTC is calculated, and $\Delta\,\vec{v}$ is the difference between the velocity vectors of both road users ($\Delta\,\vec{v} = \vec{v}_2 - \vec{v}_1$), l and w represent the length and width of the vehicles respectively.

Note: Application of the TTC formulae relies on the identification of a collision course – i.e. a situation in which road users would collide if their speeds and paths do not change. The road users' collision course is predicted using the chosen motion prediction method and the characteristics of the road users' motion (trajectory, velocity). The formulae for TTC are only valid if road users are on a collision course.

In the context of this project, TTC is implemented using an iterative constant velocity computation in Traffic Intelligence, meaning that the computation of TTC approximates the above generic formula up to a time step. For each user pair included in the camera view over the data collection period, a time series TTC(t) is generated, with successive TTC measurements. Aggregation methods are necessary to characterize road user pairs with one value.

Two main types of aggregation methods can be used. The “minimum unique” method only considers the most severe observation for a given series of TTC values recorded over a period of time. The “15^{th} centile” method uses the same principle as the “minimum unique” method, but chooses the 15^{th} centile of the values TTC_{15} to avoid the noise associated with the minimum (St-Aubin, 2015).

In the scope of this research project, obtaining the distributions of TTC_{15} (or other statistic of the TTC time series) over a period for the user pairs tracked during that time is the basis for comparisons of the given sites (for example before and after roundabout conversion). The shift in the TTC distributions will point to improved or worsened safety, depending on the displacement of the distributions. Figure 3.7 shows an example of a TTC distribution and subsequent interpretation of a shift in the presented TTC distributions (St-Aubin et. al, 2015).

Any user pair with a 15^{th} centile TTC value below the commonly used 1.5 s threshold is usually considered as a severe conflict that may be a proxy for accidents (St-Aubin, 2015) (Laureshyn, 2016). If driver speeds and directions remain unchanged, TTC reduces over time following an even ratio. A decrease in TTC values for a user pair entails a decrease in time available for an evasive action, which entails an increase in collision probability. As mentioned by Laureshyn et. al in their scoping review of surrogate measures of safety, low TTC values are likely to be associated with higher collision probability (2016). A collision has a TTC value of 0.

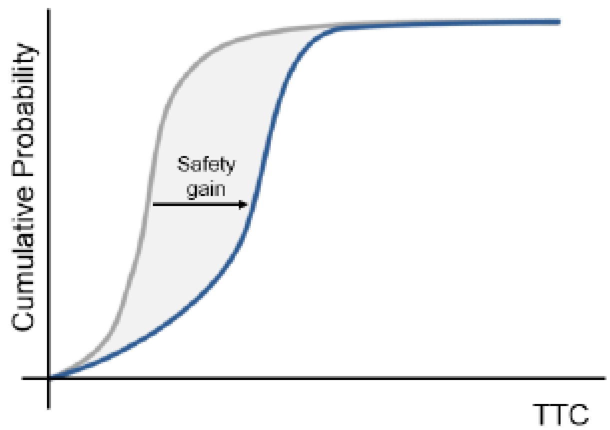

Figure 3.7: Illustration of the comparison between two TTC distributions (St-Aubin, 2015)

For each user pair, and using the defined motion prediction method, maps can be made of the predicted collision points within the intersection. Such figures are shown in the two case studies in Chapter 4.

3.4 Combined analysis resulting from the use of computer vision

As explained previously, this project uses surrogate safety methods to compare road user behaviour and safety at converted roundabouts. The source of data used here is video data, which requires analysis using software to extract the required traffic data. One of the types of traffic data required are road user trajectories, to complete the before-after analysis of safety indicators at the intersections included in the study.

3.4.1 Introducing the computer vision software

This work is primarily based on two tools: Traffic Intelligence (developed by Nicolas Saunier and collaborators) (Saunier et. al, 2010) (Jackson et. al, 2013) and tvaLib (developed by Paul St-Aubin, and collaborators) (St-Aubin, 2016).

The video data is collected over a period of several hours, using consumer grade cameras running continuously at a constant framerate, and installed above the street, high enough to ensure that the occlusion of the adjacent lanes due to passing road users is minimized. Road user trajectories are then extracted from video and projected into world space (at the ground level in real distance units, i.e. metres) using computer vision, as implemented in the Traffic Intelligence project. Furthermore, the lane alignments are drawn manually for each cluster of trajectories in each lane. These alignments are helpful in performing a variety of tasks including traffic counts. Alignments are drawn by placing the set of points corresponding as closely as possible to the centre of the lane. Alignments, if possible, should cross the intersection as a whole. TvaLib (shared source) is entirely coded in Python, while the tracker in Traffic Intelligence (open-source) is written in the C++ programming language, and other functionalities are written in Python. Proper configuration (mainly the specification of the Python path in the System settings), as well as specification of the location of the project files (for the videos and SQL databases on the one hand, and for the python script files on the other) are a necessary step to ensure the software runs with no issue.

The Traffic Intelligence project is a set of tools developed for data processing and, for the analysis of road user trajectories, behaviour and safety. TvaLib makes use of the tracking features from Traffic Intelligence and performs a variety of surrogate safety analyses, including - but not limited to – Speed Distributions, Post-Encroachment Times, Time-to-Collision calculations, as well as more standard traffic analysis features such as traffic counts.

The road markings (both in the initial intersection and in the converted roundabout) are not included in the analysis of road user safety and their impact is not quantitively measured. However, the markings are used manually to determine the allowed movements for each intersection setup, and can occasionally be used on a qualitative basis in terms of road user behaviour.

3.4.2 Output and Analysis

While the analysis of conflict points is a manual offline operation, the major part of the analyses conducted in this research project require outputs generated by Traffic Intelligence, with tvaLib used as a data validation and automation tool. The overall before-after analysis is based on the complementary analysis of two indicators: speed and TTCs, with the addition of the movement analysis method.

The analysis section (Chapter 4) presents, for each case study, the setup for each intersection: a satellite image of the initial intersection and the converted roundabout, which are used to estimate the homography matrices for each site. The aerial images are also used for the selection and presentation of the analysis zones for each site, as well as the alignments. Analysis zones define the area in which analysis of detected road user trajectories takes place. These must include the geometrical elements relevant to the study within view of the camera, and are defined according to the type of analysis required (for example, an analysis zone can be restricted to a specific quadrant within an intersection, or can include the entire intersection). The trajectories extracted by the Traffic Intelligence software are stored into SQLite databases (one database for each video sequence).

The outputs generated for the analysis rely on the constant velocity motion prediction method, and include a representation of collision point density (to identify the ‘hotspots’ within the intersections), speed (both for the entire set of road users as well as distributions for each alignment), and TTC distributions in the form of histograms and line charts respectively. The .csv files containing the speed and TTC_{15} data are then treated and graphs (examples are in the following section) are then produced manually.

Subsequently, once run, the MA module generates a plot of road user speeds and TTCs for the various movements. The module outputs .csv files containing all the user pair data for the pre-defined movement pairs to be evaluated in the Before-After comparison of conflicting movement pairs. The .csv output files, as is the case for the other tvaLib output files, are treated manually using Microsoft Excel.

CHAPTER 4 CASE STUDIES

This section presents the analysis of two different sites using the methodology described in the previous chapter. Both sites are the subject of a Before-and-After type analysis aiming to compare the safety of intersections, before and after transformation into a roundabout.

4.1 Before-and-After study – Intervale Avenue/Dawson Street intersection (Bronx, N.Y.C.)

4.1.1 Context

The first case study in this research project is in the Bronx, in New York City, and the roundabout conversion is part of NYCDOT's "Vision Zero" program, aiming at traffic calming along certain corridors. The whole Intervale Avenue corridor is in a Vision Zero Priority Area, as it has seen high crash rate (with 10.1 Killed or Severely Injured/mile) for pedestrians, and a total of 126 injuries from crashes along the Intervale Avenue corridor, between 2009 and 2013.

In terms of this research project, only the Southern-most section of the Intervale Avenue is concerned, as it is the location of a roundabout conversion. As is described by the NYCDOT, the previous intersection (described in Section 2 below) had wide lanes and a large uncontrolled crossing. The project aims to tackle safety through traffic calming with both the roundabout installation and the other installations along the Intervale Avenue corridor.

4.1.2 Initial Intersection

Figure 4.1 below shows the initial configuration (before roundabout conversion) of the Intervale Avenue intersection, with the vehicle movements and conflict points.

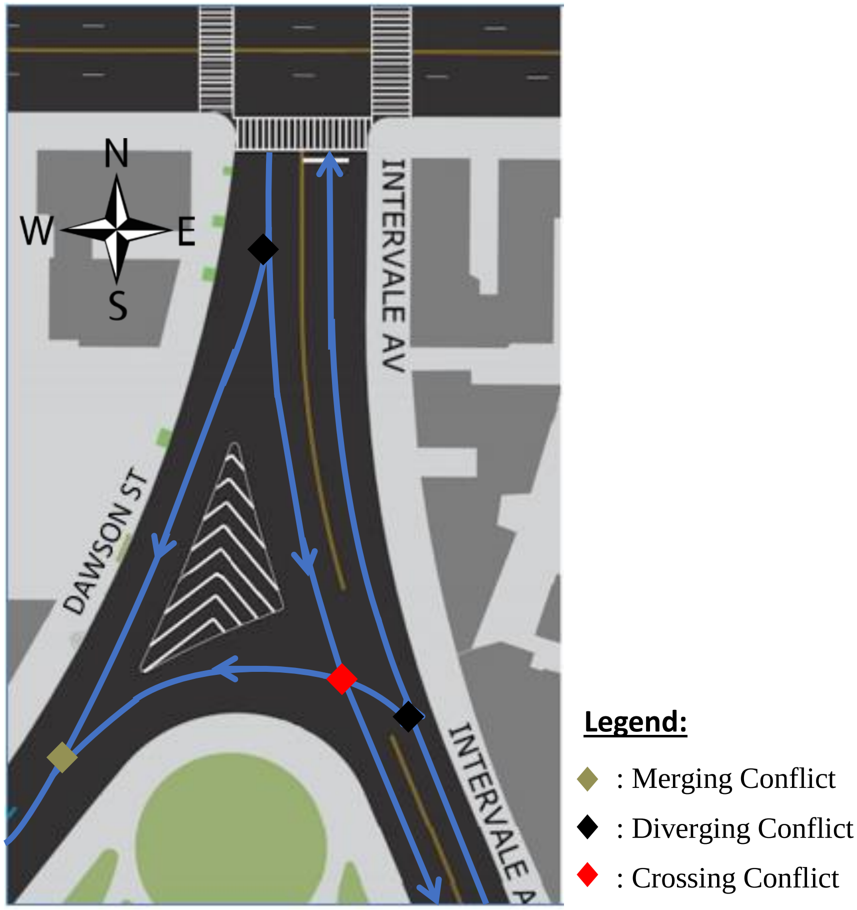

Figure 4.1 : Initial intersection configuration – Intervale Avenue/Dawson Street

The intersection setup is a peculiar one. One may notice that Dawson Street only allows for traffic flow in the southbound direction. This feature renders the initial design of the intersection simpler than classic “T-intersections” or “Y-intersections” for bidirectional roads.

If all movements were allowed (in the case where Dawson Street were bidirectional), there would be three extra conflict points, with a total of two potential conflict points in the intersection, both being of the 90-degree angle type (crossing conflict points). Both would implicate turns onto or from Dawson Street.

4.1.3 Roundabout Implementation

The implemented roundabout brings two main additional features to the initial intersection setup. Firstly, the change of geometry intrinsic to roundabouts which usually requires additional physical space for installation efficiently uses the space used up in the initial intersection by the hatched markings.

Secondly, and most crucially in terms of road safety analysis, the roundabout allows for a second direction (Northbound) on Dawson Street. This changes the conflict point analysis within the roundabout, especially in terms of comparability between the two types of infrastructure, as will be shown in the following section.

As was described in Chapter 3, the conflict chains found in the roundabout are simple converging-diverging types. Figure 4.2 below shows an illustration of the new roundabout setup on Intervale Avenue.

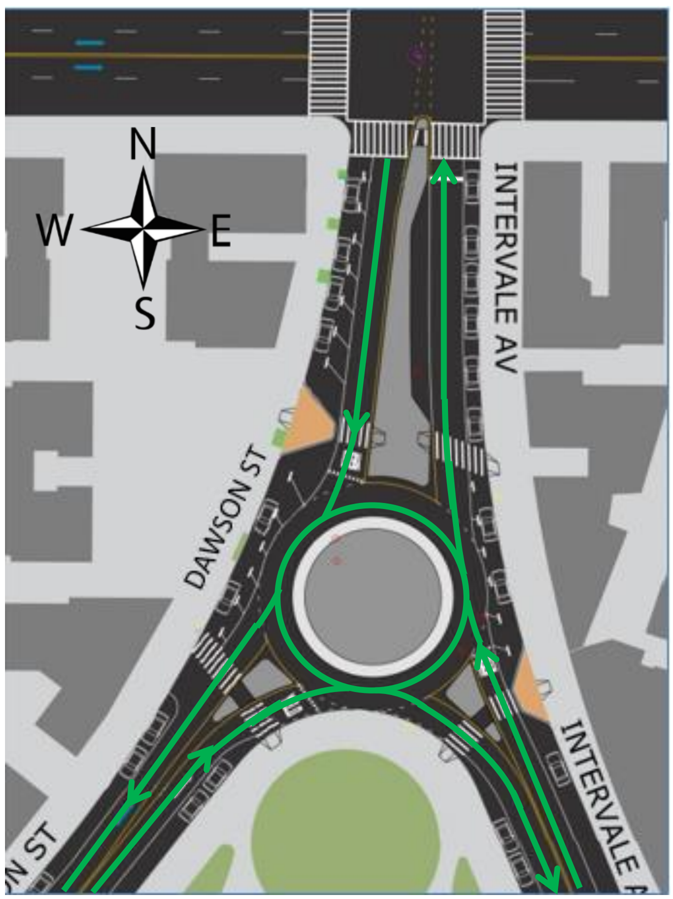

Figure 4.2 : New roundabout setup – Intervale Avenue/Dawson Avenue

4.1.4 Conflict Point Analysis

The initial intersection has two particularities: the first is that the lane enabling vehicles going South on Intervale Avenue to turn off to the right onto Dawson Street, upstream from the conflict point of the northbound vehicles turning left onto Dawson Street, separates the resulting diverging conflict point from other conflict points in the intersection.

The second unconvential feature of the intersection is the absence of traffic flow in the North direction on Dawson Street. This has several impacts in terms of road user behaviour, as is shown in Figure 4.3 below. This eliminates a total of five conflict points (including two crossing conflict points) compared to a classic “Y”-type intersection.

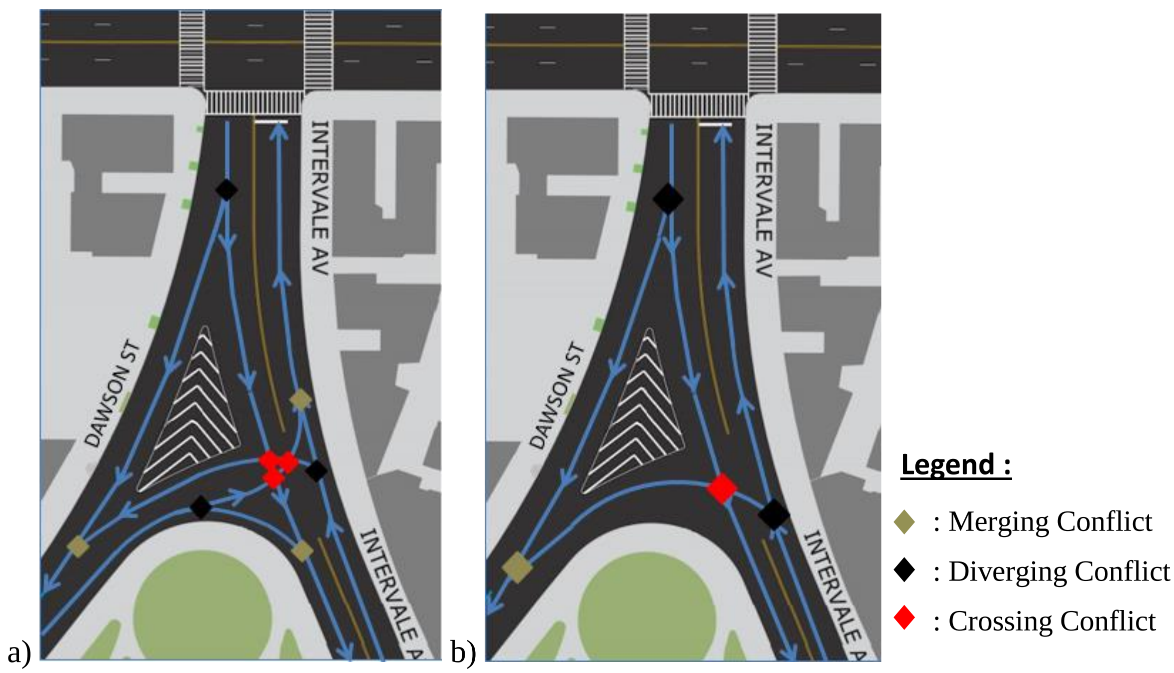

Figure 4.3: Comparison of conflict points a) in the event Dawson Street allowed two directions b) in the actual intersection

The first of these is the absence of two crossing conflict points for motorists that would be turning left (and going Northbound onto Intervale Avenue) conflicting with vehicles going in the South direction on Intervale Avenue, and vehicles from Intervale Avenue (Northbound) turning left onto Dawson Street (Southbound).

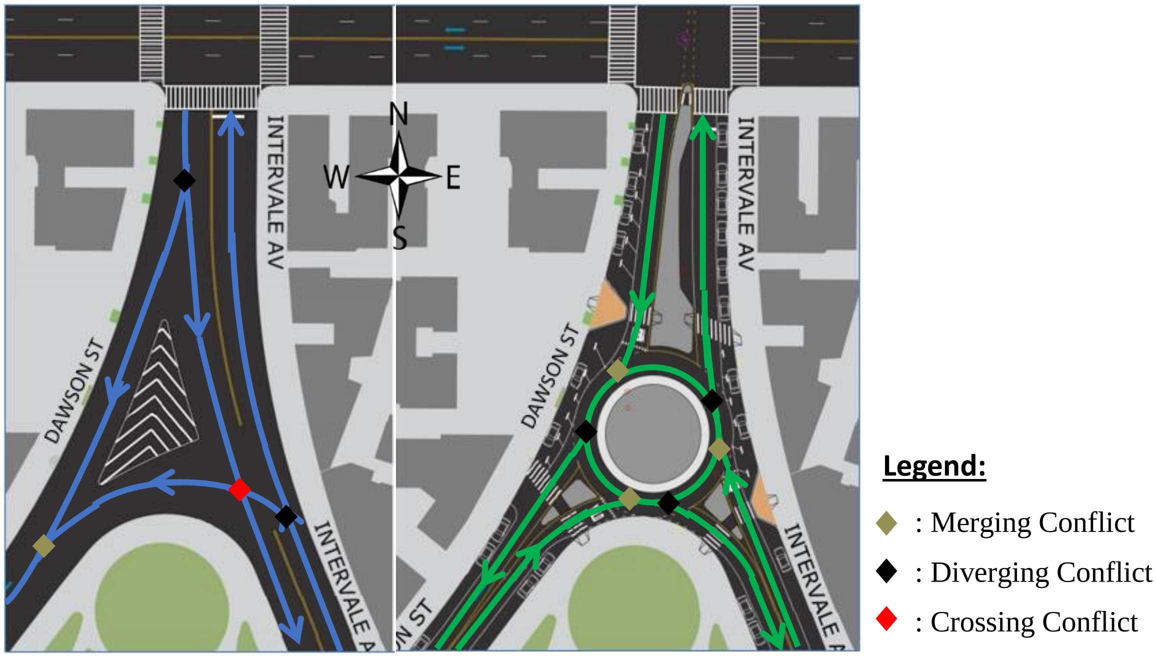

Figure 4.4: Conflict points before and after roundabout implementation on Intervale Avenue

Figure 4.4 shows more conflict points in the implemented roundabout than in the initial intersection between Intervale Avenue and Dawson Street, due to the added direction of traffic on Dawson Street, with a total of six conflict points as opposed to four in the initial setup. However, despite being less safe in terms of the number of conflict points, the roundabout eliminates the crossing conflict (in red), a conflict type which is deemed significantly more severe than merging or diverging conflicts (due to the potential collision angle) (NCHRP, 2010). Thus, in terms of overall conflict point severity, the installation of the roundabout seems to be the safer option. One also needs to consider that the initial intersection has 50 % fewer conflict points than it would have, had two directions of traffic been allowed on Dawson Street (see Figure 4.3 above for illustration).

4.1.5 Video Analysis and Observations

Table 4.1 below illustrates the main characteristics pertaining to the video data collection for the Intervale site. The footage was recorded in 2015, with both sets of video data taken during week days, during similar hours.

Table 4.1: Video data characteristics for the Intervale site

	Intervale - Before	**Intervale - After**
Geometry	3-way intersection	Roundabout
Date of footage	April 23rd 2015	October 6th 2015
Weekday	Thursday	Tuesday
Start time	08:30:00	09:05:00
End time	21:32:00	21:49:12

Table 4.2 shows a comparison of the number of vehicles detected in the intersection by the vehicle tracking algorithm, before and after roundabout conversion.

Table 4.2: Vehicle counts before and after the Intervale roundabout conversion

	Intervale - Before	**Intervale - After**
Total Vehicle count	4448	7115
Total Pedestrian count	722	367

Note: Pedestrians and vehicles are distinguished using a median speed threshold of 2 m/s (i.e. 7.2 km/h).

The number of detected vehicles shows a 60 % increase in the number of road users in the intersection after the roundabout conversion. This may be attributed to the collection of the video data after the introduction of the roundabout on a weekday during the Autumn season, which tends to be one of the busiest periods.

4.1.5.1 *Before* Scenario – initial intersection analysis

After running the analysis of the footage presented in Table 4.1 above, several results are extracted, according to the analysis method described in Chapter 3: the initial intersection is analysed using speed and TTC_{15}.

Firstly, it is important to present the site analysis setup before treatment of the video data. Figure 4.5 below shows the initial intersection along with the corresponding analysis zone and the alignments for every lane.

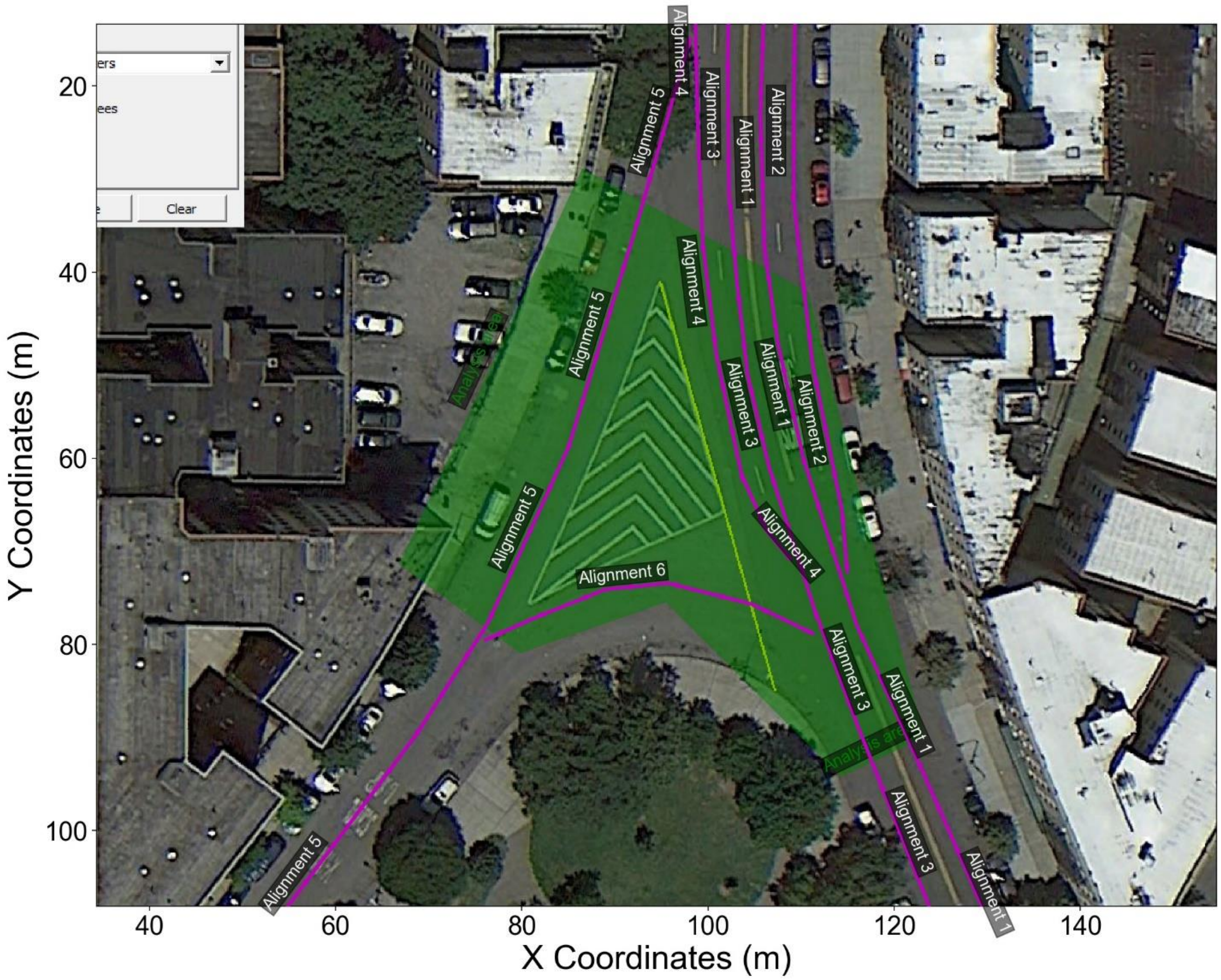

Figure 4.5: Analysis zone and alignments for the Intervale intersection

The alignments above are a set of points annotated within tvaLib and connected to produce the centre line of each lane, according to both the geometry of the site and the trajectory cluster loaded through the software. The analysis zone (in green in Figure 4.5 above) is drawn to cover all of the approaches in the intersection and as many of the vehicle trajectories as possible. The analysis zone is drawn in green in Figure 4.6.

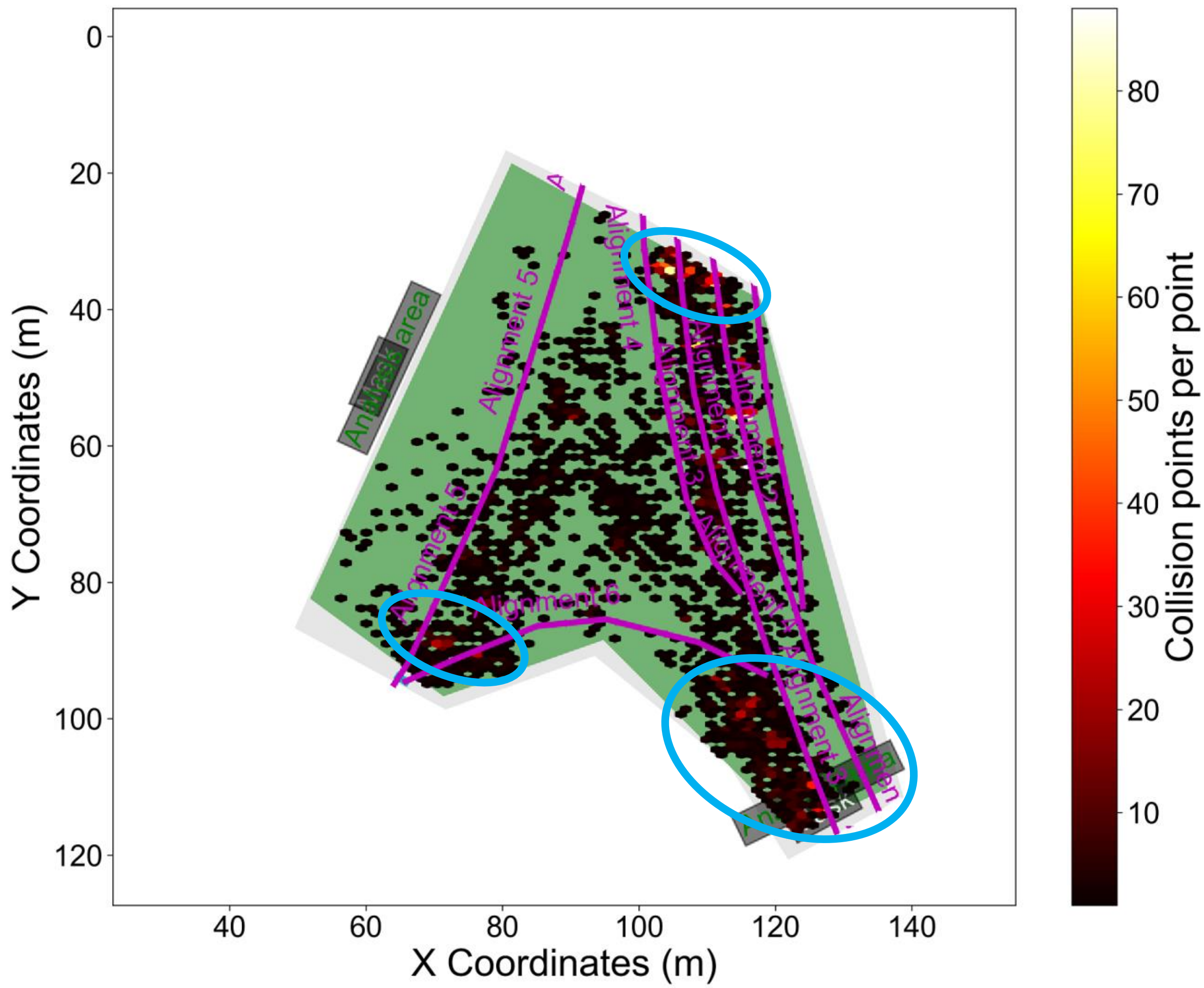

Figure 4.6: Collision point density - Intervale initial intersection

Note: The collision point density in Figure 4.6 represents the predicted collision points between each user pair's trajectories according to the constant velocity motion prediction method.

Figure 4.6 above shows the predicted collision point density between users based on motion prediction at constant velocity. Examination of Figure 4.6 yields three different "hotspots" of interest. Two of the three areas (2 and 3) with higher predicted collision points involve movements toward Dawson Street. Road user movements originating from both the North and South approaches on Intervale Avenue with destination Dawson Street therefore appear to be the most prone to be involved in conflicts. This may be caused by the conflicting directions between those sets of movements: road users going from Intervale Avenue (South approach) to Dawson Street are conflicting with southbound users on Intervale Avenue (area 3).

The final “hotspot” (area 1) does not correspond to a specific type of conflict point detailed in the conflict point analysis, but could be due to rear-end interactions between road users on Intervale Avenue. This points to one of the weaknesses of the use of the constant velocity prediction method when compared to conflict point analysis. As the constant velocity motion prediction method is unrealistic compared to real observed road user behaviour, its use in the analysis could explain why the predicted collision points shown in Figure 4.6 do not show an exact correspondence with the conflict points. Furthermore, rear-end conflicts are excluded from conflict point analysis.

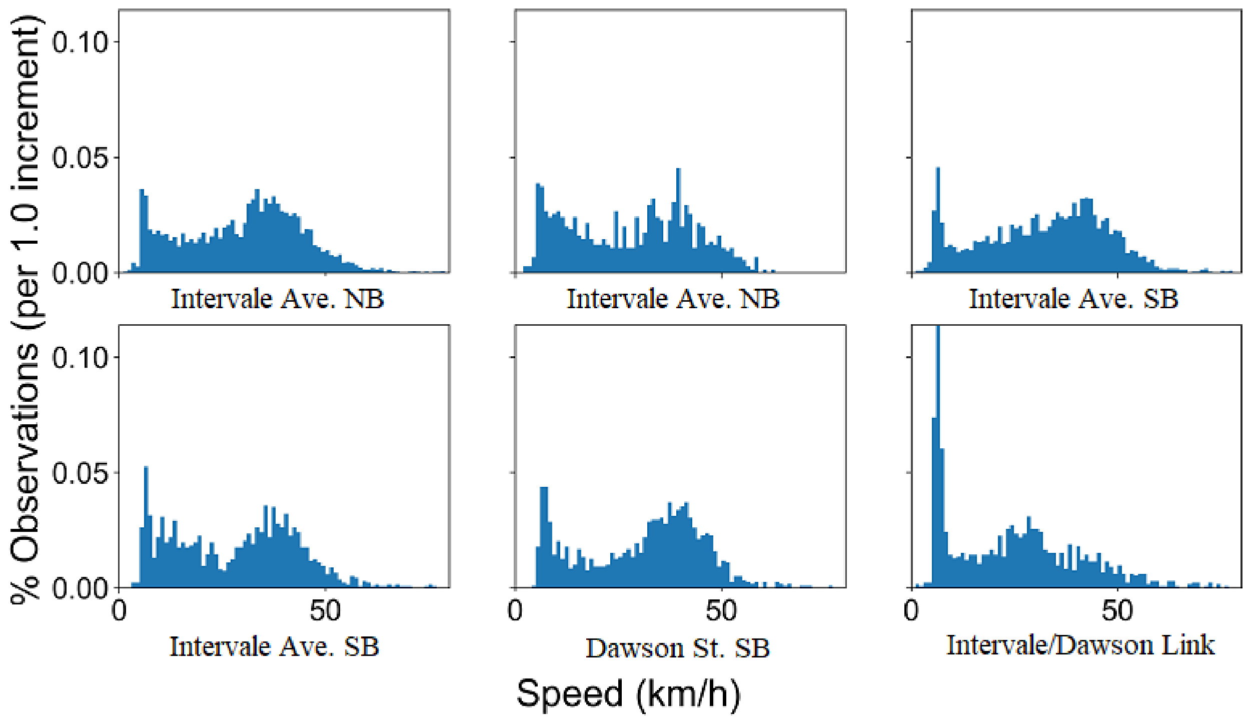

Figure 4.7: Average user speed distributions along each alignment

The above graphs show average user speed distributions along each alignment within the initial intersection. The first observation concerning Figure 4.7 above is the similarity of the distributions for each alignment. Speed distributions along the six alignments follow the same trend: a mode around the 10 km/h mark, followed by a symmetric distribution with the mode around 40 km/h. One may also notice that the speed distribution for Alignment 6 (lane enabling the turn onto Dawson St. southbound from Intervale Ave. northbound) shows a larger proportion of speeds around the 10 km/h mark than the other lanes, while its overall distribution differs from the other alignments, with the second mode around 25 km/h.

Several interpretations of the distributions can be made. The two modes in each of the distributions are the illustration of two different phenomena within the initial intersection: the first mode (around 10 km/h) shows that a large proportion of registered speeds are of motorists that must slow down and of pedestrians. The second mode represents the average speed around which most motorised road users in the intersection are travelling.

Road users turning onto Dawson St. from Intervale Ave. Northbound (along Alignment 6) tend to have slower speeds due to the nature of their manoeuvre; they are effectively completing a left-turn, and – in the case of oncoming southbound traffic on Intervale Ave. – must yield in order to complete their turn. Since these road users are not only completing a turn, but also merging into another lane with oncoming traffic (Dawson Street) – the mode of the speed distribution for the lane merging into Dawson St. is understandably around a lower value for vehicle speed.

Overall, in terms of road user speed, one can conclude that recorded speed values within the initial intersection are mostly centred around the speed limit of 25 mph (i.e. 40 km/h - New York City DOT, 2015), which entails that a significant number of road users are exceeding the allowed speed limit. The first mode at low speeds present in all the distributions per alignment indicates that a significant proportion (around 23 % of recorded speed observations are within the 0-10 km/h interval, the standard deviation is 1.35) of road users are forced to slow down to very low average speeds.

4.1.5.2 After Scenario – Analysis Post-Roundabout Conversion

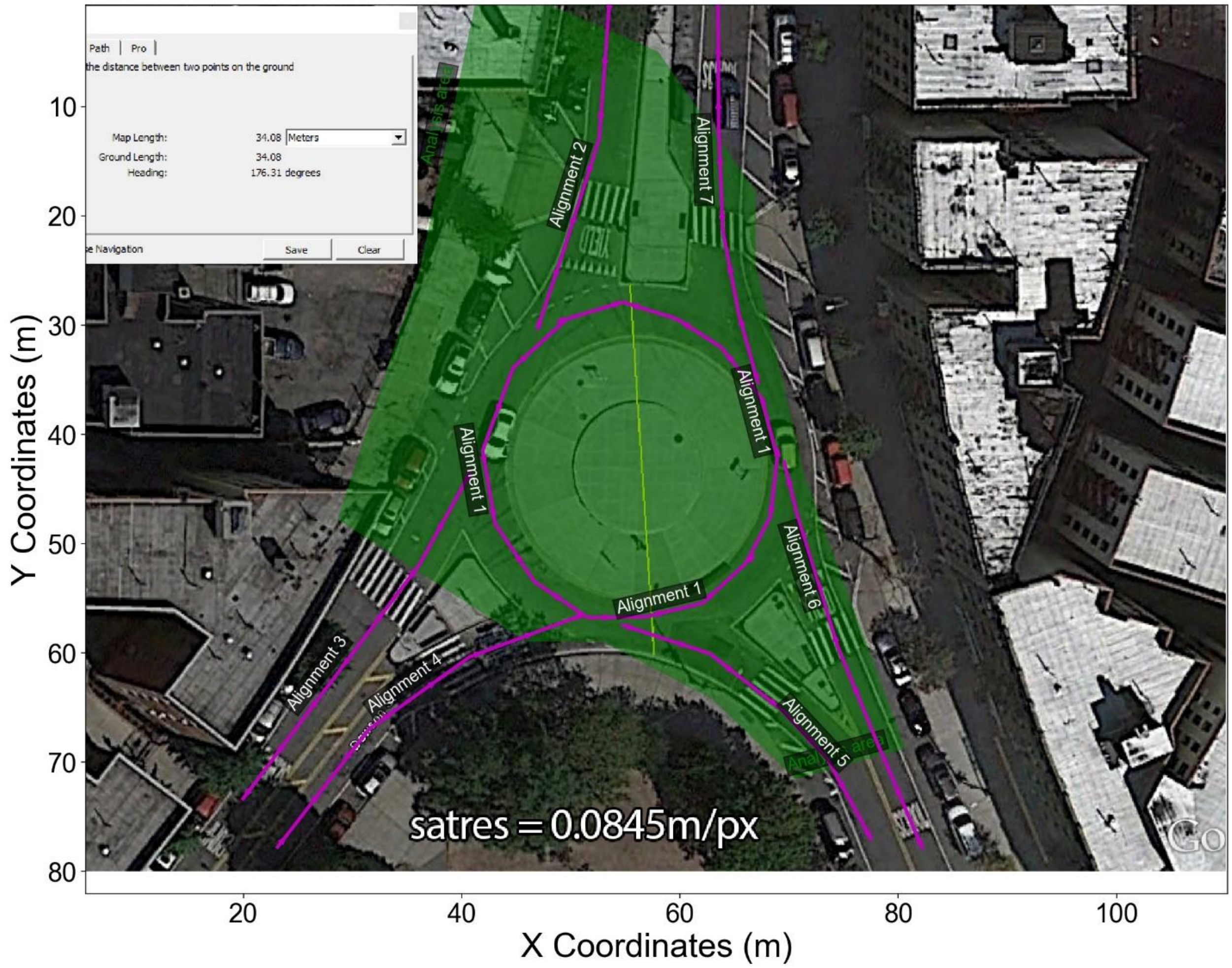

Figure 4.8: Analysis zone and alignments for the Intervale intersection (post-conversion)

Figure 4.8 above presents the analysis zone and alignments drawn for the converted roundabout. In comparison with Figure 4.5, the feature of the alignment disposition is that Alignment 1 covers the entire circulatory roadway (the curved lane around the central island), whereas Alignments 2-7 are attributed to the approaches and exits. The analysis zones were drawn to cover an area as comparable as possible with the initial intersection.

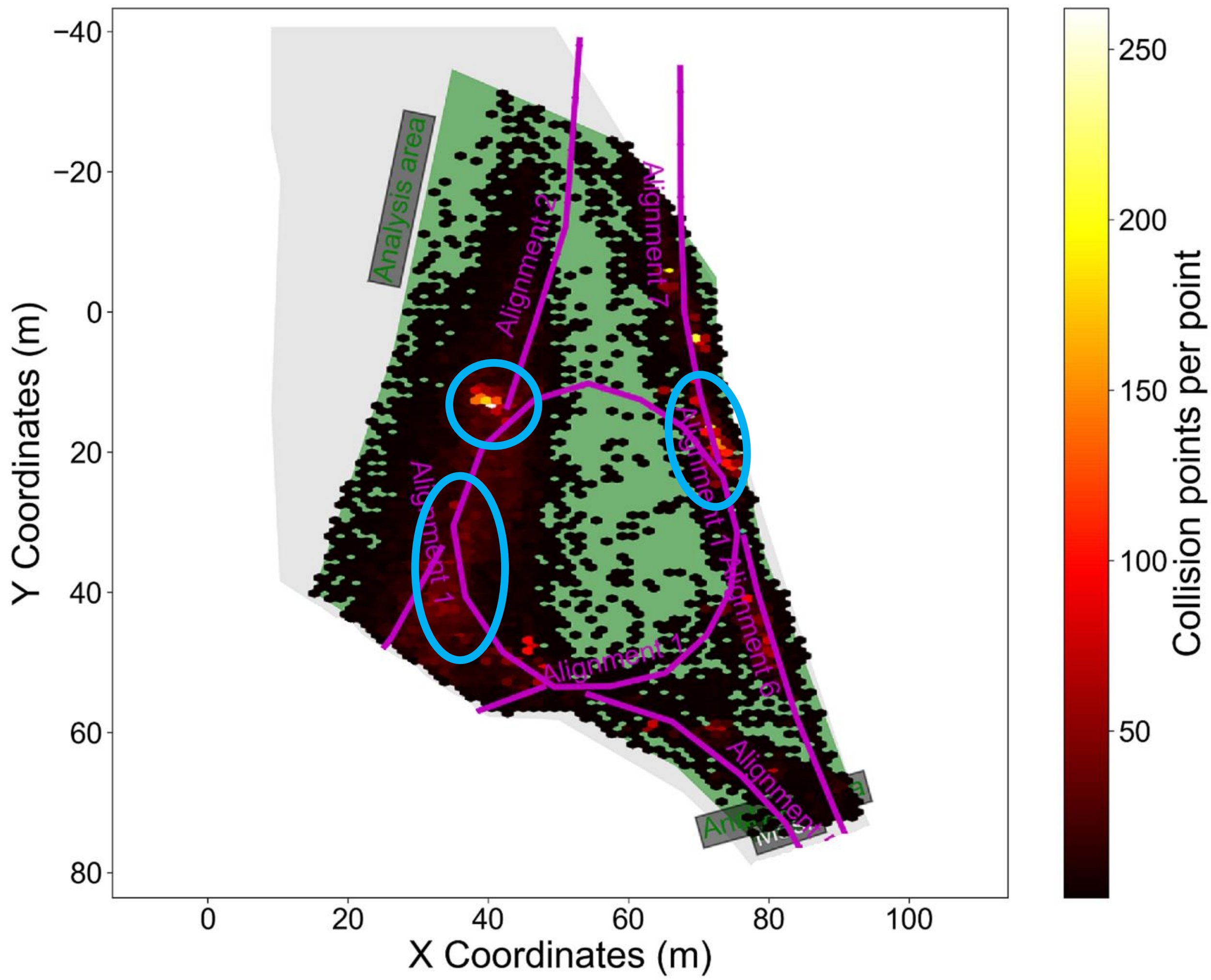

Figure 4.9: Collision point density - Intervale intersection post-roundabout-conversion

As was done for the initial intersection, Figure 4.9 represents potential collision point density for the entire analysis zone. One may firstly notice the values on the scale are much larger than the values in Figure 4.6. The figure above highlights several areas as “hotspots” for user pairs circulating within the roundabout, assuming constant velocity. The areas where collision points are most predicted are located at the three merging zones within the roundabout, shown in Figure 4.9. This illustrates an overall similarity with the conflict point analysis in Section 4.1.3, as the conflict points show close correspondence with the predicted collision points illustrated in Figure 4.9.

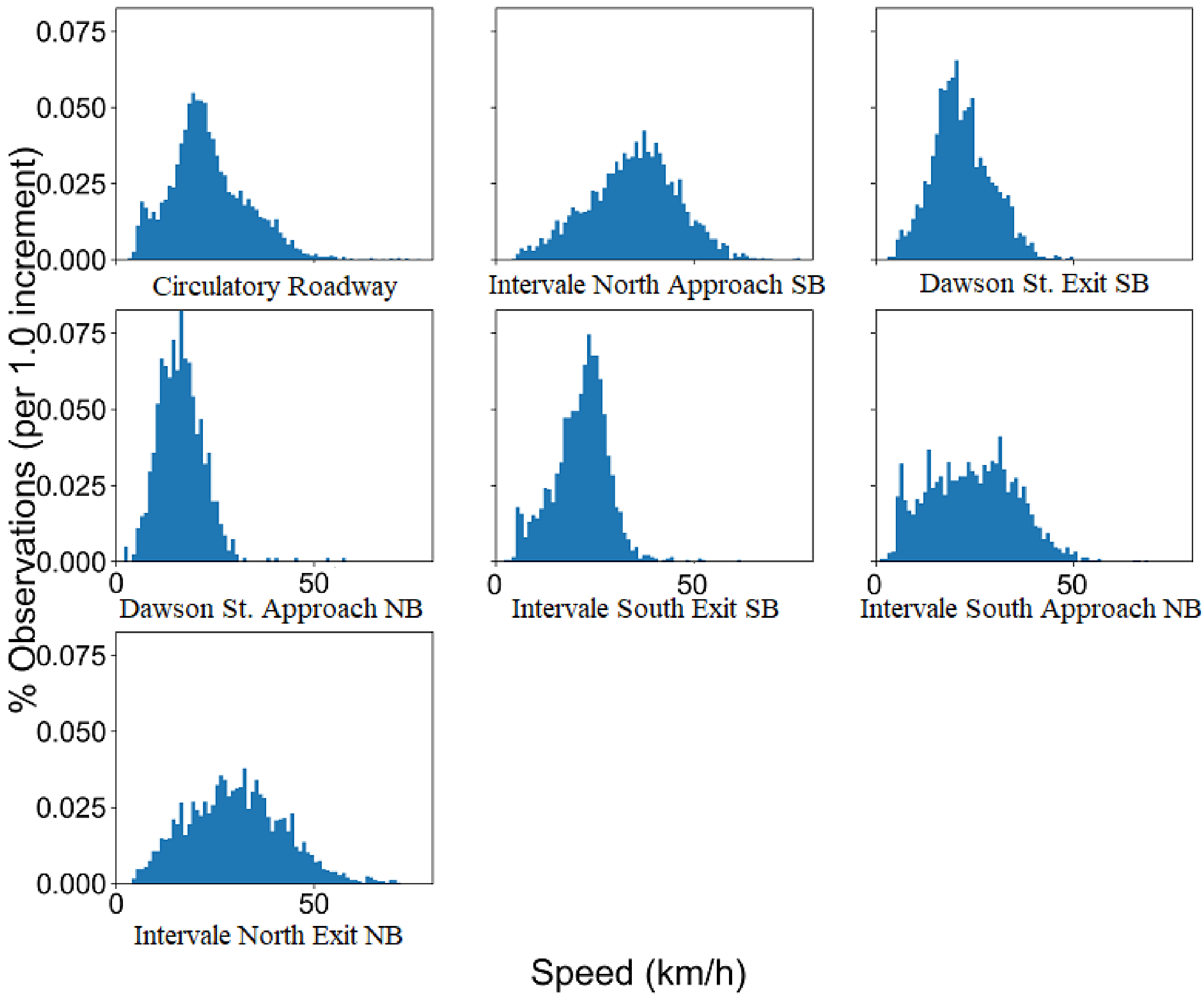

Figure 4.10: Average user speed distributions per alignment - Intervale roundabout

Speed distributions for the converted roundabout are presented Figure 4.10, for the set of alignments contained in the analysis zone (illustrated in Figure 4.8). The distributions shown for each alignment are all unimodal, and each distribution has a slightly different mode. Figure 4.10 illustrates that the mode is highest on Intervale Avenue, on the North approach. Unsurprisingly, the three lanes for which road users need to complete a turning movement (along the circulatory roadway, along Dawson St. Northbound and at the South exit on Intervale Avenue Southbound) show the lowest modes.

4.1.5.3 Before-After Comparison – Speeds and TTC

Conflict analysis illustrated the main conclusion made in the literature: the roundabout eliminated the presence of crossing conflict points within the intersection. The particularity of this conversion being that it added a direction for one of the approaches (Dawson Street) and the number of conflict points increased from four to six conflict points. However, Figure 4.3 (Section 4.1.4) shows that, had the initial intersection allowed for a northbound lane on Dawson Street, the number of conflict points before conversion would have been higher (nine conflict points, as opposed to four).

The results concerning both speed and TTC_{15} distributions were more encouraging. Figure 4.11 below shows the comparison between the average user speed distributions in both the "Before" and "After" scenarios, while Figure 4.12 shows an equivalent comparison of TTC_{15} distributions both prior to and following roundabout conversion.

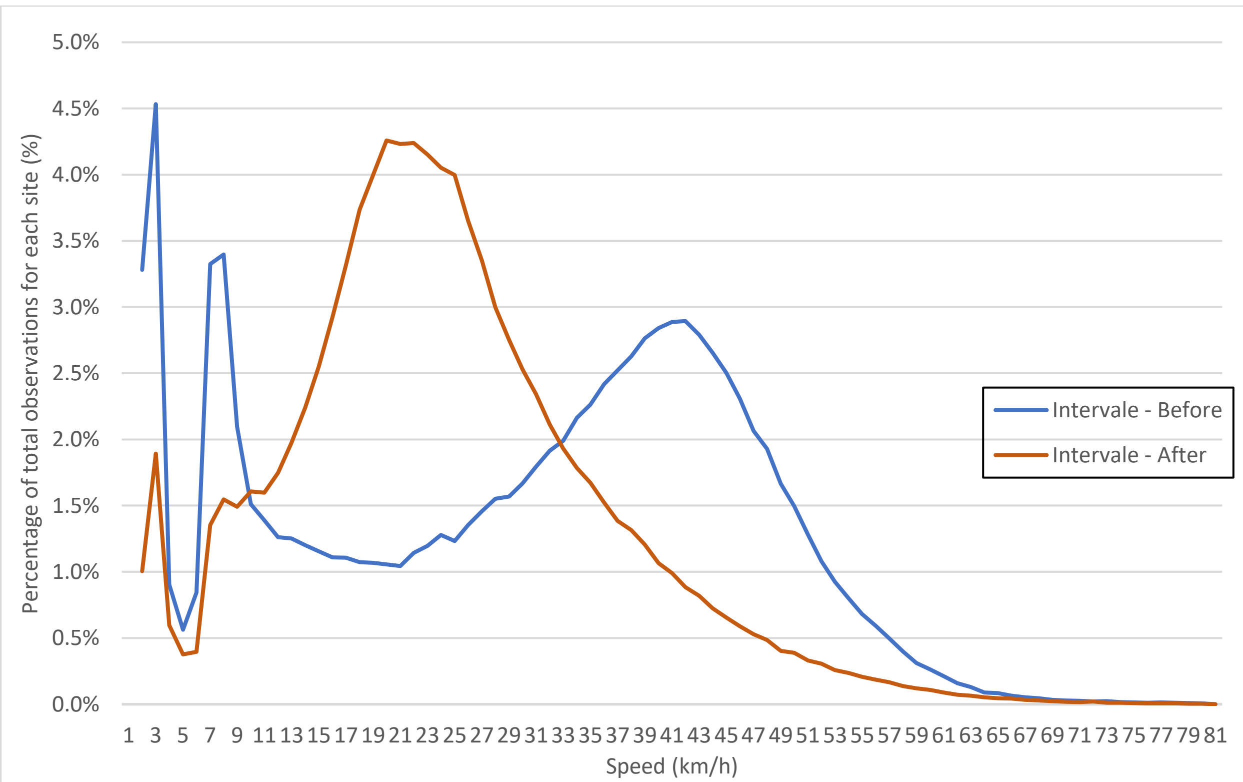

Figure 4.11: Comparison of road user average speed distributions before and after the Intervale roundabout conversion

The distribution for the initial roundabout (Intervale – Before) resembles the distributions for all lanes, as was presented previously (Figure 4.7) – the two modes (between 0 and 10 km/h, and around 40 km/h) are very noticeable. These spikes between 0 and 10 km/h are due to both the mixed road user composition (i.e. the inclusion of pedestrians in the speed distribution) and the fact that vehicles may be forced to slow down. This reduction in traffic flow was confirmed by qualitative observation of the video footage for all lanes within the intersection.

The average speed distributions for the converted roundabout are more concentrated (standard deviation of 1.05 km/h as opposed to 1.35 km/h before roundabout conversion), and centre on lower mean speeds for all alignments shown in Figure 4.7. This suggests that the geometry of the roundabout infrastructure causes users to slow down.

The speed distributions in Figure 4.11 show a decrease in average road user speed in the converted roundabout as opposed to users of the initial intersection. The average speed decreases by approximately 20 km/h over the entire intersection. Speed is a popular and proven method of evaluating safety, and especially the severity of potential accidents – as such, a decrease in overall average speed throughout the converted roundabout shows the latter provides an increase in road user safety.

The other indicator of safety used for the study – TTC_{15} – also shows positive results for the converted roundabout, with the contrast in TTC_{15} distributions shown in Figure 4.12 pointing towards an improvement for user pairs with lower TTC_{15} values.

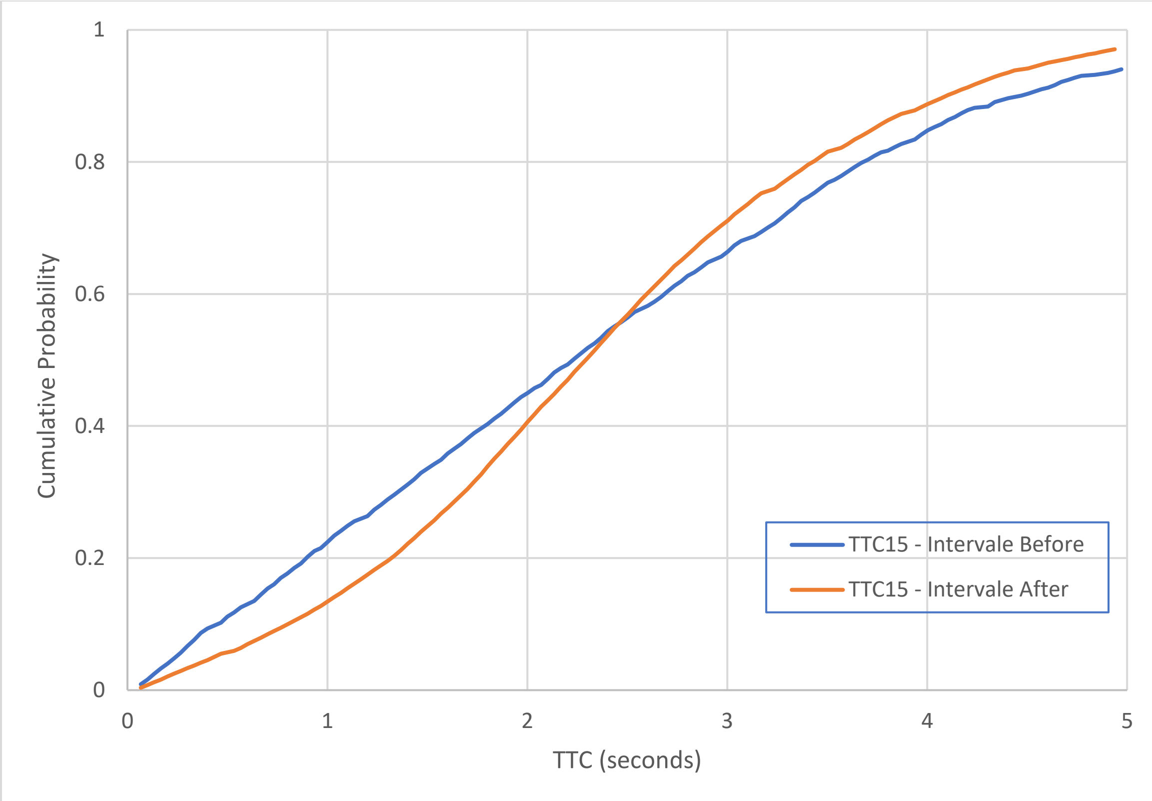

Figure 4.12: Comparison of TTC_{15} distributions - Intervale site

The distribution seems uniform for the initial intersection and the median of the TTC_{15} per user pair is 2.23 s. The median TTC_{15} value for user pairs involved in the roundabout stands at 2.3 seconds. As mentioned in the literature review, a TTC value of 1.5 s is the most common threshold used to define serious conflicts. The proportion of user pairs with TTC_{15} value below 1.5 s decreases (from 0.33 in the initial intersection to 0.25 in the converted roundabout), which points to the roundabout increasing safety.

4.1.6 Movement Analysis

4.1.6.1 Definition of comparable Origin-Destination movements

One of the main challenges in a before-after analysis, especially one where the geometry of the intersection differs greatly before and after roundabout conversion, is finding a basis for comparison of road user behaviour and safety. As has been detailed in Chapter 3, the objective is to find corresponding vehicle movements between the initial intersection and the installed roundabout. The addition of the northbound direction on Dawson Street limits the comparability of movements only to those present in the initial intersection.

To compare road user safety and behaviour before and after roundabout conversion, it is necessary to study vehicle movements for the detected user pairs, both before and after roundabout conversion. These movement pairs correspond to all conflicting movements in the form of OD pairs existing before and after roundabout conversion. All comparable conflicting movement pairs are listed for both the before and after scenarios.

The comparable conflicting movement pairs are listed in Table 4.3. Rear-end and lane change interactions are determined when movement pairs are identical (example: User 1 going from Intervale South to Intervale North, and User 2 completing the same movement). The rear-end conflicting movements are the following: Intervale South to Intervale North, Intervale South to Dawson South, Intervale North to Intervale South, Intervale North to Dawson South.

Table 4.3: List of comparable conflicting movement pairs - Intervale analysis

	User 1	*User 2*
Conflicting Movement Pair 1	Intervale South → Intervale North	Intervale South → Dawson South
Conflicting Movement Pair 2	Intervale South → Dawson South	Intervale North → Intervale South
Conflicting Movement Pair 3	Intervale North → Intervale South	Intervale North → Dawson South
Conflicting Movement Pair 4	Intervale North → Dawson South	Intervale South → Dawson South

An illustration of a conflicting movement pair is shown in Figure 4.13 below. The example chosen for the illustration is conflicting movement pair 2 from Table 4.3. In the example shown, User 1 originates from the South approach of Intervale Avenue and goes towards Dawson Avenue

(Southbound). The movement from User 1 conflicts with User 2, whose movement originates on the Intervale Avenue North approach and ends at the Intervale Avenue South approach.

The equivalent user movements are drawn for the converted roundabout. In both diagrams User 1's movement is shown in blue, and User 2's movement is shown in green. The red ellipses show the areas where the movements come into conflict.

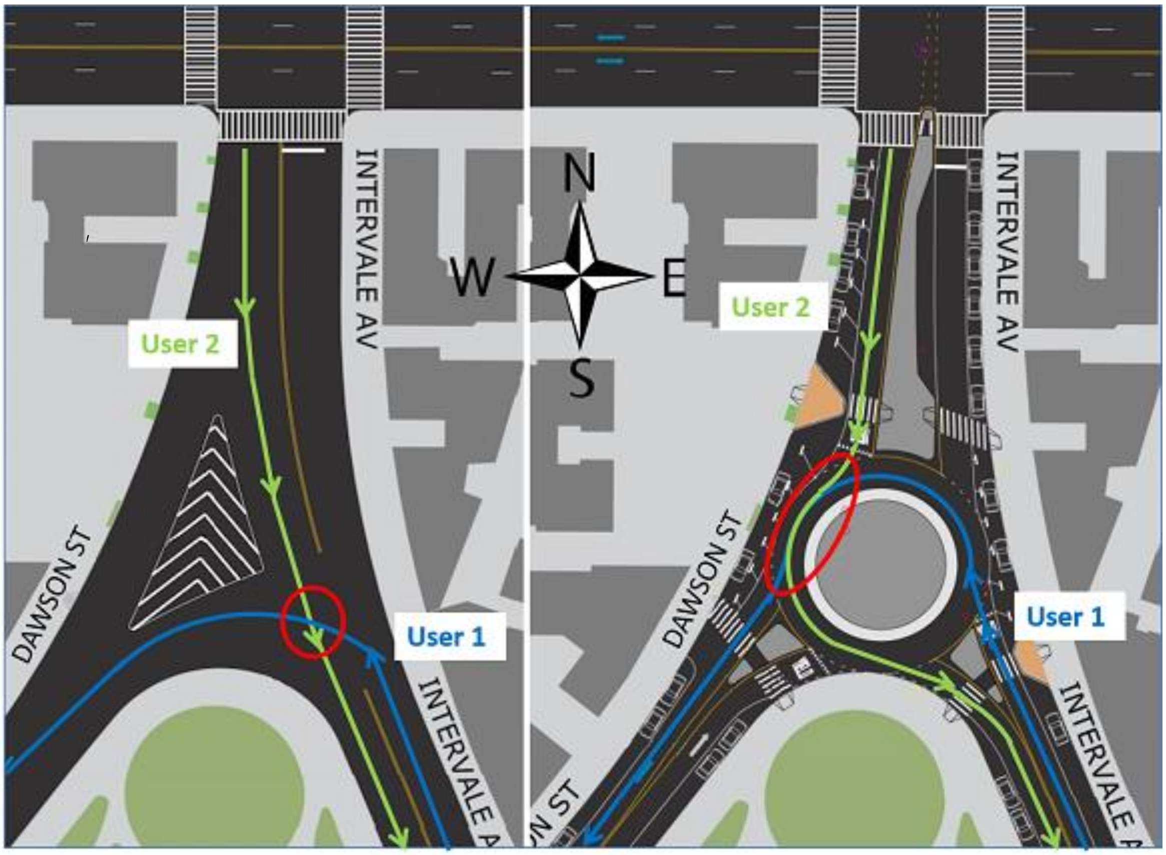

Figure 4.13: Illustration of conflicting movement pair 2 (Intervale South → Dawson South conflicting with Intervale North → Intervale South) - before and after conversion

Once all the conflicting vehicle movements are determined and provided to the MA module, the program is run for the before and after analysis cases.

4.1.6.2 Application of the MA module

The MA module analysis was performed on all the video sequences for the Intervale site, both before and after the roundabout conversion. Three different outputs are generated by the program: a table representing the number of user pairs for the movements defined below (see Table 4.4), followed by a table (Table 4.5) summarizing the average speeds and average TTC_{15} values of the user pairs. Comparative TTC_{15} distributions were not presented due to the small number of user pairs for the defined movement pairs after roundabout conversion.

Table 4.4: Number of user pairs involved - Intervale Before and After

	Number of user pairs	
	Intervale Before	**Intervale After**
Intervale South --> Intervale North /Intervale South --> Intervale North	474	0
Intervale South --> Intervale North / Intervale South --> Dawson South	90	0
Intervale South --> Dawson South /Intervale South --> Dawson South	136	7
Intervale South --> Dawson South / Intervale North --> Intervale South	3	1
Intervale North --> Intervale South /Intervale North --> Intervale South	57	0
Intervale North --> Intervale South / Intervale North --> Dawson South	0	0
Intervale North --> Dawson South /Intervale North --> Dawson South	55	0
Intervale North --> Dawson South / Intervale South --> Dawson South	96	0
Total	911	8

The results from Table 4.4 show contrasting results after roundabout conversion concerning the number of user pairs. For all conflicting movements, the number of user pairs is significantly reduced. As shown in Table 4.4, the total number of user pairs after roundabout conversion for the identified comparable conflicting movement pairs is less than 1 % of the number of user pairs in the initial intersection. The drawing of a separate alignment in the analysis zone (see alignment 1 in Figure 4.8) for the circulatory roadway combined with the fragmentation of the trajectories (caused by motorists stopping and the tracking algorithm) leads to the inability for the MA module to assign road users to their actual origin within the intersection. The discrepancy shown in Table

4.4 is therefore due to the fact that the MA module does not count these users and therefore omits the user pairs in the after configuration.

Further study concerning the trajectories in the converted roundabout was undertaken by analysing the accuracy of the tracking of road users in the roundabout. This was done by comparison of the annotated ground truth video data (i.e. by adding annotations for road users in every frame over multiple video sequences) to an automated analysis of the tracked road users' trajectories. Comparison of the trajectories detected in the automated tracking system to the annotations yields a percentage of tracking accuracy. In this case, the tracking accuracy of the automated tracking system was calculated to be 72.4 % compared to the ground truth (i.e. 72.4 % of the trajectory instants showed correspondence to the trajectory instants in the annotated video sequences). Qualitative observation of the trajectories revealed that a significant number of trajectories are interrupted at the end of the alignment on the Intervale North approach, and restarted in the circulatory roadway. Extra exploration of the MA module revealed 1 985 user pairs (all of the rear-end type) in the circulatory roadway (where the trajectories of the involved road users are incorrectly detected as originating or finishing on the alignment corresponding to the circulatory roadway).

Table 4.5: Average speed and TTC_{15} values for user pairs for all comparable movement pairs using the MA module - Intervale

	Intervale - Before	**Intervale - After**
Total average speed of road users (km/h)	46.62	35.12
Median TTC_{15} per user pair (s)	2.16	2.44
Total number of user pairs	911	8

There were very few user pairs for the converted roundabout, for the conflicting movements specified in Table 4.4. Indeed, results from the MA module after roundabout conversion show little correspondence with reality, as there are nearly 2 000 user pairs with rear-end interactions which are not included in the analysis results, as explained earlier. This outcome can be considered inconclusive, given the missing rate of the detection system.

In order to avoid the major discrepancy in the number of user pairs, the inclusion of the missing user pairs for Intervale-After could have been extrapolated by using manual vehicle counts of road users' origins and destinations using the video footage. Another method could have been to guess the origins and destinations of road users using the areas where the detected trajectories begin and end respectively.

In the initial intersection, road users turning left from the Intervale Avenue South approach onto Dawson St. Southbound are often forced to stop due to oncoming traffic. However, in the circulatory roadway in the converted roundabout, as shown in Figure 4.10 (top left subgraph), road users maintain low average speeds throughout the roundabout and traffic is less prone to stopping due to the geometry.

4.2 "Before-and-After" study – Jean-Proulx Intersection (Gatineau, Quebec)

4.2.1 Context

The second case study is the transformation of the Jean-Proulx/Saint-Joseph intersection in Gatineau, Quebec, into a two-lane roundabout. The vehicle flow along Saint-Joseph Boulevard is high, as it constitutes a main arterial in the Gatineau road network, connecting the Chelsea area to downtown Gatineau, as well as establishing a main link with Highway 5 ("Autoroute de la Gatineau") and connecting downtown-Ottawa. Jean-Proulx Avenue (in the East-West directions) is a major road through a commercial and industrial area, with over 38 000 vehicles passing through the intersection (pictured in Figure 4.14) every day (Le Droit, 2011).

4.2.2 Initial Intersection

Initially, the intersection between Jean-Proulx Avenue and Saint-Joseph Boulevard was a four-way, 2-lane standard intersection with four approaches at about 90 degrees, controlled by traffic lights. A satellite image view of the intersection is shown in Figure 4.14 below.

Figure 4.14: Satellite image of the Jean-Proulx intersection prior to roundabout conversion with allowed movements for each approach (Source: Google Earth, 2012)

St-Joseph Boulevard (North-South) had two lanes entering and exiting the intersection, as does Jean-Proulx Avenue (East-West), which has two lanes entering the intersection for both approaches. The allowed movements are detailed in Figure 4.14 above.

Several elements need to be considered in the analysis of this intersection. Firstly, St-Joseph Boulevard is considered as a major arterial in the City of Gatineau (serving as a major link to the City of Ottawa); this entails that expected vehicle flow on the North and South approaches are higher. Furthermore, Jean-Proulx Avenue contains a garage for buses of the local transit agency (STO) which causes increased traffic flow due to buses returning and leaving the garage. Finally, the Highway Code for the Province of Quebec allows for right-hand turns at red lights (outside of the Island of Montreal), which makes for many yielding-type interactions for all the approaches of the initial intersection.

Several videos were used to determine the signal timing for the initial intersection setup. Videos were examined for three periods of the day (morning peak hour, mid-day, and afternoon peak hour), to identify possible changes in signal timing. Table 4.6 below illustrates the changes in traffic light phases for the initial intersection at three separate times during the day.

Table 4.6: Jean-Proulx initial intersection traffic light phasing according to time of the day (Green Light Times are included in parentheses)

Cycle Period	Phase 1 (s)	Phase 2 (s)	Phase 3 (s)	Cycle Time (s)
Morning Peak - 6 AM	35	40	25	100
Mid-day - 11 AM	35	35	35 -East (25 s for the West approach)	105
Evening Peak – 5 PM	40	40	35 – East (25 s for the West approach)	115

Note: The All-Red and Yellow times are identical at all times – AR : 2s, Y: 3s. Green times can therefore be easily deduced by subtracting 5 s from the presented phase times. Figure 4.15 below illustrates the different traffic light phases for the Jean-Proulx intersection.

Other than the rule enabling right-hand turns during a red light, it is of note that Phases 1 and 2 (St-Joseph Boulevard North and South approaches respectively, all vehicle movements) have a flashing green light for the entire duration of the phase, signalling that all movements coming from both either approach are protected (without side conflict). This entails that chances of conflicts and user pairs are reduced for the North and South approaches. However, for the East and West approaches, all movements are allowed simultaneously, resulting in increased risk in conflicts between road users compared to the North and South approaches. Figure 4.15 below illustrates the movements associated with each traffic light phase for the Jean-Proulx initial intersection.

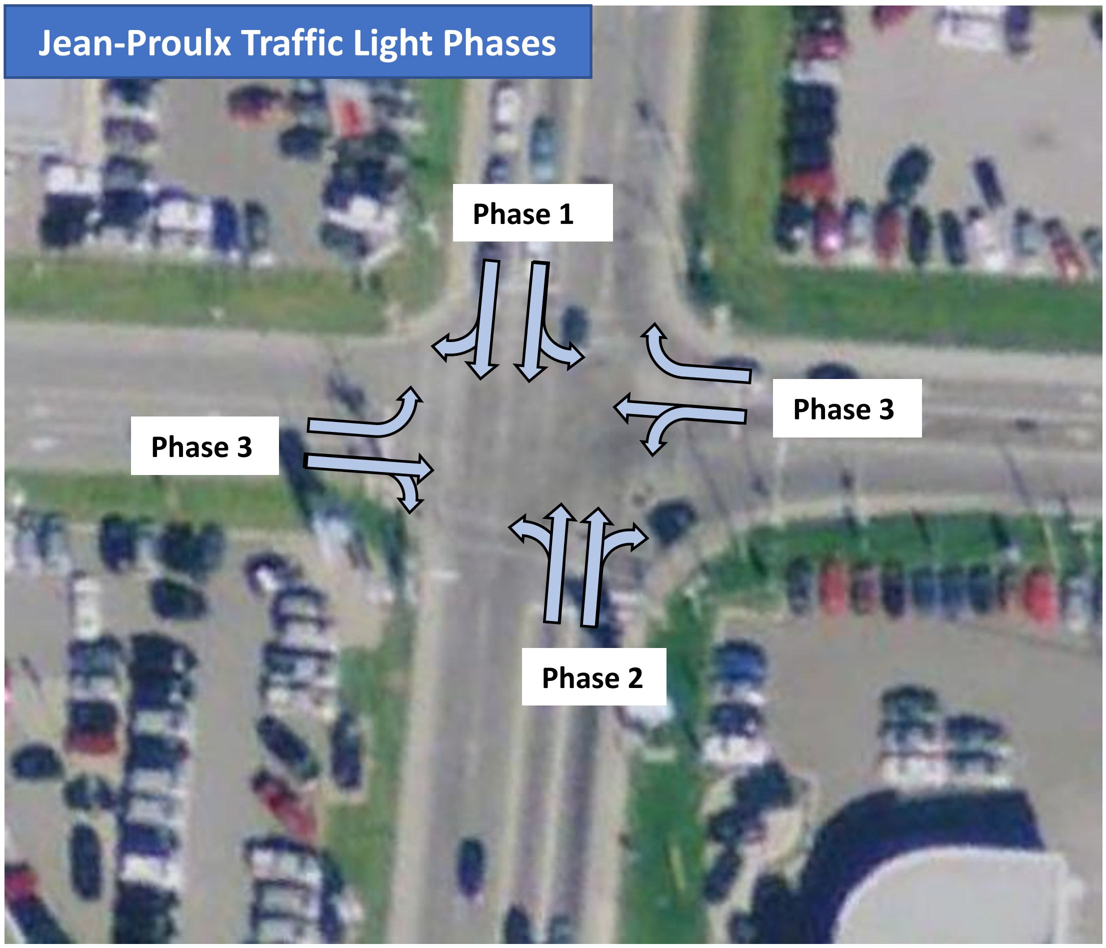

Figure 4.15: Illustration of the movements allowed in the three different phases for the Jean-Proulx/St-Joseph initial intersection

The signal timing takes place as follows: in the example of the morning peak hour, the North approach can complete all three possible movements (straight, left-turn and right-turn) for a green time of 30 seconds, which is followed by a yellow time of 3 seconds and an all-red time of 2 seconds. The same logic (with values from Table 4.6 applied to the phasing shown in Figure 4.15) applies to the two other traffic light phases and the other two types of cycles.

The first traffic light cycle lasts 100 seconds, with a single phase for both the East and West approaches of the intersection. Phases 1 and 2 (North and South approaches) are longer to allow most of the peak-hour traffic on St-Joseph Boulevard to go through the intersection.

Between the peak hours, the phasing varies slightly. The green light time for Phase 2 drops by 5 seconds, but ten seconds are added to the green light time for Phase 3 on the East approach. This creates the effect of a protected turn for vehicles originating from the East approach for ten seconds. The cycle time therefore increases to 105 s.

During the afternoon peak hours, Phases 1 and 2 are increased again, as St-Joseph Boulevard is the busiest. The change to Phase 3 between the peak hours is kept.

A priori, the protected turns allowed at the intersection are advantageous in terms of protected turns for road users compared to an intersection controlled by other means of traffic control, such as Stop signs, under the assumption that people do not violate the red light.

4.2.3 Roundabout Implementation

In place of the initial intersection setup, the City of Gatineau installed the roundabout shown in Figure 4.16. The implemented roundabout keeps the same number of lanes for the North and West approaches, and increases the number of entering lanes for 10 to 20 meters of the South and East approaches.

Figure 4.16: Jean-Proulx roundabout, post-conversion

The organisation of the roundabout is peculiar compared to other types of intersections, but usual for roundabouts in North America, as road users are forced to choose their lane leading up to the roundabout, depending on their destination. Several elements pertaining to the roundabout's design are responsible for this instance. Firstly, the centre island is not quite circular, to reserve a lane inside the roundabout for the left-turn movement of the East approach (left-hand lane). The second point of interest in the roundabout design is the disparity in the number of exit lanes for each exit branch (one for the West exit, two lanes merging into one for the East exit, and two lanes for the North and South exit branches), as well as the division of some of the approaching lanes into three lanes instead of two (as shown for the East approach – on Jean-Proulx Ave – and the South approach – on St-Joseph Blvd). This creates extra conflict points, as well as additional possibilities of potential movements for road users. In terms of lanes, there are therefore more possible trajectories after roundabout conversion than before, for the same OD.

4.2.4 Conflict Point Analysis

As was detailed for the first case study (Section 4.1), the movements for the initial intersection are drawn, as are the corresponding conflict points corresponding to the crossing, merging or diverging of the corresponding vehicle trajectories.

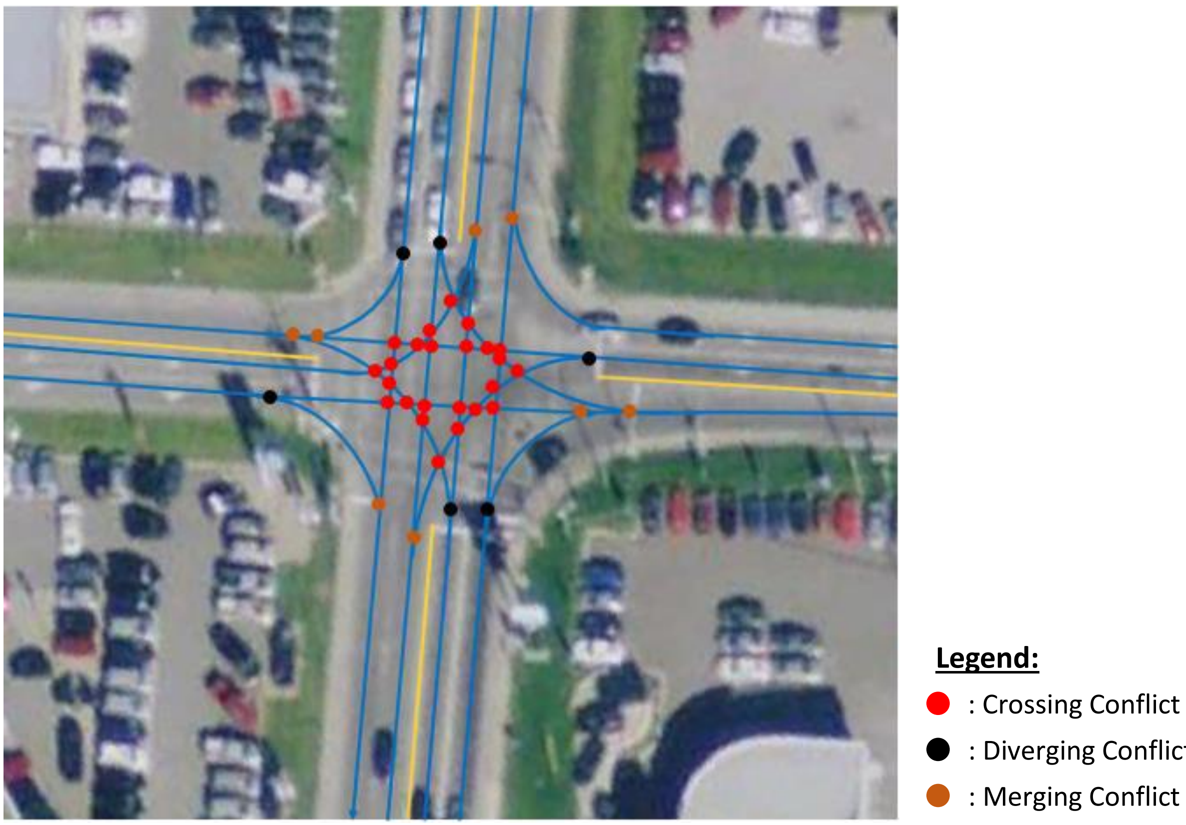

Figure 4.17: Conflict points resulting from the possible movements – Jean-Proulx initial intersection

As was detailed in Chapter 3, standard intersections have a higher number of crossing conflict points (and conflict points in general). This case is no different, with Figure 4.17 showing a total of 38 conflict points (24 crossing, 6 diverging and 8 merging conflict points). The presence of only one lane for both the East and West lanes exiting the intersection reduces the number of diverging conflict points (from eight to six in total).

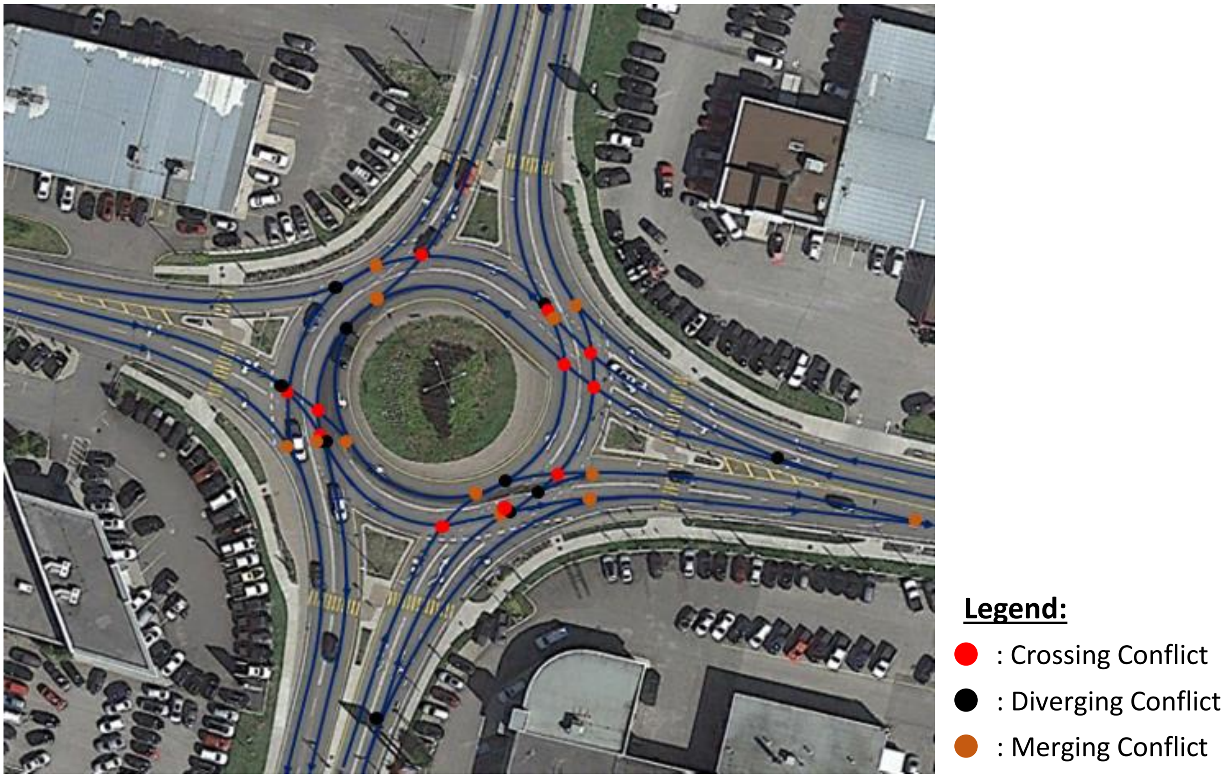

Figure 4.18: Conflict points resulting from the possible movements in the implemented roundabouts– Jean-Proulx converted roundabout

For the implemented roundabout presented in Figure 4.18, the number of conflict points in total decreases to 28 as opposed to the 38 contained in the previous intersection. This is due to a decreasing number of crossing conflict points (11 in the roundabout vs. 24 in the initial intersection), and the near-conservation of the number of merging (10 in the roundabout vs. 8 in the initial intersection) and diverging (7 in the roundabout vs. 6 in the initial intersection) conflict points. Table 4.7 below summarises the theoretical conflict points within the two different infrastructures.

It is important to note here that lane-change conflict points are not represented in Figure 4.18 or in Table 4.7, and that they are in fact not allowed (continuous lanes).

Table 4.7 : Comparison of the number of conflict points for the Jean-Proulx site - Before and After roundabout implementation

	Initial intersection	*Converted Roundabout*
Crossing Conflict Points	24	11
Merging Conflict Points	8	12
Diverging Conflict Points	6	9

A closer examination of Figure 4.18 reveals three points where all three types of conflict points may occur. These are situated in the South-West and South-East quadrants of the roundabout. The explanation is simply that the angles at the vehicles' potential collision points will differ according to the choice of direction of the vehicle. Figure 4.19 below illustrates how the type of conflict point can differ according to the vehicle trajectories involved. The two colours represent the trajectories of two different road users engaged in the roundabout; the colours are chosen for representation purposes only.

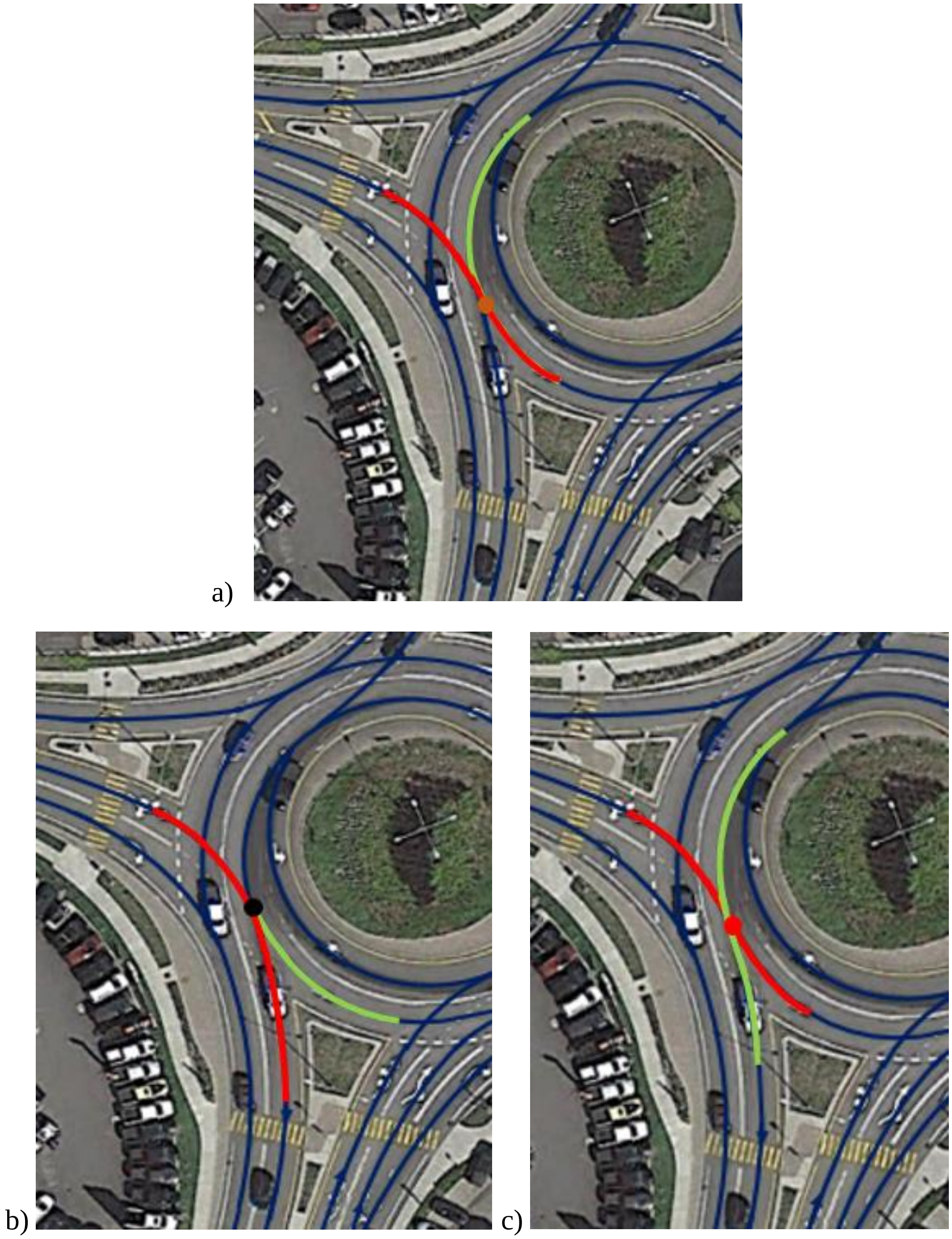

Figure 4.19 : Variation of conflict point type according to vehicle trajectories within the roundabout – a) merging conflict point, b) diverging conflict point, c) crossing conflict point

Even though the number of conflict points is still relatively high in the roundabout, the total number of conflict points is lower than the initial intersection, with a decrease in the number of crossing conflict points in the converted roundabout. An extra consideration here is that the number of entry and exit lanes changes with the converted roundabout: the South (Saint-Joseph Northbound) and East (Jean-Proulx Westbound) approaches split into three entry lanes, while the North (Saint-Joseph Southbound) and West (Jean-Proulx Eastbound) approaches conserve the same number of entry lanes. This leads to additional lane changes (and therefore, an extra possibility for lane-change interactions), and enables to allow for separate lanes for specific movements (for example, the right-hand lane on the East approach of Jean-Proulx Avenue, is specific to the right-turning movement onto St-Joseph Boulevard Northbound). The number of exit lanes is the same in the converted roundabout for all approaches, except for the East exit (on Jean-Proulx Ave.) which has two exit lanes, as opposed to a single exit lane in the initial intersection.

4.2.5 Video Analysis and Observations

4.2.5.1 Presentation of the collected data

In the same manner as was presented for the Intervale Avenue case study, the following table shows an overview of the collected data. For this case study, the data collected for both the Before and After stages of the roundabout conversion spans two days. An extra particularity for this case study compared to the Intervale roundabout conversion is the presence of two different cameras for both scenarios. The installation and use of two cameras is useful due to the geometry of the intersection, as it is difficult with the use of a single camera to cover all four approaches for both the initial intersection and the converted roundabout. The installation of two cameras allows for better coverage.

Table 4.8: Video data characteristics for the Jean-Proulx site

	Jean-Proulx Before			**Jean-Proulx After**			
	Day 1	Day 2 – camera 1	Day 2 – camera 2	Day 1 – camera 1	Day 1 – camera 2	Day 2 – camera 1	Day 2 – camera 2
Geometry	4-way intersection	4-way intersection	4-way intersection	Roundabout	Roundabout	Roundabout	Roundabout

Table 4.8: Video data characteristics for the Jean-Proulx site (continued)

Date of Footage	June 6th 2013	June 10th 2013	June 10th 2013	September 10th 2014	September 10th 2014	September 11th 2014	September 11th 2014
Weekday	Thursday	Monday	Monday	Wednesday	Wednesday	Thursday	Thursday
Start time	05:00:00	06:26:42	06:00:00	06:15:00	06:37:44	06:21:00	06:40:53
End time	07:00:00	18:12:18	17:00:00	18:46:34	15:32:14	15:15:42	08:00:00
Total time (h)	2	11.76	11	12.53	8.91	8.65	1.32

The extra camera and the two-day span of the data collection for this site represents a significant amount of data to process compared to the Intervale site analysis, and as such, the processing time was much higher for this case.

Several observations can be made from the overall characteristics of the collected data. Firstly, the days during which the video data was recorded are all weekdays, which focuses the analysis on a weekday-based demand in the intersection. Secondly, all sets of video data cover the entirety of the morning rush hours, which is generally considered to be the busiest period. All the daytime off-peak hours (from approximately 9 AM to 3 PM) are also accounted for. The collected data therefore spans very similar time periods. The videos recorded (both for cameras 1 and 2 of Day 2) for the initial intersection span both the peak and off-peak hours. However, there is less uniformity in the hours covered by the cameras for the converted roundabout, with only one camera view covering the both AM and PM peak hours and the off-peak period.

These observations are important to the analysis conducted in the following part of this section. The number of road users tends to vary during the day, along with the overall traffic conditions – this means the demand in the intersection (whether Before or After the roundabout conversion) varies with time. The fact that some camera views have not recorded data for peak hours entails that there may be room for bias in the results, as a sizable proportion of the road users passing through the intersection/converted roundabout are not accounted for in the analysis. The change in time periods between two different days of data collection is accounted for by constraining the analysis to equivalent periods of analysis (using similar start and end times for data spanning two separate days). Furthermore, the camera views cover different areas of the intersection, with the cameras installed at different viewpoints. This leads to several challenges. An installation of a camera too far from the intersection can lead to poor coverage of the opposite side of the intersection, which in turn leads to issues with tracking of road users and analysis. Likewise, an installation of the camera too close to the intersection would exclude coverage of a portion of the intersection. The latter occurrence would lead to partial coverage in terms of vehicle trajectories and subsequent analysis.

All cameras, both before and after roundabout conversion cover the entire intersection. The only one which has partial coverage is camera 1 from Day 2. While it covers the North and West approaches completely and is located very close to the converted roundabout, the East approach is occluded, and the South approach is only partially visible.

4.2.5.2 Vehicle Counts – Jean-Proulx Before and After

Table 4.9 shows the number of vehicles and pedestrians tracked within the intersection, before and after roundabout conversion.

Table 4.9: Vehicle and pedestrian counts before and after the Jean-Proulx roundabout conversion

	“Before” scenario		**“After” scenario**		
Camera Number	#1 Day 2 – Camera 1	#2 Day 2 – Camera 2	#3 Day 1 – Camera 1	#4 Day 1 – Camera 2	#5 Day 2 – Camera 1
Date of Footage	June 10th 2013	June 10th 2013	September 10th 2014	September 10th 2014	September 11th 2014
Total Time (s)	42 336	39 600	45 094	32 081	31 140

Table 4.9: Vehicle and pedestrian counts before and after the Jean-Proulx roundabout conversion (continued)

Vehicle Count (veh/hour)	2 746	215	85	168	1 665
Pedestrian Count (ped/hour)	94	11	0	3	2

Note: Pedestrians and vehicles are distinguished using a median speed threshold of 2 m/s (i.e. 7.2 km/h).

The camera views (a camera view being defined as the fixed field of view from a given camera at a specific date and covering a given time span – see Table 4.8) for the Jean-Proulx roundabout conversion analysis were only used if the following criteria were satisfied. Due to a malfunction, one of the camera views from June 6th 2013 (Day 1 – Jean-Proulx Before) and September 11th 2014 (Day 2 – camera 2 – Jean-Proulx After) were omitted, as the recording only worked for two hours, and therefore did not represent the length of time during which the analysis can be conducted.

A second criterion for the acceptance of the collected data is that, for a given camera view (and therefore for a given site and day), the analysis zones covering the physical area in the intersection where trajectories are analysed should not be superimposed, for two different camera views. The (still experimental) trajectory reconnection features in tvaLib are not enabled by default. Hence, only one of two camera views with conflicting analysis zones and dates of data collection could be kept for the analysis.

The last condition for conservation of the analysis results is based on vehicle counts. Table 4.9 shows a large disparity in the vehicle counts both between the individual camera views, but also in terms of the two general scenarios i.e. “Before” and “After” the roundabout conversion. This can be due to several elements in the data collection process (i.e. the collection of the video footage) and the video analysis including but not necessarily limited to: occlusion in the video data, camera malfunction, position, angle of view and proximity (or lack thereof) of the camera to the objects.

4.2.5.3 Sources of error – Jean-Proulx Data Collection

The previous section highlighted disparities in the collected data concerning vehicles counts between the Before and After scenarios. As such, before analysing the results of the video analysis, a consideration for the sources of error is needed to properly evaluate the validity of the results.

The main source of error in the Jean-Proulx data collection process is due to the position of the cameras and the tracking of road users.

For the initial intersection, both cameras cover the same zones (the entire intersection before roundabout conversion, including the traffic lights). However, the change in vehicle count is significant: for a similar data collection time, the difference in vehicle count is of over 2 500 veh/h (2 746 veh/h before as opposed to 215 veh/h after). The difference in vehicle counts is caused by errors in vehicle tracking due to the partial occlusion caused by the traffic light in the camera view.

According to Table 4.9, after the roundabout conversion, while the differences are smaller there are still major disparities between vehicle counts for the first (camera view #3) and second (camera view #4) camera views, and counts for the third camera view (September 11th, 2014 – Camera view #5), which are almost ten times higher. Once more, the difference in vehicle counts is due to errors in vehicle tracking due to the distance between the camera and the intersection. The tracking of road users in Camera view #5 is made easier due to the proximity of the camera to the intersection.

Following these remarks, the retained camera views for the analysis were the following: Camera 1 (#1) for June 10th 2013 (before roundabout conversion), Camera 2 (#4) for September 10th 2014, and Camera 1 (#5) for September 11th 2014 (after roundabout conversion). The analysis zones for these camera views cover the entire intersection even though the tracking reliability varies depending on the camera view and the region in the image (close or far), as is the case for camera view #5, which excludes parts of the East and South approaches. The camera view was kept, despite this issue, since the quality of the data was of significantly better quality than the other camera views. The average user speed and TTC_{15} distributions for the other camera views are therefore not considered in the analysis.

Given the aforementioned difficulties in the road user tracking and data collection, the results should be considered with a measure of uncertainty. Firstly, the initial intersection camera view is occluded by the traffic light (see Figure 4.20), though the significance of the occlusion is still to be determined. This entails that several trajectories (in this case, the ones going straight across the intersection from the North, South and East approaches) are cut and re-started beyond the last point of obstruction of the traffic light.

Figure 4.20: Illustration of the occlusion for the Jean-Proulx initial intersection camera view (view from the South approach)

The errors due to trajectory fragmentation (one road user being tracked as two different trajectories instead of one) cannot be excluded, and account for part of the reason the vehicle count is particularly high for the first day of the data collection. The double-counting of road users constitutes a bias to the recorded vehicle counts for the study.

Finally, an extra bias is possible through the placement of the cameras, as mentioned in the previous section. It must be noted that the exclusion of camera views from the analysis is not down to a simple choice of camera view but rather due the fact that the quality of the video data, the coverage of the cameras or the video resolution do not allow their analysis to be carried out. The use of different camera views was accounted for in the analysis by constraining the analysis periods to similar time periods for the data analysis.

Figure 4.21: Camera view (#5) of the Jean-Proulx roundabout - partial coverage of the roundabout

Figure 4.22: Camera view (#4) - East approach of the Jean-Proulx converted roundabout

Furthermore, Figure 4.22 shows a camera view (from Day 1 of data collection for the Jean-Proulx converted roundabout) taken from the East approach. The distance of the camera from the roundabout includes many lamp-posts and the opposite approach (West) is quite far from the camera.

An important remark here is that the footage collected by the cameras (views shown in Figure 4.21 and Figure 4.22) represents a significant quantity of video data included in the analysis – a total of approximately 21 hours of data (after roundabout conversion).

4.2.5.4 Before Scenario – Initial Intersection Analysis

Figure 4.23: Analysis zone and alignments for the initial Jean-Proulx intersection

Figure 4.23 above shows the analysis zone for the intersection along with the drawn alignments. Despite the East and West approach lanes separating into two lanes upon arrival at the intersection (to allow for a left-turn lane), only one alignment is drawn – crossing the entire intersection – for alignments 5 and 6 (on Jean-Proulx Avenue, Eastbound and Westbound, respectively).

The predicted collision point density output from the tvaLib software (as presented in the previous case study) being of poor quality due to the distance between the camera and the roundabout, as well as the smaller vehicle counts, the result was of an inconclusive nature concerning possible "hotspots" of potential collisions, and is therefore not presented in this section.

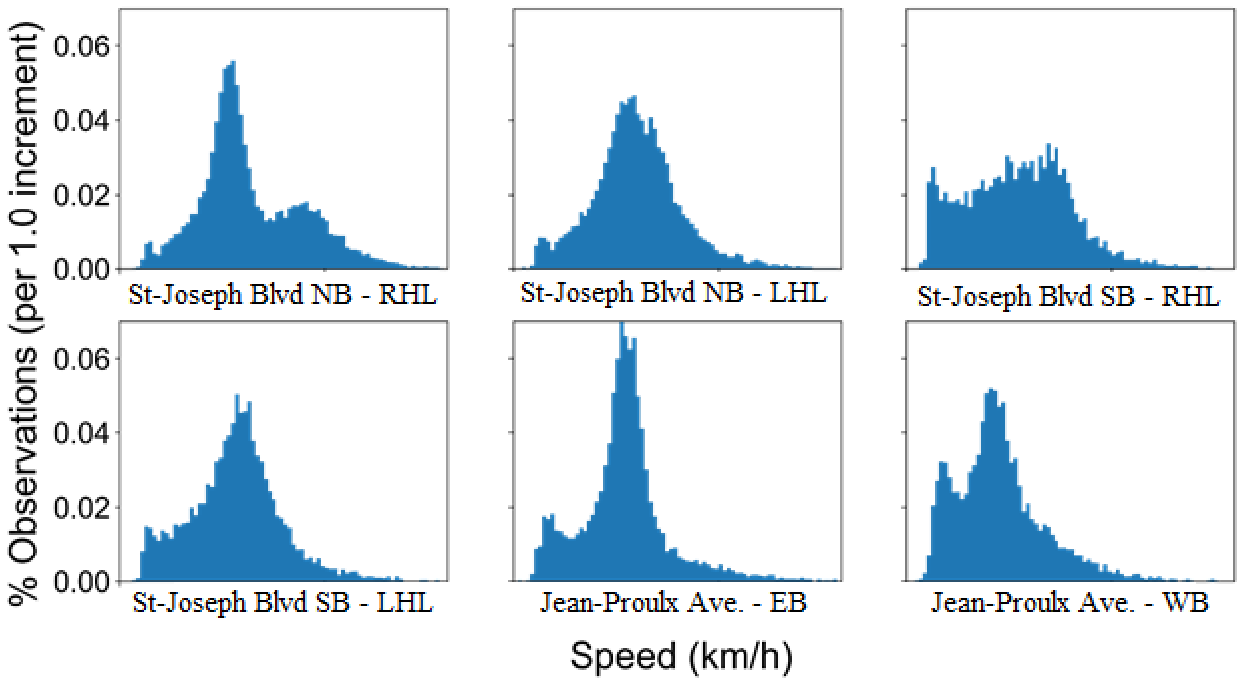

Figure 4.24: Road user average speed distributions for each alignment - Jean-Proulx initial intersection – camera 1

Note: RHL: Right-Hand Lane, LHL: Left-Hand Lane, EB: Eastbound, WB: Westbound

Figure 4.24 represents the average speed distributions for the six lanes (represented by the six alignments) of the initial intersection. With the exception of the left-hand lane on St-Joseph Blvd Northbound, the distribution of vehicle speeds contains two modes (one centred on 8 km/h, the second varying between 20 km/h and 30 km/h). A small proportion of users show high speeds (above the speed limit of 50 km/h) through the intersection – most of these users go along the first 4 alignments (i.e. on St-Joseph Boulevard, the busier of the two roads, which contains two lanes throughout). The observed trend in Figure 4.24 reflects two different occurrences: firstly, the traffic light forces road users to stop, resulting in a significant proportion of low recorded speeds.

Secondly, road users making a left- or right-turn are forced to slow down to safely complete such manoeuvres, hence speeds decreasing from the legal speed limit of 50 km/h. The traffic light also leads to congestion and queues within the intersection and at the approaches.

4.2.5.5 After Scenario – Roundabout Analysis Post-Conversion

Figure 4.25 below shows the disposition of the alignments and the analysis zone inside which road users' trajectories are collected for the Jean-Proulx converted roundabout.

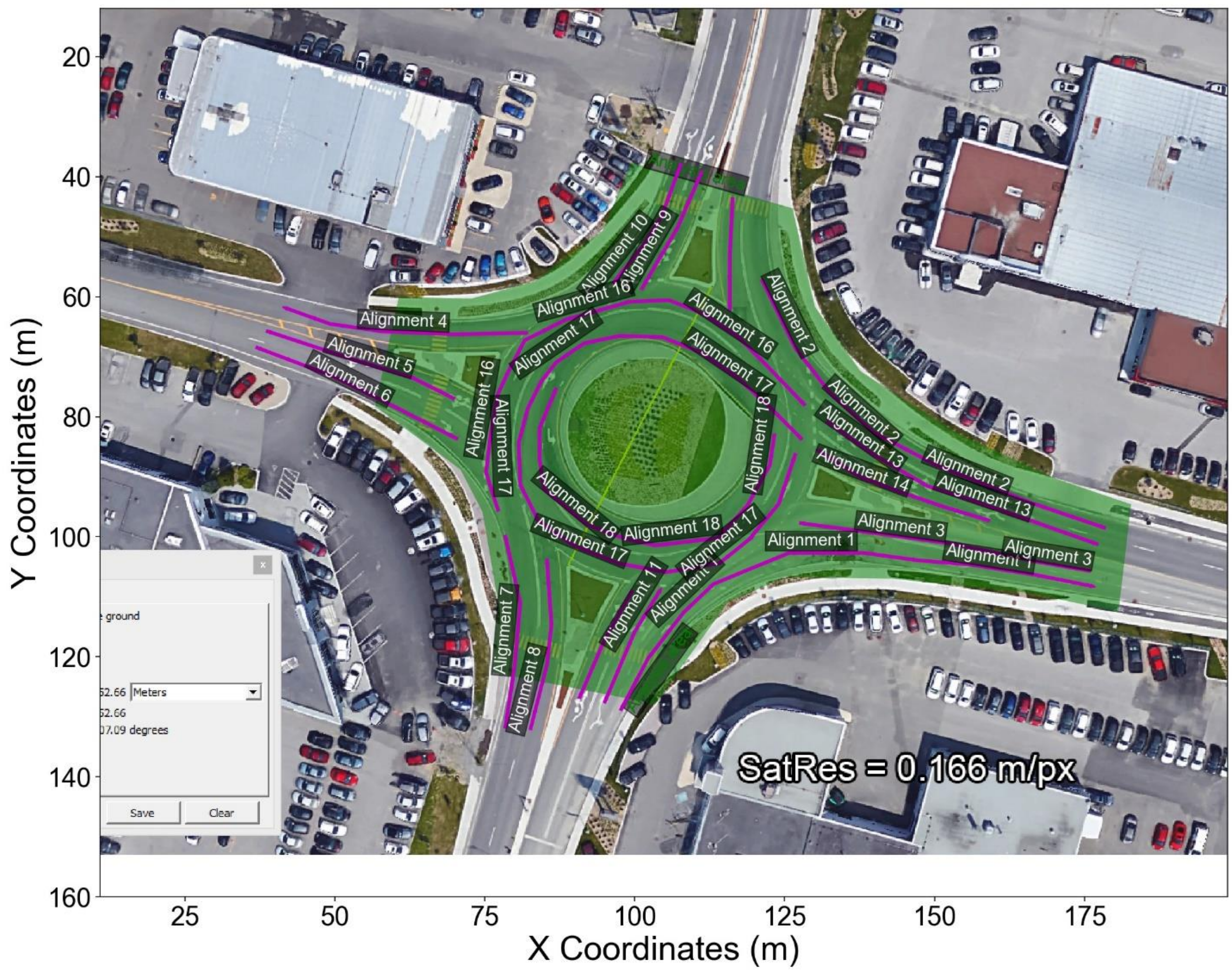

Figure 4.25: Analysis zone and alignments for the Jean-Proulx converted roundabout

The alignment setup drawn is quite peculiar, due to the roundabout geometry. Some approaches divide into three lanes at the entrance of the roundabout, while another lane divides within the roundabout (see alignment 17 and 18 in Figure 4.25 above), to allow a left-turn for vehicles coming from the North approach. The presence of two lanes inside the roundabout and the division of lanes in the approaches make the alignment drawing slightly challenging. In this case study (as was the case for the Intervale Avenue case study), the alignments around the central island are drawn to be as long as possible, thus leaving many small alignments for the approaches. In this case, there are a total of 18 alignments drawn, as shown in Figure 4.25.

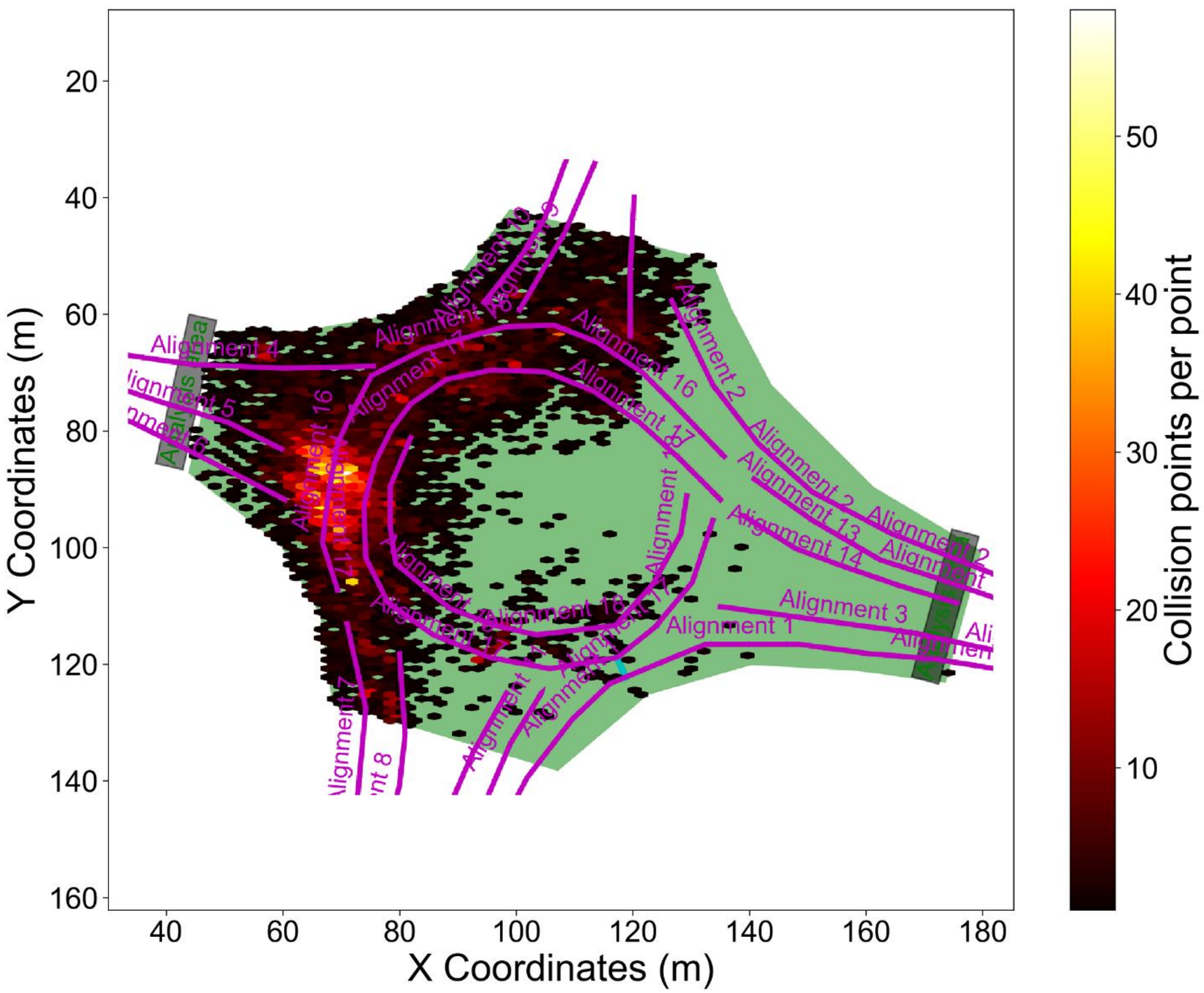

Figure 4.26: Collision point density for the Jean-Proulx converted roundabout - camera view 2

Figure 4.26 shows the predicted collision point density using motion prediction at constant velocity. The camera is located on the South approach, yet its angle excludes the East approach. The closeness of the camera to the roundabout (the high volume of vehicles detected combined with the limited coverage of the camera) is the cause of the high concentration of points in Figure 4.26. The collision point density indicates a major hotspot, which corresponds to crossing conflicts between users from the West approach crossing to East approach (or merging into the lane towards the Southbound exit) and users from the North approach going Southbound or Eastbound, as well as users from the East approach exiting at the South (see Figure 4.18 for conflict analysis diagram).

Figure 4.27 below shows the average speed distributions for road users in each of the different alignments for camera view #5.

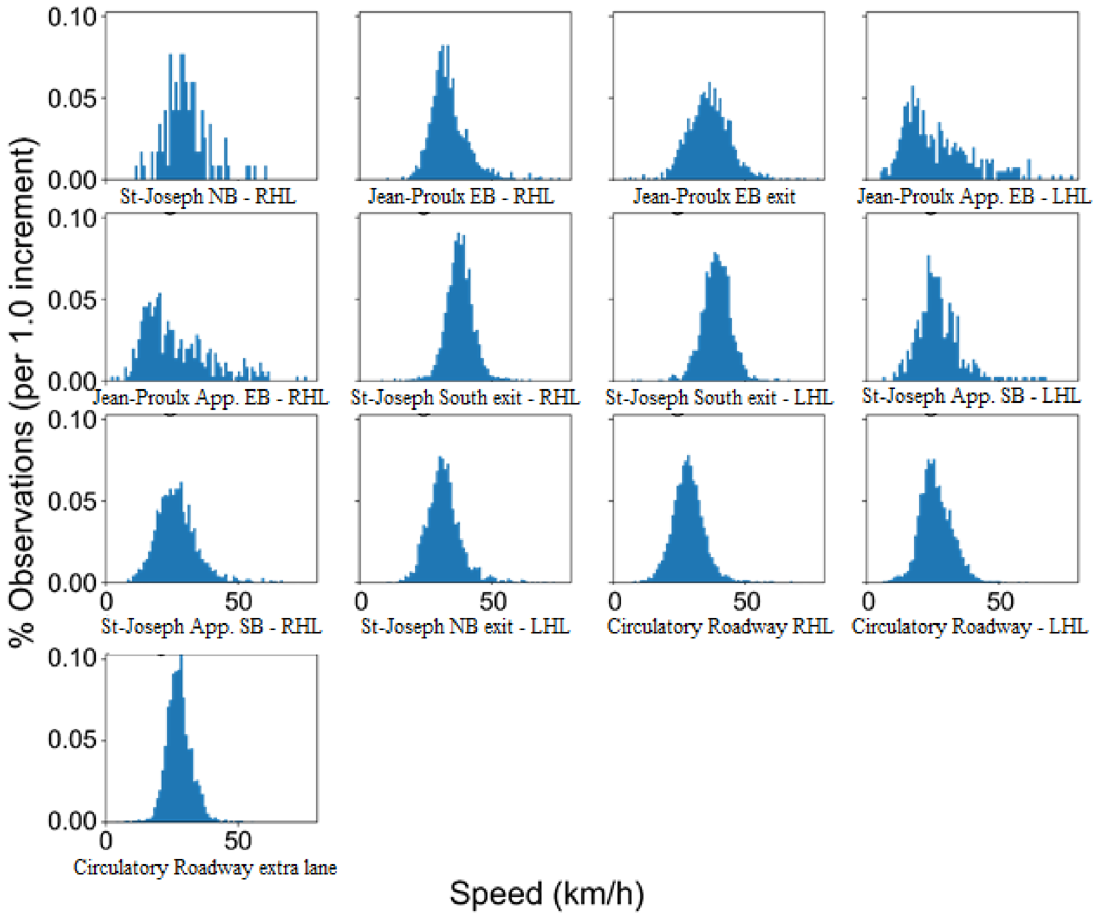

Figure 4.27: Road user average speed distributions per alignment - Jean-Proulx converted roundabout - camera view #5

Note: NB: Northbound, SB: Southbound, EB: Eastbound, WB: Westbound

The average speed on the circulatory roadway centres around 25 km/h, whereas lower average speeds are observed for the roundabout entrance lanes (average of approximately 15 km/h for the Jean-Proulx West left-hand lane (Eastbound), and average of around 20 km/h on the St-Joseph Blvd North approach (Southbound). Aside from two outliers (Jean-Proulx West approach Eastbound – RHL and Eastbound - LHL), the speed distributions also have similar shapes.

4.2.5.6 Before-After Comparison of Speeds and TTC

While the conflict analysis presented earlier in this chapter shows that the geometry of the converted roundabout contains fewer crossing conflict points, the Jean-Proulx roundabout conversion shows contrasted results based on the analysis of speeds and TTC_{15} distributions.

The observations made for Figure 4.24 can be seen clearly in the overall average speed distribution for the initial intersection in Figure 4.28– mainly due to the number of road users represented in both distributions. The distribution shows a trend with two modes: a first mode around 6 km/h, and a second mode at 25 km/h.

Given the intersection setup and the presence of a major arterial with two lanes, the average speed of 25 km/h seems surprising. However, the traffic lights and the number of road users making a left- or right-turn manoeuvre seems to reduce the average speed in the intersection.

The overall speed distribution of all the road users recorded using the Jean-Proulx roundabout during the data collection period (spanning two days) reflects the observations made earlier: the overall average user speed is 25 km/h.

Yielding to oncoming traffic at the roundabout entrances is a cause of average speed reduction. Users' behaviour in terms of speeds also varies according to the position in the roundabout, which brings about variations in the distributions for the alignments (as shown previously).

On certain alignments (according to Figure 4.27), especially the ones corresponding to roundabout exits, it has been seen that road users find the opportunity to increase their speed. The entrances show lower average speeds, whilst road users using the circulatory roadway) drive at speeds close to the average speed of 25 km/h shown in Figure 4.28.

The speed distribution shown in Figure 4.28 shows that the modes of the average speed distributions before and after the roundabout conversion are very close, around 25 km/h. In that respect, the implementation of the roundabout has not had an effect. However, the distribution shapes are slightly different, with a first mode around 8 km/h for the initial intersection. This highlights a disparity in vehicle flow: this is caused by the traffic light. The distribution also points toward a significant reduction in small speed observations (between 0 and 15 km/h) after roundabout conversion, as shown by the difference between the blue and orange distributions below. This may be because road users in the initial intersection are forced to slow down and stop when the traffic lights turn red, whereas the roundabout allows road users to decelerate less and maintain their speeds.

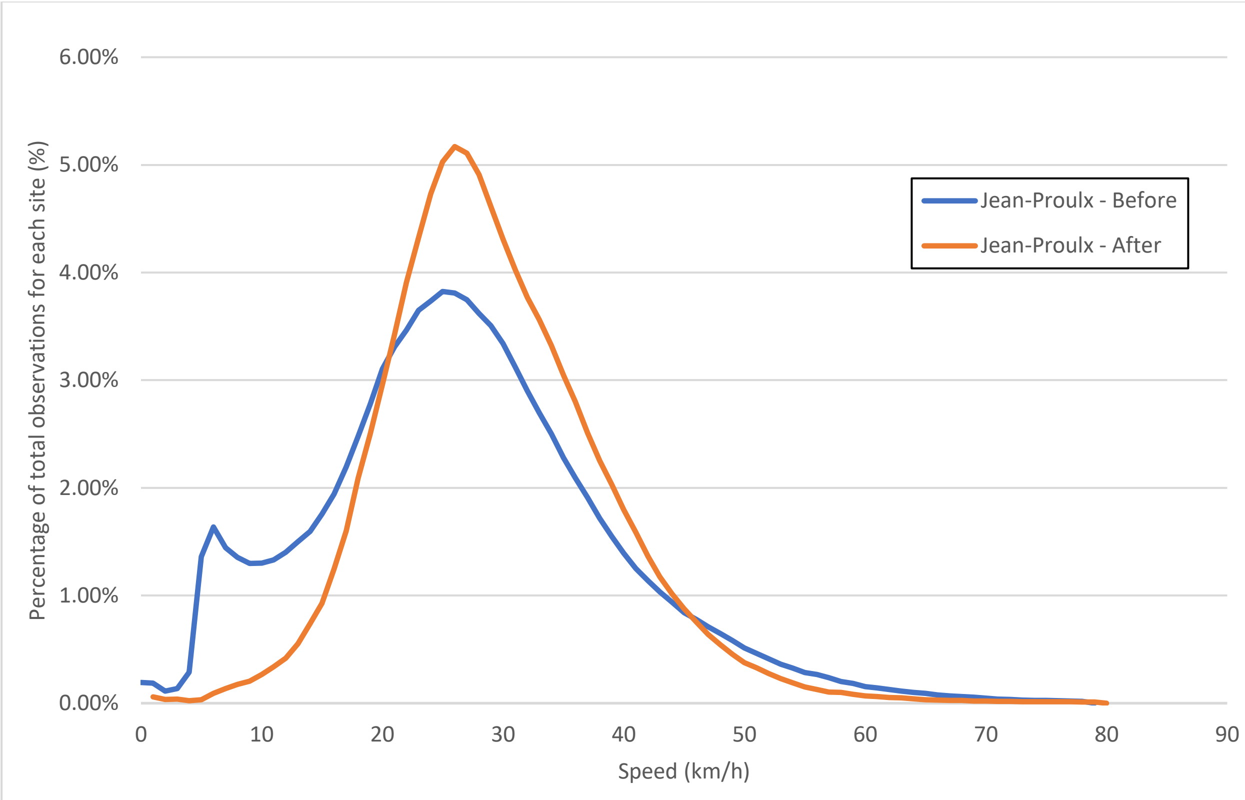

Figure 4.28: Comparative speed distributions - Jean-Proulx initial intersection vs. converted roundabout

In terms of TTC values, the roundabout shows a shift toward lower values between road users, as illustrated by Figure 4.29 below.

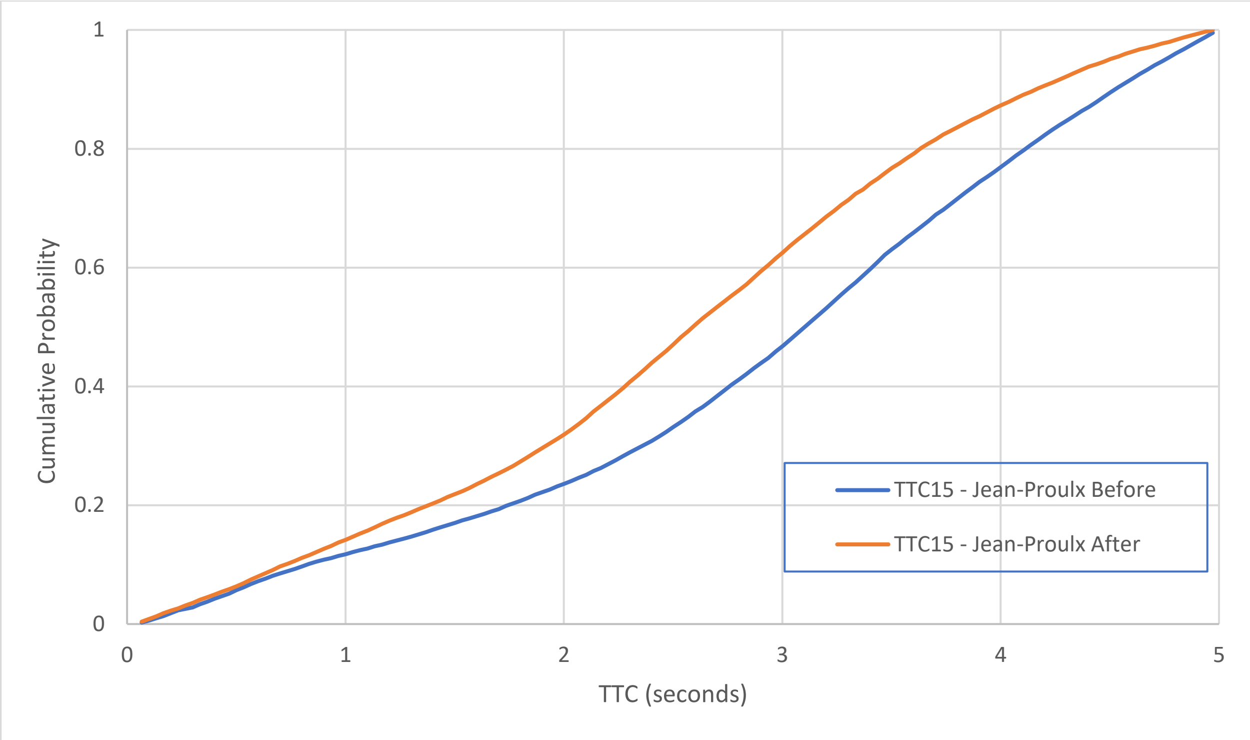

Figure 4.29: Comparison of TTC_{15} distributions - Jean-Proulx Before-After

The TTC_{15} cumulative distributions for the constant velocity prediction method shown in Figure 4.29 shows a relatively uniform distribution and indicates that the median TTC_{15} is 3.1 s for the initial intersection as opposed to 2.6 s for the converted roundabout. This value may be associated to the presence of the traffic light in the initial intersection – road users have high TTC values (or no value at all) with most oncoming conflicting traffic due to the traffic light being red for at least one user from conflicting movements, with the only source of conflicts being from lane changes and rear-end interactions.

The TTC distribution shows a low probability of user pairs having TTC_{15} values below the 1.5 s threshold (the probability for user pairs to have a TTC15 value below 1.5 s is 0.17, compared to 0.22 in the converted roundabout). The causes of such a reduction in TTC_{15} values could be due to a problem with the choice of the motion prediction method. These results point towards decreased safety with the Jean-Proulx roundabout conversion.

4.2.6 Movement Analysis

4.2.6.1 Definition of comparable Origin-Destination movements

With the use of the same method presented for the Intervale Avenue case study (Section 4.1), a basis for comparison between the initial intersection and the converted roundabout is found, to examine user pairs, for the Jean-Proulx intersection. The difficulty in terms of comparability is different compared to the Intervale intersection case study. Indeed, while the first case study had few comparable movements due to the addition of a direction of travel, the Jean-Proulx/St-Joseph intersection has many more different combinations of lanes. Furthermore, given the amount of road users detected both before and after roundabout conversion, the run time of the analysis module is long.

As the MA module uses alignments to attribute road users' ODs, the total enumeration of all possible OD and conflict chains is a long process and one that requires significant computer processing power. Table A 1 shows all the comparable movement pairs between the initial intersection and the converted roundabout.

4.2.6.2 Application of the MA module

As was done for the Intervale site, the MA module was run over all the video sequences for the Jean-Proulx site, both before and after the roundabout conversion.

Table 4.10 below shows the number of user pairs for all the conflicting movement pairs defined in Table A 1, before and after roundabout conversion. Cells containing non-zero observations are highlighted in varying degrees of yellow to red.

Table 4.10 : Table of the number of user pairs - Before and After the Jean-Proulx roundabout implementation

	Number of user pairs - Before	Number of user pairs with TTC15 values below 1.5 s – Before	Number of user pairs - After	Number of user pairs with TTC15 values below 1.5 s - After
JPE-JPW/JPE-JPW	10	0	0	0
JPE-JPW/JPW-SJN	18	1	0	0
JPE-SJN/JPE-JPW	25	2	0	0

Table 4.10 : Table of the number of user pairs - Before and After the Jean-Proulx roundabout implementation (continued)

JPE-SJN/JPE-SJN	204	16	7	0
JPE-SJN/JPE-SJS	12	0	0	0
JPE-SJN/JPW-SJN	117	9	0	0
JPE-SJS/JPE-JPW	0	0	0	0
JPE-SJS/JPE-SJS	0	0	0	0
JPE-SJS/JPW-JPE	3	0	0	0
JPE-SJS/JPW-SJS	0	0	0	0
JPW-JPE/JPW-JPE	22	2	256	96
JPW-SJN/JPW-JPE	5	0	4	0
JPW-SJN/JPW-SJN	95	8	1	0
JPW-SJN/JPW-SJS	3	0	0	0
JPW-SJS/JPW-JPE	4	0	0	0
JPW-SJS/JPW-SJS	20	2	6	0
SJN-JPE/SJN-JPE	1	0	44	5
SJN-JPE/JPE-JPW	0	0	0	0
SJN-JPE/JPE-SJS	0	0	0	0
SJN-JPE/JPW-JPE	0	0	26	3
SJN-JPE/JPW-SJN	0	0	0	0
SJN-JPE/SJS-JPE	5	0	265	73
SJN-JPE/SJS-SJN	102	8	0	0
SJN-JPW/JPE-JPW	0	0	0	0
SJN-JPW/SJN-JPW	1	0	16	1
SJN-JPW/SJS-JPW	0	0	0	0
SJN-SJS/JPE-JPW	0	0	0	0
SJN-SJS/JPE-SJS	0	0	0	0
SJN-SJS/JPW-JPE	1	0	1	0
SJN-SJS/JPW-SJN	0	0	0	0
SJN-SJS/JPW-SJS	10	0	0	0
SJN-SJS/SJN-JPE	0	0	0	0
SJN-SJS/SJN-JPW	2	0	0	0
SJN-SJS/SJN-SJS	259	21	0	0
SJN-SJS/SJS-JPW	0	0	0	0
SJS-JPE/JPW-JPE	178	14	582	118
SJS-JPE/SJS-JPE	617	52	5442	867
SJS-JPW/JPE-JPW	1	0	0	0
SJS-JPW/JPE-SJS	0	0	0	0
SJS-JPW/JPW-JPE	11	0	0	0
SJS-JPW/JPW-SJN	89	7	0	0

Table 4.10 : Table of the number of user pairs - Before and After the Jean-Proulx roundabout implementation (continued)

SJS-JPW/SJS-JPW	6	0	0	0
SJS-SJN/ SJS-SJN	7016	632	0	0
SJS-SJN/JPE-JPW	110	9	0	0
SJS-SJN/JPE-SJN	808	68	0	0
SJS-SJN/JPE-SJS	45	4	0	0
SJS-SJN/JPW-JPE	1270	108	0	0
SJS-SJN/JPW-SJN	7	0	0	0
SJS-SJN/SJS-JPE	2511	224	0	0
SJS-SJN/SJS-JPW	0	0	0	0
Total	**13588**	**1 187**	**6650**	**1 163**

Note: The abbreviations used characterise the different road user ODs, as follows: SJS: St-Joseph South, SJN: St-Joseph North, JPW: Jean-Proulx West, JPE: Jean-Proulx East.

While the number of user pairs generally decreases after roundabout conversion, the conflicting movements for which the number of user pairs (drastically) increase correspond to merging movements or rear-end interactions. However, the road user count was significantly lower after roundabout conversion (14 402 observations vs 32 293 observations before roundabout conversion). This is due to the position of the cameras on site, as the South and East approaches are only partially included in the camera view. Furthermore, while the alignment choice did not reveal any issues, as it did in the Intervale case study, the initial intersection showed issues with double-counting of road users. The results obtained from the MA module are therefore inconclusive, with most values being too small.

4.2.6.3 Validation of the MA module

While there have been many studies of speeds and TTC indicators, the addition of movement analysis requires a validation step. The aim of the validation process is to evaluate the performance of the system regarding the analysis, including the MA module.

To validate the module’s performance, the results of the MA module run through the tvaLib software tool were compared to the number of user pairs obtained manually. As the length of the video footage and the number of vehicles detected are significant in size, manual validation of the complete set would be too time-consuming to undertake for the purpose of this research project.

As such, comparison between manually and automatically detected user pairs took place over a data set of two hours of video length. The video sequences used to undertake the validation process were sequences from the Jean-Proulx initial intersection for which the results are presented in Table 4.11 below.

Table 4.11: Confusion matrix – MA module validation process

	No Manual Observation	Manual Observation	**Total**
Not detected in MA module	Undefined	8	**8**
Detected in MA module	32	543	**575**
Total	**32**	**551**	**583**

The results show a slight surplus of detections with use of the MA module as opposed to manual collection of the user pairs for the chosen sequences. The percentage of false alarms was found to be 5.6 % of all the user pairs detected in the MA module.

Most of the user pairs observed during the two sequences analysed here are rear-end interactions (road users with the same movements, with different speed vectors).

A bias in the number of user pairs detected could be due to the occlusion due to the traffic light in the camera view. View was slightly obstructed for some movements, which could have contributed to disparities in user pair counts for both the manual and the MA module collection of user pair data. This was verified through qualitative observation of the collected video footage.

Validation was also conducted with regards to user pairs for the different OD pairs, as shown in Table 4.12 below. It is worth noting that only movement pairs with large enough numbers of user pairs are shown here.

Table 4.12: Validation of the number of user pairs detected per OD

	Number of user pairs detected manually	Number of user pairs detected in the MA module
JPE-SJN/JPE-SJN	18	19
SJN-JPE/SJS-SJN	12	12
SJN-SJS/SJN-SJS	16	16
SJS-JPE/JPW-JPE	12	13
SJS-JPE/SJS-JPE	17	21
SJS-SJN/ SJS-SJN	228	236
SJS-SJN/JPE-SJN	30	33
SJS-SJN/JPW-JPE	65	65
SJS-SJN/SJS-JPE	90	94
Total	**488**	**509**

The results from Table 4.12 show good detection by the MA module, with a slight surplus (4.35 %) of detected user pairs. Those are mostly for movement pairs resulting in rear-end interactions (for example SJS-SJN/SJS-SJN). The results show that while occlusions can cause slight discrepancies in vehicle and user pair counts, the results obtained using the MA module are accurate.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This research project aimed to compare intersections and roundabouts in terms of road user behaviour using surrogate safety analysis. The main objective was to explore the described methodology and its effect on determining the impact of roundabout conversion on road user behaviour.

In order to conclude on the safety of converted roundabouts, two safety indicators were chosen to analyse observed road user behaviour during similar time frames for each site, and followed the study of conflict points within the different sites for both types of infrastructure. The chosen indicators were speed and TTC. The data used for the project was collected through the installation and operation of cameras at both sites, whilst the treatment of the data was conducted using video-based safety analysis. The MA module was created to determine the number of user pairs for selected comparable conflicting movements for the initial intersection and the converted roundabout.

Two separate case studies were evaluated in the context of this research project: both are roundabout conversions from standard intersections (one in the Bronx, NYC, on Intervale Avenue, the second in Gatineau, Quebec on Jean-Proulx Avenue). A before-after comparative analysis of both sites was made, to determine whether the roundabout implementation had a positive impact on road user safety.

In terms of speed, roundabouts seem to offer more control over road users' speeds through the intersection. The TTC results show more contrast, depending on the site and its associated specific geometry. While the implementation of the roundabout on Intervale Avenue showed an increase in the median TTC_{15} (2.16 s before vs. 2.44 s after roundabout conversion) and a shift in the cumulative distribution of TTC_{15} values, the Jean-Proulx roundabout showed lower median TTC_{15} values and a shift toward lower TTC_{15}. This can be due, as explained in Section 4.2.5, to the presence of traffic lights which reduce the chance of conflicting trajectories thanks to the traffic lights and their timing. The movement analysis was an experimental method of analysis and showed inconclusive results for the Intervale case study, due to problems with detections of road users' real origins and destinations. Should the results be considered as valid and representative of reality, the roundabout conversion in Gatineau is worse in terms of safety. Given the methodological issues concerning the study of the site, it is however impossible to conclude on any change in safety.

While the impact of pedestrians on road users' behaviour and safety was not a part of the study, it is expected that a higher number of pedestrians would be linked to a reduction of motorized road users' speeds, forcing motorized road users to stop in order to let pedestrians cross. The number of pedestrians detected at the New York site is higher than at the Gatineau site, which could account for a change in road users' behaviour (lower speeds, higher TTCs at the New York intersection than at the Gatineau intersection). In terms of the project methodology, the consideration of pedestrians would require to include vehicle-pedestrian conflicts.

5.2 Limitations of the methodology and suggested improvements

The limitations related to this research project can be divided into two categories, namely the limitations due to the data, both in terms of collection and processing, and the limitations due to the methodology applied to answer the research question.

5.2.1 Limitations due to data collection and processing

As was described in the earlier chapters of this thesis, the analysis conducted uses surrogate measures of safety to evaluate road user safety. The data collected was an alternative to accident data, as it consisted in collecting video footage of road users during a certain period. The installation is crucial to the quality of the trajectory detection, as poor camera positioning can lead to incorrect perceived trajectories and speeds or lack of spatial coverage of the intersection, as well as errors in the collected data. Furthermore, as was shown in the case of the Jean-Proulx intersection, occlusions can be problematic and result in fragmented trajectories (as illustrated in Figure 4.20). Different areas of analyses could have been used (and could be used in the future for similar roundabouts), by defining small analysis zones specific to certain quadrants within the initial intersection and the converted roundabout. However, finding an adequate position for the camera can be difficult, particularly for a larger site such as the Jean-Proulx converted roundabout.

The proper functioning of the camera itself is also crucial to the success of the application of the methodology defined. Malfunction with the camera (whether that be due to improper installation or a technical fault with the camera itself) causes inability to record footage of the traffic. The data collection for the Jean-Proulx intersection and subsequent roundabout proved challenging in that regard – many hours of video footage were lost which detracts from the comparability between sites as many road users are not detected, despite the comparison over similar time periods. However, a larger issue concerning the Jean-Proulx intersection – and on a more global scale, sites with more than one camera - is ensuring trajectory reconnection to ensure that no road users are counted twice or partially lost. This issue was particularly significant with the Jean-Proulx intersection and roundabout, as reflected in Table 4.9 – the number of detected road users varies significantly from one set of video data to the other, due to tracking issues and one camera also stopped recording after only two hours of collection.

A final important mention concerns the video data itself related to its analysis and properties. On one hand, video data tends to be quite large in terms of file size (each video sequence representing approximately 4 GB of data, and each site containing 30 video sequences for around 12 hours of video data) and processing time. The video files being so demanding in terms of size and features, the analyses take up a lot of time to run – running time is also increased depending on the number of features and required outputs. Once more, a particular example of such difficulties were shown with the analysis of the Jean-Proulx site (both Before and After scenarios), with over 30 000 road users tracked in the initial intersection for the data collection day in question.

Despite the cost in time of computer vision based surrogate safety analysis, it could be of added interest to use extra data collection days for analysis. While this entails added analysis time, it would enable the use of extra data both in the event of camera malfunction, but also as a means of observing road user behaviour over longer periods of time, and drawing conclusions on whether road users adapt to the new infrastructure in place.

5.2.2 Limitations related to the methodology

The methodology has brought up several questions in terms of its implementation and effectiveness in the comparative analysis of sites. The movement analysis has shown contrast in its application. While the determination of user pairs is an automatic process, the definition of the conflicting movements over comparable Before and After scenarios is a manual process and requires fine-tuned site analysis. While allowed vehicle movements were quite clear for the Intervale intersection and roundabout due to the simplicity of the geometry, understanding of the allowed movements in the Jean-Proulx intersection relied on manual observation of the video data rather than the geometric attributes obtained from images of the site. The Jean-Proulx converted roundabout has well-defined road markings, which, to someone who has never previously seen or used the roundabout, may cause confusion. The circulatory roadway of the Jean-Proulx roundabout also has two lanes which adds to such confusion. The road users' knowledge of roundabouts being very difficult to measure, it is challenging to conclude on their behaviour when confronted to the different markings present in the Jean-Proulx setup.

5.3 Future Work

Several research elements related to this work can be pursued as part of future work. The methodology presented here requires several manual steps in order to complete the setup of the analysis, in terms of preliminary conflict point analysis (see conflict diagrams presented in Chapter 3 and Chapter 4). The alignment drawing is also a manual process, which, on occasion can present a challenge in terms of reducing the number of total alignments within an infrastructure. Optimising the choice of alignments could, in the context of the MA module, help reduce the number of errors due to attribution of users to their correct origins and destinations, as was discussed in the application of the MA module to the Intervale roundabout conversion site. Furthermore, the preliminary analysis is time-consuming, as the definition of conflicting movements in terms of ODs has to be done according to the alignments (in terms of the tvaLib software) and is done after the conflict point analysis has been conducted.

Future work may therefore involve automation of the alignment drawing using marking detection and other relevant input data (city plans for the intersection, indications for the right to make right-turns in the presence of red traffic lights, etc.), as well as automation of the aggregation of conflicting movements per origin-destinations for automatic application of the MA module.

Finally, the central focus of this thesis was comparing the safety for road users for two very different types of infrastructures. While roundabouts are still a relatively unknown quantity in North America, there are other types of intersection designs and controls such as displaced left-turn or diverging diamond interchanges which could be used to limit hazardous situations between user pairs. In the context of safety evaluation and infrastructure choice for accident-prone intersections, comparative analyses can be made with alternative types of intersection control infrastructures to roundabouts, to evaluate the best scenarios and alternatives for safety improvement.

The impact of traffic lights on vehicle interactions also merits exploration. Dealing with the effect of the occlusion due to the physical presence of the traffic light in the camera view should constitute part of future work. The TTC results for the Jean-Proulx site seemed to be influenced by the traffic light phasing, as, by definition, the traffic lights stop vehicles for certain movements whilst others are allowed straight uninterrupted movements at high speeds. Roundabouts intrinsically constrain road users to slow down, as per their geometry. As such, extra analysis can be carried out as for the effect of traffic light phase times and allowed movements on TTC values and user pairs.

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APPENDIX A MOVEMENT PAIRS FOR THE JEAN-PROULX MOVEMENT ANALYSIS MODULE

The following table details all the comparable movement pairs for the Jean-Proulx roundabout conversion which are analysed by the MA module. Table A 1 below does not include movement pairs corresponding to potential rear-end interactions (i.e. user pairs having the same origin and destination for their movements).

Table A 1: List of comparable conflicting movement pairs - Jean-Proulx analysis

	User 1	*User 2*
Conflicting Movement Pair 1	Saint-Joseph North → Saint-Joseph South	Saint-Joseph North → Jean-Proulx East
Conflicting Movement Pair 2	Saint-Joseph North → Saint-Joseph South	Saint-Joseph North → Jean-Proulx West
Conflicting Movement Pair 3	Saint-Joseph North → Jean-Proulx East	Saint-Joseph South → Saint-Joseph North
Conflicting Movement Pair 4	Saint-Joseph North → Jean-Proulx East	Saint-Joseph South → Jean-Proulx East
Conflicting Movement Pair 5	Saint-Joseph South → Saint-Joseph North	Saint-Joseph South → Jean-Proulx East

Table A.1: List of comparable conflicting movement pairs – Jean-Proulx analysis (continued)

Conflicting Movement Pair 6	Saint-Joseph North → Saint-Joseph South	Saint-Joseph South → Jean-Proulx West
Conflicting Movement Pair 7	Saint-Joseph North → Jean-Proulx West	Saint-Joseph South → Jean-Proulx West
Conflicting Movement Pair 8	Saint-Joseph South → Saint-Joseph North	Saint-Joseph South → Jean-Proulx West
Conflicting Movement Pair 9	Saint-Joseph South → Saint-Joseph North	Jean-Proulx East → Saint-Joseph North
Conflicting Movement Pair 10	Saint-Joseph North → Saint-Joseph South	Jean-Proulx East → Saint-Joseph South
Conflicting Movement Pair 11	Saint-Joseph North → Jean-Proulx East	Jean-Proulx East → Saint-Joseph South
Conflicting Movement Pair 12	Saint-Joseph South → Saint-Joseph North	Jean-Proulx East → Saint-Joseph South

Table A.1 : List of comparable conflicting movement pairs – Jean-Proulx analysis (continued)

Conflicting Movement Pair 13	Saint-Joseph South → Saint-Joseph North	Jean-Proulx East → Saint-Joseph South
Conflicting Movement Pair 14	Jean-Proulx East → Saint-Joseph North	Jean-Proulx East → Saint-Joseph South
Conflicting Movement Pair 15	Saint-Joseph North → Saint-Joseph South	Jean-Proulx East → Jean-Proulx West
Conflicting Movement Pair 16	Saint-Joseph North → Jean-Proulx East	Jean-Proulx East → Jean-Proulx West
Conflicting Movement Pair 17	Saint-Joseph North → Jean-Proulx West	Jean-Proulx East → Jean-Proulx West
Conflicting Movement Pair 18	Saint-Joseph South → Saint-Joseph North	Jean-Proulx East → Jean-Proulx West
Conflicting Movement Pair 19	Saint-Joseph South → Jean-Proulx West	Jean-Proulx East → Jean-Proulx West

Table A.1 : List of comparable conflicting movement pairs – Jean-Proulx analysis (continued)

Conflicting Movement Pair 20	Jean-Proulx East → Saint-Joseph North	*Jean-Proulx East → Jean-Proulx West*
Conflicting Movement Pair 21	Jean-Proulx East → Saint-Joseph South	Jean-Proulx East → Jean-Proulx West
Conflicting Movement Pair 22	Saint-Joseph North → Saint-Joseph South	Jean-Proulx West → Saint-Joseph North
Conflicting Movement Pair 23	Saint-Joseph North → Jean-Proulx East	Jean-Proulx West → Saint-Joseph North
Conflicting Movement Pair 24	Saint-Joseph South → Saint-Joseph North	Jean-Proulx West → Saint-Joseph North
Conflicting Movement Pair 25	Saint-Joseph South → Jean-Proulx West	Jean-Proulx West → Saint-Joseph North
Conflicting Movement Pair 26	Jean-Proulx East → Saint-Joseph North	Jean-Proulx West → Saint-Joseph North

Table A.1: List of comparable conflicting movement pairs – Jean-Proulx analysis (continued)

Conflicting Movement Pair 27	Jean-Proulx East → Jean-Proulx West	Jean-Proulx West → Saint-Joseph North
Conflicting Movement Pair 28	Saint-Joseph North → Saint-Joseph South	Jean-Proulx West → Saint-Joseph South
Conflicting Movement Pair 29	Jean-Proulx East → Saint-Joseph South	Jean-Proulx West → Saint-Joseph South
Conflicting Movement Pair 30	Jean-Proulx West → Saint-Joseph North	Jean-Proulx West → Saint-Joseph South
Conflicting Movement Pair 31	Saint-Joseph North → Saint-Joseph South	Jean-Proulx West → Jean-Proulx East
Conflicting Movement Pair 32	Saint-Joseph North → Jean-Proulx East	Jean-Proulx West → Jean-Proulx East
Conflicting Movement Pair 33	Saint-Joseph South → Saint-Joseph North	Jean-Proulx West → Jean-Proulx East

Table A.1: List of comparable conflicting movement pairs – Jean-Proulx analysis (continued)

Conflicting Movement Pair 34	Saint-Joseph South → Jean-Proulx East	Jean-Proulx West → Jean-Proulx East
Conflicting Movement Pair 35	*Saint-Joseph South → Jean-Proulx West*	*Jean-Proulx West → Jean-Proulx East*
Conflicting Movement Pair 36	Jean-Proulx East → Saint-Joseph South	Jean-Proulx West → Jean-Proulx East
Conflicting Movement Pair 37	Jean-Proulx West → Saint-Joseph North	Jean-Proulx West → Jean-Proulx East
Conflicting Movement Pair 38	Jean-Proulx West → Saint-Joseph South	Jean-Proulx West → Jean-Proulx East

As was done for the Intervale intersection analysis, Figure A-1 below shows an illustration of a conflicting movement pair.

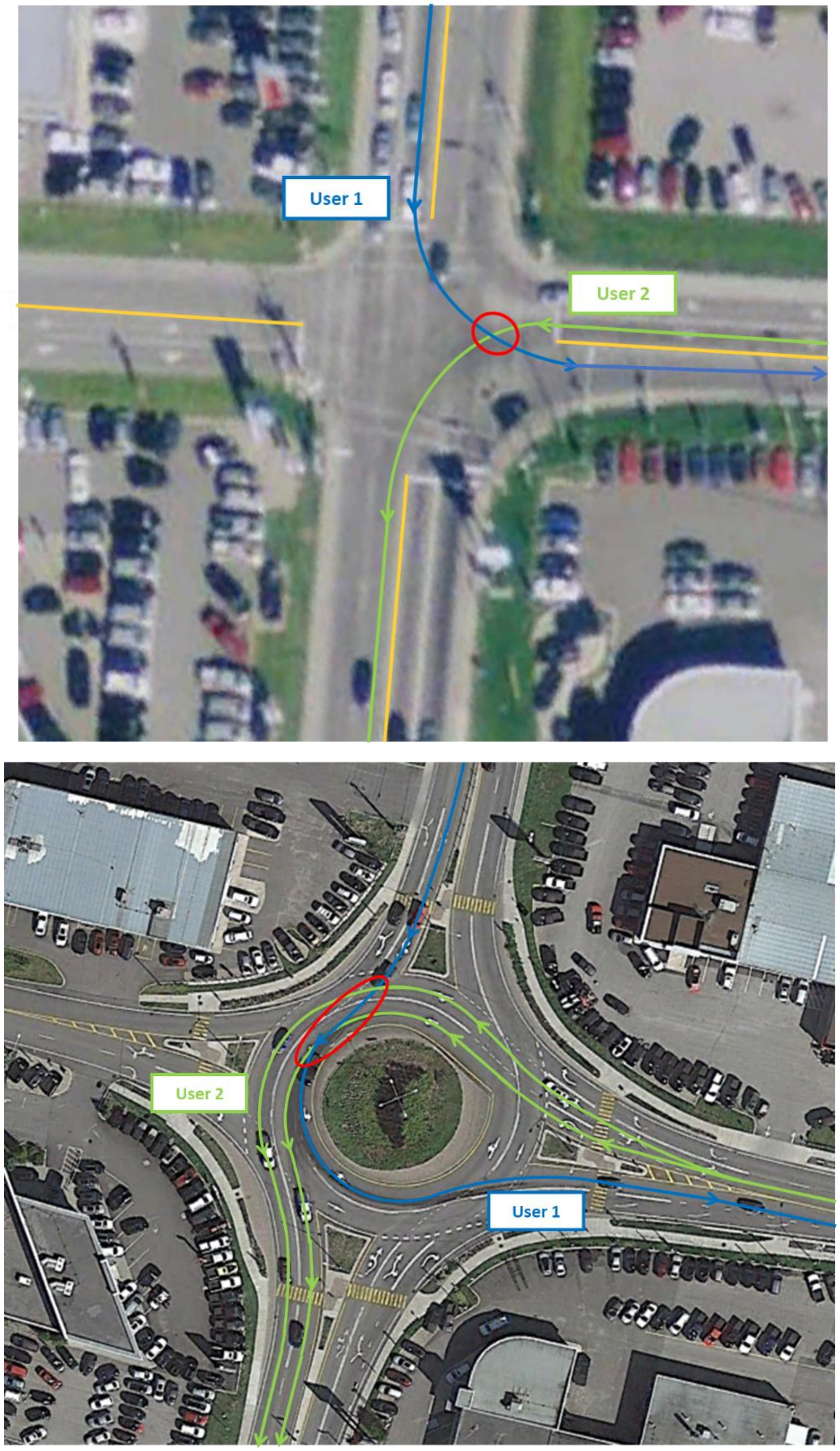

Figure A 1 : Illustration of conflicting movement pair 11 (Saint-Joseph North → Jean-Proulx East conflicting with Jean-Proulx East → Saint-Joseph South) - before and after conversion

Table A 2: List of rear-end and lane-change conflicting movements – Jean-Proulx analysis

	User 1	*User 2*
Conflicting Movement Pair 1	Saint-Joseph North → Saint-Joseph South	Saint-Joseph North → Saint-Joseph South
Conflicting Movement Pair 2	Saint-Joseph North → Jean-Proulx East	Saint-Joseph North → Jean-Proulx East
Conflicting Movement Pair 3	Saint-Joseph North → Jean-Proulx West	Saint-Joseph North → Jean-Proulx West
Conflicting Movement Pair 4	Saint-Joseph South → Saint-Joseph North	Saint-Joseph North → Jean-Proulx West
Conflicting Movement Pair 5	Saint-Joseph South → Jean-Proulx East	Saint-Joseph South → Jean-Proulx East
Conflicting Movement Pair 6	Saint-Joseph South → Jean-Proulx West	Saint-Joseph South → Jean-Proulx West
Conflicting Movement Pair 7	Jean-Proulx East → Saint-Joseph North	Jean-Proulx East → Saint-Joseph North
Conflicting Movement Pair 8	Jean-Proulx East → Saint-Joseph South	Jean-Proulx East → Saint-Joseph South
Conflicting Movement Pair 9	Jean-Proulx East → Jean-Proulx West	Jean-Proulx East → Jean-Proulx West
Conflicting Movement Pair 10	Jean-Proulx West → Saint-Joseph North	Jean-Proulx West → Saint-Joseph North

Table A2: List of rear-end and lane-change conflicting movements – Jean-Proulx analysis

Conflicting Movement Pair 11	*Jean-Proulx West → Saint-Joseph South*	*Jean-Proulx West → Saint-Joseph South*
Conflicting Movement Pair 12	Jean-Proulx West → Jean-Proulx East	Jean-Proulx West → Jean-Proulx East