Before and after traffic safety evaluations using computer vision techniques

by

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Abstract

Traditionally, road safety analysis has been undertaken using historical collision records. This approach to road safety analysis is reactive in that the analyst has to wait for collisions to take place before an action can be taken. An alternative approach is to study traffic conflicts or near misses which occur more frequently, can be clearly observed and are related to collisions. However, there are issues of subjectivity, reliability, and cost associated with the use of human observers. The use of computer vision techniques to automate the process of collecting traffic conflicts data can help mitigate these problems.

This thesis presents the results of a before-after safety evaluation of a proposed design for channelized right-turn lanes. The evaluation uses an automated safety analysis approach to identify and measure the severity of traffic conflicts. The new design, termed "Smart Channels", decreases the angle of the channelized right turn to approximately 70 degrees, and is considered to have safety benefits for both vehicle-pedestrian and vehicle-vehicle interaction. Data for three treatment sites and one control site, located in British Columbia, Canada, are evaluated using automated traffic conflict analysis that relies on computer vision for conflict detection. The results of the evaluation show that the implementation of the right-turn treatment has resulted in a considerable reduction in the severity and frequency of merging, rear-end, and total conflicts. The total average hourly conflict was reduced by a statistically significant 51 percent, while the average conflict severity was reduced by a statistically significant 41 percent.

Many different traffic conflict indicators have been proposed and studied, but the methods of combining the results has not been well examined. This thesis considers four conflict indicators and examines methods of combining or aggregating the information provided by each indicator in order to better account for all components of risk in traffic conflicts. The four indicators are time-to-collision,

gap-time, deceleration-to-safety time, and post-encroachment time. Two primary aggregation methods are studied: time aggregation and road-user aggregation. Time aggregation is appropriate for determining aggregate severity over periods of time, and road-user aggregation is used for normalizing risk to the volume of users.

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List of Abbreviations

Abbreviation	Meaning
AADT	Average Annual Daily Traffic
AHC	Average Hourly Conflicts
BA	Before-After
CDF	Cumulative Distribution Function
CPM	Collision Prediction Model
DST	Deceleration-to-Safety Time
EB	Empirical Bayes
FHWA	Federal Highways Administration
GT	Gap Time
ICBC	Insurance Corporation of British Columbia
LCSS	Longest-Common-Subsequence
MOT	Ministry of Transportation
N/S	North/South
OR	Odds Ratio
PDO	Property Damage Only
PET	Post-Encroachment Time
PRT	Perception Reaction Time
SADT	Summer Annual Daily Traffic
SE	Standard Error
SI	Severity Index
TA	Time-to-Accident
TAC	Transportation Association of Canada
TCT	Traffic Conflict Technique
TE	Treatment Effect
TET	Time-Exposed-TTC
TIT	Time-Integrated-TTC
TTC	Time-to-Collision
UBC	University of British Columbia
VIPS	Video Image Processing System
WHO	World Health Organization

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1 Introduction

1.1 Challenges

The 1900's witnessed the rapid motorization, first, in the developed world, and, more recently, in the developing world. As many as 1 billion vehicles now travel the world's increasing road network. The associated increase in frequency of traffic collisions can be regarded as a global epidemic; the World Health Organization (WHO) reports 1.3 million people die each year on roads around the world. This figure is dwarfed only by the 20 to 50 million non-fatal injuries resulting from traffic collisions (WHO, 2009).

The rate of traffic collision fatalities is significantly higher in the developing world than in developed countries. Over 90% of the world's traffic fatalities occur on the road of developing countries which have only 48% of the world's registered vehicles. However, even developed countries such as Canada are far from immune to traffic injuries and fatalities; there were 2,767 road fatalities in Canada in 2007 (Transportation Association of Canada, 2007).

There has been a decreasing trend in traffic fatalities in developed countries despite a continual increase in road-user population. Since 1996, fatalities have decreased by 10% and serious injuries by 16%. However, with the increasing motorization around the world and lower vehicle and road safety standards in developing countries, the WHO predicts that road traffic injuries will become fifth-leading cause of death by 2030. Given the high social and financial costs resulting from traffic collisions, it is no surprise that research into understanding and increasing road safety has a long history.

1.2 Observational Study of Road Safety

Road safety analysis can be applied at many levels from the macro to micro, with the goal of improving the safety of existing and planned facilities. The study of road safety can be accomplished through either experimental or observational studies. Experimental road-safety studies are generally difficult to do or are avoided because it is not acceptable to put people at risk for the purpose of study.

The decisions made in the design of components of the road or transportation network affect the safety of the users so the consequences of these decisions must be determined. A primary source of this knowledge is the 'observational before-after study'. Before-after (BA) studies attempt to measure and quantify the increase or decrease in safety due to a safety treatment by comparing observed data gathered before and after the change.

1.3 Non-conflict-based Safety Measures

Traditionally, the analysis of road safety has been done retrospectively, using historical records of crash frequency and severity. The level of safety of a specific location is measured by its history of fatalities, injuries, and property damage. A location is considered accident-prone when it produces a greater number of various collision types than is typical of similar intersections or road-segments. What is typical of specific locations is usually derived from a collision prediction model (CPM). CPMs are created from large groups of data and predict the frequency and magnitude of collisions expected at a given intersection or road section type for a given traffic volume. When the observed collision rate significantly exceeds the predicted rate, there may be additional factors at the location that lead to a higher collision rate (Sayed & de Leur, 2008).

However, the reliance on collision data for safety analysis has several shortcomings (Svensson, 1998). Because collisions are rare events, even at collision-prone locations, extended observation periods are required to determine stable trends. Also, not all accidents are reported, and the reporting level can vary from region to region.

Second, reporting of collisions is often inconsistent and incomplete. Svensson (1998) indicates that pedestrian collisions were found to be underrepresented in collision records when compared to hospital records. Collision reports are handled by local police for the purpose of law enforcement and insurance companies for the purpose of claims payments. Neither body has a primary goal of keeping a complete and consistent list of records of all collisions so that statistical methods can be applied. Also, with the focus of the reporting on the outcome of the collision, the mechanisms that lead up to the collisions often go undocumented or are entirely speculated.

As well, one cannot overlook the ethical and possible legal implications of letting several years pass while collecting collision data in order to confirm that a location is, in fact, collision-prone and not simply experiencing a statistical aberration.

Because of these shortcomings, traffic safety analysis can benefit greatly from methods that use observable, non-collision interactions to evaluate safety. Many non-collision measures or surrogate measures of safety have been proposed and used over the past few decades, leading to the creation of technical observation approaches referred to as traffic conflict techniques (TCT).

The traffic conflict technique has its origins in the Detroit General Motors laboratory in the 1960's. The first traffic conflict study is usually considered to be that of Perkins (1967) in which conflicts were identified as readily observable evasive maneuvers taken by drivers. Examples of such are the abrupt changing of lanes or the observation of brake lights and rapid deceleration. The objective of this seminal study was to determine whether vehicles manufactured by General Motors were involved in fewer conflicts than vehicles of other manufacturers.

A formalized definition of a traffic conflict was later adopted as "an observable situation in which two or more road users approach each other in space and time for such an extent that there is a risk of collision if their movements remain unchanged" (Amundsen & Hyden, 1977), and the observation method formalized in the Traffic Conflict Technique (TCT).

Following it's origination in America, the Traffic Conflict Technique spread to other regions of the world and was adopted in various modified forms. A subjective scale of severity for conflicts was added in the TCT adopted by the UK's Transportation Research Laboratory in London (Spicer, 1973). The Lund Institute of Technology in Sweden developed their own version of the conflict technique through continual development, study and application to projects during the 1970's and 1980's. The current version of the Swedish Traffic Conflict Technique is presented in Hyden (1987).

While the earlier versions of the TCT identified conflicts in terms of subjective behavior, more objective measures were developed in later versions of the TCT . These objective measures took the form of conflict indicators, which measure the spatial and temporal proximity of road users in order to calculate the associated risk. The Time-to-Collision indicator measures the time that remains until a collision will occur unless evasive action is taken, and is used as the primary indicator in the Penticton study presented in this thesis.

1.4 Computer Vision for Traffic Safety Analysis

Video analysis has been used for many traffic studies as well as real-time monitoring of traffic conditions. Video data is rich in details, recording devices are becoming less expensive, and video cameras are often already installed for monitoring purposes. In addition, video data represents a permanent record of the analyzed traffic events that can be reviewed and validated, in contrast to in-field observer-based surveys.

However having observers manually extract video data can be as time-consuming and expensive as in-the-field manual monitoring, or more so. The use of computer vision, which involves the application of computer algorithms to extract information from a digital video signal, has advanced greatly because of exponentially increasing computation power.

1.5 Research Objectives

This thesis presents an application of computer vision techniques for quantifying user safety risks in traffic facilities. Though by no means the first implementation of such a technique, the study conducted in Penticton, BC, is to the best of the author's knowledge, the largest before-after traffic study using such a technology. More than 200 hours of video data was collected and analyzed during the process. The use of a control or comparison site also appears to be unprecedented in automated implementations of the traffic conflict technique.

A primary objective of the research presented is to demonstrate the ability to carry out traffic conflict analysis using the same techniques as those employed by safety researchers on collision data records. The odds ratio method, a technique borrowed from collision record analysis, is used to account for time trend effects at the treated intersections. Conflicts are treated as rare and random events, similar to how collisions are treated, and they can be assigned a Poisson distribution and the significance of the results tested. A major advantage of using traffic conflicts over traffic collisions in safety studies is the significant shorter observation period required; data can be collected over a matter of days or weeks with conflicts as opposed to years using collision records.

Traffic conflict studies, whether completed manually or with the aid of automated technologies, typically rely on a single technical conflict indicator for the identification of high risk situations. An indicator appropriate for the studied situation is selected and used solely for risk identification. Several researchers have put forward proposals to use multiple indicators to identify independent conflict mechanisms (Ismail et al., 2011). The second objective of this thesis is to study the options and challenges one faces when combining multiple indicators, and proposes solutions that treat the information provided through the indicators in a logical and unbiased manner.

1.6 Thesis Structure

This thesis is composed of five Chapters. Chapter 2 presents a thorough literature review of the research areas covered in the body of the thesis. These include traffic safety, before-after studies, the Traffic Conflict Technique, traffic safety computer vision applications, and background on the applied treatment for the study.

In Chapter 3 a large-scale before-after safety study using computer vision detection of traffic conflicts is presented. Chapter 4 investigates a number of procedures for aggregating multiple traffic conflict indicators in a computer vision traffic safety analysis methodology. Chapter 5 presents a summary, conclusion and future research.

2 Literature Review

This chapter presents an overview of subject areas related to the research topics investigated in this thesis. The objective is to provide context on the current state of the art on which the presented research is based and builds upon.

2.1 Road Safety Studies

The definition of road safety can take two forms (Hauer, 1997):

i) the objective measure reflected in the prevalence of accidents and their harm

ii) the subjective perception of how safe one is on the road.

For the purpose of this thesis, the first definition shall be applied to the road safety: the degree of actual, not perceived, risk road users encounter. The distinction is important as the road-user's impression of a safety risk can have little correlation with actual risk (Matthews & Morgan, 1986).

2.2 Observational Before-after Studies

It is technically and ethically difficult to design laboratory experiments that mimic real-world driving conditions (Izadpanah et al., 2009). Therefore, research and safety professionals have to gather the required data through observation of the real-world traffic environment. Observational before-after (BA) studies compare conditions from before a treatment to after a treatment, traditionally using collision records. Statistical methods are employed to account for non-treatment-related factors (Hauer, 1997). The alternative approach to determining the effectiveness of a safety treatment is to use a cross-sectional study comparing similar locations, one with and one without the treatment of interest; for example two-way stop vs. four-way stop signs on rural cross streets. The cross-sectional study methodology is not examined in this thesis.

BA studies are traditionally carried out using traffic collision records from a period of time before and a similar period of time after the implementation of the treatment. Observation periods of several years are often required for statistically significant numbers of collisions to occur and be recorded. Statistically significant numbers can be attained more quickly at sites with higher collision rates (Hauer et al, 2002). A simple comparison of the number and types of collisions in the after period to the before period (assuming equal period lengths) is referred to as a "naïve before-after study". As the name implies, attributing all the changes observed to be effects of the treatment may be ignoring many confounding factors. Comprehensive summaries of confounding factors are found in Svensson (1998) and Izadpanah et al. (2009).

2.2.1 Confounding Factors

Confounding factors are effects not related to, nor caused by the treatment that influence the safety data gathered at the study location. They can be categorized as history, maturation, mean regression, and exposure effects.

2.2.1.1 History

Environmental factors or other non-traffic related conditions may influence the safety of a traffic facility. If these factors and conditions differ between the before to after conditions, they must be accounted for. Examples are seasonal effects such as rainfall or daylight that affect road friction and driver visibility. The effect of the treatment must be separated from the effects of these extraneous factors. The combination of these factors is referred to as 'history'.

2.2.1.2 Maturation

Maturation refers to longer-term trends witnessed in traffic safety in the geographic location of interest, independent of any individual safety initiative. While a decrease in the rate or number of collisions at a treated site could be attributed to the safety treatment, it may also be explained by a general improvement in safety due to, say, improved braking systems over a number of years. To

account for maturation, the collision trend in the region must be examined at a scale that a single treatment will not affect.

2.2.1.3 Regression Artifacts

Regression artifacts (collectively known as the "random effect") involve the statistical phenomenon known as "regression to the mean", or the tendency for extreme events to be followed by less extreme events. Transportation facilities experiencing high numbers of collisions may be truly unsafe, or simply experiencing a random fluctuation. In many cases, a location is selected for safety treatment because of random aberrations. When the subsequent time period records fewer collisions, the treatment is given credit for what is simply regression to mean.

2.2.1.4 Exposure

The volume of traffic using a facility has a direct effect on the number of collisions (Sayed & de Leur, 2008). A decrease in the number of collisions could simply be due to a decline in the number of users of the facility. Conversely, a treatment that increases the capacity of a facility can lead to a higher number of collisions, yet a lower rate of collisions (collisions per volume). To complicate matters further, the number of collisions has been observed to have a non-linear relationship with volume (Sayed & de Leur, 2008).

2.2.2 Overcoming Confounding Factors

The effects of history and maturation can be best accounted for through the use of a single or set of comparison or control sites. Comparison sites must be similar to the treatment site, and in the same geographic region. By comparing the safety effects at the treated site to that observed at the comparison sites, the treatment effects can be normalized for what would have happened without the treatment. This is accomplished using techniques such as the odds ratio.

2.2.2.1 The Odds Ratio

The "odds ratio" statistical method is commonly used in many fields, such as medical science, for comparing the effect of a treatment to a control or reference group. In BA traffic safety applications, the conditions pre- and post-treatment at the site are compared to the conditions at a set of control or reference sites over a similar time period (Autey et. al, 2010). The ratio is defined as the change in the control site or group divided by the change in the treatment site.

$$OR_i = \frac{A_i/C_i}{B_i/D_i}$$

where

Ai = Condition at control site before treatment carried out

Ci = Condition at control site after treatment carried out

Bi = Condition at treatment site before treatment carried out

Di = Condition at treatment site after treatment carried out

2.2.2.2 The Empirical Bayes Method

The Empirical Bayes technique is commonly employed to account for regression to the mean. The EB method assumes there are two types of clues to the safety performance of a location:

1) the site's traffic and road characteristics

2) the site's historical collision data

The EB method makes use of both sources of information, weighting more heavily the source with the most certainty. A complete description of the method is available in Hauer et al. (2002). The EB method will not be employed in the study presented in this thesis because of a lack of data, as will be explained later.

2.3 Surrogate Safety Measures

The use of surrogate measures or indicators has a long history in many fields of science when the direct measurement of a variable is difficult or impossible. In general, an acceptable surrogate measure must meet two conditions: it must be correlated with the clinically meaningful outcome, and it must fully capture the effect of the treatment (Tarko et al., 2009). In the field of traffic safety, Archer (2004) states that surrogate measures or indicators of safety must be more frequent than accidents, have a statistical and causal relationship to accidents, and have the characteristics of near-accidents in a hierarchal continuum from collisions to safe, undisturbed passages.

Surrogates for traffic safety that have been proposed, studied or implemented can be classified into two broad categories: traffic conflicts and safety-influencing factors. Traffic conflicts have near-accident properties or contain similar mechanisms to traffic collisions (Archer, 2004). Safety-influencing factors, or non-conflict-based surrogate measures, while not part of the collision mechanism, have statistical relationships with the frequency of traffic collisions.

2.3.1 Non-conflict-based Surrogate Measures

Probably the most studied non-conflict based indicator, or safety-influencing factor is excessive speed. Treat et al. (1979) found excessive speed to be the second-most frequent causal element out of fifty driver, environmental and vehicle factors. Kloeden et al. (1997) showed that the risk of a driver being involved in a collision that results in a fatality is more than twice as great when travelling 10 km/h above average speed and nearly six times as great when travelling 20 km/h above average speed.

An FHWA manual on non-accident-based project evaluation suggests speed variance, traffic violations, gap acceptance, lane occupancy, pedestrian crossing behavior, and compliance to traffic control devices among a large list as possible surrogate measures of safety (FHWA, 1981). Porter et al. (1999) investigated the safety implications of red-light running and its prevalence in the driving

behavior of the public. A study into the use of a dedicated lane for vehicle equipped with ITS (intelligent transportation systems) used a measure of shockwaves as a surrogate for safety (VaArem & DeVos, 1997). Shockwaves are the compression and expansion waves observed in traffic density in unstable traffic conditions.

2.3.2 Traffic Conflict Indicators

Objective traffic conflict indicators rely on spatial and temporal data of road-users (the set of road-user trajectories). Geometric calculations applied to the trajectories quantify proximity to collisions in unique ways for each type of indicator.

2.3.2.1 Time-to-collision

Probably the most widely used indicator for the existence of a conflict is Time-to-Collision (TTC), or some version of this concept. Using a method of predicting future positions of road users, collision courses are identified between pairs of users. Using simple kinematics, a measure of the time until this hypothesized collision will occur is calculated. The methods of extrapolating positions, as well as determining when during the conflict to extrapolate, vary with different implementations of the TTC measure.

The earliest use of TTC is found in Hayward (1972) where the TTC value, at any instant during an interaction, is defined as the time until a collision will occur if the "collision course and speed difference are maintained". A more robust definition of TTC was presented in Amundsen & Hyden (1977) as "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 remained unchanged".

In some literature, TTC is defined as a single value for each pair of conflicting road users which is calculated at the instant one vehicle initiates evasive action, and is often referred to as time-to-accident (TA)(Svensson, 1998). The TA calculation assumes vehicles continue at their current

velocity. The Swedish TCT developed at Lund Institute of Technology derives a measure of severity by dividing the TA by the closing speed which is the instantaneous velocity of the vehicle taking evasive action at the time this action is commenced (Svensson, 1998). Usually, however, TTC is defined as a continuous variable which exists whenever a collision course is observed for a pair of road users.

Head and Gettman, 2003, implement a slightly different definition of TTC. In their study, TTC is only calculated when a vehicle without right of way is in the path of a vehicle with right of way. TTC in this case, is defined as the time until the vehicle with right of way arrives at the point currently occupied by the other. In this manner, only the right-of-way vehicle's path is projected in space and time. While this may not seem intuitive, this definition overcomes an observed problem with the TTC indicator. In normal, safe driving conditions, two vehicles may often be on a collision course, but the vehicle without right of way is both aware of the situation and taking appropriate action. By requiring the vehicle without right of way to be in the path of the vehicle with right of way, the resulting TTC can be considered more valid.

The interpretation of the terms "path" and "direction" can be ambiguous in the definition of TTC and other indicators. A vehicle's current trajectory could mean its instantaneous velocity vector, or its instantaneous velocity vector and instantaneous acceleration vector. Usually only the instantaneous velocity is considered.

A vehicle's future trajectory can also be defined by a probabilistic function that uses common motion patterns for prediction of a vehicle's future position (Saunier and Sayed, 2008, Saunier et al. , 2010, & Autey et al., 2012). In these studies, a vehicle's trajectory is assigned probabilistically to common motion patterns gained through computer vision (see Section 3.3). A road user's instantaneous velocity is used to extrapolate its position along the assigned motion paths.

Two extensions to the TTC indicator are presented in Bovy & Minderhoud (2001): time-exposed-TTC (TET) and time-integrated-TTC (TIT). Both approaches aggregate the continuous TTC values calculated for a conflicting pair of road-users into a single, representative value. TET measures the duration of time that the instantaneous TTC value is below a critical, or threshold value during a conflict. This aggregation method makes no distinction to what degree the TTC is below the threshold value. The aim of the method is to account for the exposure duration of the event. The TIT method integrates the difference between the TTC value and critical value over all time periods that the TTC is below this critical value. In doing so, it accounts for both the exposure duration and the proximity of collision at all instants.

Several researchers suggest the use of the reciprocal of TTC (1/TTC) as a more applicable indicator measure (Chin et al., 1992 and van der Horst, 1990). Using this approach, a larger value indicates a more severe encounter. The non-linearity introduced using the reciprocal causes the severity to increase more rapidly as the TTC approaches zero.

2.3.2.2 Post-encroachment Time & Gap Time

Several alternative measures of traffic conflicts are proposed in Allen et al. (1978) including post encroachment time (PET) and gap time (GT). PET is defined as the time difference between the two road-users occupying a common spatial zone. PET is less ambiguous than TTC as it requires no projection of road-user positions into the future. PET values can be measured discretely through the observation of vehicle trajectories.

A shortcoming of the PET method is that it is difficult to distinguish the willingness of drivers to accept the risk (Chin & Quek, 1997). Also, there is a lack of a speed or distance dimension with the PET indicator, which makes it difficult to judge the relative severity of the situation (Archer, 2004).

The PET indicator also poses a problem for interaction where vehicles follow common courses, such as rear-end and merging (Archer, 2004). If the following vehicle has a lower or equal speed to the lead vehicle, a PET can be calculated but no collision possibility exists.

Gap time (GT) identifies the time difference between when two vehicles are to occupy a common location should their trajectories remain unchanged. This can also be described as the expected PET should road-users' trajectories and velocities remain unchanged. Gap time is also referred to as time advantage (Laureshyn et al., 2010). An additional parameter, referred to as "T2" in Laureshyn et al. (2010) is included to account for the time duration until the road-users' paths are projected to cross. This parameter allows for a smooth transition from GT to TTC should the vehicles trajectories achieve a collision course during their coexistence.

2.3.2.3 Deceleration-to-safety Time

Deceleration-to-safety Time (DST) (Hupfer, 1997) measures the required deceleration for a vehicle to attain a non-negative gap-time in relation to another road-user. In other words, for a pair of road users with a calculable gap time, it is the deceleration that one vehicle must undertake to arrive immediately following the other road user. Clearly this measure is applicable only in certain situations; it is unreasonable to always assume that the vehicle which is projected to first arrive at the conflict point must decelerate. However, this indicator is ideal for vehicle-pedestrian interactions where a vehicle must decelerate to avoid hitting a pedestrian in its path; thus it has been used primarily in pedestrian-vehicle crosswalk studies (Cafiso et al., 2010).

2.3.3 Correlation to Collisions

Many attempts, with varying degrees of success, have been made to correlate conflicts to collision rates and provide a mapping method where the frequency and type of collisions that can be expected are determined. Brown (1994) used manual observation of events with TTC values less than 1.5 seconds and attempts to correlate them to accident records. The study showed the potential for

such a correlation to exist, and found that it increased when accident types were disaggregated further. The employed definition of a conflict was a time-to-collision value, measured at the time of evasive action, split into three categories: 0 to 1, 1 to 1.5, and 1.5 to 2.0 seconds. Correlation of conflicts with collisions ranged from 0.64 to 0.81 for 11 out of the 14 intersections. Sayed & Zein (1999) found a strong relationship between collisions and conflicts for signalized intersections, but not for unsignalized intersections.

2.3.4 Traffic Conflict Hierarchy

It is well recognized that not all collisions are of a common severity, and the same applies to conflicts. Hyden (1987), Spicer (1973), and Svensson (1998) identify a continuum of severity ranging from safe passage to collisions, and even within collisions from property damage only (PDO) through injury and fatalities. Hyden (1987) represented this hierarchy as a triangle, or pyramid with the tip representing actual collisions and the base representing undisturbed passage. The cross-sectional area of the pyramid represents the frequency of that severity level of event occurring. The pyramid shape is logical as collisions are observed to occur less frequently than undisturbed passage. The exact shape or "dimensions" of the pyramid are unique to each road section or intersection studied. Locations with hierarchies that show a proportionally higher number of severe events are identified as unsafe locations. A further extension to the pyramid theory is that of a diamond (Svensson 1998). This is, in fact, a more logical shape considering that when the spatial area and temporal window of interest are limited in any fashion, say to coexisting road-users in an intersection or on a stretch of road, there always exists some risk for all pairs of users, so the bottom of the diamond tapers to zero.

If the severity of traffic conflicts are regarded as realizations of random phenomena, in much the same manner as floods and earthquakes, they become candidates for analysis using extreme value methods. Chin & Quek (1997) fit a Weibull extreme value distribution to a data set of reciprocal TTC values. Using this distribution, they were able to predict the frequency of events with TTC's less than perception-reaction time occurring. A shortcoming of this method is that it does not account for

whether or not drivers were already aware of the conflict and performing evasive action when this TTCmin value was recorded. In a similar manner, Songchitruksa & Tarko (2006) use an extreme value method to find the probability of a PET equal to or less than zero, given a data set of observed PET values. The authors report three to six weeks of PET observations can obtain safety estimates with confidence intervals similar to those from collision studies using four-year observation periods.

2.3.5 Challenges to TCT

The TCT provides many advantages to collision-record-based traffic safety analysis. Despite these obvious advantages, several shortcomings to the methods have been put forward. Several of the shortcomings have been at least partially overcome with the use of computer applications.

2.3.5.1 Consistency

The problem with consistency of definitions has been well documented (Chin & Quek, 1997, Ismail, 2010). When observer-based studies use subjective categories of driver behaviors for identification of conflicts, there exists room for judgment as an exhaustive list can never be attained. Also, some driver behaviors categorized as evasive actions, such as aggressive braking, are not always indicative of a conflict and are instead part of some drivers' normal behavior.

2.3.5.2 Validity

For the TCT to be considered valid, it must be successful in predicting road collisions. Statistically significant correlations between conflicts and collisions have been found in previous research (Sayed & Zein, 1999). However, for every study that corroborates validity, there are others that fail to find relationships between conflicts and collisions (Williams, 1981, Ismail, 2010).

2.3.5.3 Reliability

The TCT has traditionally been undertaken using trained observers in the field. Ambiguities in the definitions of conflicts and the demanding nature of hours of observing in the field can lead to both intra-observer and inter-observer variability (Migletz et al., 1985). The challenge of maintaining

consistency of identifying, scoring, and ranking conflict events between observers has been studied several times. A concise review of the results is provided by Chin & Quek (1997). As well, inconsistency can exist in repeated observations made by a single observer. On-site observations are essentially impossible to validate after the fact as no recording of the actual event is made. This can be overcome through the use of video equipment. A promising alternative to the subjective or rule-based conflict definitions is the application of an objective indicator such as TTC.

2.4 Computer Video Analysis

2.4.1 Computer Vision for Road Users

Computer vision for the purpose of traffic monitoring has its origins in the 1990's as the computation power required to process video scenes became available at reasonable costs. Coifman et al. (1998) present a comprehensive summary of the development of video image processing systems (VIPS) for traffic flow usage up to the late 1990's. The commercial VIPS systems available in the late 1990's were tripwire systems. Tripwire systems mimic the operation of loop detectors using visual information from the camera image, but do not track individual vehicles. A more advanced form of VIPS that does track vehicles, referred to as "third generation" VIPS, did so by using region-based tracking. A major shortcoming of this method is that, when one vehicle occludes another or object shadows overlap, the vehicles become a single object from the computer's view.

In the last decade, many groups have been developing vehicle and pedestrian tracking systems using more advanced methods (Gupte et al., 2002, Laureshyn et al. 2008, Malinovskiy et al. 2007, Atev et al., 2005). Tracking of road users can be accomplished through several tracking approaches.

2.4.1.1 Model-based tracking

Model-based computer vision tracking uses prior knowledge of the shape and appearance of specific objects to allow machine-based interpretation of a visual scene. The major shortcoming of this method is that the model library must be complete and of reasonable accuracy, and there must exist a

robust scaling algorithm to account for changes in size due to perspective (Malinovskiy et al., 2007). This requires intensive training and building a model library before using the algorithm.

A key issue in object tracking, and especially in tracking road-users, is partial occlusion of objects. Three-dimensional model-based tracking approaches have been suggested to deal with occlusion (Lou et al. 2005).

2.4.1.2 Region-based tracking

Region-based tracking is accomplished primarily through the use of background subtraction resulting in a 'blob' being representative of an individual road user. While this method is effective under free flow conditions, congested traffic can lead to multiple vehicles being grouped together (Coifman et al., 1998).

2.4.1.3 Contour-based tracking

In contour-based tracking, the computer algorithm attempts to identify the bounding contour of moving objects and to continually update this boundary. In this fashion, the location of the bounded object is tracked using less computation power than in region-based tracking. However, as in region-based tracking, the problem of occlusion remains.

2.4.1.4 Feature-based tracking

Feature-based tracking abandons the attempt to identify discrete objects at the tracking level and instead tracks visually distinguishable features such as points or lines on objects. The conversion of sets of features into objects, or road-users, is accomplished in a subsequent stage, defined as the grouping stage (Saunier & Sayed, 2006). This method is used for the computer vision traffic analysis system employed in the Transportation Group at UBC.

2.5 Computer Vision at UBC

Despite the potential benefits of automated traffic safety analysis based on video sensors, limited computer vision research has been directly applied to road safety, and even less so to the detection of traffic conflicts. Maurin et al. (2005) state that "despite significant advances in traffic sensors and algorithms, modern monitoring systems cannot effectively handle busy intersections". Such a system requires a high level understanding of the scene and is traditionally composed of two levels of modules: 1) a video processing module for road-user detection and tracking and 2) interpretation modules for traffic conflict detection (Saunier & Sayed, 2006).

There is past and ongoing research in the Transportation Engineering Group at the Civil Engineering Department of UBC that aims to develop an automated road safety analysis system based on video sensors. This video analysis system is based on existing state-of-the-art computer vision algorithms and has incorporated some adaptations for the study of road users.

The road-user detection and tracking module relies on a feature-based tracking method described in Saurnier & Sayed (2006). Feature-based tracking is preferred because it can handle partial occlusion. The tracking of features is done through the well-known Kanade-Lucas-Tomasi feature tracker. Stationary features and features with unrealistic motion are filtered out, and new features are generated to track objects entering the field of view. Since a moving object can have multiple features, the next step is to group the features, i.e., decide what set of features belongs to the same object using cues like spatial proximity and common motion. A detailed description of the tracking algorithm is presented in Saurnier & Sayed (2006). The tracking accuracy for motor vehicles has been measured between 84.7% and 94.4% on three different sets of sequences. This accuracy is considered reliable, especially under heavy traffic flow conditions, and should have little impact on the accuracy of the calculation of conflict indicators. This means that most trajectories are detected by the system, and the calculated conflict indicators are considered reliable.

For road safety applications, the UBC approach relies on the building of two databases: a trajectory database, where the results of the video processing module are stored, and an interaction database, where all interactions between road users within a given distance are considered, and for which various indicators, including collision probability and other severity indicators, can be automatically computed. Identifying traffic conflicts and measuring other traffic parameters can be achieved through mining these databases.

2.6 Before-and-after using TCT

The body of research on the use of traffic conflict indicators for before-and-after studies is limited. Tarrall and Dixon (2007) conducted a BA study in Atlanta to evaluate the safety effect of changes in left-turn signal phasing using traffic conflicts. Traffic conflict observation was done manually using trained observers. The authors calculated conflict rates for six conflict types appropriate to left-turning maneuvers and identified a statistically significant reduction in conflicts after eliminating the permissive phase of protected-permissive left turns at four urban intersections.

Garder (2006) studied the reduction in red-light running violations from before to after the installation of a red-light camera. Warning or infraction tickets were mailed to violators caught by the red-light camera. On-site manual observation was undertaken in both the before and after period. A decrease of approximately 28% was observed.

The traffic conflicts technique in a pre- post-treatment environment has been applied in studies of the interaction of vehicles and pedestrians at crosswalks. Malkamah et al. (2005) used computer measurement, as opposed to manual observers, of driver and pedestrian behavior at Pelican crossings in the U.K. The authors concluded that deceleration rates had a good relationship to time-to-collision values, and could be used to determine the severity of conflicts accurately.

In Valencia, Spain, the TCT was applied in a BA context to evaluate the effectiveness of new traffic-calming devices (Cafiso et al., 2010). Pedestrian and vehicle positions were extracted from

video footage of two pedestrian crossings at a four-leg intersection. Risk or severity was measured using a Pedestrian Risk Index (PRI) developed by the authors that compares the time-to-collision with the time required for the conflicting vehicle to stop safely.

Hua et al. (2008) performed BA analysis as part of a project to determine the results of the San Francisco PedSafe program, a comprehensive pedestrian safety planning and engineering project. Countermeasures at thirteen locations were investigated through manual observation and notation of video data from before and after the implementation. The selected measures of effectiveness included both conflicts, observations of driver behavior such as yielding to pedestrians, and observations of pedestrian behavior such as becoming trapped. The definition of conflicts was subjective as "an occurrence in which either the pedestrian or driver of the vehicle seems uncomfortable".

Brown (1994) used traffic conflict observation by manual observers to evaluate traffic engineering improvements at six intersections.

The feasibility of conducting a BA study using automated computer vision analysis of video data was demonstrated by Ismail et al. (2009). Video sequences for a period of two hours before and two hours after implementation of a pedestrian scramble phase in Chinatown, Oakland, California were analyzed automatically. The results of the automated analysis showed a declining pattern of conflict frequency, a reduction in the spatial density of conflicts, and a shift in spatial distribution of conflicts further from crosswalks post-treatment.

2.7 Smart Channels

Smart Channels are a type of channelized right-turn lanes where the angle of attack relative to the cross street traffic is larger than traditional sweeping right-turn channels. The design allows merging drivers a better view of the traffic stream they are to merge with, and requires them to divert their attention less from the leading vehicles.

The new design conforms to the Transportation Association of Canada's (TAC) guidelines that state drivers should not have to look more than 120 degrees back to check approaching traffic (Shaheen, 2004). Tradition channelized right-turn lanes can require head turns of as much as 150 degrees. The US Federal Highways Administration (FHWA) recognizes that older drivers have difficulty "turning [their] head at skewed (non-90-degree) angles to view intersecting traffic" and " at the end of an auxiliary (right)-turn lane in seeing potential conflicts well and quickly enough to smoothly merge with adjacent-lane traffic" (Staplin et al., 2001). An angle of approximately 70 degrees to the cross street has been recommended to balance increased driver visibility with the decreased mobility resulting from a tighter radius right-turn lane (The City of Ottawa, 2009).

Fitzpatrick & Schneider IV (2004) states that traditional channelized right-turn lanes encourage higher motorist speeds and create an uncontrolled crossing, both of which present dangers to pedestrians. Further, in such lanes, driver attention is split between looking back to merging traffic and looking forward to pedestrian crossing points in front (Zegeer et al., 2001).

The Smart Channel design has been adopted by the City of Ottawa in an effort to improve road safety (The City of Ottawa, 2009). While often referred to as "Urban Smart Channels", this thesis will use the term "Smart Channels" as their benefits extend to sub-urban and rural environments as well (Autey et al., 2010).

Traditional channelized right-turn lanes are widely implemented with the goal of increased safety and mobility for vehicles. In the United States, 95 percent of State Departments of Transportation and 90 percent of local agencies reported using the channelized right turn lanes (Al-Kaisy, 2010). It is generally recognized that the provision of these lanes provides safety benefits. Harwood et al. (2002) for example, found that the implementation of right-turn lanes was successful in reducing the number of collisions at both signalized and unsignalized intersections in both rural and urban environments. The reduction in total collisions ranged from 4 to 27 percent.

3 Before-and-after Safety Study in Penticton, BC

This chapter presents the methodology and results of a study into the traffic safety effects of a right-turn lane modification treatment, undertaken in 2010 in Penticton, BC. Three channelized right-turn lanes were converted to Smart Channels. To accomplish the study, the automated video traffic conflict analysis method pioneered in the Transportation Engineering Group at UBC is applied in a before-after context.

3.1 Background

The objective of this study is to conduct a time-series (before to after) evaluation of the safety performance of the Channel Parkway (Highway 97) intersections with Duncan Avenue, Warren Avenue and Green Avenue in the City of Penticton, British Columbia. A right-turn improvement was implemented at the three intersections in the summer of 2010. The realignment treatment decreased the angle of the sweeping, channelized right-turn lane in order to achieve an angle of approximately 70 degrees between the termination of the right-turn lane and Channel Parkway. This right-turn channel design has been termed a "Smart Channel" in previous and current practice.

Traditionally, road safety analysis has been undertaken using historical collision records. However, the reliance on collision data for safety analysis has several shortcomings (Chin & Quek, 1997). There are well-documented quality and quantity problems associated with collision data. As well, the use of collision data is a reactive approach; a significant number of collisions need to occur before an action can be taken. The use of traffic conflict observation has been advocated as a complementary approach to analyze traffic safety from a broader perspective than collision statistics alone. A traffic conflict is defined as "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 remained unchanged" (Amundsen & Hyden, 1977). Many severity indicators have been

developed to measure traffic conflicts, such as the time-to-collision (TTC). TTC is defined as the extrapolated time for the collision to occur for two road users on a collision course.

In practice, the traffic conflict techniques (TCT) involve a team of trained observers observing, recording, and evaluating the frequency and severity of traffic conflicts at a location. This allows for safety analysts to immediately observe and evaluate unsafe driving maneuvers at road locations, and to investigate the relationship between such maneuvers and the road characteristics. Traffic conflicts are more frequent than road collisions and are of marginal social cost. Therefore, before-after safety studies based on traffic conflicts can be conducted over shorter periods. However, the use of human observers to judge and quantify the risk associated with a traffic event introduces consistency problems into the analysis. Therefore, successful automation of extracting conflicts from video data can have considerable benefits for traffic safety studies.

In this study, video recordings are used as the primary source of conflicts data. The use of video data offers new opportunities for analysis because it is rich in details, recording devices are becoming less expensive, and video cameras are often already installed for monitoring purposes. In addition, video data represents a permanent record of the analyzed traffic events that can be reviewed and validated, as opposed to in-field observer-based surveys.

Continual development of an automated traffic safety tool has been undertaken in the Transportation Group at UBC since 2005, and this computer application has been employed for analysis in this study. The UBC approach involves the building of a trajectory database where the results of the video processing module are stored. This database is subsequently analyzed and traffic conflict indicators are calculated for road users sharing spatial and temporal proximity.

Before-after (BA) studies are improved with the addition of a comparison group. The use of a comparison group is employed to account for safety effects that are not a result of the treatment. These include time-trend effects such as changing seasons, weather conditions, or a shift in the demographics

and driving behaviors of road users. For this study, a comparison site at the intersection of West Bench Hill Road and Eckhardt Avenue was studied in addition to the treatment sites to account for changes in accident causal factors beyond the treatments. The effects observed at the treatment sites may then be compared to those at the control. It is assumed that had the treatment sites been left unimproved, the observed change in conflicts would be proportional to that observed at the control site.

3.1.1 ICBC Road Improvement Program

The geometric realignment of the three treated intersections was carried out as a part of the Insurance Corporation or British Columbia's (ICBC) Road Improvement Program initiative. ICBC partners with governmental entities, including city governments and the Ministry of Transportation, to identify and improve traffic facilities with lower-than-desired safety records. While the reduction in injuries and fatalities is a socially desirable end in itself, ICBC hopes to reduce claim payouts as well as premiums charged to BC drivers. To date, the program has proved successful; an independent evaluation of the program in 2009 concluded that for every dollar invested, ICBC and its customers see a return 5 to 12 times the investment.

3.1.2 Study Location

The study was carried out in Penticton, BC. With a 2006 population of only 31,000, the City of Penticton is a relatively small city located in the Okanagan Valley of the Southern Interior of BC, with most of the city located on 5 km of land between Skaha and Okanagan Lakes. Traditionally a resource-based economy, manufacturing and high-tech industries now play a role in the economy. There is a significant year-round retired population as well as a large tourism industry, mostly in the summer months as Penticton hosts a range of leisure and recreation activities.

The studied intersections are all located along a section of Highway 97 within the City of Penticton (Figure 3.1). Travelling north and south through the city, Highway 97 serves as part of the urban network as a commuter, shopping, and recreational route. The highway adopts different street

names: from south to north the highway is named Channel Parkway, Railway Street, and Eckhardt Avenue West. Highway 97 is also known in this region of the province as Okanagan Highway.

Average annual daily traffic (AADT) volumes on Highway 97 in 2007, measured at the north end of Penticton were 11,000 vehicles northbound and 11,000 vehicles southbound (British Columbia MOT Traffic Data Program, 2011). Summer annual daily traffic (SADT) volumes were approximately 8% higher than the AADT, owing to increased tourism in the summer months.

The intersections of Duncan Avenue, Warren Avenue, and Green Avenue with Channel Parkway were identified as candidates where geometric realignment treatments provided excellent cost-benefit potential. Many of the collisions occurring at these intersection sites occurred on the right-turn lanes of the minor approaches (Duncan, Warren or Green Avenues), and on these lanes' merging area with Channel Parkway. The collisions consisted of rear-end and merging collisions. The posted speed limit on the minor cross-streets (Duncan, Warren and Green) is 50 km/h, while the speed on Channel Parkway is 70km/h when intersecting with Green and Warren. The speed limit on Channel Parkway drops from 70km/h to 50km/h immediately following its intersection with Duncan Ave.

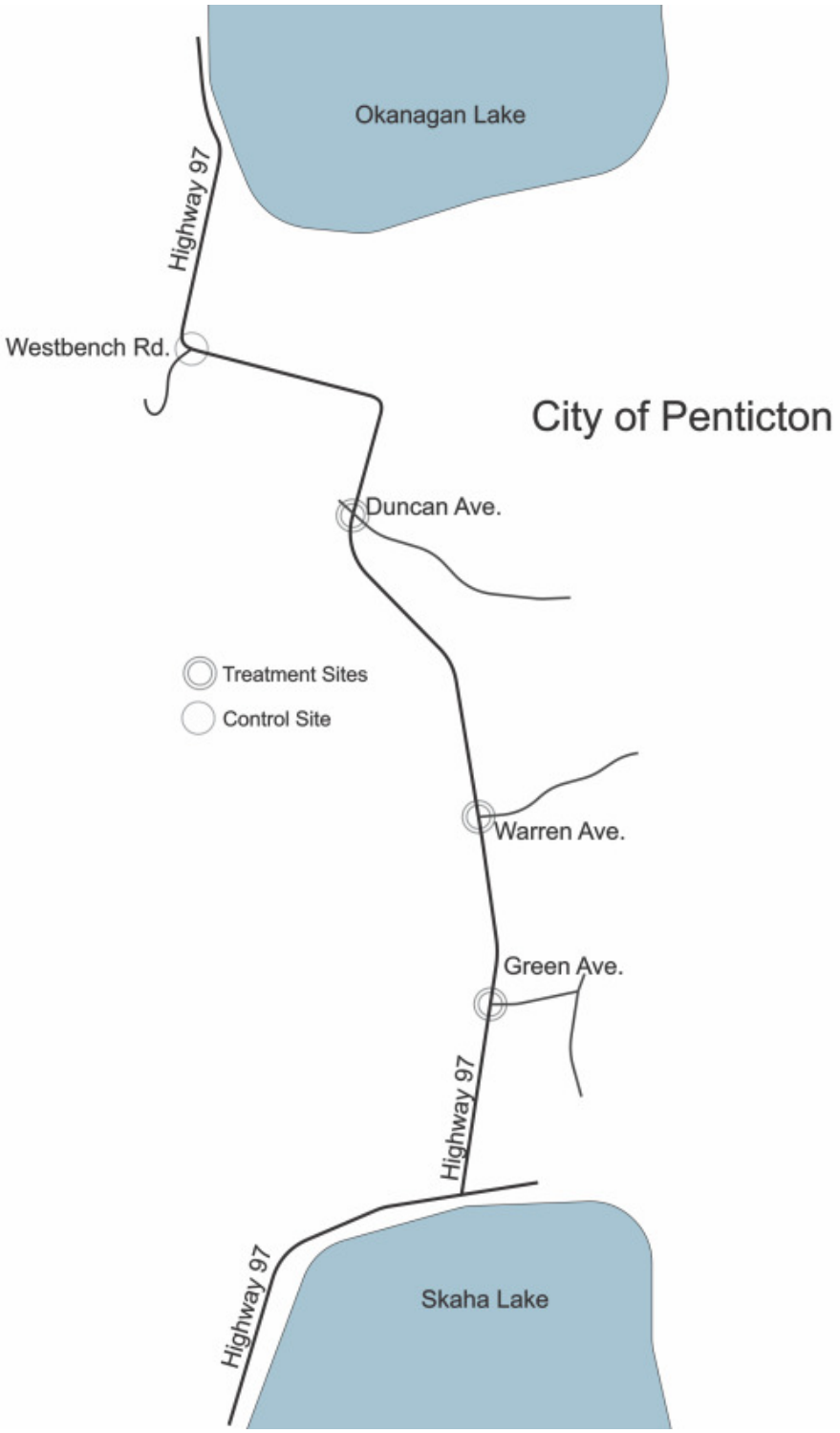

Figure 3.1 Treatment and control site in Penticton, BC

3.1.3 Geometric Realignment Treatment

At all three treated intersections, the pre-treatment configuration consisted of a channelized right-hand turning lane that merged onto Highway 97. No dedicated merging lane was provided on the highway; vehicles were required to merge at the end of the channelized right, immediately downstream of the intersection. Turning vehicles were instructed to yield to highway traffic by installed "yield" signage.

The realignment treatment illustrated in Figure 3.2 and Figure 3.3, and shown in Figure 3.4, decreased the angle of the channelized right in order to achieve an angle of approximately 70 degrees between the termination of the right-turn lane and Highway 97; the yield signage remained for the right-turn lane. The angle of 70 degrees has been advocated as a compromise between increased visibility and decreased mobility resulting from a tighter turn radius (The City of Ottawa, 2009).

The implementation of these modified right-turn channels is often advocated to allow for safer pedestrian crossing. However, the benefits also extend to vehicle-vehicle interactions since the new approach angle affords drivers a better view of the traffic stream they are to merge with.

The Transportation Association of Canada (TAC) recognizes the safety risks associated with drivers having to divert their attention from their direction of travel and states in TAC guidelines that drivers should not have to look more than 120 degrees back to check approaching traffic (Shaheen, 2004). Traditional channelized right-turn lanes can require head turns of as much as 150 degrees. The US Federal Highways Administration (FHWA) acknowledges that older drivers have difficulty "turning [their] head at skewed (non-90-degree) angles to view intersecting traffic" and " at the end of an auxiliary (right)-turn lane in seeing potential conflicts well and quickly enough to smoothly merge with adjacent-lane traffic" (Staplin et al., 2001). Given the large retired community in Penticton, this concern is heightened.

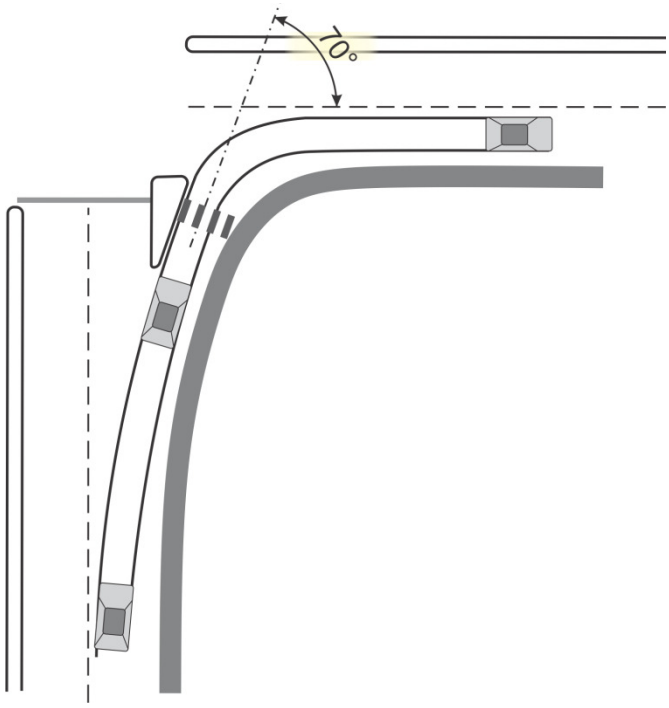

Figure 3.2 Geometric realignment treatment of channelized right-turns

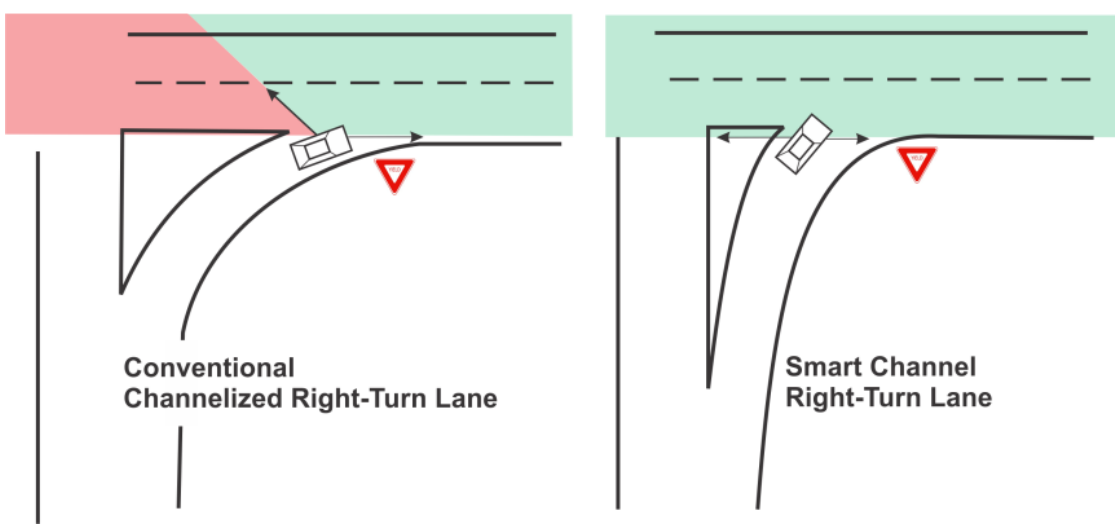

Figure 3.3 Smart Channel improved right-turn viewing angle

Figure 3.4 Geometric realignment at Duncan, Warren and Green Avenues

Other municipalities have adopted this design in an effort to improve road safety, including the City of Ottawa, ON (The City of Ottawa, 2009). While often referred to as "Urban Smart Channels", we have elected to term them simply "Smart Channels" as their benefits extend to sub-urban and rural environments as well. The Green Avenue and Warren Avenue study locations are not urban intersections, but they showed considerable safety improvements from the treatments.

3.2 Field Survey

3.2.1 Data Collection

The data collection effort for the "before" period was undertaken with a set of standard definition video cameras over the course of four days, March 29th to April 1st 2010. Each of the three treatment sites was recorded for two days by two cameras (Table 3.1 and Table 3.2). One of the two cameras was positioned so as to record the merging behavior between right-turning vehicles off of the cross avenues (Duncan, Warren and Green Avenues) and the through traffic on Channel Parkway. The second camera recorded the queue, when existing, of right-turning vehicles in order to determine the potential for rear-end conflict situations. The cameras were attached to streetlamp and power poles with assistance from City of Penticton personnel (Figure 3.5).

Figure 3.5 Mounting cameras on location

A single camera was positioned to capture both merging and queuing behavior at Westbench Hill Road and Eckhardt Avenue; a nearby hill provided a superior vantage point to the street poles so the two-camera approach was not required. The same set-up for both treatment and comparison intersections was used for the "after" collection period.

Table 3.1 'Before' video data gathering hours

		Day 1			Day 2		
Location	**Camera**	**Date (2010)**	**Start Time**	**End Time**	**Date (2010)**	**Start Time**	**End Time**
Duncan	1	Mar 29	8:35AM	6:00PM	Mar 30	10:55AM	6:00PM
	2	Mar 29	8:35AM	6:00PM	Mar 30	10:55AM	6:00PM
Warren	1	Mar 29	9:26AM	6:00PM	Mar 30	9:05AM	6:00PM
	2	Mar 29	9:26AM	6:00PM	Mar 30	9:05AM	6:00PM
Green	1	Mar 29	11:49AM	6:00PM	Mar 30	1:00PM	6:00PM
	2	Mar 29	11:49AM	6:00PM	Mar 30	1:00PM	6:00PM
W.Bench	1	Mar 31	10:00AM	6:00PM	April 01	9:00AM	2:30PM

Table 3.2 'After' video data gathering hours

		Day 1			Day 2		
Location	**Camera**	**Date (2010)**	**Start Time**	**End Time**	**Date (2010)**	**Start Time**	**End Time**
Duncan	1	Sept 27	9:15AM	6:00PM	Sept 29	9:06AM	6:00PM
	2	Sept 27	9:15AM	6:00PM	Sept 29	9:06AM	6:00PM
Warren	1	Sept 27	11:04AM	6:00PM	Sept 28	8:33AM	6:00PM
	2	Sept 27	11:04AM	6:00PM	Sept 28	8:33AM	4:13PM
Green	1	Sept 27	10:19AM	6:00PM	Sept 28	9:44AM	6:00PM
	2	Sept 27	10:19AM	6:00PM	Sept 28	9:44AM	6:00PM
W.Bench	1	Sept 28	12:00AM	4:00PM	Sept 29	10:20AM	4:30PM

3.2.2 Duncan Avenue & Channel Parkway

Duncan Avenue crosses Channel Parkway at a four-way signalized intersection (Figure 3.6). On the west side of Channel Parkway, Duncan Avenue continues for approximately 100 m before terminating at a parking lot. The study location is the right-turn lane for vehicles travelling west on Duncan Avenue, turning north onto Channel Parkway.

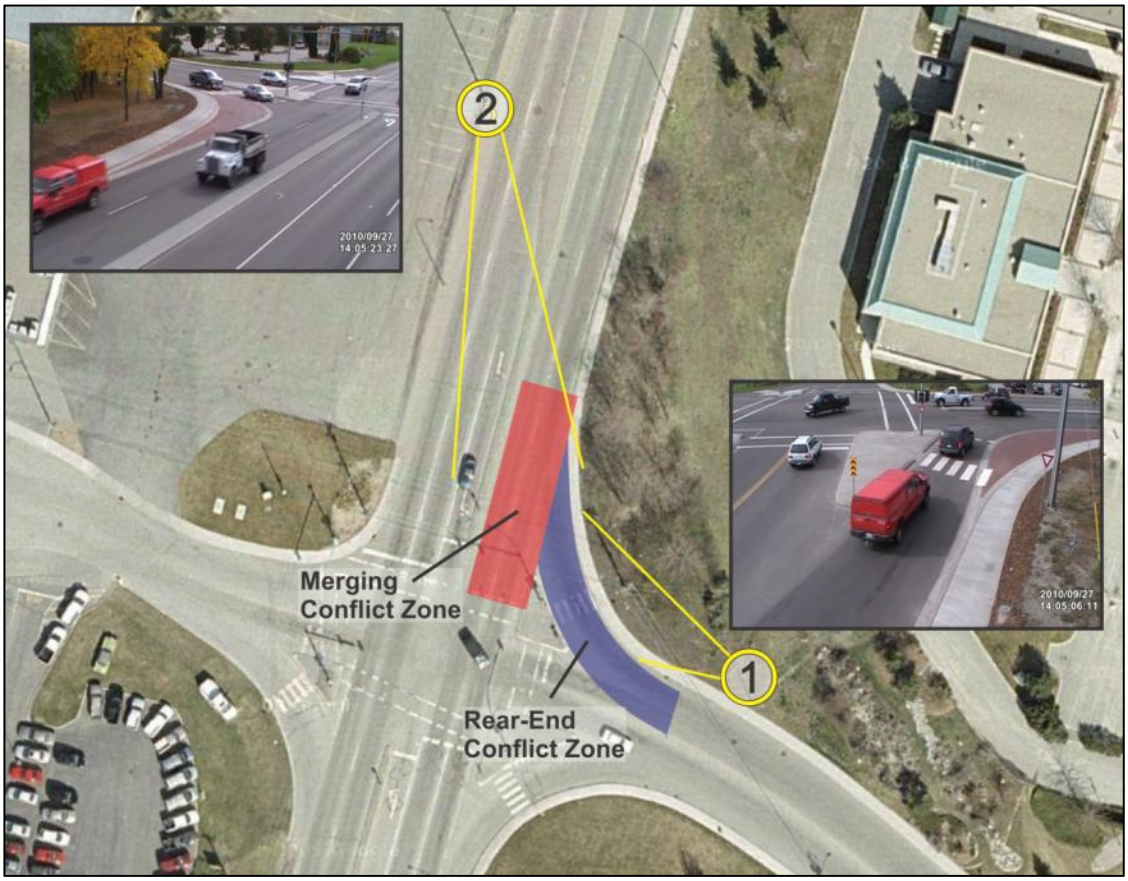

Figure 3.6 Study area at Duncan Avenue and Channel Parkway

3.2.3 Warren Avenue & Channel Parkway

Warren Avenue terminates at Channel Parkway in a "T" intersection; vehicles turning from Warren Avenue must yield at all times to vehicles on Channel Parkway (Figure 3.7).

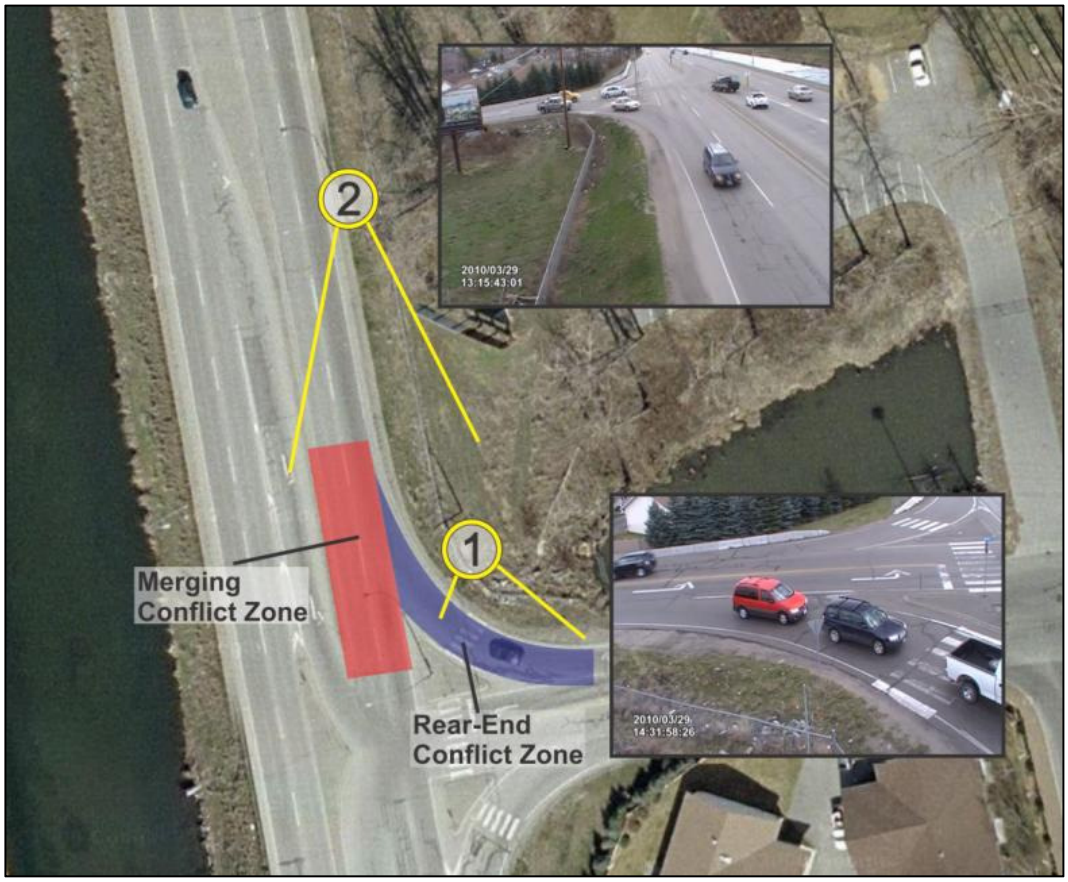

Figure 3.7 Study area at Warren Avenue and Channel Parkway

3.2.4 Green Avenue & Channel Parkway

Green Avenue terminates at Channel Parkway in a "T" intersection; vehicles turning from Green Avenue must yield at all times to vehicles on Channel Parkway (Figure 3.8).

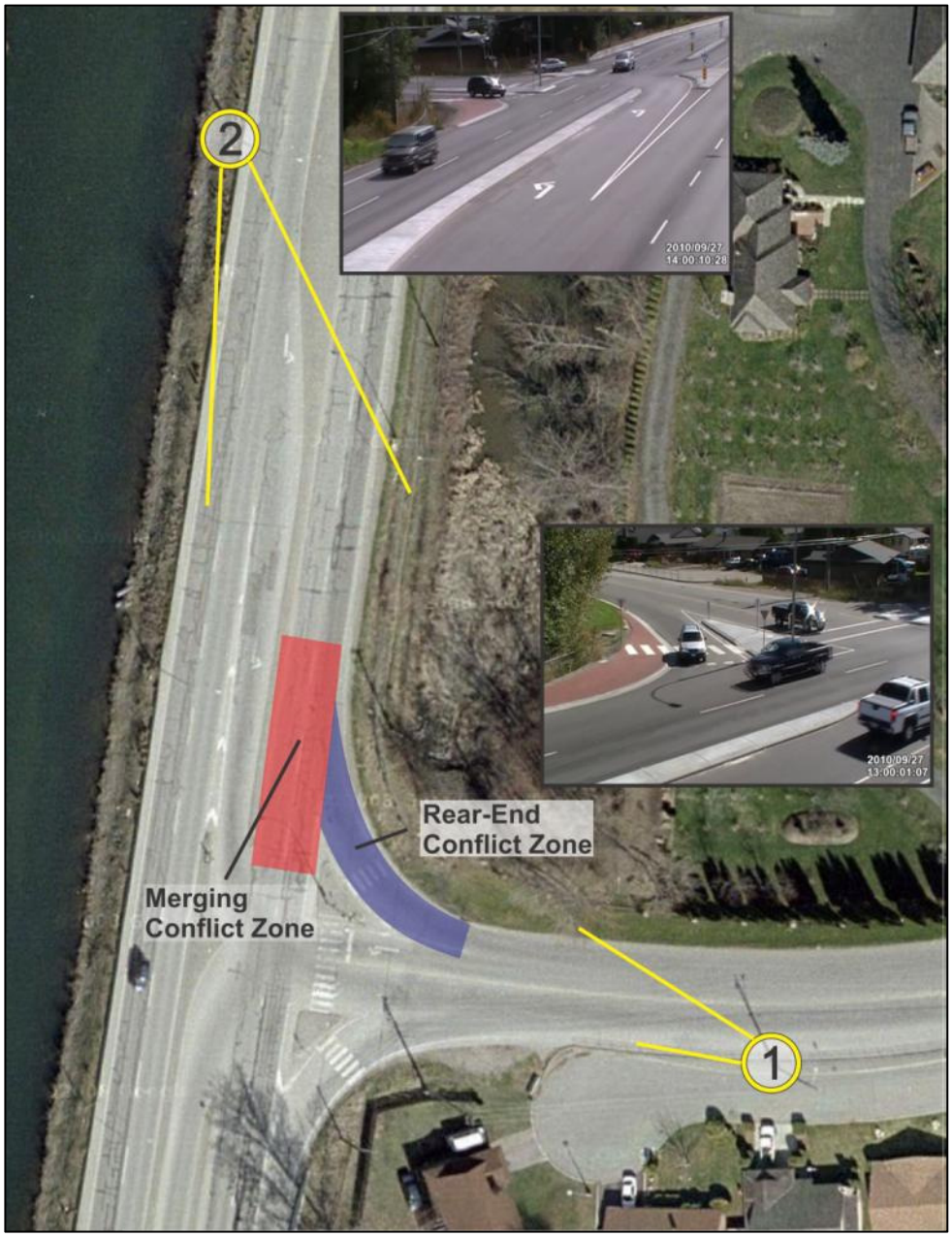

Figure 3.8 Study area at Green Avenue and Channel Parkway

3.2.5 West Bench Hill Road & Eckhardt Avenue

West Bench Hill Road terminates at Okanagan Highway, also called Eckhardt Avenue at this section, in a "T" intersection (Figure 3.9). Vehicles turning from West Bench Hill Road must yield at all times to vehicles on the highway. A channelized right-turn lane with a similar angle to that at the treatment sites pre-treatment exists for right-turning vehicles off West Bench Hill Road. The intersection remained unchanged between the "before" and "after" study periods.

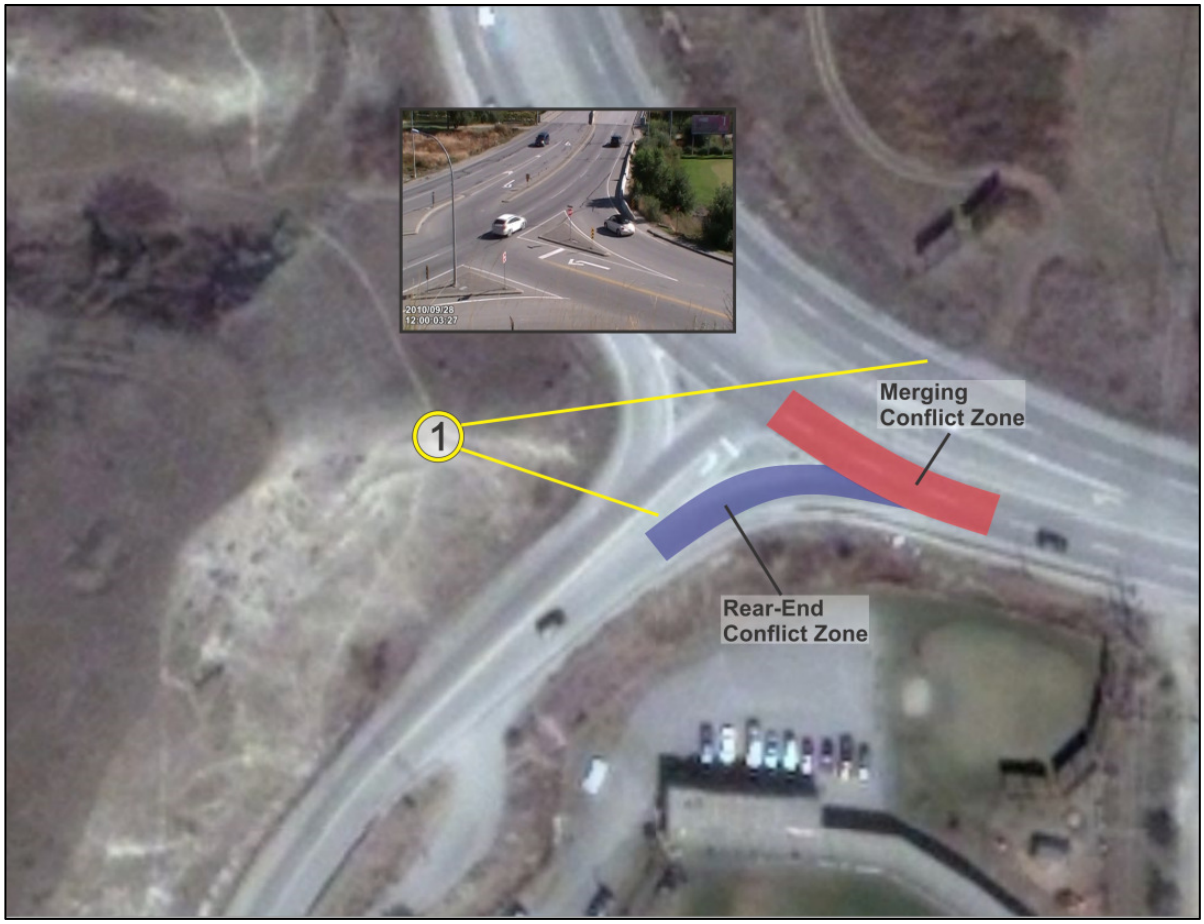

Figure 3.9 Study area at West Bench Hill Road and Eckhardt Avenue (control site)

3.3 Video Analysis

3.3.1 Overview

An outline of the video analysis procedure is shown in Figure 3.10, and briefly described in the following sections. A more detailed description of the automated video analysis procedure designed and employed in the Transportation Group at UBC is provided in the Literature Review section of this thesis.

3.3.2 Calibration of Camera Angles

The video data gathered in the field is a two-dimensional representation of traffic movements in the three-dimensional real world. In order to recover the coordinates of the objects in the real world, a transformation matrix needs to be calculated. The manual annotation of position and distance features in the camera image and real-world orthographic image allows for the determination of this transformation matrix (termed the "homography matrix" in computer vision)(Ismail et al., 2010). An optimization method is used to determine the homography matrix that best transforms, or maps the points and distances annotated in the camera image into the real-world image. This procedure is referred to as the "camera calibration" process and must be undertaken for each camera view.

The camera calibration process was carried out for each camera view in the collection of "before" and "after" data. The accuracy of the estimated homography matrix is judged by the magnitude of the error returned by the optimization algorithm. The final estimates were very good and no further error in conflict analysis was attributed to inaccurately estimated camera parameters. A visual validation of the calibration accuracy is possible through the use of a displayed grid in both the real-world image and the camera image as illustrated in Figure 3.11.

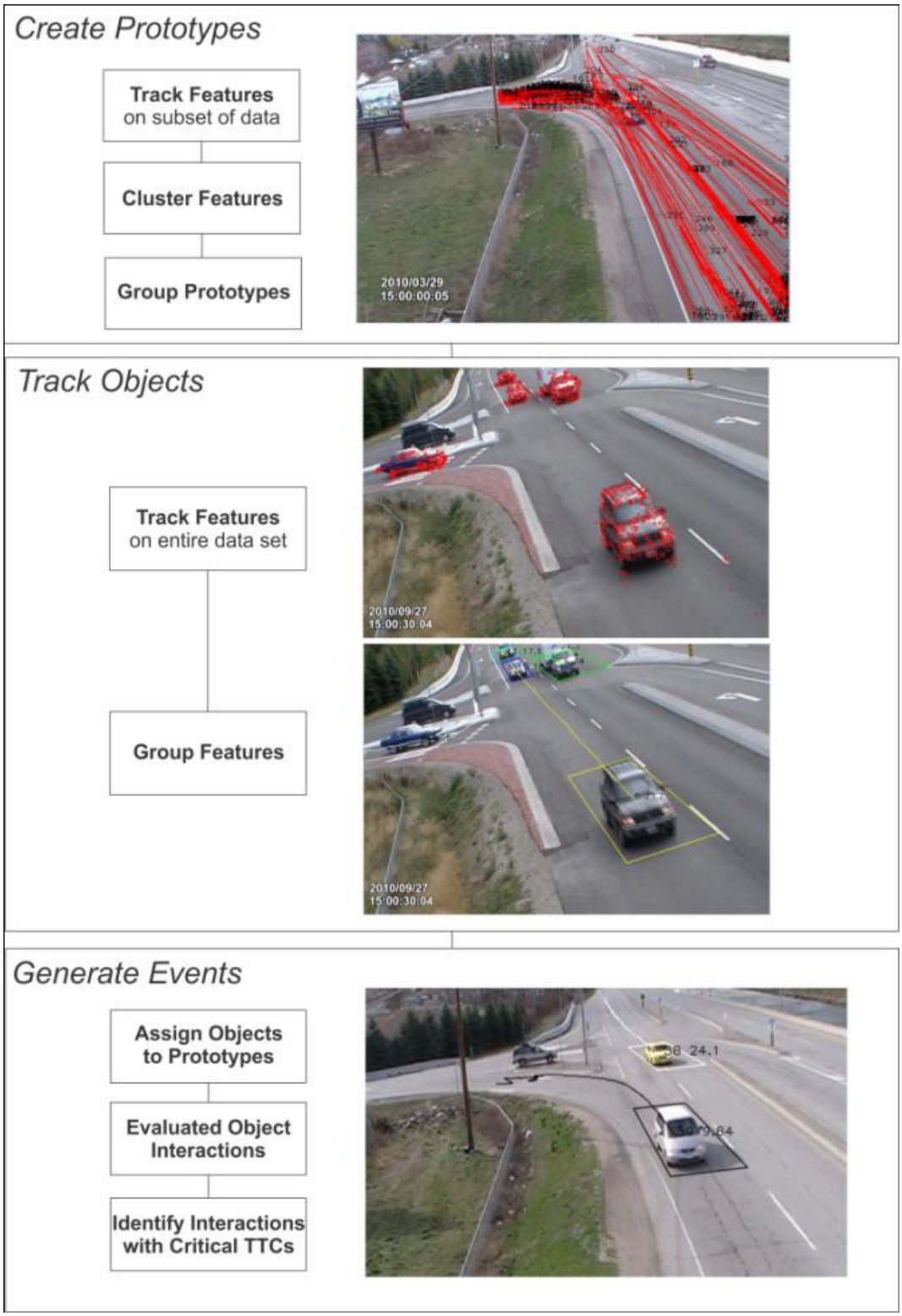

Figure 3.10 Video data analysis process

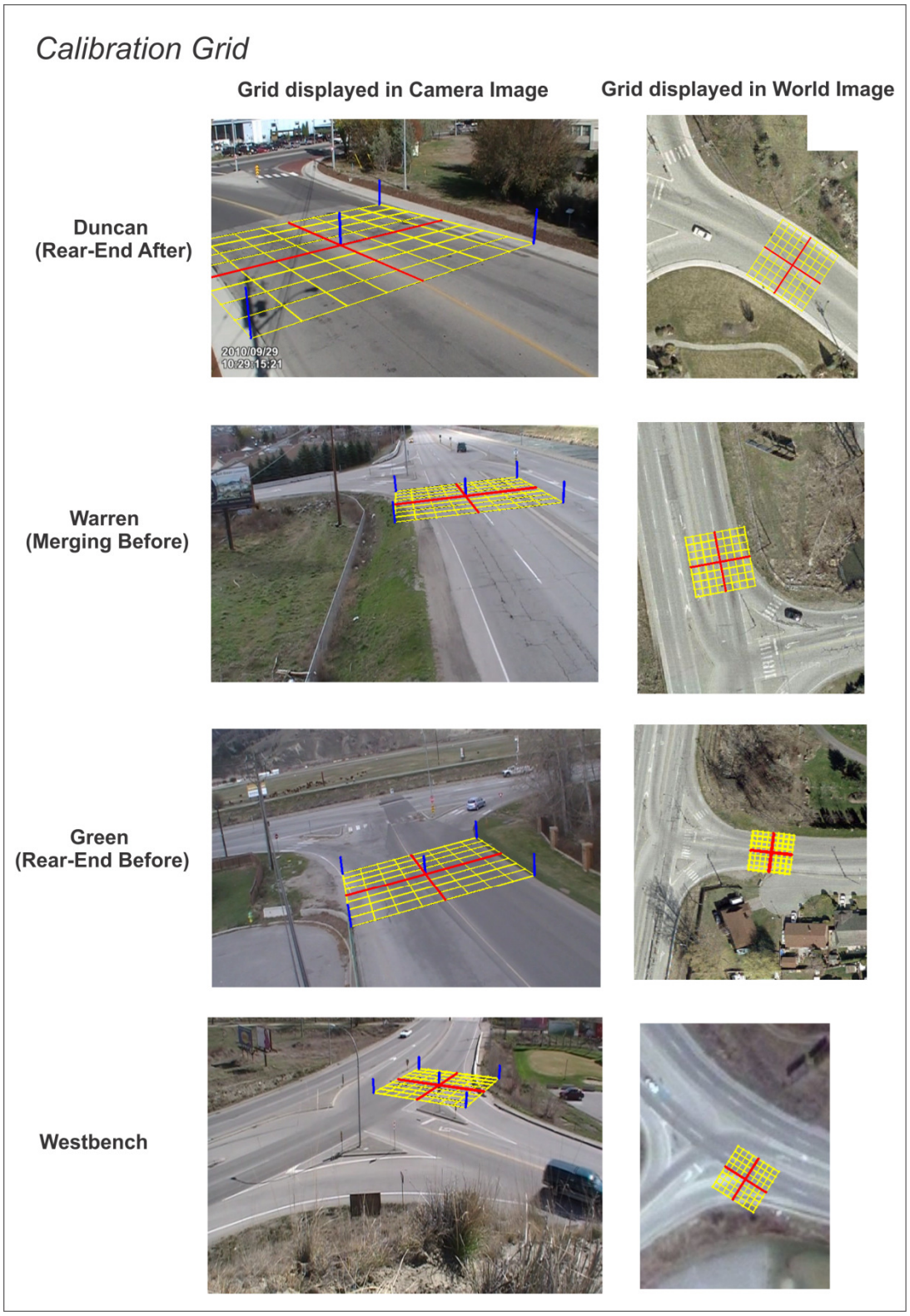

Figure 3.11 2D grid displayed in real-world and camera images

3.3.3 Feature Tracking

After the raw video data is encoded to a pre-defined format, feature tracking is conducted. Features, distinct visual elements in the video frame, are identified and tracked using an implementation of the well-known Kanade-Lucas-Tomasi Feature Tracker algorithm.

3.3.4 Prototype Generation

In the UBC automated video analysis application, the term "prototype", or more accurately "movement prototype," refers to a trajectory that is representative of a common motion pattern observed in the traffic video. For the purpose of hypothesizing the future positions of vehicles in the calculation of conflict indicators, a vehicle will be assigned probabilistically to one or more of these patterns based on how closely the vehicle's trajectory matches the prototype to the current instant. These motion patterns are learned by applying the longest-common-subsequence (LCSS) clustering algorithm on features generated from a subsection of the video. By using the clustering algorithm, patterns that occur most frequently are grouped into one or several prototypes, and motion patterns that occur less frequently fail to be grouped and are discarded.

3.3.5 Feature Grouping (Object Generation)

After feature tracking is carried out on the entire data set, the next step is feature grouping. Points that move at similar speed and satisfy other spatial and motion constraints are grouped to create coherent objects. The features are grouped according to their proximity and the similarity of their motion vectors. The newly grouped set of features, which is taken to represent a road-user, is assigned the position in the real world of the centroid of all grouped features.

3.3.6 Event Generation

Since this study is of vehicle-vehicle interactions, all grouped objects are taken as vehicles. The selection of prototype movements to include only movements taken by vehicles (and not, say, the

movement of pedestrians in a crosswalk) ensures that events are not generated for conflicts involving pedestrians. While this is an important area of study, it is not the focus of this research.

The event generation procedure analyses the trajectory database of the video frame by frame. The future position of all existing vehicles is projected into the future using a probabilistic assignment to the set of prototypes. These hypothetical future positions of vehicles are analyzed to calculate the presence and value of all conflict indicators. The presence of a conflict indicator within a set threshold is recorded as an event and added to the interactions database. The time-to-collision (TTC) conflict indicator is commonly implemented as a measure of the severity of a conflict. The TTC is defined as the time until a collision will occur if the two conflicting vehicles continue on the same path at their current speed (Figure 3.12). The minimum TTC (TTCmin) can be extracted to represent the conflict severity.

Validation of the extracted conflicts was undertaken on a subset of the events selected from the interactions database. The scope of the validation was limited to a comparison between an event's minimum TTC and a corresponding manually calculated TTC. The results demonstrated the accuracy of the automated TTC index estimation.

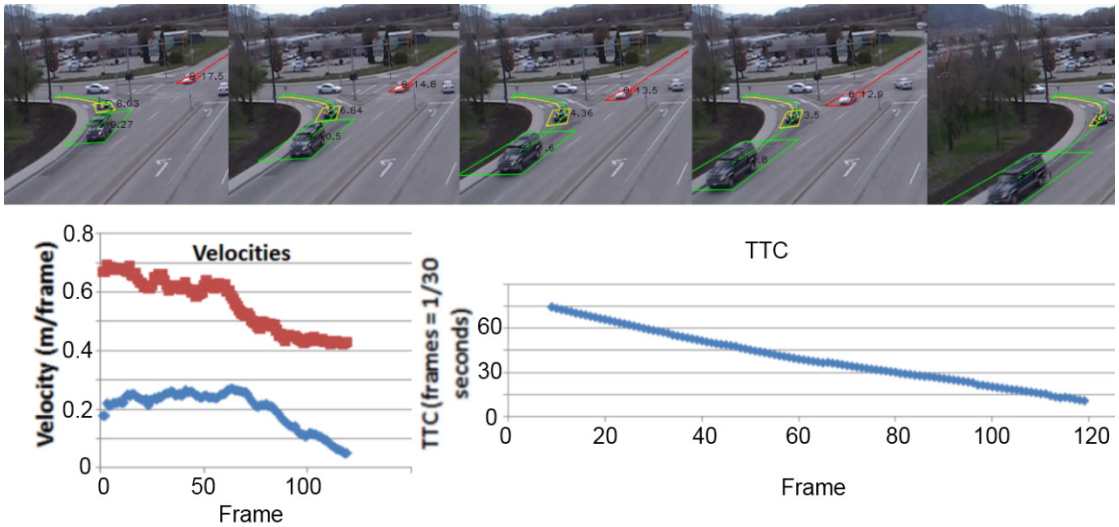

Figure 3.12 Time-to-collision for merging event

3.4 Summary of Findings

The distributions of the calculated conflict indicator (TTC) and the severity rate both before and after the treatment are shown in the following sections. In general, there is a considerable reduction in the frequency and severity of traffic conflicts which suggests a positive change in safety for rear-end, merging, and total conflicts.

3.4.1 Reduction in Conflict Frequency

The average frequencies (conflicts per hour) of rear-end, merging, and total conflicts, or average hourly conflicts (AHC), are compared below from before to after the treatments. Subsequently, the addition of the control site in the comparisons allows for non-treatment conflict causal factors to be accounted for.

3.4.1.1 Comparison not including Control Site

Figures 3.13, 3.14, and 3.15 show the frequency distributions of conflicts at the treated intersections both before and after the treatments. Rear-end, merging, and total conflicts are displayed separately; total conflicts is the sum of rear-end and merging conflicts. Subfigures a), b), and c) plot the average hourly conflicts (AHC) over a range of TTC values from zero to three seconds.

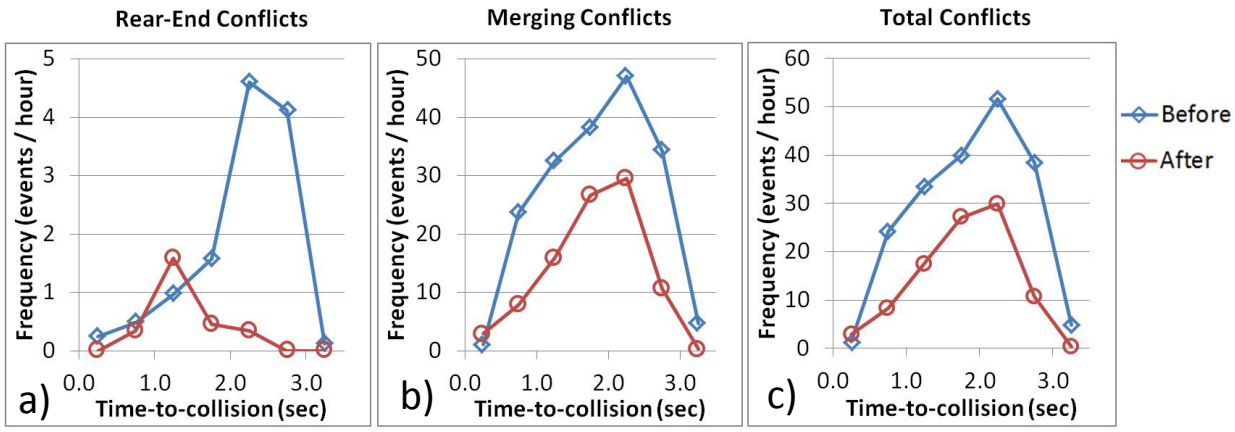

Figure 3.13 Results of the before-and-after study at Duncan Avenue and Channel Parkway. Subfigures a), b), and c) show the before and after rear-end, merging, and total (rear-end and merging combined) conflicts per hour for a range of TTC values from 0 to 3 seconds.

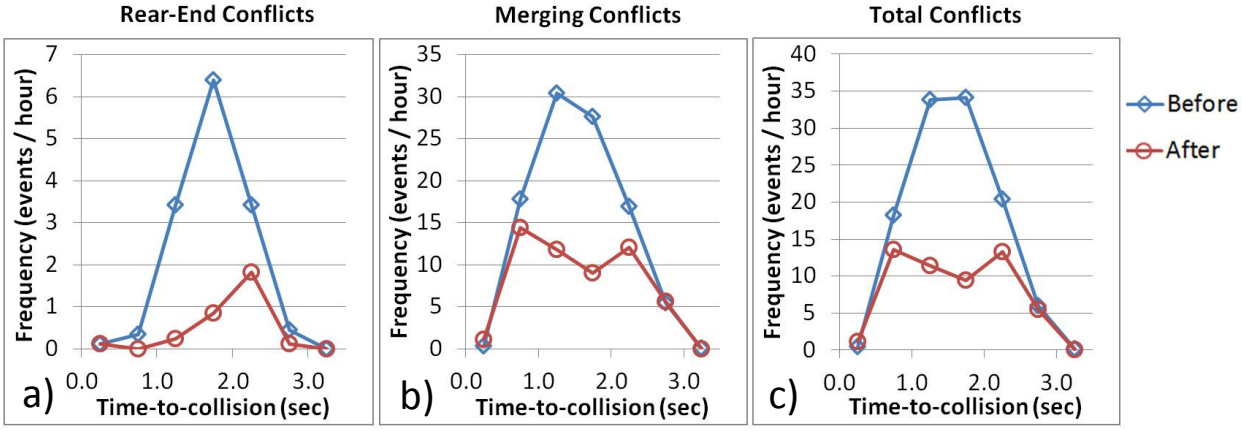

Figure 3.14 Results of the before-and-after study at Warren Avenue and Channel Parkway. Subfigures a), b), and c) show the before and after rear-end, merging, and total (rear-end and merging combined) conflicts per hour for a range of TTC values from 0 to 3 seconds.

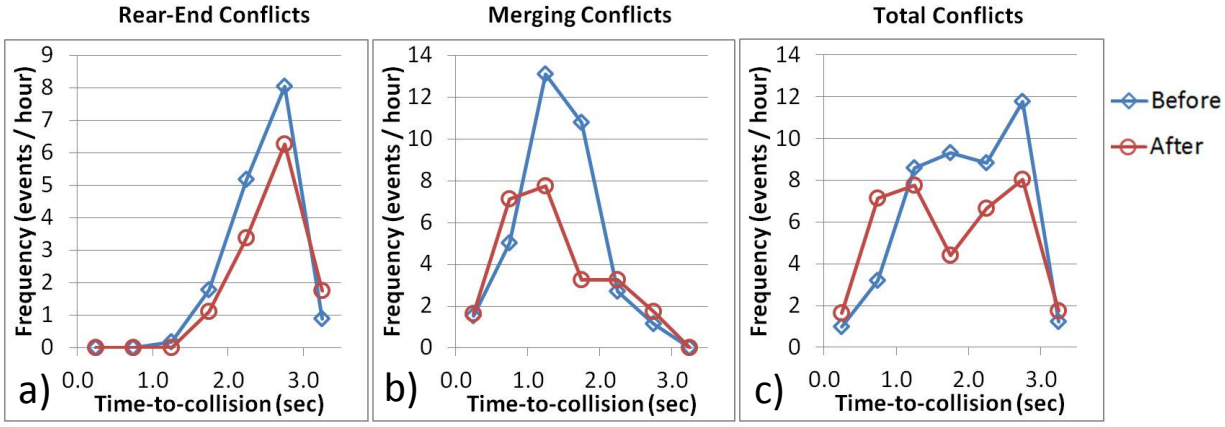

Figure 3.15 Results of the before-and-after study at Green Avenue and Channel Parkway. Subfigures a), b), and c) show the before and after rear-end, merging, and total (rear-end and merging combined) conflicts per hour for a range of TTC values from 0 to 3 seconds.

The figures show that for all intersections and all conflict types, there has been a considerable reduction in conflict frequency. The reductions of the average hourly conflicts of each event type, considering events with TTC values of less than 3.0 seconds, are summarized in Table 3.3.

Table 3.3 Safety improvement after treatments (in percent reduction of AHC), control site not incorporated

Conflict Type	Intersection		
	Duncan	Warren	Green
Rear-End	78%	78%	22%
Merge	48%	45%	28%
Total	50%	52%	26%

The intersections of Duncan Avenue and Warren Avenue with Channel Parkway show consistent improvements between the two intersections: reductions of approximately 75% in rear-end conflicts, 45% in merging conflicts, and 50% in total conflicts. Reductions in conflicts at the Green Avenue intersection were less dramatic, ranging from 22% to 28%. The results are shown in Figure 3.16.

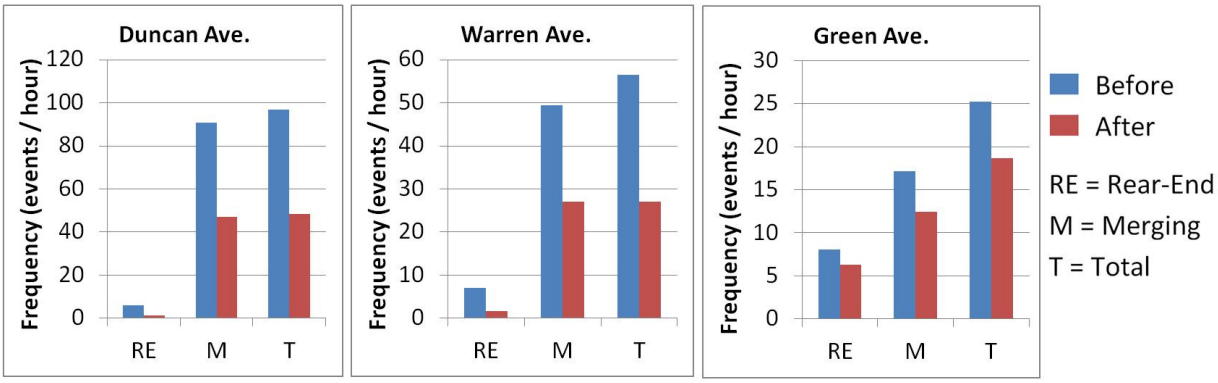

Figure 3.16 Average Hourly Conflicts frequencies before and after treatments

3.4.1.2 Control and Treatment Sites in an Odds Ratio

In this study, the control site is the right-turn lane at the intersection of West Bench Hill Road and Eckhardt Avenue. Figure 3.17 shows the before-and-after AHC distributions at the control site.

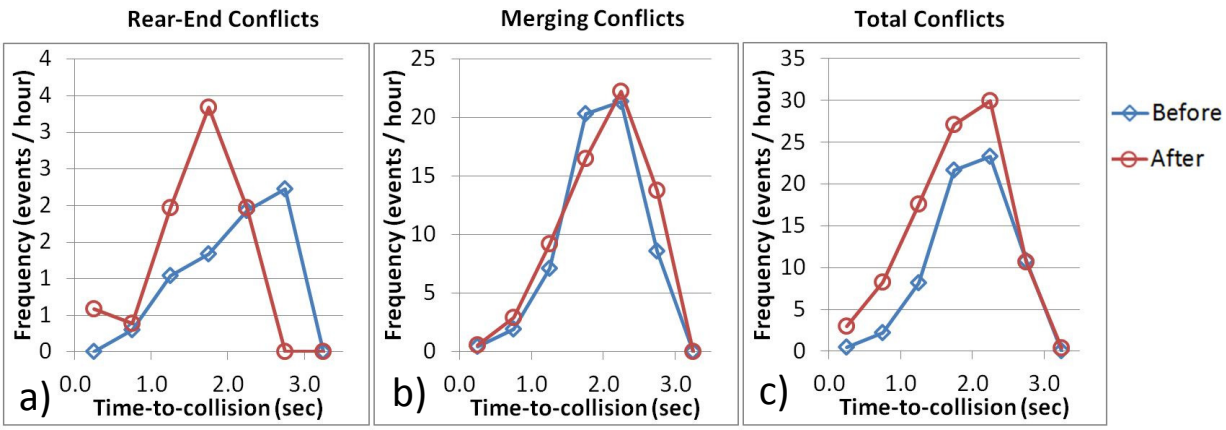

Figure 3.17 Results of the before-and-after study at West Bench Hill Road and Eckhardt Avenue. Subfigures a), b), and c) show the before and after rear-end, merging, and total (rear-end and merging combined) conflicts per hour for a range of TTC values from 0 to 3 seconds.

In a similar manner to the treatment sites, these results can be aggregated into observed changes in the frequencies of conflicts with TTC values or 3 seconds or less (Table 3.4). The average number hourly conflicts was observed to be higher during the "after" study period.

Table 3.4 Change in AHC at control site

Conflict Type	Change
Rear-End	(+)21%
Merge	(+)9%
Total	(+)10%

The “odds ratio” statistical method is commonly used in many fields, such as medical science, for comparing the effect of a treatment to a control or reference group. In before-and-after traffic safety applications, the conditions pre- and post-treatment at the site are compared to the conditions at a set of control or reference sites over a similar time period. The ratio is defined as the change in the control site or group divided by the change in the treatment site.

$$OR_i = \frac{A_i/C_i}{B_i/D_i}$$

where

A = Condition at control site before treatment carried out

C = Condition at control site after treatment carried out

B = Condition at treatment site before treatment carried out

D = Condition at treatment site after treatment carried out

The control sites are viewed as representative of what changes in traffic safety would have been observed at the treatment site had no treatment been carried out. An odds ratio of "1" indicates all changes observed at the treatment site are explained by similar changes at the control sites; i.e., none of the changes are due to the treatment. The change in conflicts, once the control site is accounted for, is referred to as the “treatment effect” (TE). The TE is calculated simply as

$$TE_i = OR_i - 1$$

and represents the change in conflicts observed after implementation of the treatment, controlling for time-trend effects measured at the control site. The percent reduction in conflicts is $100\% * (TE)$. The treatment effect for the treated intersections is summarized in Table 3.5.

Table 3.5 Treatment effect (in percent reduction of AHC) for individual intersections

Conflict Type	Intersection		
	Duncan	Warren	Green
Rear-End	81%	82%	36%
Merge	53%	50%	34%
Total	55%	57%	33%

To estimate the total treatment effect, the individual intersections need to be combined in a weighted average and the statistical significance determined. The odds ratios are always positive as there cannot be a negative number of collisions, which leads to a common assumption that they follow a lognormal distribution. The log of the odds ratio is used for the combining and weighting procedures. The variance is calculated on the assumption that conflicts are rare and random events, and therefore follow a Poisson distribution.

The standard error of the individual intersection's log odds ratio is approximated by

$$SE_i = \sqrt{\frac{1}{A_i} + \frac{1}{B_i} + \frac{1}{C_i} + \frac{1}{D_i}}$$

so that asymptotically:

$$z_i = \frac{ln(OR_i)}{SE_i} \sim N(0,1)$$

The total treatment effect is found through a weighted average of the individual intersection results. Weighting is done according to the inverse variance of each intersection. The weighting factor for intersection "*i*" is calculated as

$$w_i = \left(\frac{1}{A_i} + \frac{1}{B_i} + \frac{1}{C_i} + \frac{1}{D_i}\right)^{-1}$$

The total log odds ratio is therefore defined as

$$ln(OR) = \frac{\sum_{i=1}^{n} w_i \times ln(OR_i)}{\sum_{i=1}^{n} w_i}$$

If the weightings are proportional to the inverse of asymptotic variance, a standard normal distribution can be attained using

$$z = ln(OR)\sqrt{\sum_{i=1}^{n} w_i} \sim N(0,1)$$

The null-hypothesis, or the hypothesis of no treatment effect (H_0=OR=1), is rejected whenever the approximate tail probability of the standard normal probability density function is smaller than the significance level. The significance of the combined odds ratios for rear-end, merging, and total collisions is presented using the p-value (Table 3.6).

Table 3.6 Treatment effect (in percent reduction of AHC), for all intersections aggregated together

Conflict Type	Reduction	p-value
Rear-End	67%	0.0665
Merge	48%	0.0014
Total	51%	0.0002

3.4.2 Reduction in Conflict Severity

To go beyond simply frequency, and assign a severity rating to each conflict requires a means of mapping from TTC to severity. The minimum time-to-collision (TTC) of each event can be mapped to a severity index (Figure 3.18) using a transform proposed in previous research in the Transportation Group at UBC:

$$SI = e^{-\left(\frac{TTC^2}{2PRT^2}\right)}$$

SI is the severity index and PRT is the perception and braking reaction time, which is assumed to be 2.5 seconds. Figure 3.18 shows a depiction of this severity mapping. The severity index is a unit-less measure of severity that ranges from 0 to 1, with 0 being uninterrupted passages.

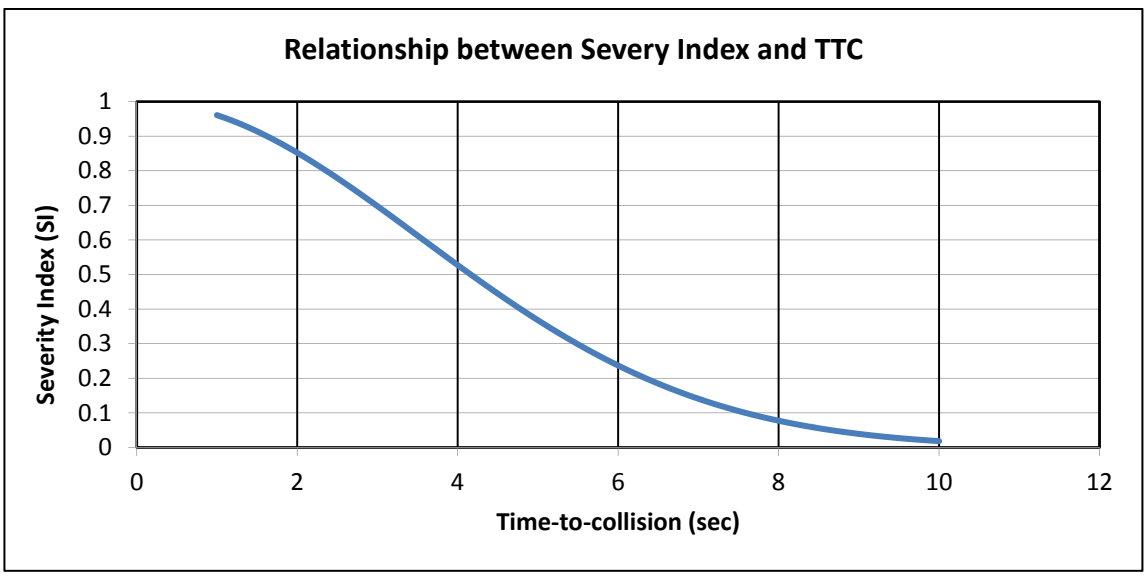

Figure 3.18 Mapping from TTC to a Severity Index SI (source: Ismail et al. 2011)

After the severities of all events are aggregated, normalization is required to account for differences in observation period and exposure from "before" and "after." The exposure measure is the maximum theoretical number of events, which is the square root of the product of the hourly volumes for conflicting traffic streams.

$$SIRate = \frac{SI}{Maximum\ Theoretical\ Exposure\ (millions)}$$

For both merging conflicts and total conflicts, the exposure measure is computed by taking the square root of the product of all through vehicles on Channel Parkway and right-turning vehicles at the treatment sites. The rear-end conflict exposure, similarly, is the square root of the right-turning volume square, which simplifies to the volume of right-turning vehicles.

3.4.2.1 Severity Distributions

Figures 3.19, 3.20, and 3.21 show the severity distributions of conflicts at the treated intersections both before and after the treatments. Rear-end, merging, and total conflicts are displayed separately; total conflicts is the sum of rear-end and merging conflicts. The frequency of conflicts, normalized to exposure, are shown in subfigures a), b), and c) over a range of severity values. While the severity scale ranges from 0 to 1, determining the frequency of events with severities of less than 0.4 requires analyzing events with TTC values of greater than 3 seconds. The camera angles, or fields of view, did not accommodate reliable analysis of events with TTC values greater than 3 seconds.

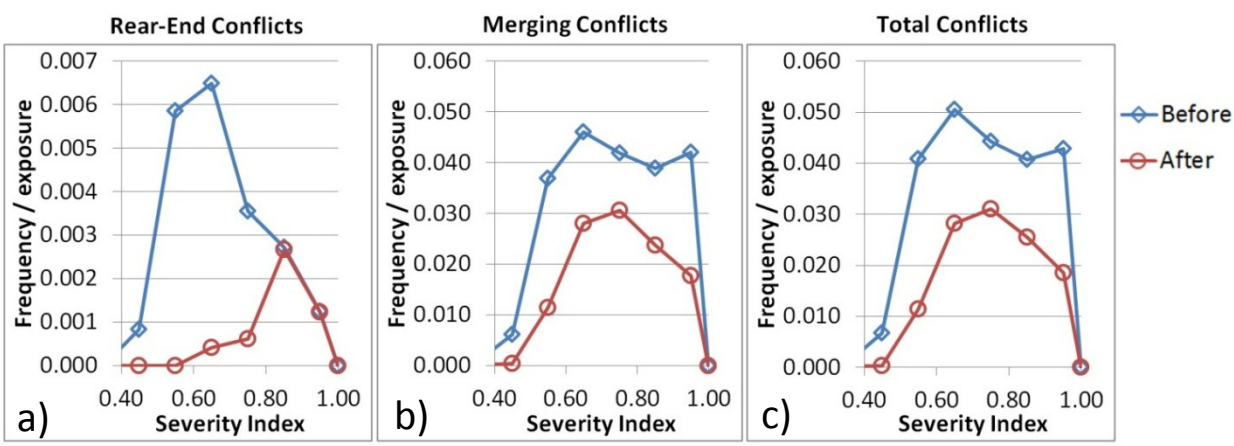

Figure 3.19 Results of the before-and-after study at Duncan Avenue and Channel Parkway. Subfigures a), b), and c) show the frequencies of conflicts, normalized to exposure, over a range of severities from 0.4 to 1.

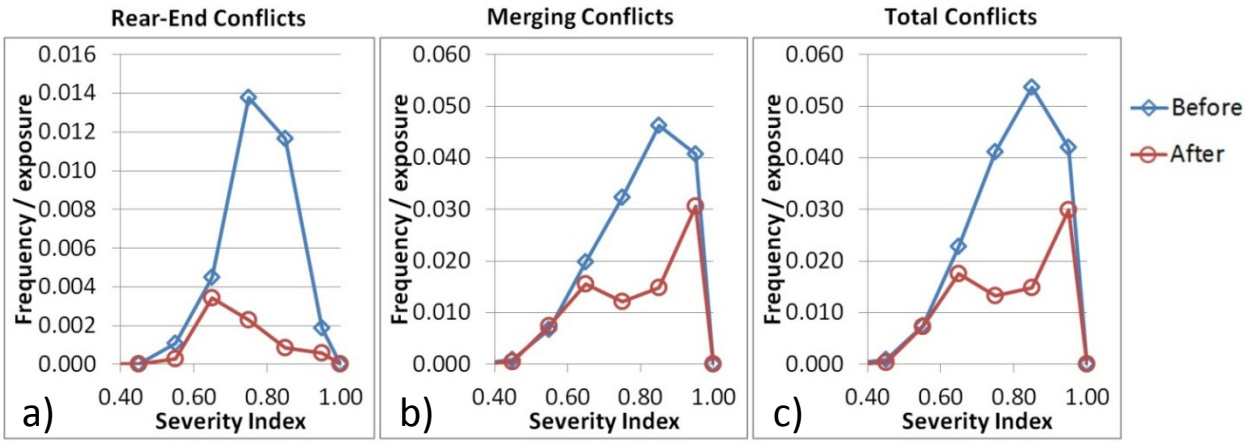

Figure 3.20 Results of the before-and-after study at Warren Avenue and Channel Parkway. Subfigures a), b), and c) show the frequencies of conflicts, normalized to exposure, over a range of severities from 0.4 to 1.

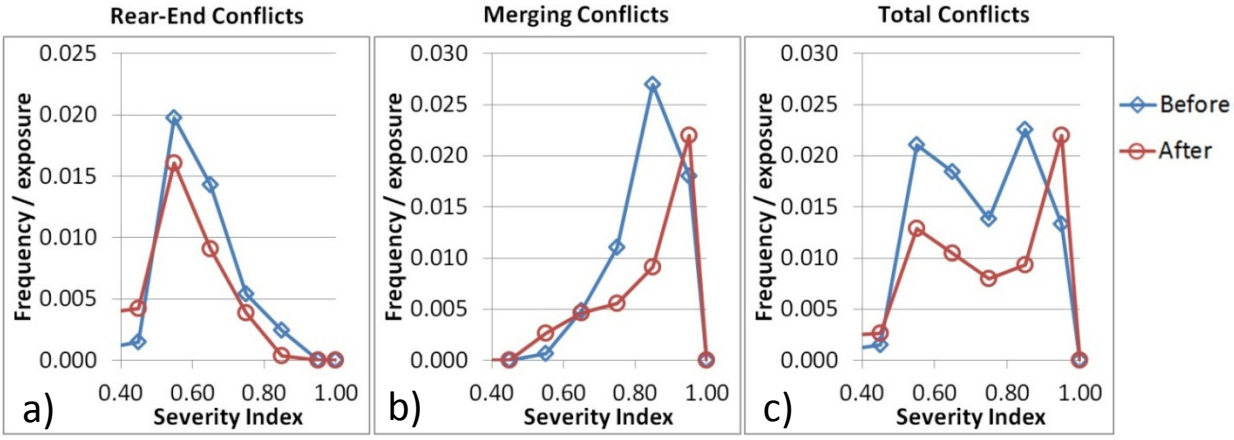

Figure 3.21 Results of the before-and-after study at Green Avenue and Channel Parkway. Subfigures a), b), and c) show the frequencies of conflicts, normalized to exposure, over a range of severities from 0.4 to 1.

Figure 3.22 and Table 3.7 aggregate the results into average hourly conflict values and severity indexes for the studied intersections. The graphs compare the values from before and after the treatments for rear-end, merging, and total conflicts. In all cases, there is a decrease in frequency and severity, which represents a reduction in conflicts at the treated intersections.

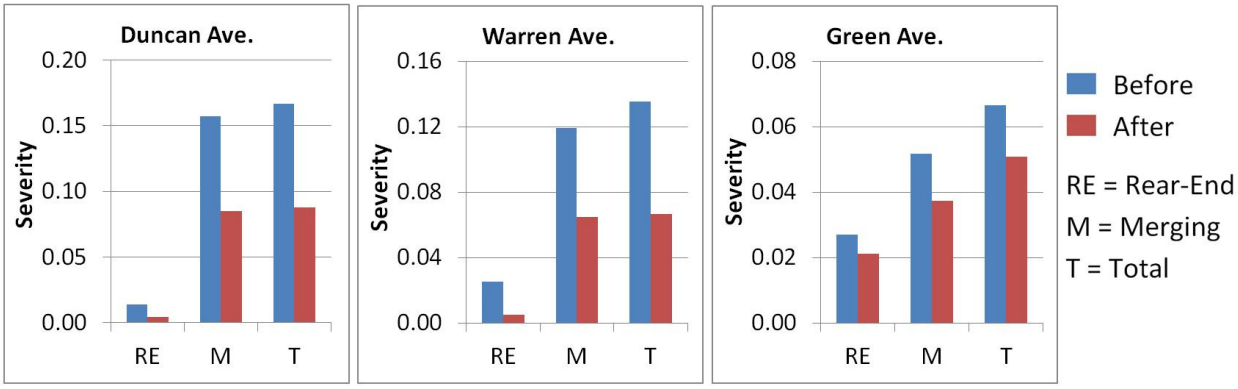

Figure 3.22 Total conflict severity before and after treatments

Table 3.7 Safety improvement in percent reduction in severity

Conflict Type	Intersection			Average
	Duncan	Warren	Green	
Rear-End	70%	79%	22%	57%
Merge	46%	45%	28%	40%
Total	47%	51%	24%	41%

3.5 Conclusions and Future Work

It is concluded that the safety treatment at the intersections of Duncan Avenue, Warren Avenue, and Green Avenue with Channel Parkway has resulted in a considerable reduction in both merging and rear-end conflicts. The overall reduction in total conflicts was estimated at approximately 51%. The total severity of all conflicts, normalized to traffic volumes, was observed to decrease by approximately 41% following the treatments. The safety improvements observed at the Green Avenue

study location were significantly less than those observed at the Duncan Avenue and Warren Avenue locations. This may be because the average hourly conflicts measured during the before period at Green Avenue were approximately half those at Warren Avenue, and a quarter those observed at the Duncan Avenue site. This could indicate that there may be a baseline level of conflicts beyond which reductions become very difficult to achieve. Also, the Green Avenue location is the furthest from the downtown district, and thus may be used primarily by local drivers as opposed to tourists. These drivers would know the location well and their driving behavior may be less influenced by geometric changes.

Although the geometric design of Smart Channels is beyond the scope of this thesis, future work could be undertaken to find an optimal angle of approach for each unique situation. While the recommended angle of approach, relative to the cross-street, is 70 degrees, it is possible a situation could warrant a larger or smaller angle of attack. Location characteristics such as sight obstructions, speed limits, number of lanes, pedestrian volumes, signalization, and required capacity could all affect the safety-mobility balance and necessitate a modified approach angle.

The completion of this study demonstrates the ability to apply automated traffic analysis using computer vision in a traffic safety context. Validation of the technique can be completed through comparing historical collision records from both the before and after periods to the treatment effect predicted through analyzing traffic conflicts.

4 Aggregation of Multiple Indicators

The ability to extract the microscopic trajectories of road-users in an automated manner allows for the generation of large and rich data sets which would otherwise be unavailable for conflict analysis. After attaining this trajectory information, many conflict indicators can be calculated through analysis of the data. As outlined in the Literature Review chapter, many objective conflict indicators, calculated using the spatial and temporal data of road user trajectories, have been proposed and studied. This chapter investigates methods for including several of these indicators in the calculation of a severity index in the traffic environment. The process of combining the information provided by extracting multiple indicators is referred to as indicator aggregation, with the final product being a measure of risk normalized to some measure or unit of exposure.

4.1 Introduction

In the Penticton study presented in Chapter 3, a single technical conflict indicator was used: time-to-collision. In order to achieve a more robust analysis of traffic conflicts, it is desirable to include more than one indicator. In this chapter four indicators will be used to examine the traffic conflict environment:

1) time-to-collision (TTC)
2) gap time (GT)
3) deceleration-to-safety time (DST)
4) post-encroachment time (PET)

Detailed descriptions of these indicators are provided in the Literature Review chapter. Despite the large body of technical conflict indicators, many are simply derivatives of others. Ismail et. al (2011) suggest that they can be divided into two categories: those that require the presence of a collision course, and those that measure temporal and spatial proximity. TTC is the most common example of the former, and GT, PET, and DST are examples of the latter. This chapter examines

aggregation options and methods, recommends aggregation procedures, and presents three case studies which use applications of indicator aggregation.

4.1.1 Continuously Calculable Versus Single Value Indicators

Conflict indicators are either continuously calculable indicators or single value indicators. This differentiation is of importance during the aggregation process. Most indicators, including TTC, GT, and DST, can potentially be calculated at all times that a pair of road users spatially and temporally coexist. Continuously calculable indicators require that trajectories be analyzed at each frame to see whether the geometric requirements of the indicator are fulfilled and, if so, what the indicator value is.

Alternatively, single-value indicators such as PET can only have one value for each pair of road-users. While continuously calculable indicators rely on some form of extrapolation to determine future positions of vehicles and possible conflicts, PET requires no hypothesizing, and is simply a single observation of the time between road-users sharing a common spatial location.

4.1.2 Relation Between Calculability of Indicators

Throughout the course of an interaction between a pair of road users, more than one indicator may be recorded. However, at any one instant some combination of indicators may be mutually exclusive. The presence of a TTC implies a collision course, so there can be neither a GT at this instant nor a DST, which is a derivative of the GT indicator. The converse is also true: a GT implies there is no collision course at this instant and, therefore, no TTC. While a DST requires a GT, the reverse is not true. According to the definition of DST provided in the Literature Review section, a DST requires that deceleration is necessary to avoid a collision.

A PET value can only be recorded at the instant one road-user's trajectory crosses that of another road-user. At this time, it is no longer possible to calculate values for the other indicators, and thus PET is mutually exclusive of the others.

For an event as a whole, any combination of indicators can be observed as road users adjust their trajectories. It is possible, and in fact likely than an event will contain multiple instances of TTCs, GTs, and DSTs as well as a PET value.

4.2 Methods for Mapping Indicators to Severity

The value of an indicator is calculated and recorded in a unit or scale that is native to the indicator, and cannot be directly compared to the values of other indicators. For example, while TTC and GT both return values in the units of time (or frames), they cannot be directly compared to determine the severity of the interaction. For this reason, a method of converting indicator values to a common scale is required. The output of this mapping process is a severity scale normalized to between zero and one.

For mapping to be possible, the most important feature of the indicator values is that they are ordinal with respect to risk. The magnitude of the indicator values and the magnitude of the associated severity are linked via the non-linear severity mapping function. Ismail et. al (2011) describe two mapping methods: functional form mapping and distribution mapping.

4.2.1 Functional Mapping

Function mapping of indicator values assumes a closed form equation to relate indicator values to a severity scale. The shape of the mapping function must be calibrated to some known standards or benchmarks of severity. In their study into indicator aggregation methods, Ismail et. al (2011) summarize a set of benchmarks from previous literature for converting indicator values to a scale of severity from minimal to very severe, represented as a severity scale from 0 to 1.

Table 4.1 Severity benchmark values for constructing mapping functions (source: Ismail et al. 2011)

Severity	TTC (s)	PET/GT (s)	DST (m/s^2)
0.8	1.6	3	6
0.6	5	-	4
0.4	8	-	2
0.2	11	8.5	1

A closed-form equation for mapping from indicator values to severity measures is presented in Ismail et al., (2011), as the following:

$$I(x) = e^{-\frac{x}{\beta}}$$

The same and subsequent authors later introduce an exponent parameter (Sayed et al., 2012, and Autey et al., 2012):

$$I(x) = e^{-\left(\frac{x}{\beta}\right)^2}$$

The value used for beta in the above studies is a function of the perception reaction time (PRT): $2 \times PRT^2$. PRT is taken to be 2.5 seconds in the studies.

The similarity to the extreme-value Weibull distribution is clear. The cumulative distribution function (CDF) of the Weibull distribution is $F(x) = 1 - e^{-(x/\lambda)^k}$, used to describe the processes where higher values are less likely, such as floods or earthquake magnitudes. For an indicator like TTC, where lower values are more severe and therefore less likely, the modification of the CDF to $F(x) = e^{-(x/\lambda)^k}$ is logical. The scale and shape parameters can be fit using the severity benchmarks. Table 4.2 presents shape and scale parameters for the mapping functions for the studied indicators, and

are based on the benchmarks presented in Table 4.1. The TTC mapping function, plotted with respect to the benchmarks is displayed in Figure 4.1. The form $SI = 1 - e^{-(x/\lambda)^k}$ is used for DST because higher indicator values represent more severe events.

Table 4.2 Shape and scale parameters for severity benchmarks

Severity	TTC			PET/GT			DST		
	Value	α	β	Value	α	β	Value	α	β
0.8	1.6	1.12	8.12	3	1.90	6.61	6	1.1	3.8
0.6	5						4		
0.4	8						2		
0.2	11			8.5			1		

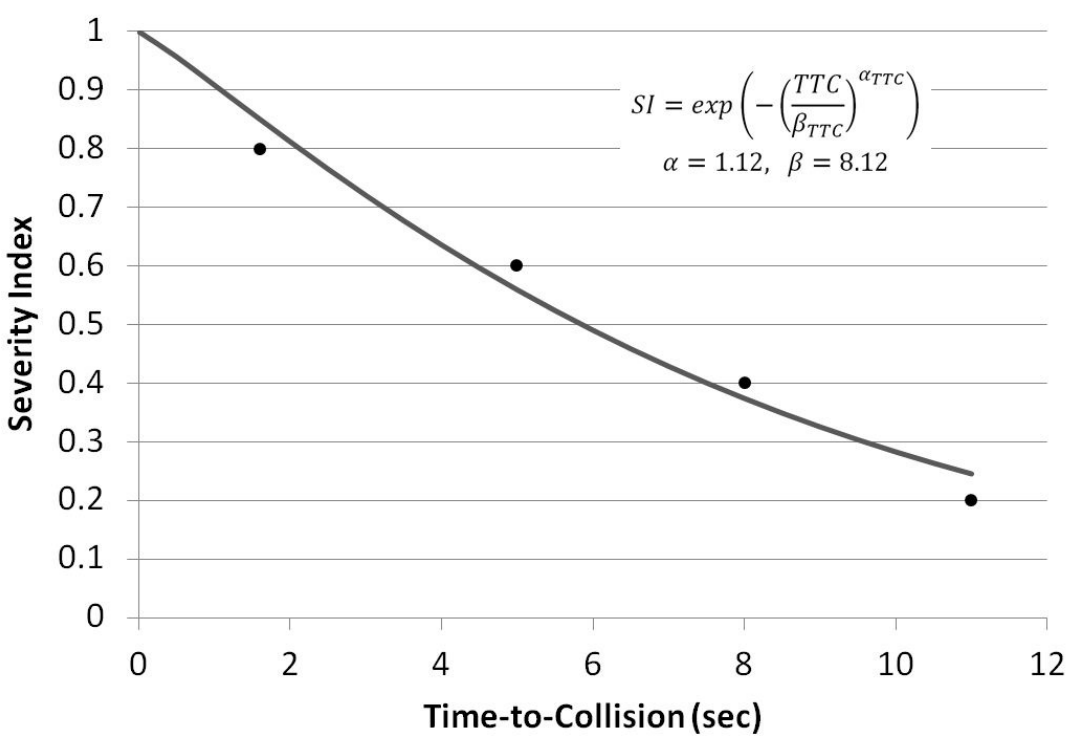

Figure 4.1 Mapping function for TTC fit from benchmark severity values

4.2.2 Distribution Mapping

The second approach, distribution mapping, relates the severity of an indicator value to its frequency of occurrence, or more specifically its rarity. This approach is based on the Traffic Conflict Hierarchy theory which states that severe events occur more rarely than less severe events. Given a large enough sample size of traffic events, the severity of a given indicator value can be determined from its frequency distribution. This approach involves fitting a distribution to the available set of indicator values, and using the cumulative distribution function as a closed-form mapping equation as used in functional mapping. Appropriate distributions for the fitting operation would be either versatile distributions such as beta and gamma distributions, or extreme value distributions which are designed for describing increasingly rare natural phenomena.

The primary challenge in using distributional mapping is that it can only be accomplished through the acquisition of an adequately large sample of indicator values. Currently such a dataset does not exist, but there are ongoing studies in the UBC Transportation Group aimed at attaining such a data set. Further, unique distributions can be fit for different types of traffic facilities or maneuver types. For example, rear-end conflict indicators and pedestrian-crossing conflict indicators can have distinct distributions.

4.3 Aggregation of Multiple Indicators

Ismail et al. (2011) studied the interaction and correlation between the indicators TTC, GT, DST and PET and concluded they represented “partially overlapping independent measures of risk”. Through combining the clues independently provided by the individual indicators, a more accurate picture of the total risk of an event can be realized. This process is referred to as indicator aggregation. Ismail et al. (2011) proposed this could be accomplished in a one-step integration process through a function with multiple independent variables which are the indicator values. However, they concluded that this function could only be estimated through the use of an adequately large data set, which is currently unavailable. Instead, they recommended each indicator be mapped to a severity scale using

either functional form or distribution mapping methods. Subsequently, the normalized severity values can be aggregated.

The goal of the aggregation process is to attain a total measure of risk, normalized to a measure of exposure, for the conflict type and area of interest. For a given conflict type and area, risk can be represented as:

$$\frac{Risk}{Measure\ of\ Exposure}$$

Three approaches to aggregation will be presented in this section: time aggregation, road-user aggregation and event aggregation. The process of aggregation can be regarded as successively collapsing different dimensions of the traffic environment, obtaining representative values at each stage. The three dimensions (Figure 4.2) that need to be aggregated, or collapsed, are:

1) indicator dimension: the set of all indicators at each instant

2) time dimension: all frames of video

3) event dimension: pairs of spatially and temporally coexisting road-users

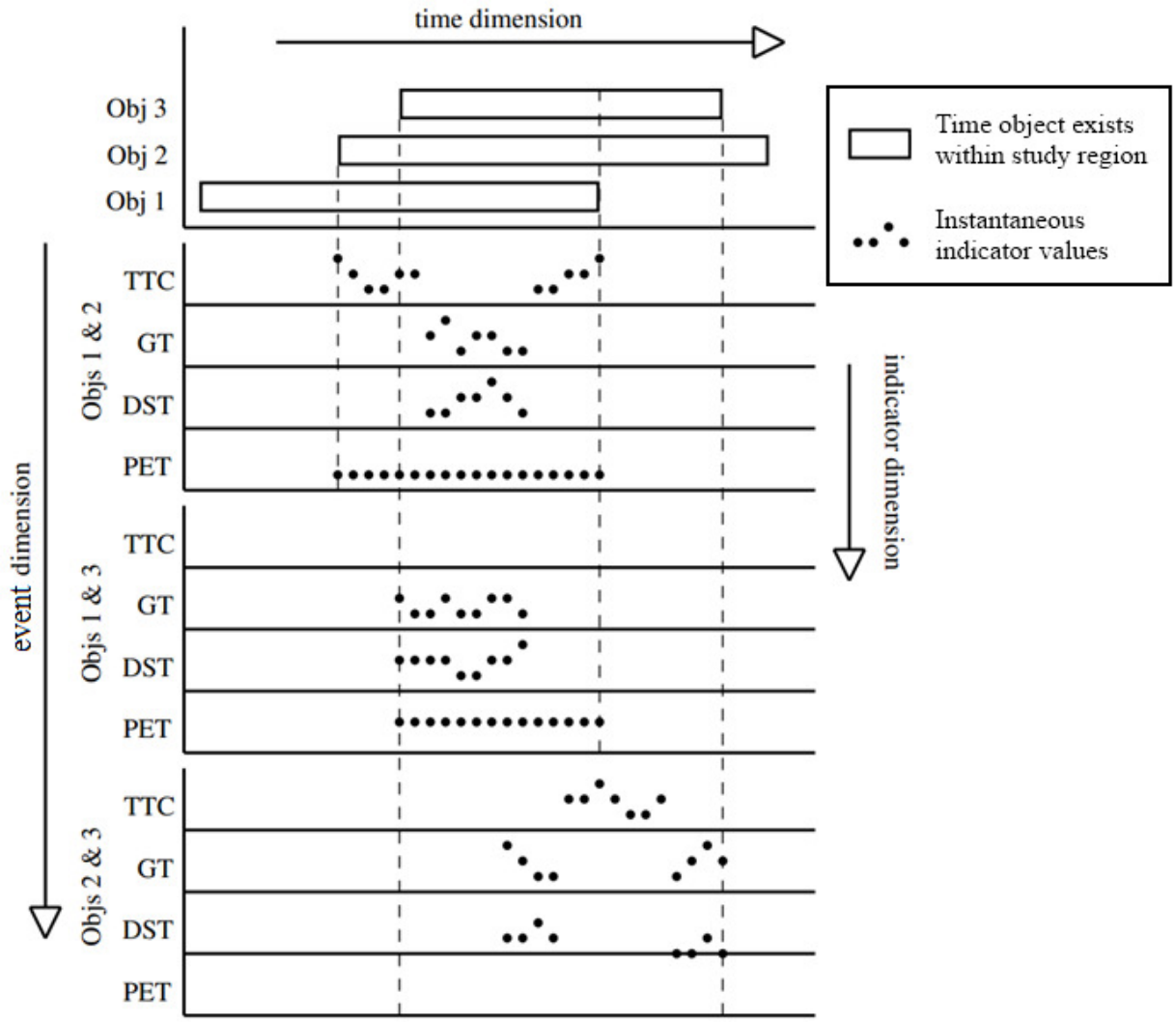

Figure 4.2 Time, event and indicator dimensions during aggregation

The order in which these are aggregated and the operators used to do each stage of aggregation are the main parameters that define the aggregation method.

4.3.1 The Time Dimension

The time dimension refers simply to the sequential frames of the video. To aggregate over, or collapse the time dimension is to reduce the values from a succession of frames to one representative value.

4.3.2 The Indicator Dimension

The indicator dimension is the set of indicators calculated for each pair of conflicting road users at an instant of time or frame of video. If only one indicator is used (e.g., as in the Penticton study where TTC was the only indicator), the dimension has a size of 1, and thus cannot or need not be aggregated. However the use of multiple indicators requires, at some point in the overall aggregation process, that multiple indicators be reduced to one representative value.

4.3.3 The Event Dimension

The event dimension could be referred to as the "road-user pairs dimension", since a pair of road-users is required for a conflict. In the future, this research may be extended to conflicts between road-users and inanimate objects in the environment, but, currently, only conflicts with other road-users are considered. Aggregation over this dimension collapses all events occurring in the study area, either at an instant in time or over a specified time period, into a representative value.

4.3.4 Operators for Aggregation

At each of the levels (time, indicator, and event), a representative value must be extracted from a continuum or set of values. The mathematical function that achieves this can be referred to as the selected operator. Several potential operators will be studied:

1) extreme value: maximum or minimum

2) mean

3) percentile: quantile or median

4) summation

The selected operator must be appropriate for the circumstance. An investigation into the applicability of each operator for the given aggregation method is presented in the following sections.

4.4 Event Aggregation

Using event aggregation, the interaction between each pair of conflicting road users is represented by a single severity value. To achieve this, the time and indicator dimensions must be collapsed. There are, therefore, two options (Figure 4.3):

1) time -> indicator

2) indicator -> time

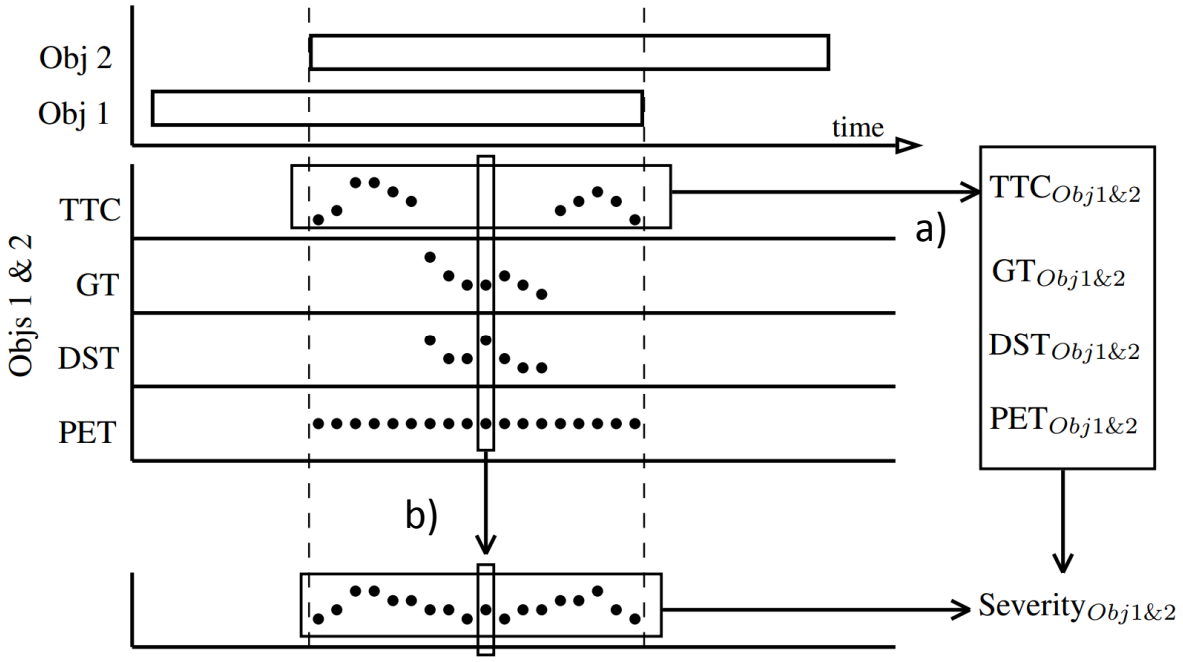

Figure 4.3 Event aggregation methods. a) time->indicator b) indicator->time

In this first option, the first dimension to be aggregated, or collapsed, is the time dimension. For each pair of coexisting road users, the indicator severity values for each indicator are aggregated into a single, representative value (for each indicator). Subsequently, this set of representative indicator

severities is aggregated into a single severity value to represent the severity of the interaction between the pair of road-users.

In the second option, the set of indicator severity values for each frame that a pair of road users coexist is reduced to a single severity value. These severity values, one for each frame, are next aggregated into a single severity value using the selected operator. This single value represents the severity of the road-user pair's interaction, or event.

4.4.1 Recommended Event Aggregation Procedure

The recommended option is to aggregate first over time (i.e., collapse all frames into a single value for each indicator), then aggregate over the indicators. The reason is that when using an indicator such as PET, which is calculated only once for each pair of road-users, there is no clear answer as to which frame to apply it to. Applying the PET indicator value to all frames that the road-user pair coexist could lead to overweighting of the value. Also, since many indicators are mutually exclusive (i.e., only one or the other can exist and a given instant), there is less reason to believe they work together to indicate the total severity at any instant.

When aggregating over frames for a given indicator, the recommended operators are either maximum severity or sum of severities (sum of the severity at each frame for the indicator). The reason is that percentile or averaging operators are sensitive to the size of the sample set, or more accurately, the shape of the distribution. However, the shape of the distribution or size of the sample set does not affect the maximum. For example, a prolonged period of low severity at the beginning or end of an event will lower all percentiles and the average without necessarily representing a less severe event. It is therefore recommended that only the maximum or summation operator be used for collapsing the time dimensions.

After collapsing each indicator to a single value, (aggregating over the time dimension for each indicator), a representative value must be extracted for the event by aggregating the indicators.

To accomplish this, the maximum severity value of the set should be used rather than an average, percentile, or summation operator. There is no reason to believe that an event that registers multiple indicators (for example a TTC, GT and PET value) is more severe than an event that registers only one indicator, especially if the severity value of the single indicator is higher than the maximum of the set.

To summarize, the preferred aggregation order is to aggregate first over time (i.e., the frames that make up the event). This will serve to return a representative value for each indicator for the given pair of vehicles. The maximum value is the preferred operator for this operation. Subsequently, the maximum value of the indicator set is taken as the representative severity of the road-user pair's interaction.

4.5 Road-user Aggregation

Road-user aggregation aims to report measures of risk for road users. Therefore, road-user aggregation must return a value for each road user that represents the overall severity of conflicts the road user encounters during its travel through the study area. Any given road user can be involved in a discrete number of events. The first stage in road-user aggregation is to attain a severity value for each of these events. Subsequently, an operator is used to aggregate all the events a road user is subject to into a single value.

4.5.1 Recommended Road-user Aggregation Procedure

The first stage, attaining a representative severity value for each event a road user is involved with, is simply event aggregation and the recommended event aggregation process is therefore used (Section 4.4.1): time -> indicator. Next, the events need to be aggregated into a single value to represent the severity encountered by the road users. The recommended operators are either maximum, or sum for the reasons outlined in Section 4.4.1.

4.6 Time Aggregation

The goal of time aggregation is to return a measure of the severity experienced in a period of time. The periods of interest could be very small; for example, a period length of 5 seconds would allow for determining whether there was a significant increase in risk during the inter-green periods at an intersection. A longer period, such as an hourly interval, would allow for monitoring the change in risk during, for example, the peak and off-peak periods throughout the day.

As with road-user aggregation, there are two options for collapsing the higher dimensions:

1) indicator -> road user

2) road user -> indicator

4.6.1 Recommended Time Aggregation Procedure

The aggregation of road users before indicators is illogical and can be ruled out immediately; the instantaneous value of say, TTC, for road users 1 and 2 has very little to do with the instantaneous TTC value for road users 3 and 4. Because there would be less connection between a given indicator's values over all coexisting road-user pairs than within the multiple indicators for each pair, the employed sequence should be to first aggregate over the indicators and then aggregate over road-user pairs (Figure 4.4). Using this method, a representative severity value is returned for each road-user pair for each frame. As outlined in Section 4.4.1, the recommended operator for this aggregation is the maximum value. Following indicator aggregation, the road-user pairs are aggregated at each frame, or instant of time.

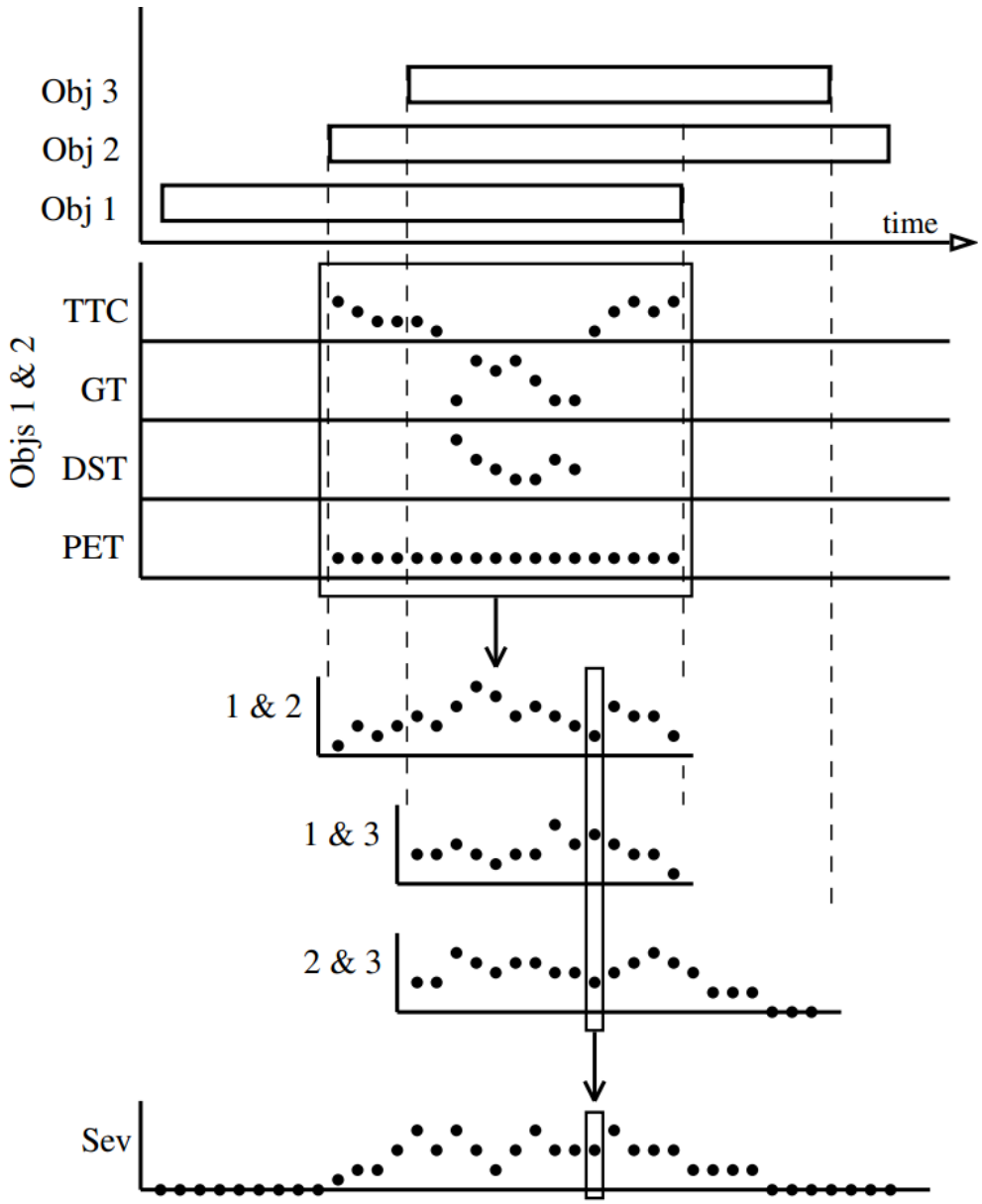

Figure 4.4 Recommended time aggregation procedure

The end result is an overall severity value for each frame or a continuum of severity for the traffic flow over time. In the final aggregation step, time aggregation, the time dimension is separated into bins. The bins can be short intervals of a few seconds or longer hourly intervals depending of the study requirements. For this aggregation stage, any operator can be used; the selection is dependent on how the user wants to report the study's findings.

4.7 Smoothing the Indicators

Any computer vision tracking system involves an inherit amount of noise. This noise in the vehicle trajectories will lead to noise in the calculation of indicators. Short fluctuations in indicator values are of concern when using an extreme value operator such as the maximum. To solve this problem, the use of a smoothing or filtering function on the indicator severity values is recommended. While the simplest would be a moving average, the non-continuous nature of indicator values over time creates a challenge. Most indicators are not calculable for every frame. For example, the TTC indicator is calculable only when there is a collision course. Over the course of an event, the TTC indicator may be present, then not, then again. Also, during the time period when there is a collision course and the TTC is present, individual frames or a sequence of frames may fail to register a TTC because of a slight shift in vehicle trajectories. For example, Figure 4.5 shows an event in which there are two distinct TTC periods, and noise within the periods that cause a loss of the indicator.

The proposed smoothing method makes the assumption that there are two causes of non-continuity in indicator values:

1) The road-user trajectories and behavior have changed such that, for a period of time, the indicator is no longer calculable or valid.

2) Noise in the tracking, or slight random behavior in vehicle trajectory extrapolation, results in a brief period during which the indicator cannot be calculated.

To deal with the first cause, each TTC period should be treated and smoothed as a separate collision mechanism during the interaction. In cases involving the second cause, smoothing should be used to fill in the missing TTC values. The distinction between the two types of missing indicator periods must be defined by thresholds for the smoothing function. In Figure 4.5, a threshold of "*t*" is used to determine which smoothing operation to take.

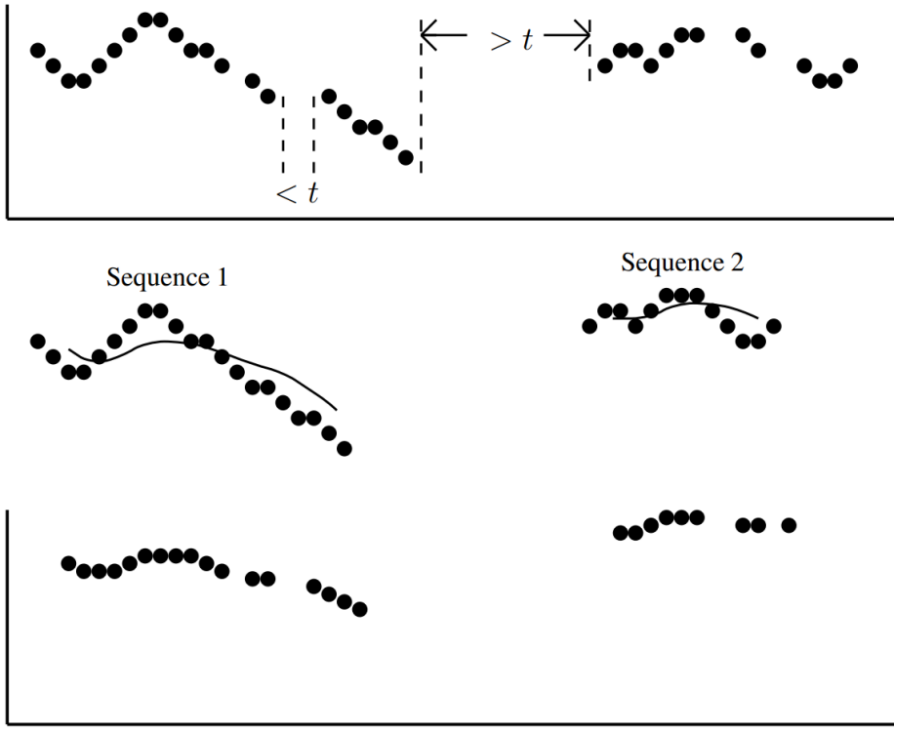

Figure 4.5 Severity value smoothing procedure

Smoothing has the effect of removing extreme values when they are not sustained for a duration of time. When high severity values are recorded after smoothing over a large span (averaged over many periods), it means that the severity must have been high for a considerable period of time. More than simply eliminating noise in the signal, smoothing can be used to add weighting to the period of time a severity level was observed.

4.8 Accounting for Exposure

After completing either time, road-user or event aggregation, the returned value must be reported in relation to some measure of exposure for the results to be meaningful.

4.8.1 Road-user Exposure

Road-user exposure, which is used to normalize road-user aggregation, is simply the total number of road users for which severities were calculated.

4.8.2 Event Exposure

The final value reported for risk at the event level must be normalized to some measure of event exposure. The objective of this exposure measure is to account for the possibility of interaction between road-users. An obvious candidate is total entering volume. However, this measure does not account for how much of this volume is conflicting. For example, in a merging scenario, if most of the volume is on the through, and merging vehicles are rare, then the possibility for conflict is much less than a more even split of through and merging vehicles. Ismail et al., (2011) proposes using the product of conflicting traffic streams. A possible improvement on this exposure measure is to use the square root of the product of conflicting traffic streams (Autey et. al, 2011). Collision rates (collisions per million entering vehicles) are known to decrease as traffic volumes increase because of congestion. Introducing the square root function may help to achieve a similar effect in the exposure calculation.

4.8.3 Time Exposure

The calculation of a time exposure measure leaves fewer options than that of road-user exposure. The simplest measure is that of a time period. The duration of the time periods selected depends on the study requirements. When the studied area is an intersection, or some form of signalized traffic facility, time aggregation over the cycle is possible. While the exposure measure is still a time period, it is a time period of a specific cycle stage. Cycle aggregation is presented in Section 4.9.3.

4.9 Case Studies for Time, Event and Road-user Aggregation

This section presents three case studies demonstrating the implementation of time and road-user aggregation.

4.9.1 Utilized Mapping Method

Functional form mapping is used for the presented case studies. It was found that the severity benchmarks gathered from the literature were not appropriate for the data sets because of the limited

field of view used to gather the sample data sets. This is because events of low severity were not registered because vehicle tracking did not extend far enough upstream to catch such events. Instead, a new set of benchmarks is used to allow for a more diverse continuum of severity values. This allows for the results and differences between different aggregation methods to be more easily distinguished (Table 4.3). However the suggested benchmark set and aggregation results are hypothetical and are used only for demonstration purposes. Any benchmarks used in practice must be properly calibrated according to the researchers' needs and the validity of the benchmarks in the field of traffic safety.

Table 4.3 Suggested benchmark set used for case studies

Severity	TTC			PET/GT			DST		
	Value	α	β	Value	α	β	Value	α	β
0.8	0.5	0.9	2.26	0.5	1.1	1.95	7.5	0.9	4.83
0.6	1						5		
0.4	2						2		
0.2	4			3			1		

4.9.2 Case Study 1: Time Aggregation at a Macro Scale

This case uses time aggregation at the hourly scale to monitor the changing occurrences of conflicts over the course of a day. As volume increases during peak periods, the occurrence of conflicts could be logically assumed to increase. However the lower speeds often resulting from increased volume may work to reduce the number of conflicts. This behavior can be studied through time aggregation with hourly bins.

A major intersection in Vancouver BC is used for this case study. A sweeping, channelized merge lane joins the major approach just downstream of the intersection in the southbound direction. Merging conflicts are aggregated into hourly bins or periods. In this example, aggregation was carried

out in the manner recommended in Section 4.4.1. First, indicators were aggregated for each frame for each pair of road users by taking the maximum severity. For each frame, the road-user dimension was collapsed by summing the instantaneous severity of all road-user pairs. The summation operator was again used to find the total severity in each one-hour period. The results, displayed in Figure 4.6 show that conflicts decrease during the midday hours, then proceed to rise into the afternoon peak.

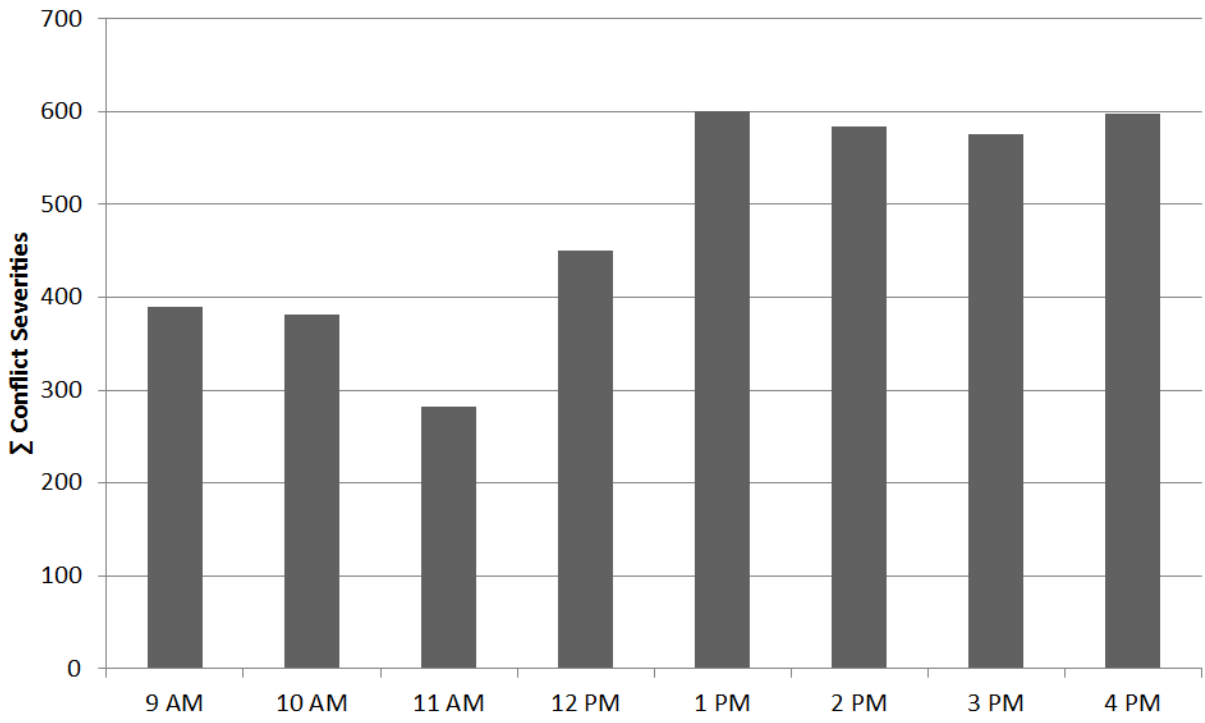

Figure 4.6 Time aggregation, hourly time periods

4.9.3 Case Study 2: Time Aggregation over Intersection Cycles

Over the course of an intersection's cycle, there exist potential conflict situations that are unique to certain phases. For example, an approach with a permissive left-turning movement has opportunities for conflicts during the green phases, when the permissive movement is active, but not during the red phase (excluding, of course, red-light violations). During the red phase, right-turn-on-

red vehicles now have an opportunity to create conflicts. For diagnostic purposes, analyzing the times during the cycle that result in the most conflicts can help determine the cause of a safety issue.

Since conflicts are rare events, the best way to analyze conflicts at different points in the cycle is to superimpose many cycles so that patterns may become visible. This process can be termed cycle aggregation since information from multiple cycles is compiled. To accomplish this, bins or intervals are created that represent the same time period in every cycle. For example, a bin is created that represents the time interval from 5 to 10 seconds after the start of the North/South (N/S) green phase. The conflict rate for a time interval starting at time t_i after the start of the green phase, with an interval duration of Δt can be defined as:

$$Conflict\ Rate_{t=(t_i,\ \ t_i+\Delta t)sec} = \frac{\#\ of\ conflicts_{t=(t_i,\ \ t_i+\Delta t)sec}}{\#\ of\ cycles}$$

The study location of Duncan Ave. and Channel Parkway, in Penticton BC, was studied for merging conflicts. The analysis of one day's data from this study location serves as a case study for cycle aggregation. This intersection is 2-phase; all left-turning movements are permissive only. The studied phase is the green phase for North/South traffic on the main approach, Channel Parkway.

This traffic signal is actuated; the N/S green phase will continue until East/West traffic triggers in-road detectors. As a result, the duration of the North/South green phase in each cycle varies; therefore, some N/S green phases will contain more or fewer intervals than others. So, while the N/S green phase of every cycle will generate data for the first time bin of the phase, only some will generate data for later time bins. For example, some N/S green phases may not have data for the time interval of 40-to-45sec because the actuated signal switched phases before this time interval is reached. The conflict rate is therefore calculated as:

$$Conflict\ Rate_{t=(t_i,\ \ t_i+\Delta t)sec} = \frac{\#\ of\ conflicts_{t=(t_i,\ \ t_i+\Delta t)sec}}{\#\ of\ cycles\ that\ containing\ interval\ (t_i,\ \ t_i+\Delta t)sec}$$

Figure 4.7 presents the results of cycle aggregation at Duncan and Channel Parkway over the course of eight hours. The white bars indicate the number of N/S green phases whose duration contained the 5-second intervals plotted along the horizontal axis. The scaling for the number of phases is plotted on the left vertical axis. For example, the time interval from 10 to 15 seconds after the start of the phase (third bar from the left) was observed in 400 cycles, while the 85-to-90sec time interval was observed in only 50 cycles. The superimposed black bars indicate the number of conflicts with TTC less than 3 sec that were recorded during each time interval over all observed N/S phases. The conflict numbers can be read from the scale on the right axis.

For example, in the studied period, there were approximately 265 N/S green phases that included the time interval 40-to-45sec, measured from their respective starts. During these 265 five-second time intervals there was a total of 21 conflicts.

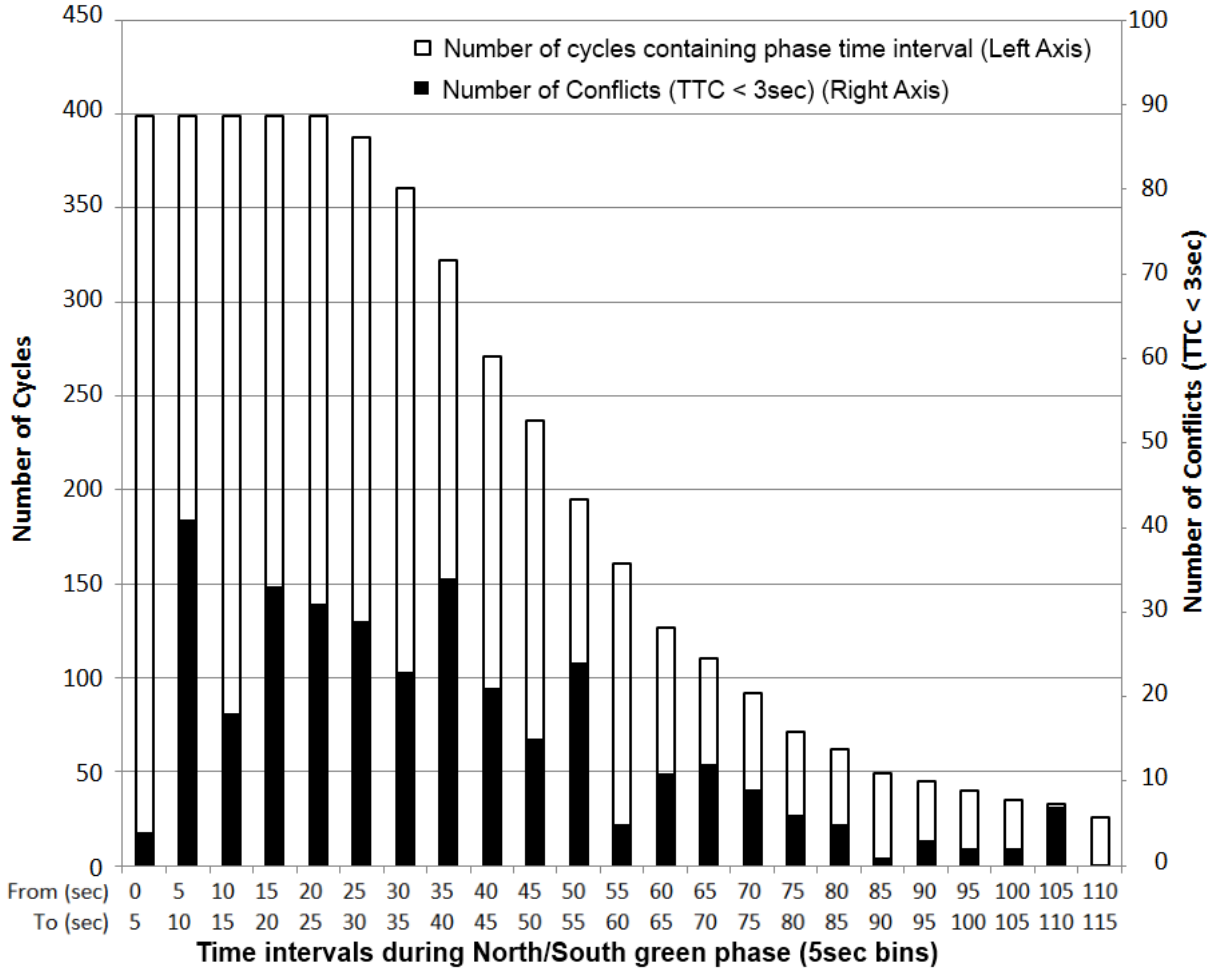

Figure 4.7 Time aggregation for N/S green phase using 5-second intervals

For the 40-to-45sec time interval, the conflict number can be converted to a rate equal to 21 over 265, or 0.079 conflicts per phase. Figure 4.8 presents the rate of conflicts for each 5-second time interval during the N/S phase.

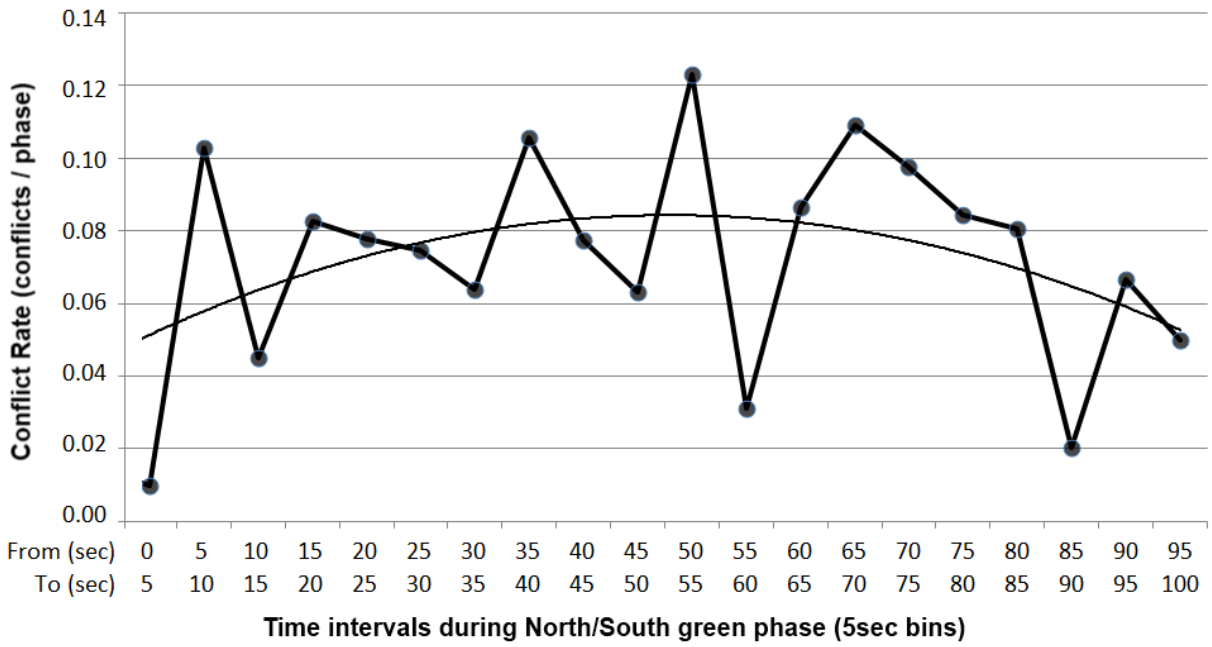

Figure 4.8 Conflict rate for N/S green phase using 5-second intervals

The observed trend can be analyzed in the following manner. The first 5sec period of the green phase shows very few conflicts. This may be due to the higher density of through vehicles at the beginning of the phase, preventing merging vehicles from even attempting to merge. In subsequent periods, as through traffic thins, merging vehicles that have queued begin to accept gaps and the rate of conflicts is seen to increase. Towards later periods in the cycle, conflict rates become more erratic as merging behavior becomes less predictable; some vehicles attempt to merge without stopping while others slow or stop to wait for an acceptable gap.

4.9.4 Case Study 3: Event Aggregation using Smoothing

For a study into the different event aggregation methods, one day of conflict analysis at the Penticton, BC, Westbench Hill road location is used. This location is selected because of its above-average tracking quality resulting from a high camera viewing angle from a nearby hill. The data was re-analyzed to include four indicators: TTC, GT, PET, and DST. Aggregation was accomplished by

first collapsing the time dimension (all coexisting frames for the pair of road-users), then taking the maximum value. The four indicator values were then aggregated by taking the maximum.

Before aggregation is carried out, smoothing is applied to the severity values in order to account for extreme fluctuations. Smoothing periods of 5 frames and 30 frames, representing 1/6 second and 1 second respectively, were used (Figure 4.9).

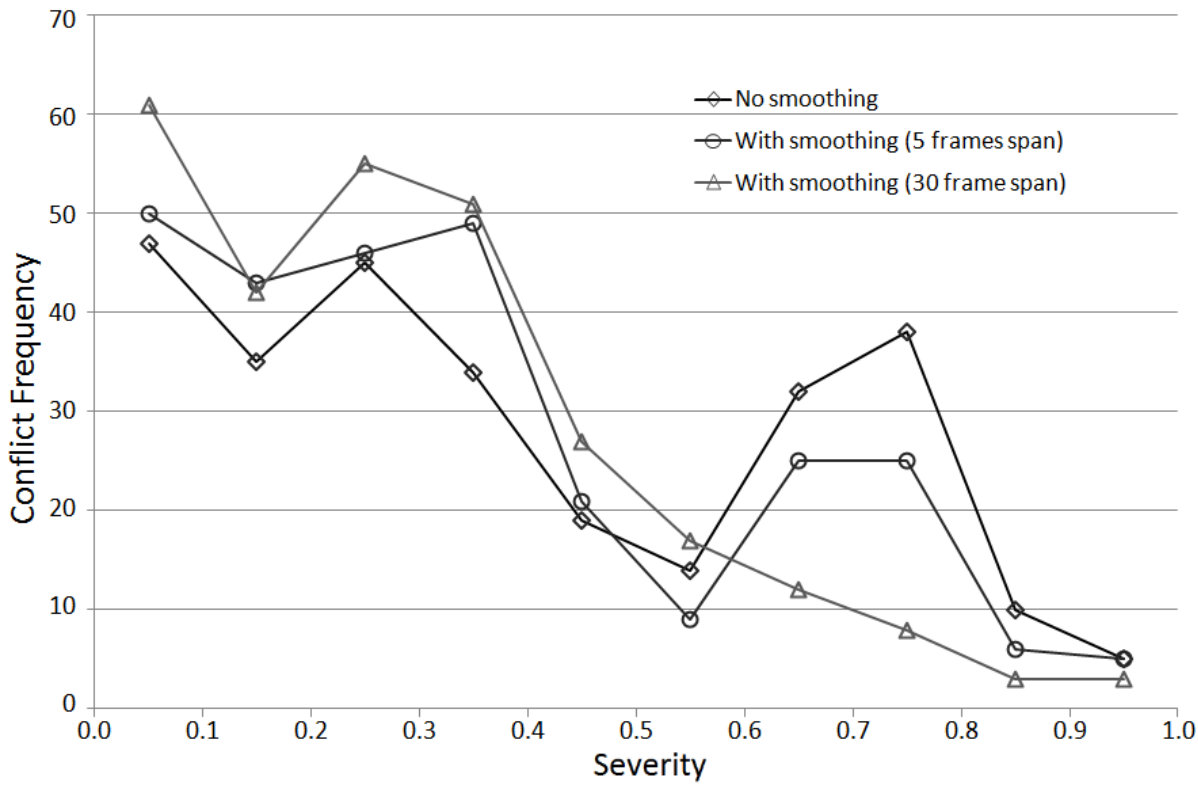

Figure 4.9 Effect of smoothing indicator severity values

It can be seen that the application of smoothing tends to reduce the frequency of high severity events. What is occurring is that the high severity values are being tempered through smoothing even before aggregation is conducted. The events that retain their high severity rankings must have experienced enough high severity values that even after smoothing these values remained and thus are truly severe events.

4.9.5 Case Study 3: Road-user Aggregation

To demonstrate road-user aggregation the same dataset as Case Study 2 is used: one day of data from the Westbench Hill Rd. study location in Penticton. Using the procedure recommended in Section 4.5.1, the frequency distribution for road users involved in at least one conflict calculated (Figure 4.10).

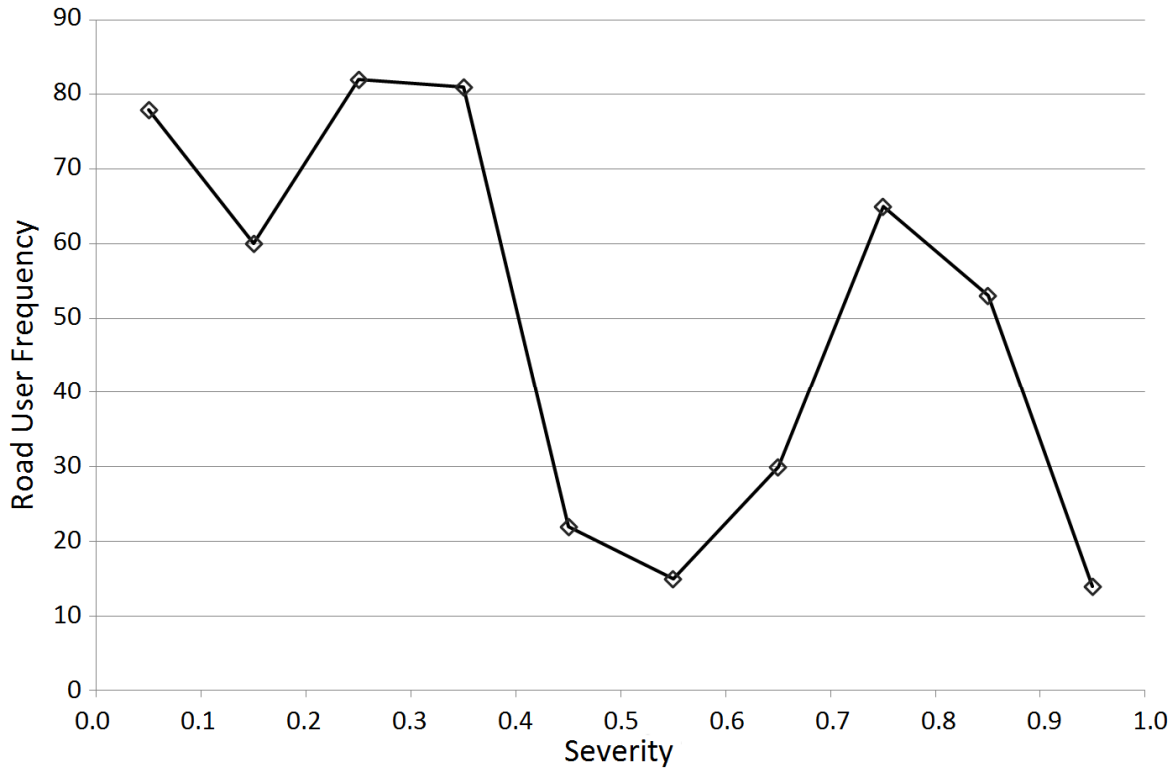

Figure 4.10 Severity frequencies for road users involved in at least one conflict

Because most road users who are involved in a conflict do not experience a second conflict during their 'lifespan', the frequencies of road users' severities should be close to double that of the event severities; if each event involves two unique vehicles, the event gets assigned to each road user in road-user aggregation. This similarity can be seen by comparing the data plot in Figure 4.10 to the unsmoothed plot in Figure 4.9. In more dense traffic environments road users can encounter multiple conflicts during their passage.

The majority of road users do not experience conflicts during their passage through the study area. This is what is described as "undisturbed passage" in the traffic conflict hierarchy. By including these road users in the data presentation (Figure 4.11), the risk the average road user experiences during their passage through the study area can be better understood.

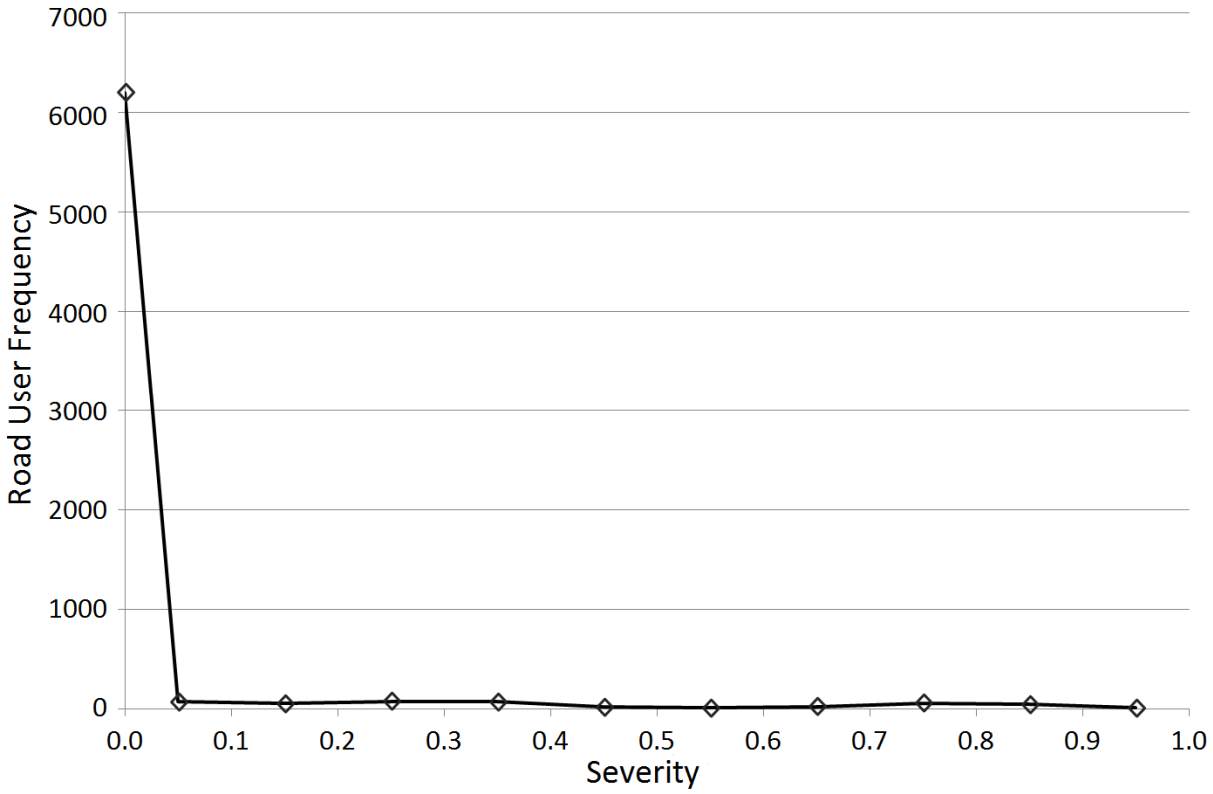

Figure 4.11 Severity frequencies for all road users

4.10 Conclusions and Future Work

This chapter serves as an introduction to the many options available for aggregating the large body of information made available through computer vision traffic analysis using multiple traffic conflict indicators. Methods for mapping the different conflict indicators to a common scale were proposed; however, further research is required to achieve a thorough understanding of what risks each indicator represents and how they can be equated. This understanding will subsequently allow the proposed aggregation procedures presented in this chapter to be reviewed for logical consistency.

Three primary aggregation methods were studied in this chapter: time, event and road-user aggregation. Time aggregation is appropriate for studying aggregate severity over time, either over short time periods, such as inter-cycle lengths, or over longer periods such as hourly periods. Short time periods allow for studying risks unique to certain movements and phases over the course of an intersection's cycle, whereas hourly time aggregation is appropriate for analyzing changing severity throughout the day.

Road-user aggregation is used for normalizing risk to the volume of users. It relates to the risk that the average user of the traffic facility will experience and is therefore very useful in determining the safety of the facility. The purpose of event aggregation is either as a step leading to road-user aggregation, or as a means of investigating the characteristics of events occurring at a location.

To eliminate noise and consequent inaccurate results, smoothing, or a moving average, should be applied to the raw severity values before aggregation. It was found that applying smoothing reduced the likelihood of an event being categorized as severe simply because of a temporary spike in severity at the level of a single indicator. Instead, a more substantial period of high severity was required for the event to be registered as a high-risk situation.

When performing a traffic safety study using traffic conflict data, the selection of the aggregation method to be used is dependent on the purpose of the study. For example, when working at a transportation planning level, time aggregation using longer periods, such an hour, would be an appropriate way to report conflict data. Hours are an aggregation unit that is easily understood conceptually, and hourly time periods will have less random fluctuations than shorter time periods. On the other hand, a traffic safety engineer interested in the risk to the average driver navigating a traffic facility would use road-user aggregation to evaluate the design. As a third example, a traffic manager responsible for setting signal timings would be interested in identifying risks during specific signal

phases. In this case using time aggregation over the intersection's cycles would be used to determine if, for example, intergreen periods are adequate, or if a dedicated turning phase is required.

5 Summary, Conclusions and Future Work

5.1 Conclusions

The need for viable alternatives to traffic collision records as data sources for analysis and evaluation of traffic safety has long been recognized and has resulted in a considerable body of research work into surrogate measures of traffic safety. There are obvious ethical and moral issues with compiling a data set that relies on death and injury on the roads, and the accuracy of the resulting data set has been rightly considered questionable.

This thesis presents an application of an automated implementation of the traffic conflict technique (TCT) using computer vision. A before-after (BA) traffic safety study was carried out using traffic conflicts, identified using the time-to-collision (TTC) indicator, to evaluate the effectiveness of the conversion of three sweeping, channelized right-turn lanes to "Smart Channels". Smart Channels improve road-user safety by changing the right-turn lane's angle of approach with the cross street so that it is closer to 90 degrees, which improves driver's visibility during the turning maneuver.

At the treatment sites, conflict frequency was observed to decrease by 67 percent for rear-end and 48-percent for merging conflicts; the total reduction of conflict frequency was 51 percent. Total conflict severity decreased by 57 percent and 40 percent for rear-end and merging conflicts respectively. It can be concluded that the implementation of Smart Channels is effective in reducing the occurrence and severity of traffic conflicts.

This thesis demonstrates that a statistically significant change in the frequency of conflicts, measured using the time-to-collision (TTC) indicator, could be determined using data collection from only two days before and two days after a realignment treatment is implemented. The reduction in total conflict frequency was calculated as being significant at the 99th percentile. It was also demonstrated that non-treatment effects could be accounted for with the use of control or comparison sites.

In Chapter 4, it is demonstrated that there are logically valid methods of combining, or aggregating the information provided by multiple indicators. The method of aggregation to be employed is dependent on the desired presentation of the data, and the type of information required from the study. Aggregation over time is shown to be a means of identifying hazardous times during the day as well as during short periods over the cycle length at a signalized intersection. Alternatively, a measure of risk normalized to the volume of road-users can be gained through aggregation over road users. This method allows for a determination of the risk present to the average road-user, and is effective for BA studies, as demonstrated in the BA study presented in Chapter 3.

5.2 Summary of Contributions

To the author's knowledge, the BA study presented in Chapter 3 is the first application of automated traffic conflict identification in a BA environment. While the traffic conflict technique (TCT) has often been applied in BA studies, this study marks the first application of computer vision, a fully automated procedure, to extract results.

The use of a control site to account for non-treatment effects in the BA results is not commonly applied in applications of the TCT in a BA context. The statistical methodology used, an odds ratio, was borrowed from traditional collision based BA study methods. This combination of traditional methods of analysis using collision records and more efficient methods of automated conflict analysis is a significant step towards facilitating wider implementation of conflict analysis.

The objectivity provided through completely automated conflict identification eliminates many of the criticisms of the TCT about the subjectivity of human observers. The ability to include multiple objective indicators in the process further increases the robustness of this objective procedure. Chapter 4 presents logically defendable approaches to combining the information provided to a degree not yet available in TCT literature.

5.3 Future Work

The future of the TCT and its acceptance into mainstream traffic safety practice will depend on continually improving the ability of conflict indicators to predict collision occurrence and measure the safety level. Conflict reduction on its own carries little weight in the eyes of the public without an associated collision reduction. Improvement in objective conflict definitions to best identify collision mechanisms must be the goal.

At present, conflict indicators do not account for the velocities and physical masses of vehicles, and for visibility constraints of road users. Properties of the environment, including sight obstructions, pavement characteristics, weather conditions, and the traffic facility's right-of-way rules are not accounted for either. It is understandably difficult to incorporate all such variables in indicator definitions; however, it is well known that such variables play a role in collisions, and thus a continued effort must be made to account for them in conflict analysis.

Using computer vision to identify conflicts makes it possible to measure, in real time, the changing risk level in traffic flow over periods of time. However, tracking and classifying road users and analyzing the resulting data is computationally expensive, and, at this point, requires powerful computers. Along with advancements in computer processing capacity, the development of scalable, cloud processing will put real-time computer vision analysis within reach. Raw data is becoming more readily available as many traffic networks are already subject to video monitoring by municipal authorities. This will make it possible, through real-time computer vision analysis to provide a “safety barometer” for networks or individual intersections. Measurement of higher than acceptable risk levels could then trigger countermeasures such as increased inter-green times or advanced timing of warning signals.

Driver behavior remains an elusive field of study. The behavior of drivers during normal or undisturbed passage driving conditions can be reasonably described using the many car-following,

lane-changing, and similar models. It is, however, in unexpected and potentially dangerous driving situations that driver behavior is less understood and less adequately modeled. The identification of conflicts can aid in the study of driver behavior in such situations.

Evasive action taken by drivers in conflict situations can be studied using computer vision techniques. In any study location, the types of conflict situations are limited in number and tend to repeat. For example, the study presented in Chapter 3 observed two primary types of conflicts: merging conflicts between right-turn and through traffic, and rear-end conflicts in the queue of waiting right-turn vehicles. For a given conflict type, the type of evasive action taken by the driver is reflected in the temporal patterns in the conflict indicators. When multiple indicators are used, as presented in Chapter 4, the types of the evasive action may be more easily identified. For example, in a merging conflict situation, the merging vehicle may decelerate aggressively to avoid the collision, or accelerate aggressively to merge ahead of the conflicting through-vehicle. Each of these maneuvers will return different patterns in the set of conflict indicators. Using pattern recognition, it may be possible to group avoidance behaviors and study their relative frequencies. At a minimum, the automatic identification of traffic conflicts allows for manual review and study of these unique situations without the need for the researcher to look through the entire duration of the recording to find such situations.

The study of traffic conflicts will lead to a better understanding of the mechanisms that lead to collision. By analyzing the trajectories of conflicting vehicles at very small time steps, the exact time that drivers take action, and the type and magnitude of the action can be recorded. The implementation of countermeasures can then be designed to reflect the mechanisms leading to conflicts at specific locations.

Traffic simulation can be improved through the use of computer vision tracking of road-users, and conflict analysis. Traffic simulation models and the parameters that govern them can be calibrated and validated using trajectories from real-world driving environments captured by computer vision.

Current micro-simulation traffic models tend to be based on what would be considered safe driving behavior. The study of traffic conflicts can aid in the creation of driving models that are more applicable to situations where there is limited sight distance, heavy interaction between conflicting traffic streams, or excessive stop-and-go behavior. Presently, behavior in such situations tends to be idealized in micro-simulation since it less well understood, difficult to model, or contains too much inherent randomness.

Finally, effective post-treatment analysis is necessary to determine the relation between the observed conflict reduction and the associated collision reduction. This can be carried out only after an adequate post-treatment time period has elapsed. At that point, the results of conflict analysis can be compared to the recorded change in collisions. Large traffic conflict studies, including the study presented in Chapter 3, provide excellent opportunities for establishing statistical links between conflicts and collisions. It is important researchers revisit conflict studies to gather collision records and make comparisons with conflict data. Only through continual validation of the technique can this new and promising method of improving safety on the road network be established.

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