AUTOMATED DIAGNOSES OF SAFETY PROBLEMS AT COLLISION PRONE INTERSECTIONS USING COMPUTER VISION TECHNIQUES

by

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Abstract

Road safety studies attempt to develop solutions to deficiencies by identifying causes and prescribing remedies. Most often, traffic safety engineers use collision information to detect potential problem locations and to provide assessments of treatments. The main short-coming of this technique is that it analyzes past information to determine whether a problem exists. This reactive approach requires an expert tasked to improve safety having to stand by and wait for collisions to occur. Many experts have recognized the need for a more proactive approach in order to reduce the analysis period and provide timely safety improvements.

One particularly promising alternative is the use of traffic conflicts as surrogates to actual collisions. Conflict data collection offers many benefits to that of collisions, including their relative frequency, and marginal social cost. Traffic conflict studies can be deployed in any location, need little planning, and do not require a vigilant database maintenance. However, since trained human reviewers are required there are significant costs associated with in-situ conflict observation studies. Furthermore, traffic conflict studies also rely on human judgement, which introduces subjectivity into results. The goal, therefore, is to find a way to harness data-rich traffic conflicts that is both efficient and fundamentally objective.

This thesis presents the novel use of an automated traffic conflict detection tool to diagnose safety issues at intersections with known safety deficiencies. Two intersections were analyzed to determine which movement types were over-represented. Once the most dangerous movements were identified, characteristics of the road user, environment, and conflicts themselves were analyzed to provide an educated recommendation for safety improvement. When the treatments had been implemented for some time, additional data was collected and similarly analyzed to determine whether it had achieved the intended goal.

The outcomes of this research provide evidence that objective and surrogate safety indicators can effectively be used to identify safety problems at intersections. In addition, the rich data collected using the automated traffic conflict technique can be mined to understand the mechanisms leading to and resulting in offending conflicts. This information can help traffic safety experts make informed decisions for focused countermeasure implementation.

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1 Introduction

1.1 Background

One of the defining features of developed nations is transportation networks that facilitate the flow of goods and people. At the turn of the 20th century, the surge of automobile use provided an efficient mode of travel that facilitated a higher quality of life to develop. Today, nearly 60% of Canadians own an automobile (Office of Energy Efficiency 2008); and the use of automobiles has transitioned from a mere convenience to a necessity that permeates all aspects of society. As with many technological advances, the benefits of automobiles have been tempered by the safety risks they pose.

With the coupling of speed, human and environmental effects, driving is a complex task that can lead to disastrous outcomes. Automobile collisions are a tragic by-product of the many benefits of improved personal transportation. The efficiency of road networks is inexorably tied to its safety and, as the demand for improved road infrastructure has grown, the trade-off has often been safety (Campbell 1992). In more recent decades, the impact of traffic casualties on society has become a more pervasive issue, leading to greater focus on safety issues.

Unfortunately, traffic collisions continue to be one of the leading causes of preventable death for all demographics throughout Canada. Of special concern is for drivers aged 25 and under, as traffic accidents are the most common cause of accidental death (70%) for this age group (Ramage-Morin 2008). Although collision rates per capita continually decrease (Ministry of Public Works and Government Services 2012), the total number of lives lost, or significantly affected by traffic accidents, is still unacceptable.

Traffic safety experts cannot only fault drivers as the cause of many collisions, but must strive to remove any perceived impediments to safe travel. The importance of reducing the social and economic costs associated with road collisions cannot be overstated (Sayed et al. 1995). Collisions are not merely a

Canadian problem, as the global number of road collision fatalities was approximately 1.3 million in 2004, and predicted to be the 8th most common cause of death by 2030 (Mathers 2005).

1.2 Traffic safety analysis

Traffic safety diagnosis has been traditionally undertaken using historical collision data. Such observational studies rely on crash data from individual locations that have been collected over a defined period of time. Typically, a municipality or road authority will record this data for many or all significant locations within their jurisdiction, and group similar locations together to compare against one-another and determine whether the incidence of collisions is abnormally high. Most often, similar intersections are ranked based on the frequency of collisions and normalized to its traffic volume. The baseline to determine the expected number of collisions is derived from a probabilistic model built from the combined data for similar locations. There are a number of ways in which these models can be calibrated, all of which use different statistical distributions to create the volume-dependant reference. If a given location exceeds the value predicted by the model, this is an indication that a safety deficiency exists (Sayed & de Leur 2008). In some cases, the severity of a collision is also considered, and a heavier weight is applied for more severe collisions. Once a location is identified as an outlier, the mechanism of failure may be further studied in order to determine a suitable countermeasure.

These observational studies identify macroscopic safety issues and provide quantifiable proof that a preventative action is required. As countermeasures are nearly always implemented by a government agency, they require an expenditure of public funds. Having a numerical method of identifying problems is important to provide a defendable rationale for these projects. Therefore, traditional safety analysis programs have been an invaluable tool for traffic safety professionals and respective agencies.

There are well-recognized problems of availability and quality associated with collision data (Svensson 1998), and in many jurisdictions, the quantity and quality of collision data has been degrading over the

past several years. Since the vast majority of collisions are relatively minor, they may not be attended by emergency personnel and, therefore, may go unreported. When a collision is significant enough to warrant police presence, the resulting data still may not provide useful information about its cause. As resources for police are increasingly spread out, those tasked with recording collision data often have little time to do so accurately. Since collision data is also recorded based on witness testimony, there is a tendency for accounts to be inaccurate, or intentionally embellished for personal protection. In addition, the use of collision records for safety analysis is a reactive approach; a significant number of collisions have to be recorded before action is taken (Sayed & Zein 1999). These extended time periods are required to ensure that increased reporting of collisions indicates a systemic problem at a location and not just a statistical anomaly. This presents a moral quandary, in that to improve safety authorities must first allow a significant number of collisions to occur. Unlike other engineering disciplines, however, experimental safety measures are not acceptable as they may expose road users to unknown risks.

Due to these shortcomings, alternative methods of safety evaluation play an increasing role in traffic safety. A common approach is to use an approximation to collision or "surrogate" method, that measure safety by using a proxy to the actual collision. This vicarious type of measurement is common in many scientific fields where it is simpler or more efficient to test for an indication of the presence of the target result. The simplest surrogate for traffic safety is using the exposure of a road user to measure the likelihood of being involved in a collision. This measure relies on the premise that the more time or distance accrued by a road user, the greater risk of a potential collision. While this is generally true, collisions occur randomly and each trip made in a vehicle is an individual case. Therefore, exposure is too blunt a measure to readily prescribe collisions based on magnitude. In 1967, researchers looked to 'near-accidents' or conflicts as a potential indicator of collisions (Perkins 1967). If a given movement or location experienced a significant number of events that nearly resulted in a collision, it was reasoned to be of a higher risk to experience elevated collision levels as well.

The observation of traffic conflicts has since been advocated as an alternative or complementary approach to analyze traffic safety from a broader perspective than collision statistics alone (Perkins 1967; Amundsen & Hyden 1977; Hyden 1987). A conflict is defined as "an observational situation in which two or more road users approach each other in space and time to such an extent that a collision is imminent if their movements remain unchanged" (Amundsen & Hyden 1977). The Traffic Conflict Technique involves observing and evaluating the frequency and severity of traffic conflicts by a team of trained observers. Since traffic conflicts are more frequent than collisions, their study can give detailed information about safety in an abbreviated study period. The technique, therefore, provides a means for the analysts to immediately observe and evaluate an unsafe driving manoeuvre at an intersection.

In practice, the Traffic Conflict Technique is deployed by first training a group of observers to detect near miss situations. The United States Federal Highway Administration (FHWA) has prescribed a methodology for standardized conflict analysis which sets out a criterion to easily recognize conflicts (FHWA 1989). Using this reference, observers are instructed to use the sights and sounds of the road environment to watch for conflicts. Potential clues include rapid acceleration or deceleration, screeching tires and other indications that one or more drivers are acting under duress. Observers are instructed to observe a single approach, or conflict type, which then can be compared to controlled locations or used in isolation as proof of unexpectedly regular dangerous manoeuvres.

Incomplete conceptualization and the cost of training observers and collecting conflict data have been factors inhibiting extensive application of the technique. Unlike traffic volume or turning movement counts, conflict observation requires continuous and vigilant observation. Furthermore, although guidelines exist, it has been proven difficult to generate a consensus on the constitution of a true conflict. When viewed in real time, the speed at which a conflict occurs may preclude an observer from detecting it or properly ranking its danger level. Reviewing recorded video footage has been suggested as a way to make a traffic scene more accommodating to human perception, while also providing a rich and permanent source of data. Although video data can be valuable, this method still leaves the detection of

conflicts to subjective review and can prove to be time consuming as the ability to re-review a scene can lead to decreased confidence in one's own analysis.

As such, the successful automation of extracting conflicts from video sensors data using computer vision techniques appears to have practical benefits for traffic safety analysis. Some of the most promising approaches rely on video sensors and intelligent techniques to interpret video data, including computer vision and machine learning. Vision-based systems for traffic monitoring would reduce the workload of human operators and help improve our understanding of traffic behaviour. Video sensors for traffic monitoring have a number of advantages, such as ease of installation, the possibility of securing rich traffic description, as well as scope of area covered by a camera.

1.3 Research objectives

In this thesis, road users are tracked using automated systems that rely on large volumes of video data. Once detected, the trajectory of a road user is used to measure an interaction by calculating the immediacy of a potential collision. This tracking and analysis of a road user employs techniques developed by Transportation Engineering research group at UBC. Drs. Tarek Sayed, Nicolas Saunier and Karim Ismail, whose efforts have successfully demonstrated the ability to identify various road users and extract useful data about their speed, acceleration and direction of travel. Other research has also used this tool to detect and count pedestrians and provide accurate before and after analysis of safety countermeasures.

The automated analysis tool can be extended to identify safety problems at specified collision prone locations. The main objectives of this thesis can be stated as follows:

1. Identify over-represented conflict types that are surrogates for most common collision types
2. Identify deficiencies that are most likely the cause of specific types of conflicts, and recommend targeted treatments

3. Evaluate the implementation of the safety countermeasures and determine if they resulted in a reduced number of conflicts

To the author's knowledge, this study is the first attempt to provide quantified evidence for targeted countermeasure implementation. The study intended not only to detect conflicts as indicators of safety deficiencies, but to do so in a specific and localized manner. While previous work had been calibrated to count predefined event types, the challenge of this research was to identify all conflict types occurring in the recorded scene simultaneously. Using this data, the researchers would provide a municipal client with a safety treatment selected through objective review of the information generated by the automated tracking algorithm. Just as historical data can provide a rationale for investment in a given location; this technique is meant to provide traffic safety practitioners with a tool to justify specific countermeasures.

With aide from the City of Surrey, approximately 85 hours of video data of two intersections was collected using existing traffic monitoring cameras that required no additional setup or cost to undertake this study. A total of 54 hours was used to identify the types of conflicts most over-represented at either intersection, and once the most dangerous movement was identified, recommendations for countermeasures were made based on the characteristics of the recorded events and existing safety research. The City of Surrey took these recommendations into account and implemented a design change to correct the dangerous movement. The remaining 32 hours of video data was collected specifically to analyze the effectiveness of the recommended treatment using an automated before and after study.

1.4 Thesis structure

This thesis is divided into seven chapters that present the past, present and future pursuits in traffic safety diagnosis. Chapter two is a review of the literature which has led to and aided in developing methods devised for the main study. Chapter three describes the methodology used in the analysis, including a detailed explanation of the automated tracking algorithm. This section also presents techniques created to improve and append existing algorithms, as well as innovations that facilitated diagnosis. Chapter four

presents a proof of concept study in which a short segment of video was analyzed using the automated tracking procedure. The results of the study were compared with a manual review to confirm the accuracy of the methodology. Chapter five presents the main diagnosis study conducted on two collision-prone locations in the City of Surrey, British Columbia and the findings and recommendations of the diagnosis. Finally, Chapter seven presents a before and after study that evaluates the effectiveness of the countermeasure implemented by the City of Surrey.

2 Literature Review

The literature reviewed in this section is the basis of this thesis. Described herein are topics that provide the motivation for this research as well as the background information on the tools used for the technical analysis.

2.1 Introduction

In response to traffic safety concerns, many road authorities have established Road Safety Improvement Programs (RSIP). According to The World Bank, these programs are the cornerstone of traffic safety initiatives:

"A national medium or long term Road Safety Plan is a prerequisite for achieving sustainable improvements in road safety" (The World Bank 2002)

RSIP provides a framework in which safety-deficient intersections can be 'screened' (Hauer et al. 2002) and the underlying issue identified and corrected. Typically, a RSIP consists of the following three procedures:

1) Location Identification (Detection): selecting 'collision-prone' intersections that can be treated – with engineering measures – to reduce the number of collisions.
2) Deficiency Identification (Diagnosis): determining the cause of safety issues at the identified collision-prone locations.
3) Countermeasure Implementation (Remedy): making changes to the existing intersection to remedy the problems identified in item 2).

Hauer (2005) identified a fundamental deficiency of RSIPs as the lack of evidence-based decision making to diagnose specific problems. In an effort to introduce objective analysis into safety diagnosis, researchers at the University of British Columbia (UBC) have developed a vision-based system to track

road user trajectories (Sayed & Saunier 2007). This system is used to identify 'near-misses' in road user interactions, and are used as supplementary safety measures (Ismail et al. 2009).

The following is a review of the current state of practice for steps 1) and 2) of a typical RSIP program as well as the standards for surrogate safety studies and automated traffic safety analysis.

2.2 Location identification

There are a number of different methods to identify collision prone locations by comparing the occurrence of collisions to some reference group or standard. The method of choice can vary by road authority and is dependent on the available data and a user's level of comfort with a given method. The following describes the most commonly used methods as well as their benefits and shortcomings.

2.2.1 Blackspot programs

Blackspot programs identify locations that have a statistically verified and elevated collision potential. The collision potential for a location can be measured by an accident measure such as the rate, frequency or severity of the collision that occurred. The underlying assumption in a Blackspot program is that the identified locations have engineering deficiencies which are at least partially at fault for the decreased safety. Blackspot studies are conducted by comparing similar study locations, such as intersections, defined segments of road sections or groups of either one. The locations can be further categorized by its area or type of location, such as urban, rural, freeway or arterial. The following are the most common methods used to determine whether an intersection suffers from an elevated risk of collisions.

2.2.2 Frequency

Collision frequency is the simplest detection method in that it considers only the total number of collisions that have occurred over a defined time period. Locations with the highest number of collisions

are considered the most dangerous and are consequently targeted for improvement. The rationale behind this method is that regardless of the traffic volume, wherever the most collisions occur is the most dangerous in its category. Since this method does not take into account the exposure to collisions for a location, it fails to consider that areas with higher volumes are expected to experience more collisions. Furthermore, without exposure it is impossible to differentiate between intersections with a collision per 100 or 10,000 entering vehicles that are treated equally.

2.2.3 Rate

Using collision rates to identify dangerous locations improves upon the frequency method by adjusting for traffic exposure. The total number of collisions at a location is divided by the total number of entering vehicles (for intersections), or the number of vehicle kilometers travelled (road sections). The use of collision rates is useful to compare locations with similar characteristics and different traffic volumes. However, the use of collision rates may introduce a bias as locations with low exposure will tend to have higher rates and a higher chance of being identified as collision prone.

2.2.4 Frequency-rate

Using both the frequency and rate, road authorities make use of the best aspects of the two aforementioned methods. Generally, a frequency threshold is defined as above, to find a location that may be a candidate, and the rate method is then used to determine which of the candidate locations require the most immediate attention. The process can also be applied in reverse order, or by setting limits for both frequency and rate in that an intersection must meet to be selected for treatment.

2.2.5 Severity

The severity method can be used as a supplement, or in place of either the frequency or rate method. The severity method rates the danger of a location by the sum of the severity of all of the collisions. Generally

three severity intervals are used (i.e. property damage only, injury, and fatality), to which an increasing weight is applied. This method accounts for the fact that the most severe collisions (fatalities) have a substantially higher social and economic cost than the lowest (Property damage only). The collision weighting is done by multiplying the proportion of each type of collision by a corresponding weighting factor (i.e. 1, 10, and 100). Different institutions may use different weights for each collision type, but this depends on the cost associated with each collision.

2.2.6 Data collection issues

A fundamental problem in collecting data to evaluate the safety of an intersection is that collisions are rare events. Collisions are subject to randomness which exists for infrequent events, and it is difficult to extrapolate long-term trends based on brief observation periods. The solution to this problem has been to collect data over a longer period of time, of generally up to three consecutive years. The consequence of this extended observation period, however, is that in order to collect meaningful data, the researchers must wait and observe a significant number of collisions that they can then try to prevent from occurring. This paradox is not only counter-intuitive, but in the case of vehicle-pedestrian collisions, can result in serious injuries or deaths occurring, in order to be thorough.

2.3 Diagnosis

When a location is identified to have an unacceptable safety level, it is necessary to determine the exact deficiency. This falls to traffic safety engineers who use all the data available to determine the cause, and to also suggest possible remedies. There is no universally accepted diagnostic methodology and it is common for individual road authorities or consultants to have their own procedure. While the allocation of significant public funds is dictated by these reviews, researchers and practitioners in the diagnostic field are limited. The following is a review of the available literature, including the procedural outlines of one local road authority.

2.3.1 ICBC technique

The Insurance Corporation of British Columbia (ICBC) is a crown corporation that provides insurance for British Columbia drivers. As the sole provider of primary automobile insurance, ICBC has a vested interest to improve road safety conditions. ICBC works in concert with British Columbia municipalities and traffic safety consultants to implement safety countermeasures in locations that exhibit inadequate safety. In 2000, ICBC employed a number of traffic safety experts to create a reference manual for traffic safety engineers. One section, authored by Dr. Tarek Sayed of the University of British Columbia (UBC), details the steps to diagnose specific intersection issues (Sayed & Ho 2000).

The ICBC training manual concedes that determining specific collision causes is a difficult undertaking. The author states that the process of countermeasure selection is a combination of technical analysis and engineering judgement. While engineering judgement requires experience in conducting safety studies, standardized procedures make analyses more reliable. The ICBC manual identifies the following aspects as being critical to safety diagnosis:

1. In office review;
2. On site observation;
3. Identifying causes/countermeasures; and
4. Economic analysis.

2.3.1.1 In-office review

The initial analysis of a location requires a review of data available from traffic counts, collision records and other relevant sources. Using available traffic engineering software, a capacity analysis should be undertaken to determine the level of service (LOS) of an intersection. If the intersection is operating beyond capacity, safety deficiencies may be attributable to operational problems. If any specific movements are over capacity, they should be considered more carefully during subsequent review steps.

If available, detailed collision data should be reviewed to determine if there are any over-represented movements, and a collision diagram should be used to consider independently each of the two-movement collision types. To determine whether a collision type is over-represented, the proportion of each type should be compared to the expected proportions of similar locations. The ICBC manual recommends using the chi-square test to compare the percentage of a specific collision type to that of a reference group. The selection of a reference group is not a trivial matter and should consist of locations that have similar characteristics. The chi-square equation and corresponding confidence table are used to determine whether a collision type occurs more frequently than expected.

In-office analysis should be completed by consulting with people who are familiar with the locations. A reliable source is police records as well as the officers who respond to these serious collisions. Even when records may not provide full details, Officers can provide further insight, or relate anecdotal accounts of the locations. Additionally, local engineering staff may have an understanding of problem locations in their municipality. While such reports may not have significant technical merit, they can provide a starting point on which to base the analysis.

2.3.1.2 On-site analysis

A thorough site visit should be conducted after the initial in-office review has been completed. A site Visit is necessary to get an accurate view of the geometric design, as well as the surrounding environment and traffic conditions. If any specific time period or road conditions (e.g. peak hour, rain) during the in-office analysis are identified as being especially dangerous, a site visit should be undertaken.

While on-site, safety engineers will gain an understanding of the location that cannot be attained from data analysis alone. Issues with the pavement quality and geometric design are factors that are immediately evident as a source of safety deficiencies. While a geometric design may conform to standards, an engineer should traverse the location to determine whether there are any unexpected or counterintuitive elements present. All vehicle manoeuvres should be attempted, while paying particular

attention to the movements identified as over-represented in the in-office analysis. The surrounding land uses should be noted and photographs taken from each approach for a permanent record.

The site visit also provides the greatest opportunity for the safety engineer to exercise their judgment. Experience from previous safety studies can guide a review of the intersection's operation, and identify features that can likely cause problems. Though this review is largely subjective, knowledgeable engineers are often able to form an accurate judgment within a one or two-hour on-site visit. An overview of deficiencies at the location will also confirm the countermeasure recommendation by the engineer that relies heavily on past experience and judgment.

The ICBC training manual suggests a number of physical and operational features that should be reviewed during an on-site visit (Table 2.1).

Table 2.1 Site visit checklist

Physical Features	**Operational Features**
Sight distance obstructions	Obstruction limits sight distance
Channelization	Conflicts, heavy turning volumes
Vertical and horizontal alignment	Speed differential
Parking operations	Friction, sudden lane change
Pavement width, parking lanes	Operating speed, congestion
Driveway related problems	Conflicts
Intersection turning radii	Correct turning path
Pedestrians, cyclists, transit, trucks	Potential conflicts
Traffic signal operation	Compliance/violations, gap acceptance
Pavement marking and signage	Driver confusion
Pavement condition	Erratic driving
Lighting	Driver slow down, erratic behaviour
Operating speed, posted speed limits	Excessive weaving, lane change

2.3.1.3 Collision causes and countermeasure selection

Using both the in-office and on-site evaluations, the causes of over-represented collisions should be identified. Given the location characteristics, and using the checklist (Table 2.1), possible causes can be narrowed down to only the most plausible. The type of collisions that are overrepresented will provide an idea of the deficiency of a location, and coupled with the on-site analysis, a safety engineer should be able to select the most likely reason the intersection is failing. In some cases, the cause may be more obvious than others, but the cause of the collisions for all cases is a combination of one or more of the issues listed in Table 2.2.

Table 2.2 Possible collision causes

Possible collision causes
Physical road condition
Location visibility
Traffic control device function
Adequate channelization
Heavy turning movements
Adequate capacity
Driver expectation
Driver compliance

The selection of a countermeasure follows directly the identification of the main collision cause. At any location, there are a finite number of possible changes that can alter the physical infrastructure. From these possible changes, the safety engineer must choose the most relevant and applicable solution to remedy the identified problem. This decision is mostly qualitative since it is difficult to predict the exact effect of a treatment before it is implemented. Engineers rely heavily on their judgement for countermeasure selection as well as from their experience on past successful projects.

Due to the significant capital expenditure to implement countermeasures, recommendations should not be given lightly. While determining the most suitable solution, a safety engineer should compare it to both

the current situation as well as all possible alternatives. Before implementation, therefore, an engineer should consider how all road users may be affected by the countermeasures. The selected treatment should minimize the identified collision types without compromising the safety of all road users. Finally, the countermeasure should be as efficient and economical as possible, provide safety benefits that outweigh the monetary investment.

2.3.1.4 Economic evaluation

Often a major deciding factor in countermeasure implementation is to determine which solution is the most economically feasible. Road authorities usually have limited budgets and so the treatment ultimately selected must provide a significant return on any investment. In road safety, their return is realized as a decrease in the number of collisions or injuries. Economic analyses are not unique to traffic safety and a number of methods are well-established throughout the engineering field. The most common evaluation technique is to compare potential returns and investment capital in a benefit-cost analysis (B/C)

B/C analysis compares the present value (PV) of both returns and expenditures, accounting for time to implementation and the length of time over which the benefits are realized. Present value calculations are heavily dependent on the selected discount rate and which should reflect the return on an investment in a 'do-nothing' situation. As such, the present value of a set of benefits can vary for different agencies or for different economic outlooks. The B/C value evaluated is the ratio of the present value of benefits and the present value of costs. If this ratio is greater than one, then the treatment will have a positive return and can be considered for implementation.

When considering multiple possible solutions, multiple countermeasures may meet the B/C criteria. Some options may be prohibitively costly and can be immediately ruled out. For the remaining options, if the highest B/C ratio is the least expensive, then it is most likely the best option. If treatments with the highest B/C ratio are also more expensive than others, then the worth of spending more should be tested with an incremental B/C comparison (ADOT 2009). The incremental B/C evaluation determines whether

the higher benefits of a more expensive option are in proportion to the extra money it will cost to implement.

Costs for different treatments stem from different aspects of their physical installation and operation which can include product and land procurement, and all costs associated with construction and ongoing maintenance costs. The cost for any countermeasure can be estimated with some accuracy based on past projects and from detailed take-offs from construction engineers. Each location will have its own physical and environmental characteristics that will affect the cost of a treatment. The suitability of each countermeasure must be carefully considered before proceeding with implementation.

The savings from a countermeasure are less definitive than the costs, but it should be given equal consideration nonetheless. The savings stem from both safety and operational improvement that should be realized from each treatment. Operational savings come from decreased travel time, improved level of service, and reduced vehicle operating costs and these savings are difficult to quantify and often treated as a by-product of the main safety benefits. Safety benefits are more obviously realized as a reduction of the frequency or total severity of collisions at the location. The decrease is calculated using collision modification factors (CMF) that many road agencies record from studies of past treatments (BCMOTI 2008).

Determining the financial savings from a number of prevented collisions requires assigning a dollar value to each collision avoided. Assigning cost to a collision is a contentious issue that poses both logistic and moral concerns. Costs are defined as being either directly or indirectly related to the collision. Direct costs result from physical damage, transportation, medical treatment, and legal fees. Indirect costs are poorly defined and are related to the impact on society resulting from a collision that includes pain and suffering and a decrease in the economic activity of the persons involved (Kragh et al. 1986).

The two most common approaches to assigning value to indirect costs are the human capital approach and the willingness to pay approach. The human capital cost attempts to apply a value to the real losses of the individual involved in the collision and society at large. This method has been criticized as its use in B/C analysis suggests that future lives are discounted compared to current lives (Revesz 1999). In contrast, the willingness to pay approach attempts to measure the value that an individual would place on their pain and suffering and quality of life. The latter approach tends to place a higher value on a life and is more widely acceptable for use in B/C analysis.

2.3.2 Diagnosis shortcomings

The procedure described above for identifying and diagnosing safety issues is used with little variation by many road authorities. While the steps to identify a problem location and the economic analysis of possible treatments have sound technical merits, the actual diagnosis procedure has some subjectivity. The in-office analysis procedure provides quantitative results for over-represented collision types, but it relies on specific attributes which need to be recorded for each event. For a variety of reasons, collision reports are often not sufficiently detailed, and collision data is commonly underreported.

Collision documentation is largely inconsistent because different jurisdictions require different information. Reporting of collisions is most commonly done by attending police officers, who are not traffic safety experts. While officers do a commendable job at the scene of a collision, their objective is to ensure that all parties are safe and that the location is cleared expediently. The exact cause of a collision may not be immediately evident and details may have to be learned from those involved. Some people may try to downplay their responsibility for a collision, and this leads to inaccurate accounts of the collision attributes. Collision data should be viewed cautiously, as reports are completed hastily and so minor collisions are often not reported, available (Woods 2003).

The limitations of current diagnostic procedures are also evident in the on-site analysis methodology. Accurate judgment of on-site issues is a product of many years of traffic safety expertise. Even if such experts were reliable, there are simply not enough members of the profession to meet the safety demand. As a result, safety audits can be expensive and time consuming and potentially discouraging to municipalities. The subjectivity of safety audits is also a concern to their credibility, as audits may be difficult to reproduce and defend to budget control authorities. Traffic safety researchers have identified the discrepancy between location identification and diagnosis. As Hauer (1996) states: "Much less has been written about, or taught to engineers, how to conduct a detailed safety analysis of a site. Yet, not common sense, practical experience or the usual highway and traffic engineering lore is a sufficient guide."

There is a clear need to provide traffic safety engineers with a more reliable diagnostic approach. One solution would be to train more traffic safety engineers and conduct more widespread safety reviews. As a whole, transportation engineering is a fairly small field, and it is unlikely that a large influx of new traffic safety experts can be expected. This solution also does not account for the inadequate formal training that safety engineers receives, and leaves the diagnosis expertise to be learned over many years of practice. While this may be sufficient in other fields, traffic safety directly affects public spending and the quality of life. Kononov & Janson (2002) liken the issue to the medical field in which the completion of medical school is followed by a multi-year internship, during which time they learn to recognize and treat conditions; something he contends is missing from the repertoire of a transportation engineers.

While several traffic safety researchers discuss the limitations of current methods, research has yet to uncover a widely applicable solution. Much of the current research relies on further analysis of the same data that may or may not be available. Taking the guess-work out of the diagnosis process requires a method that can provide repeatable and quantifiable results that can identify the shortcomings of a location. The methodology described in this research is a step towards this goal, and builds on new techniques and deployment of intelligent transportation systems (ITS) for safety purposes.

2.4 Alternative safety analyses

Collision data deficiencies require traffic safety professionals to use alternative methods to assess the safety of a location. One solution is to use surrogate measures for actual collisions in safety analyses. Using surrogate measures is a common to evaluate treatments in the medical community, since outcomes can generally not be calculated during its course. To be useful, a surrogate indicator must be fully correlated with the actual outcome and fully capture the effect of a treatment (Tarko et al. 2009). The surrogate measure should also be easy to measure and preferably provide a permanent record. Finally, the measure should be a phenomenon that occurs more frequently than collisions themselves (Archer 2004).

2.4.1 Individual measures

The FHWA published a manual on the use of indicators other than collisions to evaluate safety treatments (FHWA 1981). This document describes a number of factors that affect the potential of a road user to be involved in a collision. Considerations such as speed, gap acceptance, and compliance, are all described as having significant impact on the experienced number of collisions. This sentiment is echoed in other research where high speeds are especially identified as increasing collision risk (Kloeden et al. 1997). Although these factors are more readily measured than collisions, they provide only a macroscopic view of safety problems, and by their very nature rely on a behavioural measure in isolation that attributes the safety deficiency to a single source. While speed (or any other road user characteristic) may account for some of the risk involved at a dangerous location, it is impossible to know what role it plays without getting more information about the mechanisms of failure.

2.4.2 Traffic conflict technique

The Traffic Conflict Technique (TCT) relies on detectable and near-miss situations where there is some likelihood of collision. The TCT satisfies the criteria for a suitable surrogate and is described above by Tarko et al. (2009).

The Traffic conflict technique is included in a broad category of proactive safety approaches, which can be used to identify concerns before significant damage has occurred. A traffic conflict is defined specifically 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 remain unchanged." (Amundsen & Hyden 1977).

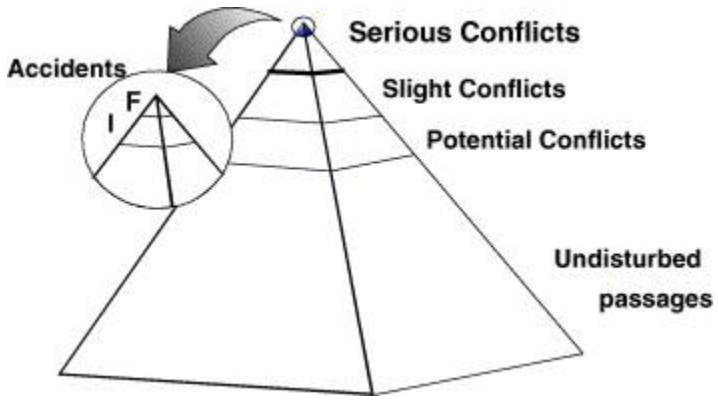
Traffic conflicts are thought to share many of the same mechanisms as collisions, with the most severe conflicts resulting in a collision (Guo et al. 2010). Collisions have many causal factors which must occur for the collision to take place. Traffic conflicts may be considered as situations where many factors took place, but where enough did not occur so that a collision was avoided (Laureshyn et al. 2010). The severity of a conflict is the measure that defines how near the road user was to a collision.

All road user interactions occur with some degree of infringement on safety, and Hyden (1987) described the degree of safety as a pyramid (Figure 2.1). The pyramid analogy states that the base represents the majority of road user interactions and does not require evasive manoeuvring. As the pyramid narrows, the proportion of all interactions becomes smaller and more dangerous, and the apex of the pyramid represents collisions. Its small size demonstrates the absurdity of basing all traffic safety decisions on such a small percentage of all traffic interactions (Svensson & Hyden 2006). The TCT exploits the conflict region of the interaction pyramid, which although small can occur more frequently than collisions.

To determine its impact on safety, all interactions must be placed somewhere on the vertical axis of the pyramid. The position of an interaction can be thought of as its severity, with higher placements approaching fatal collisions. Collision severity is defined by its outcome and is affected by collision, environmental, and road user characteristics. Typical reporting and categorization separates collisions into three categories:

- Property Damage Only (PDO): the least severe collision type. PDO Collisions may result in damage to private or public property and minor unobservable injuries.
- Injury: collisions resulting in non-fatal injuries are considered as medium severity collisions where significant property damage and possible debilitating injuries may occur.
- Fatality: fatal collisions are the most severe and result in the death of one or more people involved. Fatal collisions are treated with high sensitivity as all deaths have a high economic and social impact.

Figure 2.1 Traffic interaction severity hierarchy (Hyden 1987)



Collision categories are both descriptive and easy to identify with a definite outcome based on its characteristics. Conflicts generally do not have perceptible outcomes as a near-miss does not cause any damage, and because of the lack of visual indications, it is more difficult to rank conflicts based on their severity. The FHWA traffic conflict manual (Parker & Zeeger 1989) uses overt visual cues such as screeching tires and lurching movements to identify evasive manoeuvres. While these situations would certainly qualify as a conflict, only the most extreme cases would demonstrate the necessary qualities to be detected this way. Further measures are needed to identify conflicts up to and including the most severe cases.

2.4.3 Conflict indicators

There is significant research dedicated to measuring conflict severity between road users. A number of conflict indicators have been defined, all of which relate two road users by their speed and proximity at any given time. The following is a description of three of the most commonly used traffic conflict indicators.

2.4.3.1 Time to collision

The time to collision (TTC) is one of the commonly used conflict indicators. The calculation of TTC is based on the projected trajectory and current speed of two road users. If the road user trajectories intersect then there is a potential for both to occupy the same area coincidentally. In cases where the existing speed and distance to the intersection point will lead to a co-occupation, a TTC can be determined. The calculated value is the temporal proximity to a collision if one or both users do not alter their behaviour. The lower the TTC, the nearer the road users are to a collision (Hayward 1972). The calculated TTC value is sensitive to the defined area of coincidence and smaller areas result in fewer calculable instances.

Although it is widely used in traffic conflict studies, the TTC is ineffective in capturing certain types of conflicts. The existence of a TTC in itself signifies the imminence of a conflict, since evasive action must be taken to avoid a collision. In this study, TTC was proved to be unable to detect many left turn opposing conflicts that could lead to some of the most dangerous collisions. This deficiency is due to the nature of these types of conflicts. Very few left turn opposing conflicts occurred due to drivers being unaware of one-another, but rather due to poor gap acceptance. For this reason, TTC could not be used in isolation for the purposes of this study.

2.4.3.2 Gap time

Gap time (GT) measures the time by which two road users will miss occupying the same road space. The GT is measured similarly to the TTC, in that it relies on the projected path of the road user. Unlike TTC values, road users need not be on a path to collision to record a GT value. Gap times can be calculated for

many more situations than TTC, since many road users eventually travel over the same point. Gap time conflicts, therefore, are not always as severe as TTC events but can still provide a good measure of an interaction.

2.4.3.3 Post encroachment time

The post encroachment time (PET) is the actual time difference between two road users occupying the same space. The PET is calculated after an interaction occurs and provides a post-hoc measure. The PET is the simplest measure to calculate and can be used in conjunction with either of the previously described indicators. The lower a PET value, the closer a collision was to occurring.

2.4.4 Problems measuring indicators

Although the TCT provides a robust framework for measuring conflicts, a number of challenges hinder its use. Indicator values are calculated using the speed and distance between two road users at a given time, and a human observer cannot reasonably be expected to calculate these values in real time. As a result, manual conflict reviews are simplified to asses each event with a severity score based on estimated values. However, even with this simplification, manual reviews are difficult to conduct and require observers to make decisions about the presence and severity of interactions in busy field conditions.

Difficulties in conducting traffic conflict studies reduce their reliability and make its widespread use unattractive. Unlike collision data that is available as recorded data from historical records, conflicts must be recorded by trained surveyors. Regardless of their training, however, different reviewers may produce varying results in conflict reviews (Glauz & Migletz 1984). The variation is explained by the subjectivity inherent by a human reviewer and what they estimate constitutes a conflict. Subjectivity is present in all conflict reviews, making the results difficult to repeat and therefore often unsatisfactory for comprehensive safety studies. Despite significant research in the area, there is still no consensus of what a conflict is and how to apply it to safety reviews (Ismail et al. 2010).

2.4.5 Conflicts and collisions

Though there is a logical link between traffic conflicts and traffic collisions, a direct corollary has proven to be less than concrete. Most significantly, studies have shown that conflicts and collisions have a positive correlation. Multiple studies have attempted to quantify the correlation between the two; however the link appears to be subject to many environmental factors. For the purposes of this research, the work by Brown (1994) presents compelling enough findings to warrant the use of conflicts. Brown showed that for specific types of conflicts, correlation to the resulting collision type can be as high as 0.81. Since the diagnosis presented in this study compares only movements within a single location, the understanding that more conflict reflects a higher risk and so is considered sufficient justification for its use.

2.5 Automated analysis tools

Intelligent transportation systems (ITS) continue to develop as new technology finds practical uses. One of the most promising areas of this research is the development of automated road user tracking algorithms (Kamijo et al. 2000). These systems allow for accurate and efficient data collection and continue to evolve for safety analysis purposes (Atev et al. 2005). Current and past research at UBC applies well-developed computer vision-based techniques to analyze traffic data. Vision-based algorithms require the collection of video sensor data which is easy and cheap to collect with the aid of local road authorities. A detailed description of the UBC method is described by Sayed and Saunier (2007).

The most significant contribution of the UBC method is the ability to track individual road users in busy locations. Scenes with heavy traffic were previously considered the greatest obstacle to automated traffic analysis using video data (Maurin et al. 2005). This is achieved by using feature tracking that is based on the Kanade-Lucas-Tomasi algorithm. Before a road user is identified as a whole, constituent parts are tracked based on their movement against the stationary background. Individual tracked items are then grouped based on common movement patterns and proximity, while stationary and unrealistic features are

discarded. Tracking in this manner allows partially occluded objects to be identified, which alleviates the problems in busy scenes.

The UBC automated safety analysis combines the tracked road user trajectories with traditional conflict detection principles. The first step is to allow for unsupervised learning of representative vehicle movements from a typical segment of collected video. Each road user is dynamically matched to one or more of these prototype movements that are based on its trajectory as well as on a set of LCSS matching parameters. The result is a continually updated set of possible movements for each road user that is captured by the video sensor. The potential movements of any two road users and the distance between them can then be used to calculate the imminence of an interaction. Any interaction meeting a set of safety criteria is classified as a conflict that can be further catalogued by the type and severity.

The severity of a traffic conflict can be calculated by any of the aforementioned time-dependent measures. In a manual conflict review, calculation of these values is difficult, as computations of distance, speed and angle are required. The automated process makes the availability of vehicle tracks and projected movements a realistic undertaking. The measure or indicator used to rank conflict severity in this study is the gap time (GT). The GT is calculated by considering the projected trajectory of two road users to determine the point in space that they will both occupy at some time. By including the velocity of each user, the time between each one reaching this point is calculated as the GT. Due to changes in the velocity and position of a vehicle, the indicator value constantly changes and is continually recalculated for each video frame. The video refresh rate in this study is 30 frames per second (fps) as each conflict calculation is updated at regular 1/30 second intervals.

To the author's knowledge, no other work has been published in automated diagnostic studies. Although there is limited automated road safety research in general (Kononov & Janson 2002), diagnostic studies have been particularly elusive. A main issue in the past has been the inability of automated tracking systems to accurately track locations with many coexisting road users. The algorithm developed at UBC

by Sayed and Saunier (2007) bypasses this issue by using feature-based tracking developed by Kanade et al. (1991) and allows for tracking of partially occluded objects (Kanade & Tomasi 1991).

2.6 Before and after studies

Before and after (BA) studies are a means to analyze the effectiveness of an implemented safety measure. BA studies are a classical research methodology used in a wide variety of fields. In traffic safety for example, BA studies provide economic and practical validation for the use of a safety measure. There are a number of ways to conduct a BA analysis and all have their own protocol and data requirements. The following provides some context for BA studies and the justification for use in this research.

In principle, traffic safety BA studies are simple where the danger of a location should be improved after a treatment is installed. Traditionally, the number of collisions is used as the objective measure of danger, and the number of collisions is usually adjusted by the volume for a fair comparison in both situations. Hauer and Persaud (1984) first identified the need for an added level of complexity by citing the effect of regression to the mean. Regression to the mean is the tendency for extreme observations to be followed by values close to the long term average value, or nearer to the opposite extreme.

In a traffic safety context, regression to the mean affects the number of collisions expected at a location. Locations that are targeted for treatment have elevated collisions for a specific time period and some of these collisions may be attributable to random fluctuations (Svensson 1986). In subsequent time periods, this random fluctuation would likely be lower and result in fewer collisions. If a treatment is implemented, this natural reduction in collisions may be unfairly credited to the treatment. BA studies must account for the expected reduction in collisions if no action had been taken.

BA Studies must also consider environmental factors that affect the resulting number of collisions. A change in collision frequency in an after period of a study may be fully or partially attributable to changes other than an implemented treatment. These changes are referred to as confounding factors as they distort

the actual effectiveness of the treatment. The most common confounding factors include volume changes, dramatic weather difference, or changed driver comfort in the before and after periods.

The most common way to control for regression to the mean and other confounding factors is to include a control or comparison location. Ideally, a control site would be part of a group of similar locations identified as having high collision occurrence. Of a set, one location would be randomly selected for treatment while an equally dangerous location would be untreated. After controlling for volume, the change in the treated location is normalized by that in the untreated location using the Odds Ratio:

$$OR_k = \frac{A_i/C_i}{B_j/D_j} \tag{2.1}$$

where: $\mathrm{A_i} = \text{Condition at control site i prior to treatment}$

$\mathrm{C_i} = \text{Condition at control site i after treatment}$

$\mathrm{B_j} = \text{Condition at treatment site j prior to treatment}$

$\mathrm{D_j} = \text{Condition at treatment site j after treatment}$

The odds ratio can be described as the proportion of reduced collisions attributable to random fluctuation. The remaining percentage of reduced collisions can be reasonably assumed to have resulted from the addition of the safety measure which is called the Treatment Effect:

$$TE_k = OR_k - 1 \tag{2.2}$$

The treatment effect is typically a simplified version of the raw results of a before and after study, but can sometimes be magnified. This occurs when a reduction in collisions is accompanied by a spike in exposure. In either case, using the odds ratio provides a truer assessment of the actual effect of a safety countermeasure.

2.6.1 Automated before and after studies

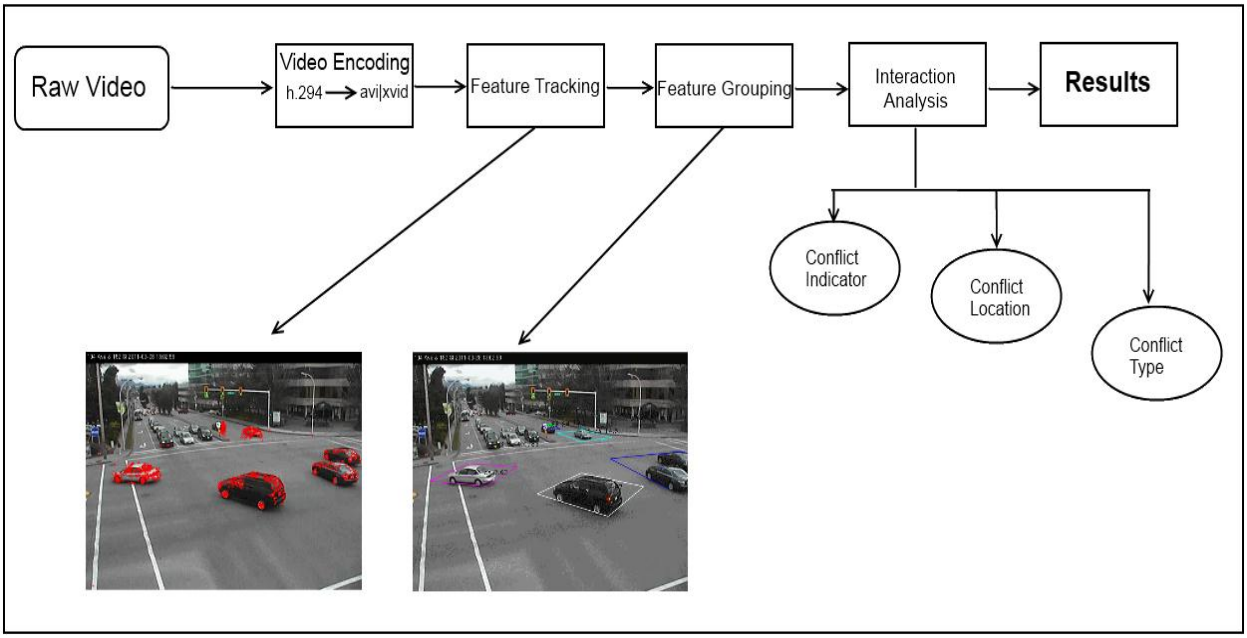
An issue with the traditional before and after process is that in order to review a countermeasure the same data collection shortcomings are present. After a treatment is implemented, reviewers may require several years to pass before they have sufficient data to compare it to the before case. During this time, significant changes may have occurred to driver behaviour in that area that the significant change may not be explained by the treatment alone. As collision data is rarely consistent, it may be difficult to measure the direct impact of the treatment on the target collision type, even when the data is collected. Furthermore, since significant social and political change may occur over a few years, the significance of the treatment can fade over time. In these instances, post-hoc reviews may not occur at all so that the decision of the engineers will not be qualified.

Building on the techniques used for traditional before and after studies, researchers at UBC have presented a method to employ traffic conflicts in place of collisions. This method uses the previously presented methods to compare the quantity, frequency, and severity of the traffic conflicts before and after a countermeasure is taken. Conflicts improve on many of the shortcomings of traditional before and after studies, including significantly shorter data collection periods, more available data recordings and more specific data. The tracking algorithm employed in this study has been used in previous and ongoing before and after studies for several municipalities (Ismail et al. 2010). In these studies, one or more specific treatments were reviewed by focusing tracking capabilities on specific movements.

3 Methodology

This section details the tools, methods, and analysis protocols used in this research. The study draws from several techniques presented in past research studies. Some of these tools were developed expressly for traffic safety purposes, while others were identified as potential solutions to safety analysis problems. This research was not undertaken to create a new analysis tool but rather to assemble existing and disparate ideas for a common outcome, and develop a repeatable procedure to aide traffic safety practitioners using state of the art techniques. The following details how each tool works, and how it fits into a traffic safety diagnosis protocol.

Figure 3.1 Methodology Process Flow



3.1 Computer vision based road user tracking

3.1.1 Pre-processing

The use of a computer algorithm to track road users is central to the objective nature of automated safety study. The algorithm used is a powerful tool that analyzes a video segment frame by frame to extract pertinent information about road users. Before this can be done, however, some basic pre-processing is

necessary. The following steps provide a frame of reference for the system so that the output is in useful units.

3.1.2 Camera calibration

Conflict analysis relies on accurate positional data of tracked road users, and the video captured from the onsite camera translates the 3-D real world space into a 2-D representation. The conversion is based on a number of properties such as the position of the camera's location and height, and the focal length, skew, and radial distortion of the lens. For analysis sake, the true positional data of a scene is of value, and the representation of the camera needs to be deconstructed to retrieve it. In this study, the relation between the camera image and world coordinates is specified by a transformation or homography matrix. Homography is a geometric concept used in many video applications where it is necessary to translate a camera image to meaningful data. For road user tracking, homography is used to translate objects moving in the camera field of depth to a position on a planar surface.

As each camera angle has different properties, a homography matrix must be defined for all study angles. To do so efficiently a method of calibration was devised using observable features of a given scene. The calibration procedure used in this study was first defined in previous work at the University of British Columbia (Ismail et al. 2010). By annotating points in the camera image and corresponding points in a Google Earth satellite image, an optimized homography matrix is defined. To create the optimized matrix, the procedure uses the four types of annotations listed as follows.

3.1.3 Distances

If distance in the camera image is known, the homography matrix can be created by finding the best possible solution to maintain the fidelity of all the measurements. Distances should be given for areas in the foreground and background of the field of view, as the same length will appear markedly different in

each case. While more input distances makes optimization more difficult, it also provides a more accurate transformation.

3.1.4 Corresponding points

Distinct features from the camera image, along with the corresponding point in the world image are selected. When multiple points are selected, the optimization algorithm calibrates the translation such that the distances between points are maintained. Corresponding points can be used or in place of distances, since it can often be difficult to retrieve the distances in the field. All locations in this study are major arterial routes with heavy vehicle volume that travels at high speed. Corresponding points were used as a surrogate as it would have been dangerous and impractical to physically collect distances at these locations.

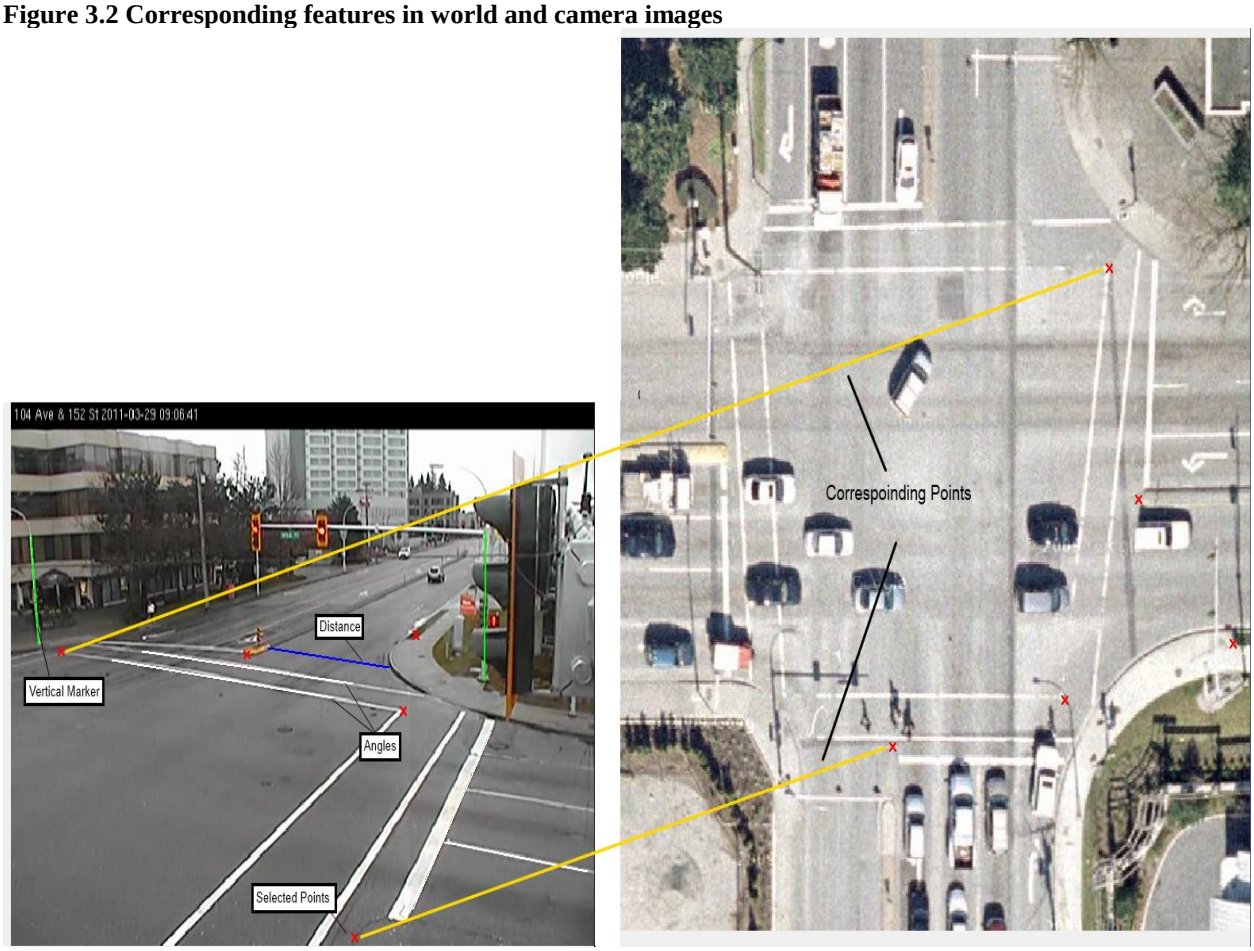
3.1.5 Angles

Known angles can be included so that the projection onto the world plane maintains the specified angle. Inclusion of angles is especially important as they help to define depth in the camera image. As it is difficult to determine many specific angles, parallel and perpendicular lane and intersection markings are most often used.

3.1.6 Vertical features

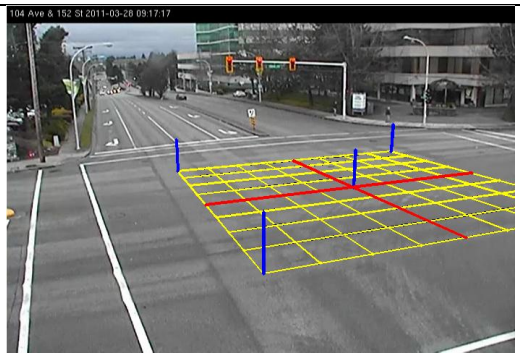
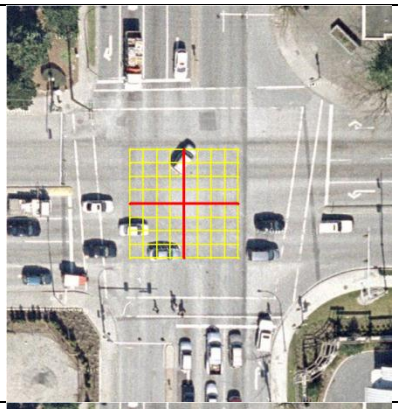
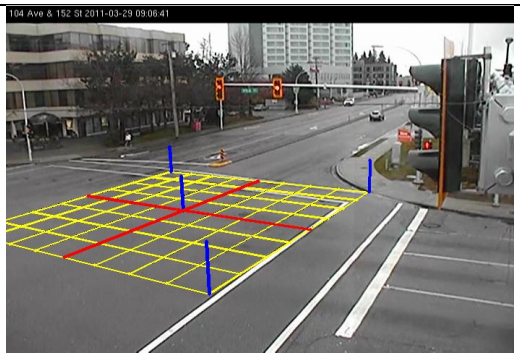
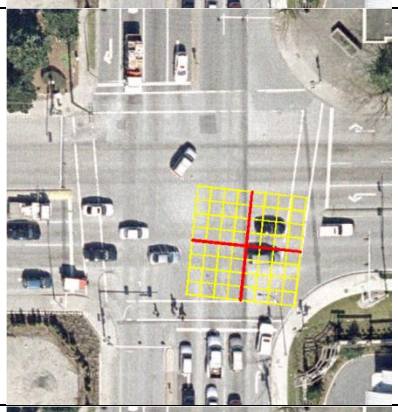
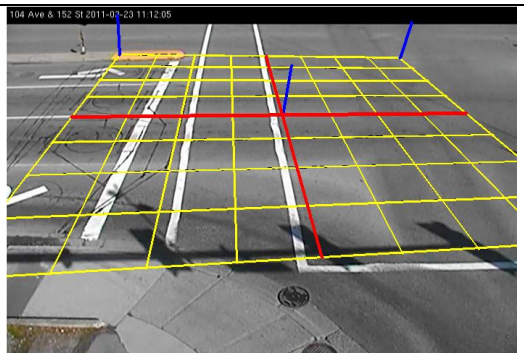
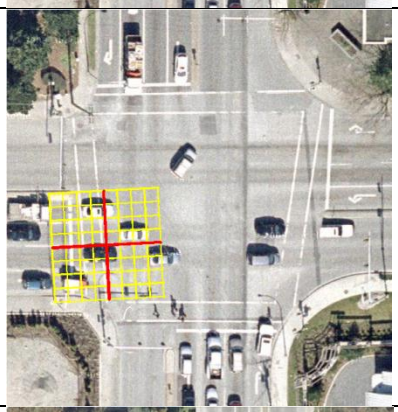
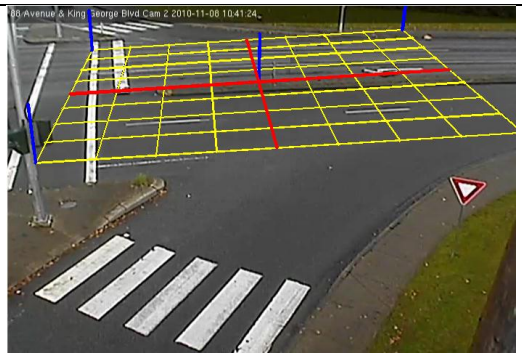
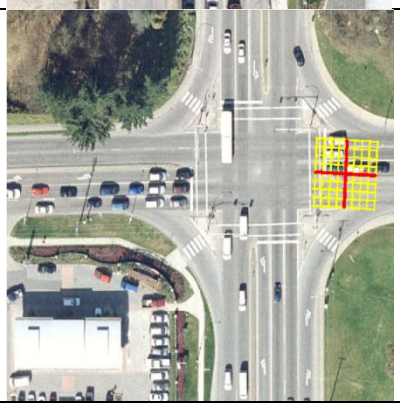
Telephone poles, lamp posts and other vertical landmarks are traced to define the three dimensional aspect of the camera image. Vertical markers should be perfectly orthogonal to the road surface as they define the tilt of the road surface relative to the camera or any barrelling effects of the camera lens itself.

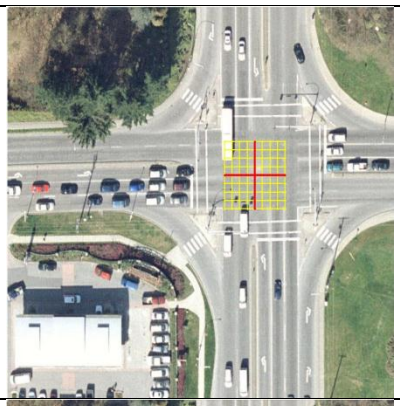
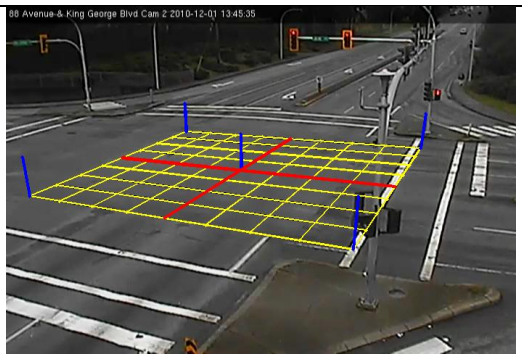
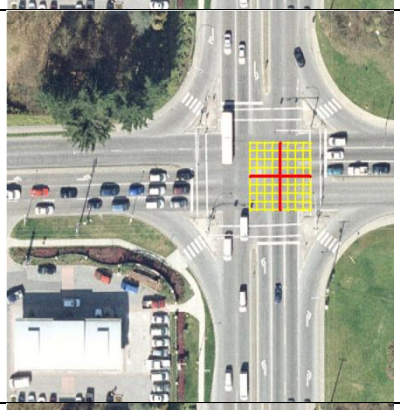
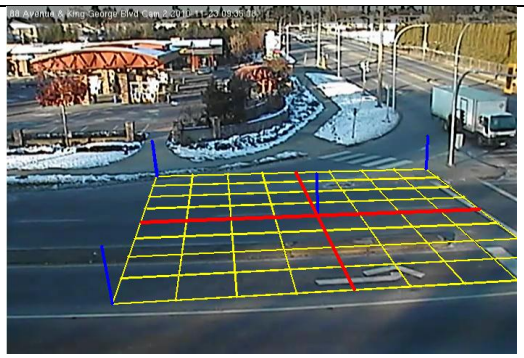
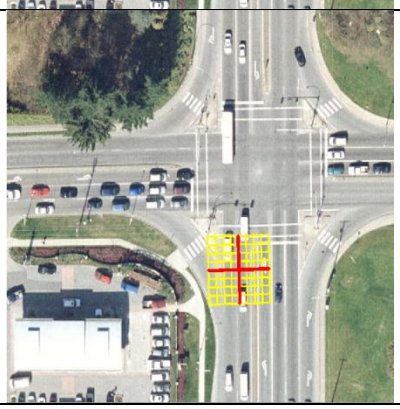
Figure 3.2 Corresponding features in world and camera images



Each camera angle requires a separate calibration as the zoom, rotation and field of view produce variations in the homography matrix. For each view, an optimized homography matrix is created by using the previously mentioned annotated points as constraint. The optimization algorithm attempts to maintain the fidelity of each specified calibration parameter, however a small margin of error is expected. The correspondence of camera points to their real world is very good and no significant tracking discrepancy is attributed to this error (Figure 3.2). Once the camera angles have been calibrated, the real world positions of all road users in a given camera image can be determined, and this is the fundamental process for automated safety analysis.

Table 3.1 Grids demonstrating accuracy of camera calibration for each camera angle

Calibration Grids	Grid Displayed in Camera View	Grid Displayed in World View
152nd Street @ 104th Avenue – View 1		
152nd Street @ 104th Avenue – View 2		
152nd Street @ 104th Avenue – View 3		
King George Boulevard @ 88th Avenue – View 1		

Calibration Grids	Grid Displayed in Camera View	Grid Displayed in World View
King George Boulevard @ 88th Avenue – View 2		
King George Boulevard @ 88th Avenue – View 3		
King George Boulevard @ 88th Avenue – View 4		

3.2 Processing

The processing stage is when the main constituent parts of the automated study are defined. This stage is characterized by four distinct phases, namely feature tracking, prototype generation, feature grouping, and interaction identification. Each of these tasks is completed by automated processes; however, they do require some user interaction. The processing is highly sensitive to a large set of parameters defined by the researchers who first devised the tracking algorithm. These parameters are defined before the start of

processing, by completing trial and error experiments on small portions of the analysis video. The fine tuning of the parameters was done in a largely ad-hoc manner and only completed after accurately accounting for all the road users in the test scene. Once finalized, the parameters are recorded in a configuration file that is referenced by the tracking algorithm at each processing stage. The following details the function of each processing phase along with the procedure used in this study.

3.2.1 Feature tracking

The basis for the positional analysis of road users is the ability for the tracking algorithm to differentiate between moving objects and the background image of the camera. The identified features are tracked through each video frame using the Kanade-Lucas-Tomasi tracking algorithm (Kanade & Tomasi 1991), tracked and then filtered to remove any that exhibit unrealistic acceleration or movement as well as those that remain stationary for multiple frames. Calibrating the parameters of feature tracking plays a pivotal role for the proceeding analysis since all calculations and extrapolations are based on the movement of the features.

Since the camera views are wider in these diagnosis studies, the sensitivity of the algorithm to moving features is set very high which, in any given frame results in significantly more features identified than the number of road users. Many vehicles travelling in the middle of the frame have dozens of features identified, many of which are redundant (Figure 3.3). For road users on the periphery of the frame, however, there is more distortion and typically fewer distinct features identified. Although the volume of features recorded for some objects is unnecessary, it does not deter from the analysis, and only slightly increases the processing time. Of benefit is that essentially all road users are tracked with an imperceptibly low margin of error.

Figure 3.3 Sample vehicle feature tracking

For the sake of expediency, the feature tracking stage for an entire analysis scene uses the same parameters. While there may be slight changes in the environment over the course of the day, a brief validation shows little difference in tracking performance. Once the parameters are manually optimized, the algorithm is set to run with the data recorded as text files containing the spatial and temporal properties of each feature. Although it depends on the vehicle density at any given frame, the feature tracking stage can take approximately five minutes for every minute of recorded video. For a full eight hour day of recording the feature tracking may take up to two days of total time to complete and is the most time consuming stage of this research, fortunately it does not require human interjection and often multiple angles are processed simultaneously.

3.2.2 Prototype generation

Prototypes are representative trajectories that encompass all road user movement in a video segment. Prototypes are used in the interaction identification stage of the analysis and help to define the potential movements of a vehicle from a given point. Prototypes are generated using a subsection of video footage that shows typical behaviour for the intersection. The video clip should include road users making all possible movements so that representative trajectories can be created for all movement types.

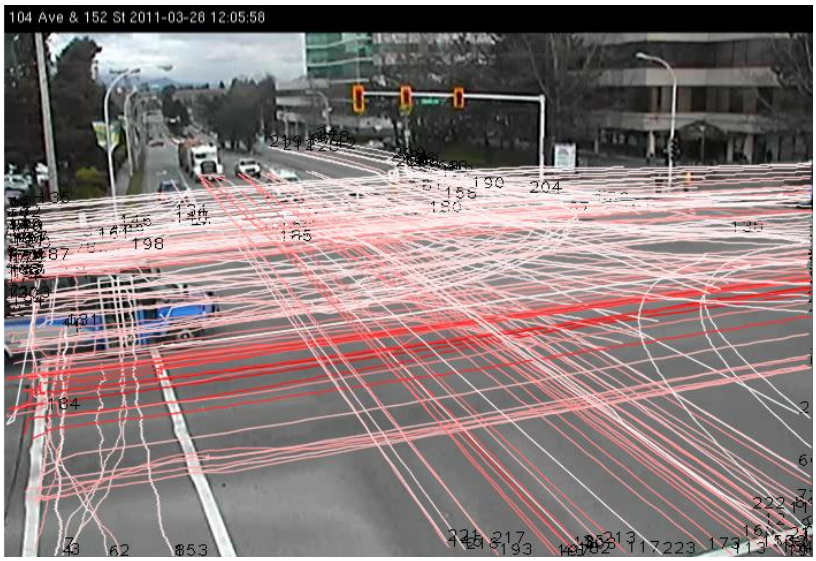
Prototype generation is an automated process using an unsupervised Longest Common Sub-Sequence (LCSS) clustering algorithm. Based on the movement of individual features, the clustering algorithm combines multiple features into a single representative movement. Not all movements of a type have the exact same trajectory, and so multiple prototypes will exist for any one road user movement. The final set of prototypes should display trajectories that encompass nearly all of the possible movements within the study intersection. Truly accurate representative prototypes are extremely important to have since the validity of interactions is highly sensitive to them.

In this research, prototypes were generated using a ten minute video segment for each camera angle. The selected clips were identified as having a high enough volume to capture the most probable movements. Not every feature tracked in this segment creates a new prototype, but rather many similar movements are grouped into one. Having many prototypes can provide a more precise interaction measure, but it also has a significant impact on the processing time. During the interaction stage, each road user is matched to the prototypes that it may be following in each frame. The more prototypes for an object to be matched to, the more interaction possibilities that need to be checked. The goal is to select a number of prototypes so that the interaction analysis can provide accurate results without severely impacting the processing time.

3.2.3 Pedestrian prototypes

The challenge of retrieving representative pedestrian prototypes was first discovered in the proof of concept study (Chapter four). In scenes where pedestrian activity is found to be sporadic, the ten minute video used to generate vehicle prototypes may not contain sufficient pedestrian activity to do the same. To achieve the same consistency with the pedestrian prototypes for each scene, five shorter video clips are identified in which multiple pedestrians are walking in a normal patterns. The prototypes from each of these segments are combined with the vehicle prototype file (Figure 3.4).

Figure 3.4 Sample vehicle and pedestrian prototypes



3.2.4 Feature grouping

As discussed in feature tracking, most road users will have several features tracked during their time in the field of view and as such, it is impossible to conduct a safety analysis with just the tracked features. To simplify the process, features within a given spatial constraint that exhibit sufficiently similar behaviours are grouped into an “Object”. The grouping process uses separate adjustable parameters to determine which features belong to which individual road user. The parameter optimization process is not trivial and must often be reassessed for different camera angles, and the same process is used to determine the optimal parameter definitions. Some of the most important parameters which determine whether features will be grouped are described in Table 3.2.

Table 3.2 Important feature grouping parameters

Parameter	Description
Connection distance	Connection distance for feature grouping
Segmentation distance	Segmentation distance for feature grouping
Maximum feature distance	Maximum distance between features for grouping
Velocity cosine	Minimum velocity cosine between features for grouping
Number of features group	Minimum number of features to create a vehicle hypothesis

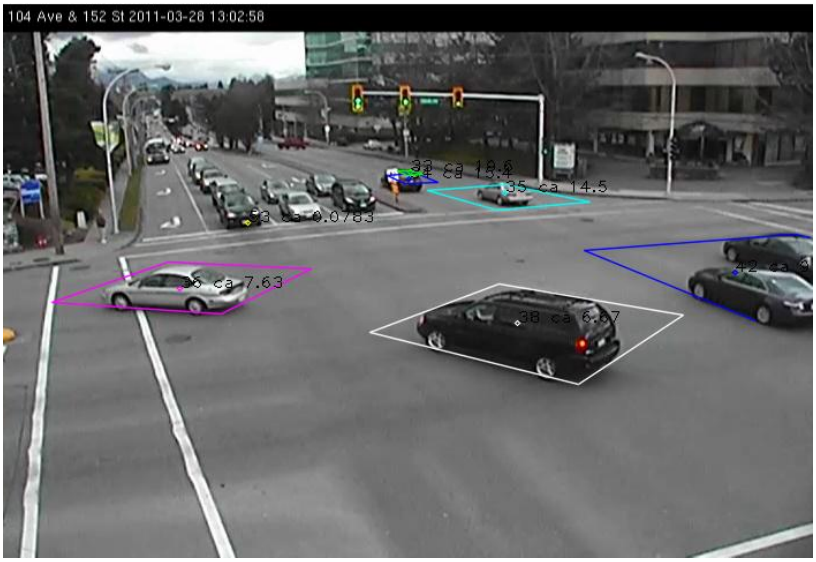
The feature group, or object, is defined spatially by the center of mass and extents created by the included features. For interactions, the object is reduced to a point, which is located at the center of mass. While this neglects the larger extents of vehicles, it provides a more consistent result as the vehicle extents can often be distorted in busy situations. Features in a group are already selected for their velocity and trajectory similarities, and so these features are simply averaged to get a single value for the object.

Feature grouping essentially groups the amorphous tracked features into the most important information and once grouped, the features become actual representations of the vehicles, cyclists and pedestrian. By itself, this rich and permanent dataset of identifiable pieces of traffic information can provide valuable information to traffic engineering practitioners. Other research efforts have focused on the ability to count, identify and provide quantitative data about the types of road users in a scene (Li et al. 2012; Hediyeh et al. 2012). These applications have incredible promise as many road authorities and municipalities are beginning to set up cameras for this exact purpose, but only in a manual capacity.

Since vehicles and pedestrians move differently and are of considerably different size, grouping both types of road users in the same scene proves challenging. Since only one set of grouping parameters can be used at one time, a balance must be struck between accurately grouping each type. Over-segmentation

and over-grouping, are two extreme groups that combine features in very fragmented or very broad groups. As a compromise, multiple pedestrians walking together are considered together, or over-grouped, as events between each member of the group are not significantly more.

Figure 3.5 Sample of multiple features identified as a single object



3.3 Interaction identification

3.3.1 Detecting conflicts

Interaction analysis determines which vehicles are in conflict with one another and provide the main safety analysis output. At each frame interval, an object is assigned to a set of prototype movements based on an LCSS trajectory matching algorithm. Once matched, a road user has a set of potential movement types with an associated probability dependent on the strength of the match. The potential movements of all coexisting objects are compared along with the relative speed, to determine whether potential collisions exist.

As conflicts are the central decision making tool derived from this analysis, it is important that this stage is conducted accurately and consistently between the difference scenes. The strongest factor in influencing interactions is the number or type of prototypes to which a road user is matched. All vehicle movements can be separated into a finite set of possibilities, but multiple movement types may share

starting and ending locations. As a result, vehicles can be matched to prototypes that are not actually in their direction of travel, improper matching slows the processing time and produces potential interactions that have no practical value. To control matching, therefore, the distance from a prototype and the percentage of time a road user spends within this region can be altered as needed.

Figure 3.6 Example of a right turn side-swipe conflict

For diagnosis purposes, prototype matching must be carefully considered and set so as that the types of conflicts recorded are not significantly impacted. There are typically no more than two or three different kinds of prototypes in studies focused on one or two conflict types. The challenge in these studies is to ensure a road user is not assigned to another movement type. In general intersection diagnosis, however, there can be upwards of ten different prototype classes used in processing one scene. Road users are unavoidably assigned to some prototypes that are not the actual movement they are making. To minimize this, the percentage of the trajectory of a road user that must match a prototype is 85%. Due to the variation in pedestrian movement, however, the distance of a match for a prototype was is to 2.0m. This distance represents approximately one half of the cross-walk width, which is deemed to be the maximum distance a pedestrian can be expected to deviate from the nearest prototype.

3.3.2 Conflict indicators

A number of conflict indicators can be used to measure the potential for collisions. However, not all conflict types are mutually exclusive, as over the life of an interaction it may be possible to calculate different indicators. For the diagnosis portion of this study, the GT indicator is selected to identify conflicts, as it provides the largest amount of conflict data. The GT is calculated as the projected time difference between one vehicle leaving a conflict area and a second vehicle arriving at the same point. Gap Time is calculated at each time step and is based on the projection of each vehicle's future position which changes with speed and specific prototype assignment. In this context, a lower GT signifies a narrower interval for safe passage and, therefore, a more severe conflict.

For the before and after study, a combination of GT and TTC were used as indicators for conflicts. For a given instant, a TTC is materially more dangerous than a GT, as it presents evasive action that needs to be taken. In ranking events, then, an event that contains a TTC is always considered as an event that is more serious. Post encroachment time was also calculated for events, but was excluded from the final analysis. Unlike GT and TTC, a post-encroachment time is only recorded in cases where one of the other indicators is also present. Not every event will have a post-encroachment time, so events with and without a recorded value are not compared. Finally, post-encroachment time will always be less severe than the lowest recorded GT or TTC value. As it is already known that the event is less severe than it may have appeared (a near miss), it is redundant to update the data with information that tempers the initial prescription.

3.3.3 Indicator smoothing

A conflict between two objects is generally not a discrete instance but a fluid event over a number of frames. From the moment that two road users are calculated to be in conflict, each subsequent frame may also show the conflict. The indicator value in successive frames can be more or less severe but this depends on whether the velocity changed for either road user. Since a road user velocity is calculated

based on its constituent features, there may be an instance when an outlying feature may cause a temporary illogical fluctuation. This in turn affects the conflict indicator and appears as a brief spike or dip but without physical explanation. A smoothing algorithm was developed to minimize the effects of spikes. The smoothing is applied by looking at successive five frame splices of the indicator value. The third value in this string is the target frame, which is replaced by the average of the two values on either side, Equation (3.1). Due to the nature of this smoothing procedure, the first and last two indicator values cannot be smoothed and are, therefore, removed from the sequence.

while:

$$ind(t_i) = x_i$$

$$y_j = smooth(x_i)$$

$$y_j = \frac{\left(\sum_{i=j-2}^{j+2} x_i\right)}{5} \tag{3.1}$$

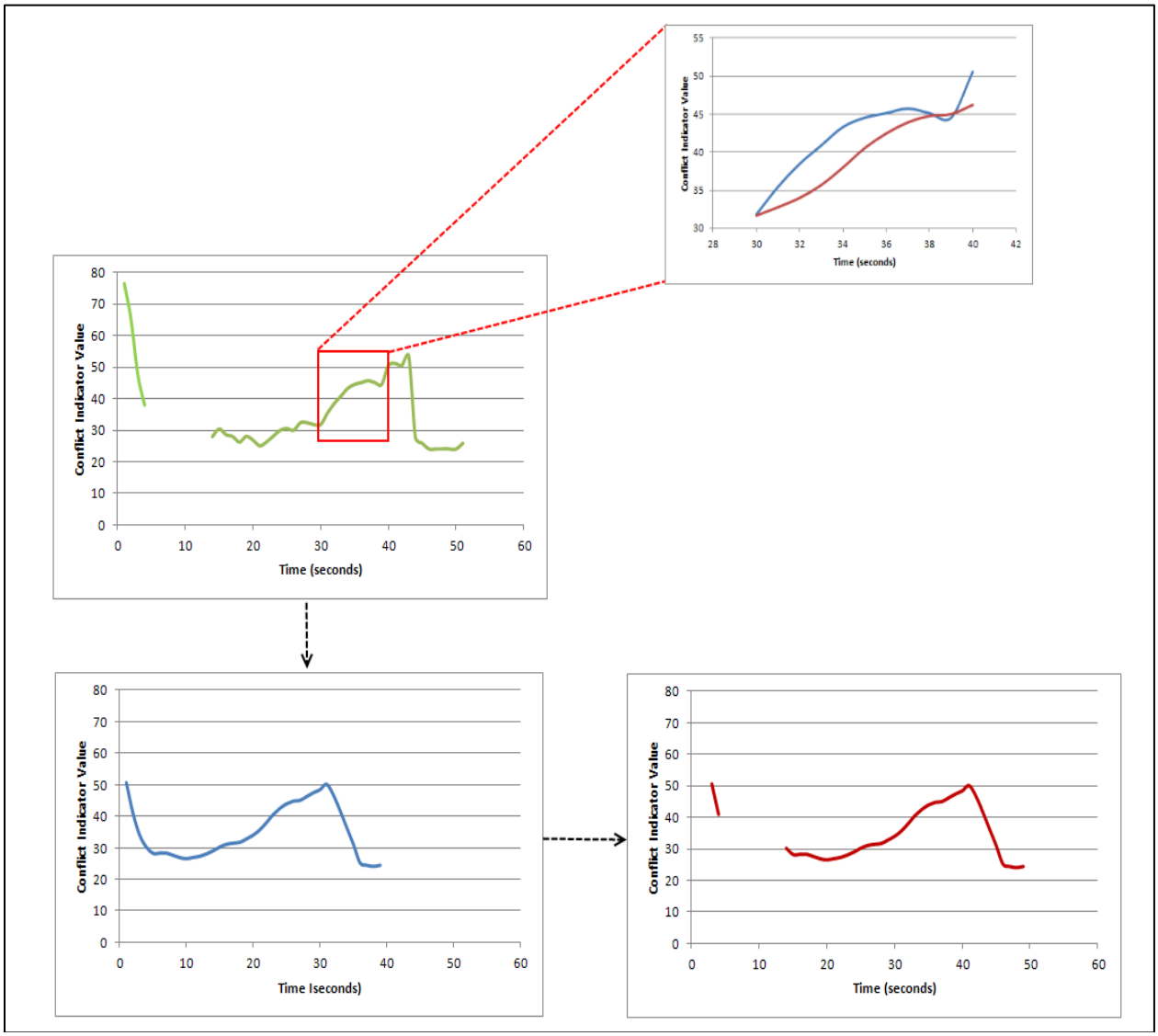
where:

$$j = 3 : N - 2$$

$$N = Length(x)$$

A conflict that occurs over discontinuous frames presents a different challenge, and to smooth it would require several frames' indicator values be dropped. Discontinuities may occur for several reasons, including road users temporarily stopping, indicator values going above the maximum threshold, or anomalies in feature behaviour. After reviewing the progression of several events, a solution was derived in which the gaps between recorded indicator values were removed. The smoothing process is then applied as normal, after which each indicator value is returned to its original frame position. This solution is deemed acceptable since no instances are found where the before and after breaks of the indicator value changed more than 10% (Figure 3.7).

Figure 3.7 Example of discontinuous severity indicator smoothing



3.3.4 Severity ranking

For analysis, each conflict is represented by a single indicator value and spatial position, in a single frame. This value is taken from the lowest (most severe) indicator value of a conflict. If an event represents a movement upwards in the conflict pyramid, its apex is the most dangerous value, and at this point, the two road users have the highest potential to eventually collide if no evasive action is taken. The maximum indicator threshold in this study is one second, and above this a conflict begins to resemble the normal driving behaviour.

To provide a meaningful ranking scheme, three severity tiers were defined. The maximum indicator value for severity is 60 frames (1 second) and the minimum is zero frames. Within this range, three designations are specified for low, medium, and high severity conflicts. The ranges of indicator values are shown in Table 3.3. In this hierarchy of events, all conflicts recording a time to collision are ranked in the most severe category. This distinction is made due to the immediacy of a time to collision value, as described in Section 2.4.3.1.

Conflicts are ranked for all parts of this study, but are of most importance to the before and after study than the diagnosis. There is no baseline in the diagnosis study, and having more events of a given severity does not significantly enrich the data. For this portion, the frequency of conflicts is more important for determining which conflict types are over-represented. In the subsequent before and after study, the severity values play a more important role as a significant shift in concentration within a given threshold may provide clues to the mechanisms at work.

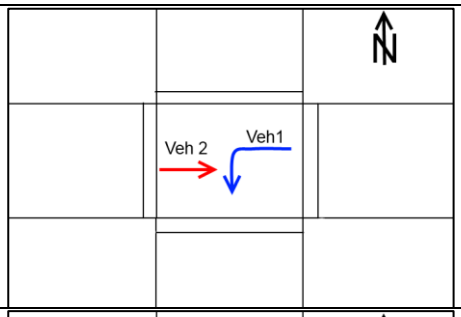
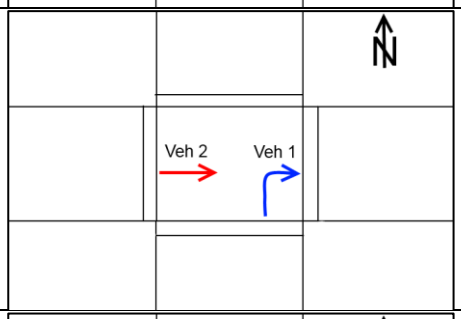
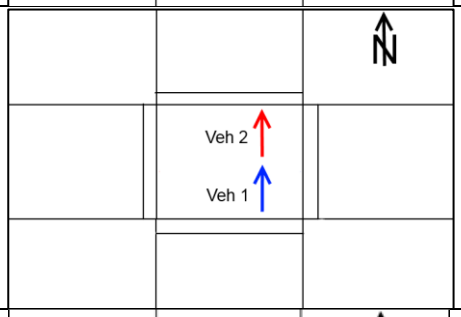
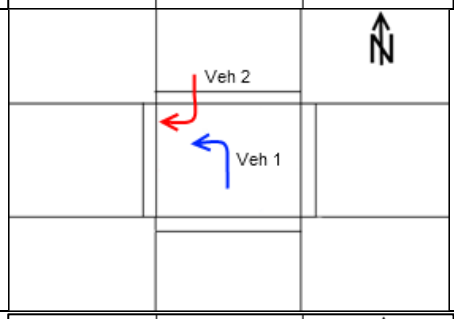
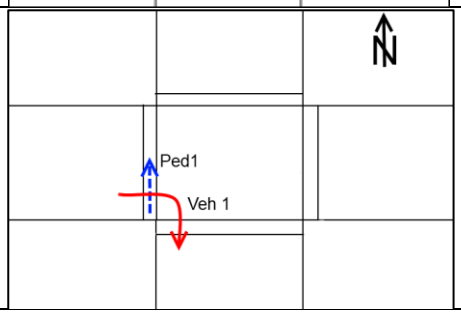
Table 3.3 Definition of severity rankings

Severity	**GT range**
Low	30 – 60 Frames
Mid	15 – 30 Frames
High	0 – 15 Frames + TTC Events

3.3.5 Movement identification

An important aspect of the automated analysis is the ability to identify the type of conflict created between road users. Knowing the location of a conflict is valuable, but any conflict point may have multiple configurations. To obtain more information about a conflict, the trajectories of each road user should be included, as well as their type and movement. Each pair of movements has only one possible conflict outcome, so the determination of conflict type can be reduced to a simple set of rules. The types of conflicts that can possibly occur and must be considered are shown in Table 3.4.

Table 3.4 Conflict Types at Four-Leg Intersections

Conflict Type	Schematic
Right Angle	
Turning Rear End	
Through Rear End	
Turning Sideswipe	
Pedestrian	

3.3.5.1 Movement type

To determine which movement an object has made, a simple procedural algorithm was devised. The procedure requires the user to demark in an interface predefined areas of the intersection. These areas are commonly the four approaches, which are the locations that the road users travel to and from. These areas are outlined in the global coordinates of each intersection, and common to each view at a location. Once the interest areas or "end zones" is set, the algorithm extracts the first and last coordinates of each road user and compares it to the list of start and end areas. Each pair of start and end zones is unique to a certain movement type, so there is no need to break down further the coordinates of the object. The algorithm cycles through the set of constraints until it reaches one that fits its coordinates. Each object takes on a number in the feature grouping stage and is assigned a new alpha-numeric code based on the type of movement it has made. This code is then stored in a database structure and then indexed to its original assigned number.

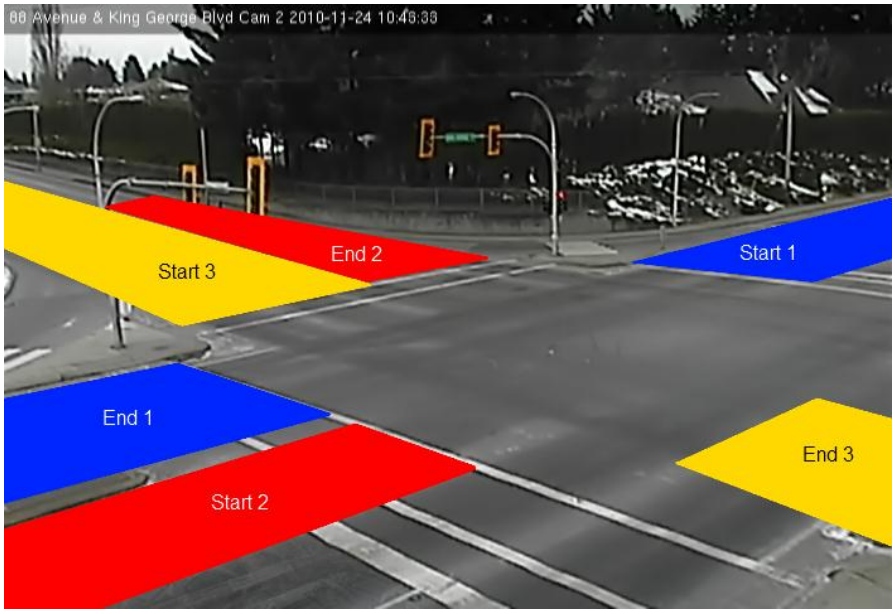
3.3.5.2 Conflict type

The motivation to extract this information was to efficiently categorize each conflict. To do so, a universal set conflict types was defined that was based on the finite set of legal manoeuvres through an intersection. Table 3.4 shows schematics of these conflicts and their constituent movement types. Although this process requires manual specification, the set of rules is valid for any typical four leg intersection where no movement or directional constraints exist. To extract this information, a simple querying algorithm was created to with the conflict data, the road user movement code database and the conflict type rule structure.

The two road users involved in each event are first identified by their original assigned number. Another movement type database is searched to identify the direction of travel code of each object. Finally, the two codes are compared to the conflict type rules from which the type of conflict is revealed. While this small addition to the automated system is simple, it significantly improves the usefulness of the analysis. The entire analysis of results focuses on determining which type of conflicts are over-represented, and

why. To manually sort through and categorize the thousands of events would be time consuming and defeat the purpose of an automated system.

Figure 3.8 Sample start and end zones selected for vehicle movements



3.3.5.3 Validation testing

To test the accuracy of the conflict categorization algorithm, a validation test is conducted on a random sample of conflicts. In this test, all events from the proof of concept case study as well as one thousand events from each intersection in the main study are randomly selected and manually categorized. For these events, the reviewer identifies the type of conflict that is based on the same set of rules defined for the automated system. The manual categorization is then compared to the automatically generated results for the same conflicts to determine if the accuracy was sufficient for widespread use. For the case study intersection, the accuracy is 98%, while the two intersections in the main study have 92% and 94% correct identification.

The higher success of the rate first intersection is likely due to the significantly smaller sample size where there is less opportunity for tracking anomalies. The correspondence rate from the remaining intersections is considered adequate both for the relatively high success rate as well as the nature of the failures. Those

incorrectly categorized are not classified as other types of conflicts, or not at all. Further inspection shows the problem to be in the movement classification of one of the objects involved in the conflict. In each case, the object in question has a tracking anomaly where it is improperly tracked at either at the beginning or end of its trajectory, it was improperly tracked. These objects are not assigned codes in the movement type database, and subsequently failed to return a value for the conflict classification. Since the total number of instances is low, the unclassified events from the full data sets are manually classified for consistent data.

3.4 Analysis methodology

To carry the automated methodology past the conflict identification stage, a standard set of information is extracted from each event. The idea behind this is that quantified road user behaviour data detected by the tracking algorithm can be used to identify systemic causes for specific conflict types. Although the same data is extracted for all conflict types, the varying nature of conflicts means that each was used in a different way (e.g., the way speed is used). Speed limit violations can be an important indicator for left turn opposing conflicts, but it rarely plays a part in pedestrian conflicts where dangerous speed levels are much lower. The following details the type of data that was extracted and how it was used to draw conclusions.

3.4.1 Speed

The most easily quantifiable and evident cause of collisions is speed as it plays a role in nearly all conflicts. The speeds of both objects in a conflict are extracted for their entire existence and not only during the conflict period. In some cases, the speed of one road user indicates poor driving behaviour, while in other situations the combined speed of both users creates a problematic situation. The speed of road users can also be combined with other factors to provide a complete picture of a cause.

3.4.2 Time

Although the time at which a conflict takes place is less obvious a factor than speed, it bears a real impact on safety. In a macro sense, the time of day heavily influences a driver's attitude and behaviour in that during the morning and afternoon peak hours, a driver is more likely to be in a rush and, as research has proven, more aggressive during typical commuting hours. Time can also impact the occurrence of a conflict within the length of a traffic signal in that nearing the end of the signal cycle a driver is more likely to make an aggressive or impatient manoeuvre to beat the changing light. This trend is especially evident in left turn opposing conflicts, where a driver waiting in the left turn queue is likely to accept a smaller gap that is based on their waiting time and expectation of oncoming drivers stopping.

To use the time of a conflict as causal indicator, reference information is required for both a macro and micro level comparison. On a larger scale, traffic volume data is analyzed for each intersection to determine the morning and afternoon peak hours within the recorded period. Additionally, a snapshot is taken four seconds before and after each event to see if a traffic signal change is imminent. This can be done on a continuous basis for the recorded video and the time it would take to do so manually is inhibiting. When combined with speed, time effects can easily be reasoned to play a role in many conflicts. The challenge was then identifying how the two combined to cause a dangerous situation.

3.4.3 Environmental factors

In many, if not all conflict cases, there are some environmental factors that play a significant role in its underlying cause. Unfortunately, this data is rarely quantifiable based on the measurement techniques used in this study. To identify these causes, the reviewer has to be able to step into the time of the event to see if evidence of some deficiency presents itself. To facilitate this, a video clip of each conflict is extracted and can be reviewed by researchers or traffic safety professionals. Included with the video of the event are the trajectories of the road users, their instantaneous speed and the conflict indicator and potential collision point at each frame. Armed with this data, the reviewer can make a much more informed analysis of the conflict and add quantitative measures to their qualitative traffic safety training.

4 Case Study 1: Proof of Concept Study in Downtown Vancouver, BC

This chapter presents a study with the purpose to prove the usefulness and accuracy of the methodology presented in this thesis. This study helps to develop and fine-tune the procedure used in the complete study and was invaluable as a confirmatory base. The focus of this work is vehicle-pedestrian interactions at a busy intersection which involve many inherent automated tracking problems. The findings derived from automated analysis are independently verified through manual review. Though the results in this study were not provided to any external bodies, and played a large role in being confident that the diagnosis process could yield useful results.

4.1 Background

Throughout North America, cities actively encourage citizens to make walking a more regular part of their daily commute. Whether it is to minimize congestion or promote a less sedentary lifestyle, this goal has resulted in significant policy shifts (Puccher & Dijkstra 2000). While some regions have passive measures in place, such as education programs, others pursue this objective more aggressively by improving the physical pedestrian infrastructure (Vernez Moudon 2001). While there may not be an immediate influx of new pedestrian traffic, changing conditions around the world will undoubtedly contribute to this trend. In the past, the marginal cost of congestion proves to be an insignificant factor in road users moving away from vehicle usage. As fuel and parking prices continue to climb, the additional real cost to drivers that has been effective in reducing vehicle usage in some cities. Coupled with increased environmental awareness, it is reasonable to believe that the coming years will see increased pedestrian activity in many North American cities.

As pedestrian volumes increase, so too does the exposure to being involved in a collision (Qin & Ivan 2001). Many factors influence pedestrian behaviour and because they have a less rigidly defined right of way, it is difficult to predict how they will act at any given intersection. Some studies have attempted to categorize pedestrian attributes, such as walking speed, on their demographics. While this can help

predict individual user behaviour, the heterogeneous nature of a road user group means that this may not help predict the overall risk at a given intersection or road section. Allowances can be made in areas where certain demographics are more prevalent (e.g. longer crossing times for pedestrians near a retirement community), but it is difficult to tell whether these and other intersections are especially susceptible to vehicle-pedestrian interactions.

4.2 Study location

The focus of this research is on an intersection that experiences high pedestrian volume along all four approaches and is located in downtown Vancouver, British Columbia. The location is the intersection of two main thoroughfares named Robson Street and Homer Street, both of which are two-directional. Surrounding the intersection are a number of amenities that include Vancouver's largest public library, a large hotel, and a number of coffee shops and restaurants. The video footage was captured through a third floor window of the public library by City of Vancouver engineering staff. The weather conditions remain largely unchanged for the duration of the video segment, although some sunshine is more prevalent towards the first portion. The video depicts typical road user behaviour, except for a short period during which an emergency vehicle blocked one approach.

Figure 4.1 Satellite image showing intersection and surrounding environment

Source: "Robson Street at Hamilton Street." 49°16'43.89"N 123° 06'57.37"W. Google Earth. April 3, 2009.

Figure 4.2 Northwest facade of public library from which video footage was shot

4.3 Study purpose

The goal of this study is to demonstrate the ability to automatically pinpoint problem areas within an intersection based on the frequency and severity of conflicts. Unlike previous work, no specific problems were indicated prior to the study so no conflict type or region of study could be ignored. Due to the

limited available video footage, it was unlikely that any significant policy decisions would be derived from an analysis of this intersection. Rather, the hope was to show that in a short period of time an unsupervised tracking algorithm could show trends in the direction of travel and point of conflict between road users involved in potentially dangerous conflicts.

The study most significantly compares the automated identification of events to a conflict analysis performed by a trained traffic conflict expert. The reviewer was asked to conduct a conflict analysis using the protocol specified in the FHWA Traffic Conflict Observer Guide (Parker & Zeeger 1989). This review was used as a validation measure against which to compare the results of the automated analysis. The merit of this review was highly regarded due to the short segment, as well as the ability to watch the footage multiple times. In addition to recognizing the occurrence of a conflict, the observer was also asked to rate the severity of the conflict on a scale of one to three, with one being the least serious.

This intersection presented a number of technical challenges, including the volume and density of pedestrians as well as a number of impedances to tracking. Due to the irregular behaviour of pedestrians, automated tracking is always difficult, especially so with groups walking together. In this particular situation, a number of traffic signal poles temporarily hid objects from the view of the camera. As a result, the algorithm is unable to track the road user features and cause a temporary loss of their track. In previous studies these types of problems were avoided by using a greater control of camera placement. Therefore, by obtaining meaningful results, this study demonstrates the capability of this automated tracking procedure, even when circumstances are not ideal.

4.4 Methodology

This section presents methods that are unique to this portion of the study. All work contained herein is undertaken as testing for a more widespread deployment of the automated diagnosis tool. Please refer to Chapter three for the more general methods used to track road users and identify conflicts.

4.4.1 Tracking performance

The reliance on any automated system to track conflicts rests on its ability to properly track all road users through space and time. To ensure that the algorithm output of important conflicts can be trusted, it is important that the system is accurate in tracking road users. For any one ground truth object (real road user), there are four possible tracking outcomes: correct tracking (one tracked object to one ground truth object); over-grouping (one tracked object to multiple ground truth objects); over-segmentation (multiple tracked objects for one ground truth object); and missed tracking (no object tracks for one ground truth object).

Figure 4.3 Example of vehicle being assigned one object track (good tracking)

Figure 4.4 Example of multiple pedestrians being assigned one object track (over-grouping)

Figure 4.5 Example of vehicle being assigned multiple object tracks (over-segmentation)

The occurrence of each of these outcomes is based on the parameters manually set for the tracking algorithm. Most importantly, feature grouping (Section 3.2.4) is controlled by the connection distance ($D_{connection}$) and the segmentation distance ($D_{segmentation}$). These values represent, the maximum distance over which to connect two features, and the maximum range over which two features can be considered in one group, respectively. There is no universal optimal for these values as they are highly dependent on the type and spatial density of objects being tracked as well as the location and view angle of the camera.

While generally not desirable, over-grouping and over-segmentation were not considered to be detrimental for the purpose of this study. For diagnostic purposes, being able to separate many pedestrians into individual tracks was deemed unnecessary because a vehicle conflicting with multiple pedestrians in the same instant should not be considered as multiple events. The aforementioned parameters were then set, then to minimize only the number of missed tracks. The accuracy of the tracking was found by analyzing a sample 1000 frames (34 seconds) of representative video and included both vehicle and pedestrian tracks. Using an iterative process, a tracking rate of 100% was obtained. This value is important as it confirms all road users can be tracked as the first step in a useful safety analysis. Although many users were assigned multiple tracks, they were not taken to be detrimental to the conflict analysis.

4.4.2 Road user classification

In order to accurately tracked conflicts, it is important to correctly classify road user types. Speed classification and trajectory classification methods have been used in the past to classify objects. Speed classification relies on a pre-set threshold of speed, below which any object is classified as a pedestrian. The problem with this method is that in many cases, vehicles making turns start at low speeds and are thus classified as pedestrians. To compensate for this deficiency, a method was previously developed to classify objects based on the trajectories they follow (Ismail et al. 2010). This method assigns a numerical code to each prototype and is, based on the behavior of its movement. Pedestrian prototypes are clearly identifiable by the irregularity in the motion (Figure 4.6). This motion is caused by the inconsistency in human stride patterns that involve multiple distinct motions. When trajectories are tracked they reflect the irregularity in the motion of pedestrians. In contrast, vehicles have no cyclical motion and so their tracking is a smooth straight or curved line.

Figure 4.6 Comparison of pedestrian and vehicle prototypes

With each prototype classified, an object classification algorithm is run in which road users are assigned to a prototype in the same way they would be in the interaction identification stage. Depending on which type of prototype they are assigned to, each object is also given a number that represents a pedestrian or vehicle. This classification is useful in the post-processing phase when sorting through the output events. Conflicts can now be sorted easily by vehicle-vehicle interactions and vehicle-pedestrian interactions.

4.4.3 Analysis and results

The 45 minute video segment was analyzed in order to determine the number of vehicle-pedestrian conflicts. There were also a number of vehicle-vehicle conflicts but they were ignored in this study. The severity of each conflict was based on the minimum TTC between the vehicle and pedestrian involved. Three threshold TTC values were set at 1, 2, and 15 seconds to denote increasingly severe conflicts. Another key element of the diagnostic study was being able to determine the spatial density of conflicts. Based on the intersection of the theoretical trajectory of each road user, a conflict point was defined for each event with a TTC within the defined thresholds.

A significant portion of the study focuses on validating the quality of the automated event detection. To do so, a traffic engineering specialist was asked to review the same video segment and perform a manual conflict analysis. While manual conflict analyses suffer from the shortfalls previously described, the length of this video allowed for an extremely vigilant review. Each conflict was described by the manual reviewer in detail so that it could later be compared to the automatically tracked events. The description included the direction of travel of each road user, as well as the general area in which the conflict took place (Figure 4.7). Each conflict was also assigned a severity rating by the reviewer. Though this measure was highly subjective, it was deemed to have sufficient merit as the engineer had experience in such reviews. The total number of manually reviewed events is 62, with 1, 17 and 44 conflicts ranked in the high, middle and low severity categories, respectively. Further break down of manual conflicts shown in

Table 4.1. The location of each conflict is specified by the broad regions shown in Figure 4.7**Error! Reference source not found.**, with the density of total conflicts shown in Figure 4.8.

Table 4.1 Frequency of conflicts by road user direction

Vehicle Direction		Pedestrian Direction		Frequency
2	12	1	10	1
		10	1	7
2	6	4	7	2
		7	4	2
2	9	4	7	1
5	3	1	4	2
		4	7	1
5	9	4	7	1
		7	10	5
		10	7	4
5	12	7	4	1
6	9	10	7	1
8	12	1	10	7
		10	1	13
8	3	1	4	1
8	6	4	7	5
		7	4	4
11	3	1	4	1
11	9	1	10	1
		7	10	2

Figure 4.7 Grid to manually specify location and direction of users involved in conflicts

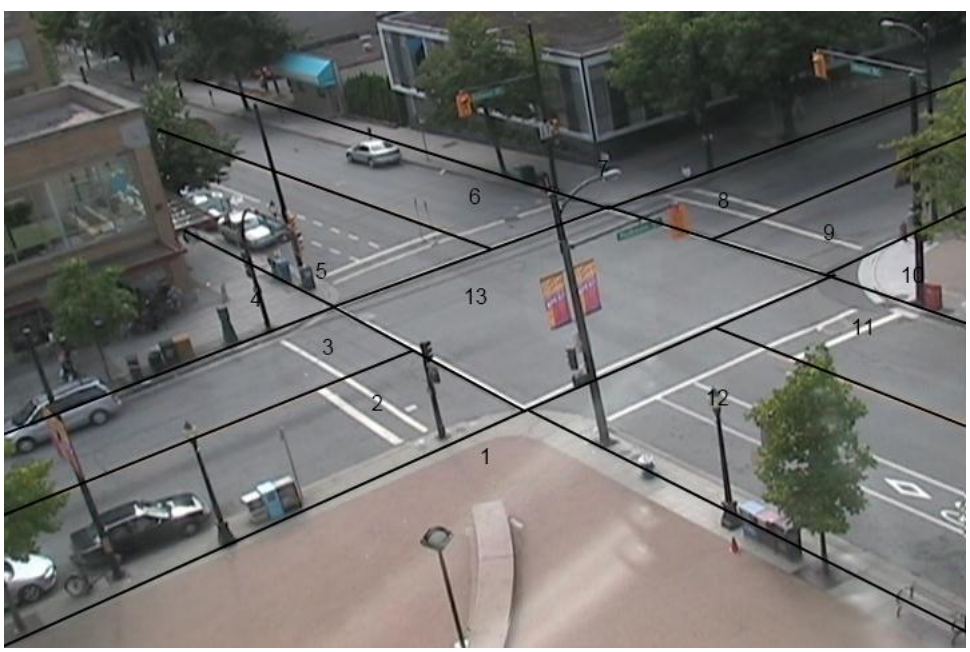
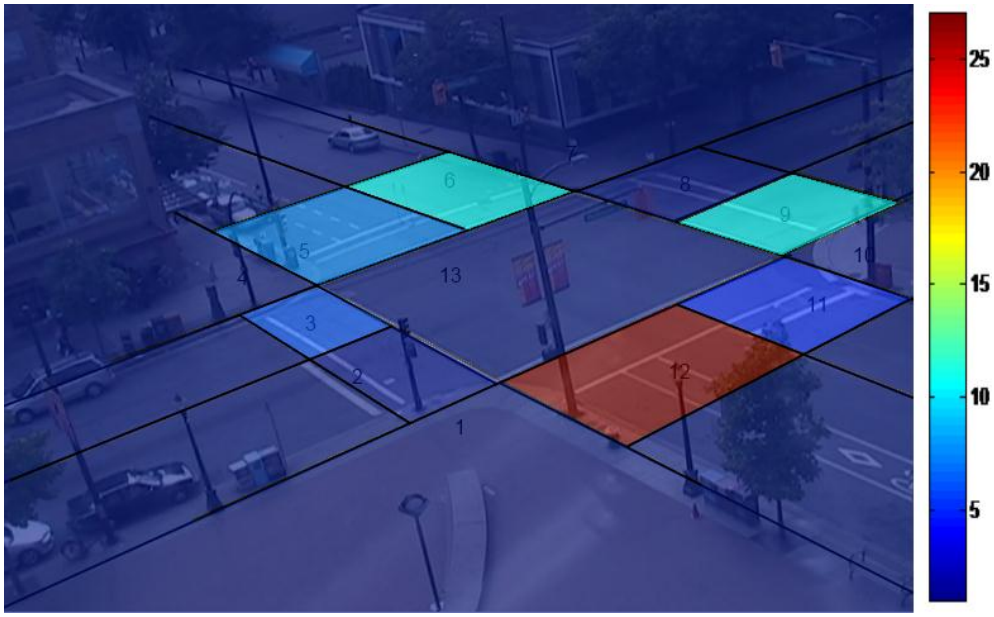


Figure 4.8 Density of manually identified conflicts



The automated analysis was conducted at an approximate rate of two minutes per video/hour. Once the parameters are set for the sample segment, the remainder of the video is tracked unsupervised with each two minute segment being considered independently. The number of events tracked is 66, with 25, 31 and 10 in the high, middle and low severity categories, respectively. Using the extrapolated collision points, the spatial density of all conflicts is also plotted with a colour that represents the severity of each event. Figure 4.9 shows the event of each location determined by the automated conflict analysis.

Figure 4.9 Collision point of each vehicle-pedestrian conflict

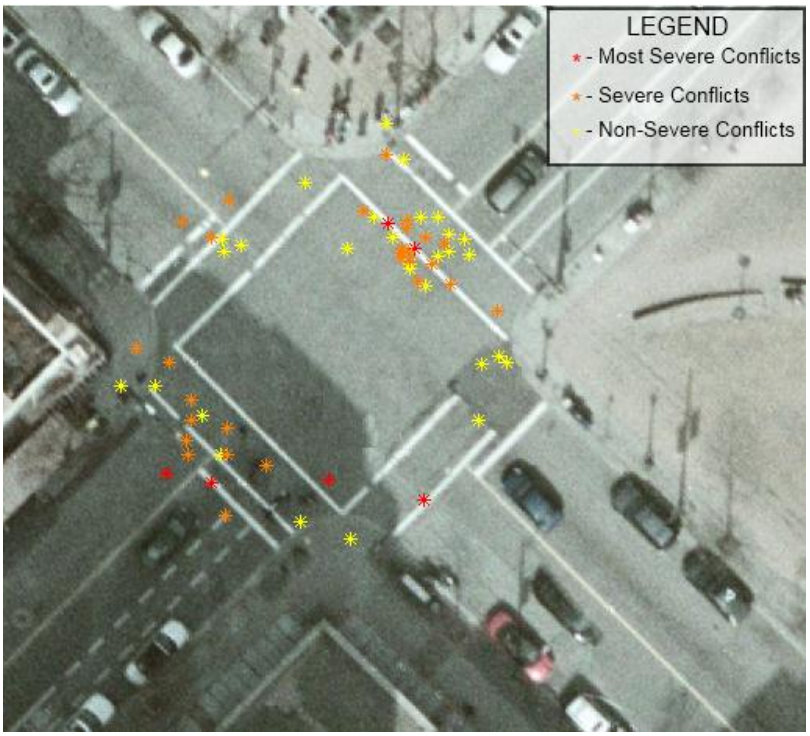


Table 4.2 Comparison of conflict severity for manual and automated reviews

	Review type	
Severity level	**Manual**	**Automated**
1	44	25
2	17	31
3	1	10

For the purpose of this research, the traffic conflicts that are manually detected are taken as ground truth events. As such, the automatically detected events are compared to those recorded by the safety expert. Of the 62 events manually detected, 53 were also detected by the tracking algorithm. Upon further investigation of the nine untracked events, six are found to involve road users who could not be tracked due to occlusion. Another three track both road users, but do not record a TTC below the threshold level. Finally, the automated tracking algorithm detected 13 events that are not manually counted, are objectively determined to be conflicts.

Table 4.3 Location of conflicts recorded in manual and automated counts

	Conflicts			
Approach	Manual		Automated	
North-East	29	47%	34	52%
North-West	13	21%	7	11%
South-West	15	24%	18	27%
South-East	5	8%	7	11%

The comparison between automated and manual events has a consistency of 85%, to show that unsupervised automated analysis can provide at the very least, a similar level of conflict detection to trained reviewers. The additional events identified by the automated algorithm are re-evaluated and determined to be viable events which further illustrates the inherent subjectivity in even the most careful of manual reviews. The location specification of each event is also consistent with the manually detected events as seen in Figure 4.8 and Figure 4.10.

Figure 4.10 Density of conflicts per 2m^2, as generated by the automated conflict analysis

The most significant finding of this analysis is the ability to determine which road user movements are the most dangerous. By extracting the tracks from the road users involved in each conflict, the direction of travel of each road user involved in a conflict is determined. Figure 4.11 shows the raw output of vehicle tracks generated by the tracking algorithm, while Figure 4.12 shows the breakdown of conflict types by the direction of the movement of the involved vehicles. Together with the conflict density shown in Figure 4.9 and 4.10, a clear trend emerges in the most common type of conflict. In just 45 minutes of analysis, it is already clear that pedestrians walking along the North-East approach of the intersection are involved in a disproportionate amount of conflicts with nearly 50% of all conflicts detected.

Figure 4.11 Automated tracks from road users involved in conflicts

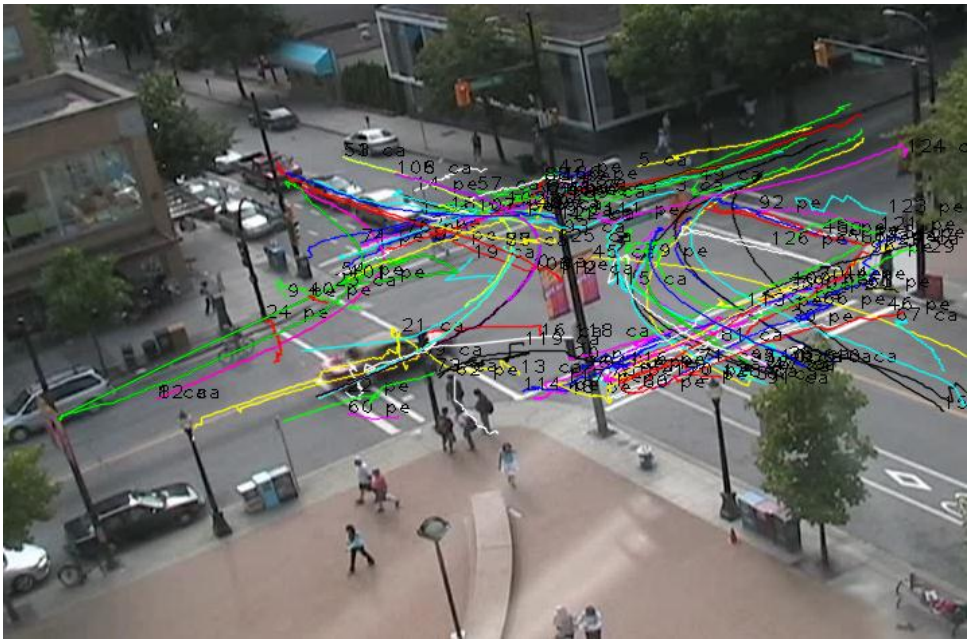
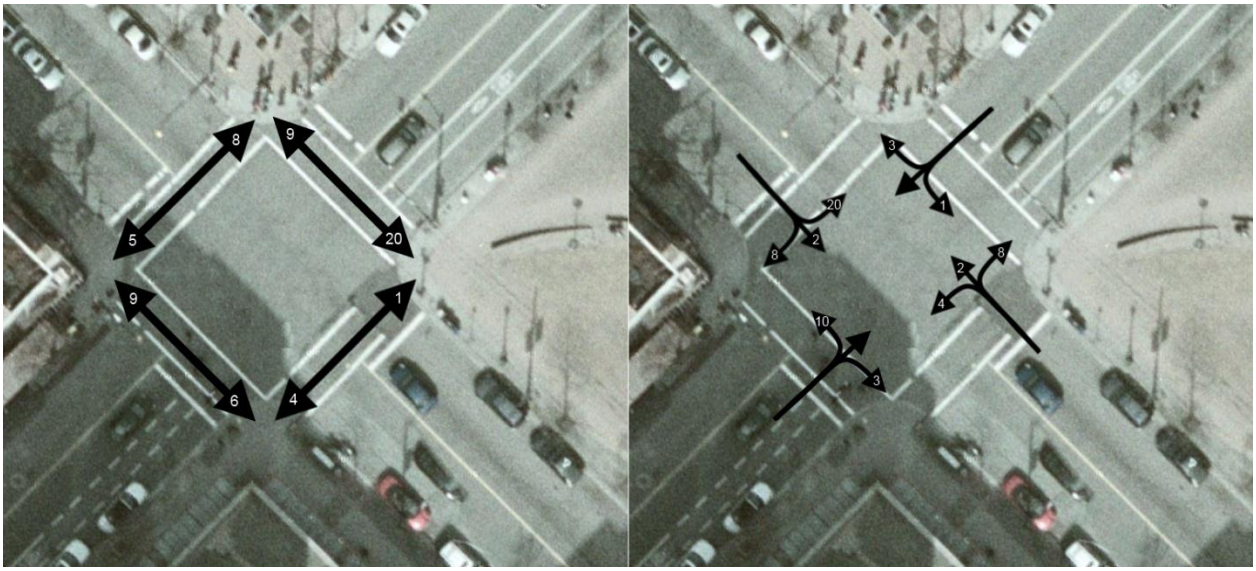


Figure 4.12 Pedestrians and vehicles involved in conflicts; classified by movement in manual review



4.5 Conclusion and continuation of work

This study demonstrates the ability to automatically detect conflicts between vehicles and pedestrians with a high level of accuracy. The length of the video segment allows for an extremely vigilant manual review of conflicts, to be used as a measuring stick for the automated analysis. The resulting 85% of confirmed events shows that the automated tracking system exhibits a sufficient level of accuracy to be used in diagnostic studies. Furthermore, the 13 automatically detected events that were not recorded by the manual reviewer proved that the algorithm can provide more consistent results than even a trained human.

The ability to diagnose locations of interest within the intersection is also shown to be possible, based on the automated extrapolation of two road users' theoretical collision point and direction of travel by each user. The density of collision points indicates a clear trend in the location of recurring conflicts as well as those areas that experience the most dangerous events.

Using the tracks from vehicles involved in the conflict, specific movements can be further studied if determined to be problematic. In the hands of a traffic safety engineer, this data can provide the insight to implement targeted improvement measures that can prevent future vehicle-pedestrian collisions. The accuracy of the spatial analysis is confirmed by the manual analysis, for which the spatial component of each conflict can be considered as an absolute truth. Both show similar densities of conflicts in corresponding regions even though the automated review provides a much higher degree of precision.

This study proves, on a small scale, that automated diagnostic programs can be accurately performed on a busy intersection with high pedestrian volumes. The continuation of this work will be to perform the same analysis on a much larger scale and using the information to determine possible solutions to existing deficiencies. The same framework can also be applied to diagnosing collision prone areas for vehicle-vehicle interactions. This type of study will require further refinement of the process as the number of possible conflict points is significantly higher.

5 Diagnosis Study in Surrey BC

5.1 Background

This portion of the thesis presents the methodology for using an automated safety analysis approach using traffic conflicts to identify safety concerns and their causes at intersections. As one of the fastest growing municipalities in Canada, the City of Surrey faces a dynamic range of issues related to its growth. One issue is road safety, which was identified by the City as a top priority in the development of the Strategic Transportation Plan (City of Surrey Transportation Strategic Plan 2008). To accomplish this, a proactive approach to road safety is required where measures are taken to prevent collisions before they occur.

The selection of a study location is predicated on providing a practical analysis for road improvement purposes. Working closely with the City of Surrey Traffic Operations Department, two study locations were selected. The two intersections were selected based on their collision frequency and the availability of traffic monitoring cameras. The two intersections studied are:

- King George Boulevard at 88th Avenue, and
- 152nd Street at 104th Avenue.

These locations represent the most dangerous intersections in Surrey for Vehicle-Vehicle collision and Vehicle-Pedestrian collision, respectively, as identified by their collision frequency.

5.2 Location details

In coordination with the City of Surrey, these locations were selected to demonstrate the abilities of the automated diagnosis technique. Furthermore, both intersections have remote controlled traffic monitoring cameras already installed and so no additional data collection cost was incurred. All data collection was done through a single camera at each intersection collecting different views on different days. The videos for King George Boulevard at 88th Avenue were collected on weekdays in the Winter of 2010/2011,

while those for 152nd Street at 104th Avenue were collected on weekdays in the Spring of 2011. All collection dates were consistent with typical traffic data collection standards as neither was taken on a day that would see markedly changed volumes or behaviour. Exact dates and characteristics of each day is shown in Table 5.1 through 5.7.

5.2.1 King George Boulevard at 88th Avenue

This intersection was selected because it topped the Insurance Corporation of British Columbia (ICBC) list of collision prone locations in Surrey, as described in an unpublished study. All approaches have a posted speed limit of 60 km/h, but as the intersection is relatively far from nearby intersections, the actual speeds are often much higher. In recent years safety devices have been installed in recent years in an attempt to remedy the long standing problem at King George Boulevard at 88th Avenue. Both advanced warning flashers and a red light violation camera are used to deter aggressive driving, especially at the end of a phase. Despite these added measures, safety issues persist to make this intersection a strong candidate for a more in-depth safety analysis.

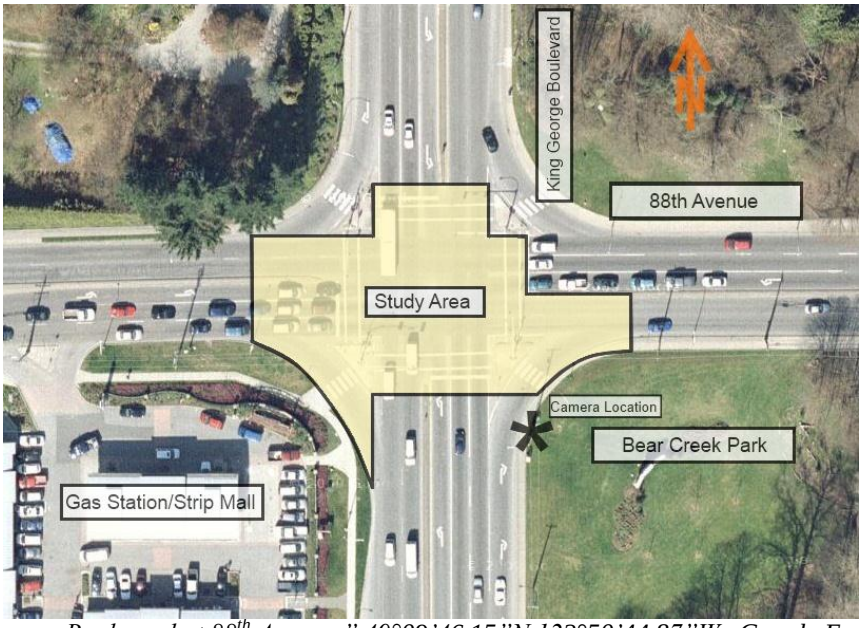
King George Boulevard (formerly King George Highway) is a major Surrey arterial that runs north-south from the Pattullo Bridge Fraser River Crossing to the Peace Arch Canada-USA border crossing. In both directions, King George Boulevard has two through lanes that are separated with channelized right turning lanes and separated protected-permissive left turn movements. King George Boulevard experiences heavy traffic volume in both the north and south directions, with a combined average annual daily traffic (AADT) volumes of 42800 vehicles/day.

Also, 88th Avenue is another major Surrey road that runs east-west from the Trans-Canada Highway (Hwy 1) in Langley through Delta to the East-West Connecter (Hwy 91) and Alex Fraser Bridge. In both directions, 88th Avenue has two through lanes that are separated, with channelized right turning lanes and separated protected-permissive left turn movements that brings not only heavy traffic volume from both

east and west directions, but also a combined average annual daily traffic (AADT) volume of 35700 vehicles/day.

While there is little development immediately surrounding the intersection, there are many residential and commercial developments a short drive in all four directions. In addition to having the highest vehicle-vehicle collision frequency, King George Boulevard at 88th Avenue is known to have issues with throughput volume. Although King George Boulevard is considered the major road, 88th Avenue also carries heavy volumes of commuters throughout the day. The City of Surrey actively addresses delay issues at this intersection by implementing a number of unique signal timing plans that are based on changing demand. Of particular importance is the throughput of left turning vehicles from the minor 88th Avenue approaches onto King George Boulevard. Queues for these movements often stretch well beyond the left turn storage bays, and cause additional delays for both left turning and through vehicles.

Figure 5.1 Layout of the intersection of King George Boulevard @ 88th Avenue



Source: "King George Boulevard at 88th Avenue." 49°09'46.15"N 122°50'44.87"W. Google Earth. April 1, 2008.

Figure 5.2 Northbound traffic approach of intersection of King George Boulevard @ 88th Avenue

Source: "King George Boulevard at 88th Avenue ." 49°09'46.15"N 122°50'44.87"W. Google Earth. August, 2011.

5.2.2 152nd Street at 104th Avenue

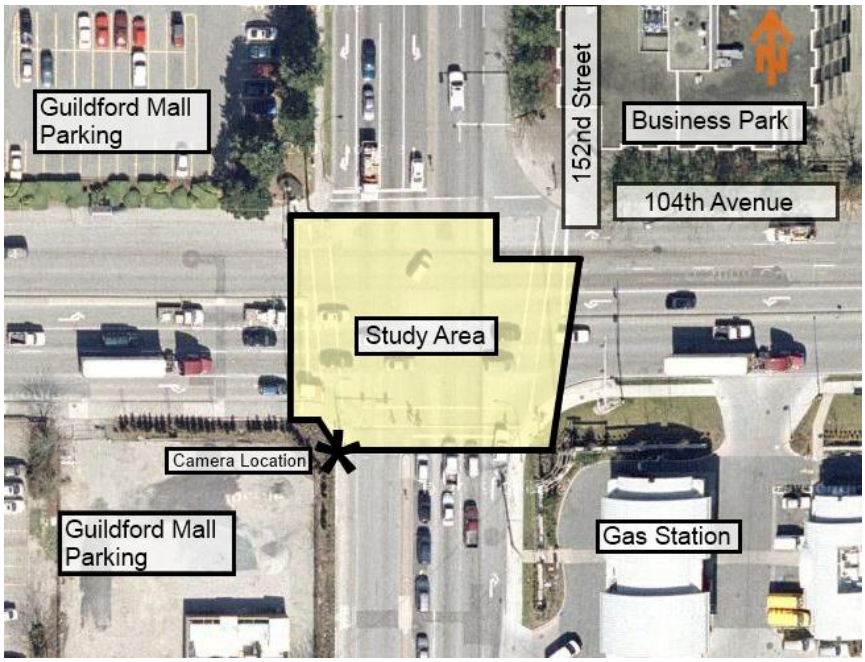
This intersection was selected because it represents the most collision-prone location for vehicle-pedestrian incidents. There are many factors that affect the safety at this location, including a high number of pedestrians moving along all four approaches. The area immediately surrounding the intersection has a variety of commercial services and amenities that cater to different demographics. With a major shopping center immediately adjacent to the intersection, entry and exit driveways further complicate driving conditions. Of particular interest at this intersection is the mechanism of pedestrian and vehicle movements that lead to collisions and what specific countermeasures can be adopted.

Another major Surrey arterial is 152nd Street, which runs north-south from the Trans-Canada Highway (Hwy 1) to White Rock beach, respectively. At the time of this study, both the north and southbound approaches had two through lanes, separated right turning lanes, and separated, protected-permissive left turning movements. While the right-of-way changes are planned, this study only considers the geometric design seen in the collected video. With a combined average annual daily traffic (AADT) volume of 37800 vehicles/day, 152nd Street experiences heavy traffic volume in both north and south directions.

Another busy route running east-west in the north Surrey area is 104th Avenue. Both its approaches have two through lanes, a designated right turn lane and a designated protected-permissive left turn lane. This road experiences moderate traffic volume in both north and south directions.

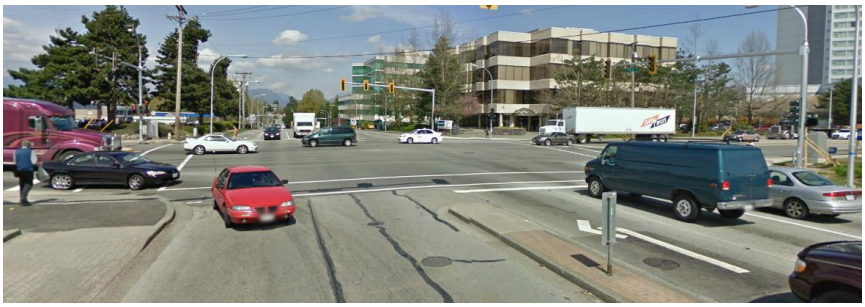
The pedestrian activity at this intersection is the main focus of the safety analysis. The intersection experiences heavy pedestrian volumes in all four cross walks; however only pedestrians using the west and south crosswalk can be analyzed. As the surrounding developments encompass a variety of commercial land uses, pedestrian demographics vary considerably. No pedestrian categorization was conducted, but other research in automated pedestrian tracking may help to further diagnose problems regarding specific road user groups (Li et al. 2012).

Figure 5.3 Layout of the intersection of 152nd Street @ 104th Avenue



Source: "152nd Street at 104th Avenue." 49°11'29.32"N 122°48'03.16"W. Google Earth. April 1, 2008.

Figure 5.4 Northbound traffic approach of intersection of 152nd Street @ 104th Avenue (Google Earth 2011)



Source: "152nd Street at 104th Avenue." 49°11'29.32"N 122°48'03.16"W. Google Earth. August, 2011.

5.3 Data collection

The automated safety analysis employed in this study requires adequate video footage of each intersection. This study employs city traffic monitoring cameras to collect the required data. Use of these cameras is attractive since no additional time or cost is required for data collection. The permanence of these cameras makes any subsequent reviews very simple as data can be obtained with little prior planning. Furthermore, central control from the City of Surrey Traffic Operations Center means multiple angles can be recorded to conduct a full analysis from a single camera.

At both intersections, the location of the monitoring camera is such that the entire intersection cannot be viewed in one shot. Multiple angles are required to ensure that many conflict types can be encompassed. The selection of camera angles is not trivial and the automated tracking quality is largely dependent the ability to see individual road users clearly. The following shows the recorded views as well as the time and duration of their recording.

5.3.1 King George Boulevard at 88th Avenue

Figure 5.5 Sample image from View 1

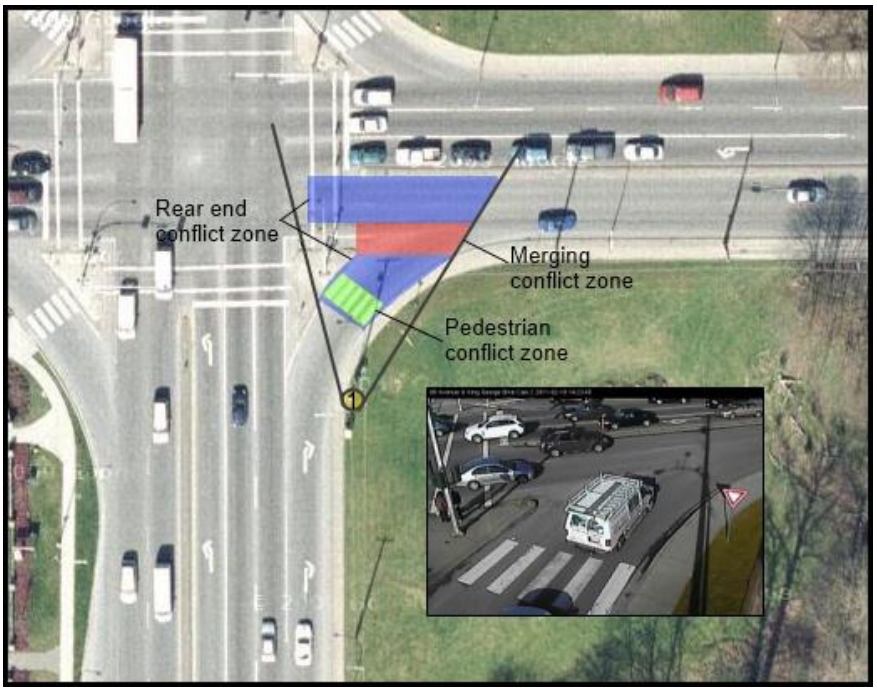


Table 5.1 King George Boulevard @ 88th Avenue - View 1

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Fri Feb. 18, 2011	8:58 AM	4:58 PM	**10:00 AM**	**4:00 PM**	**6**

This view shows the area to the immediate east of the intersection, with the camera pointed northwards. The main movements observed in the scene are the east bound through and north bound right turning vehicles. Although west bound through vehicles are also visible at the top of the screen, these vehicles are not considered in this view and are excluded from the tracking. Four conflicts are considered in this view:

-North bound right turn rear end

-East bound through rear end

-North bound right turn vs. East bound through merge

-North bound right turn vs. Pedestrians

Figure 5.6 Sample image from View 2

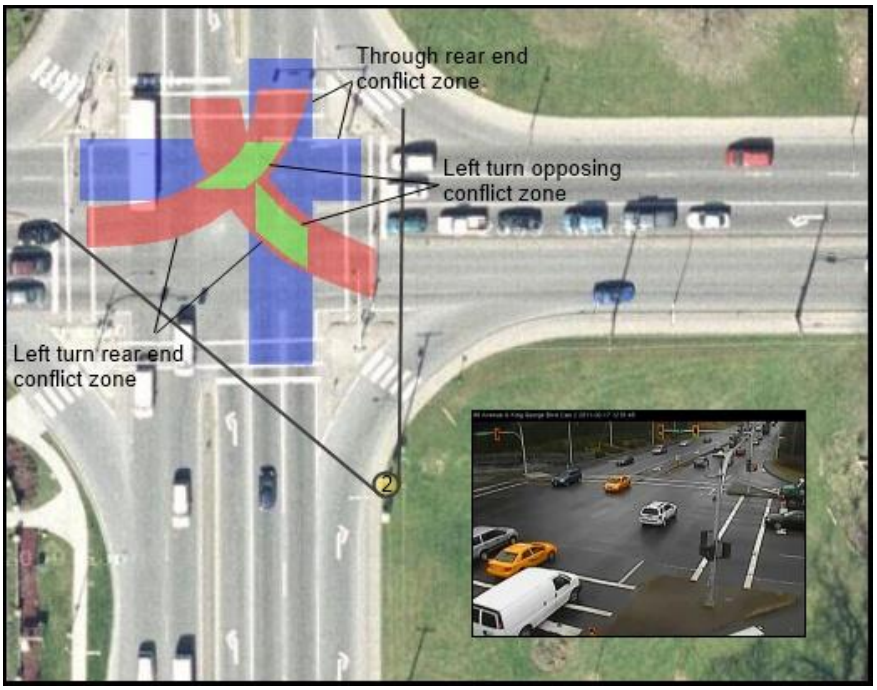


Table 5.2 King George Boulevard @ 88th Avenue - View 2

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Thur Feb. 17, 2011	9:50 AM	5:50 PM	**10:00 AM**	**4:00 PM**	**6**

This view shows the center of the intersection, focused mainly on the north and east regions. The main movements observed are north bound through, south bound left turn, west bound through, and east bound left turn vehicles. While a number of other vehicles are also visible in this angle, they are not tracked in this view. The six conflicts seen in this view are as follows:

-North bound through rear end

-West bound through rear end

-West bound left turn rear end

-South bound left turn rear end

-West bound left turn vs. East bound through opposing

-South bound left turn vs. North bound through opposing

Figure 5.7 Sample image from View 3

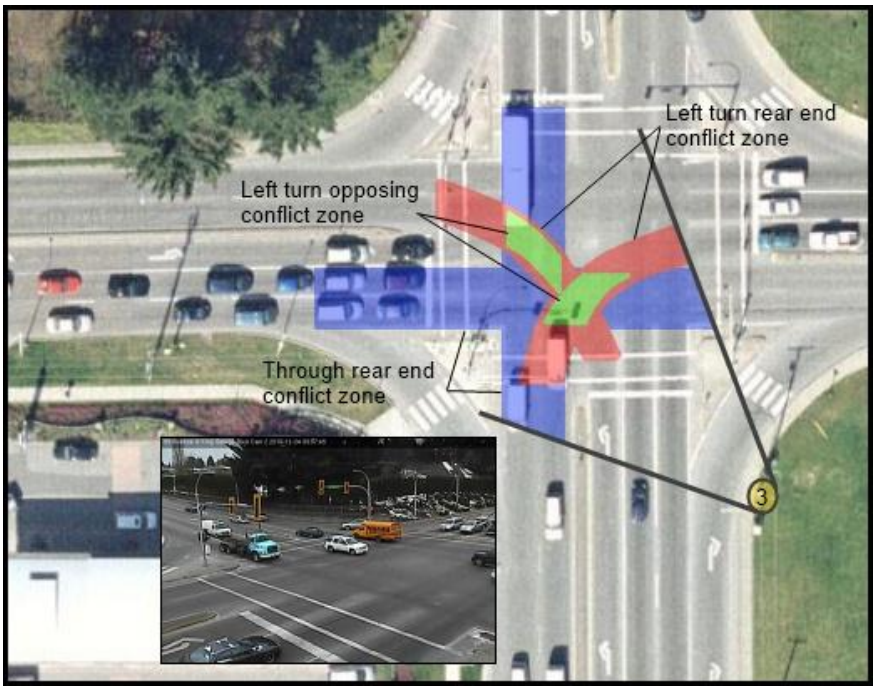


Table 5.3 King George Boulevard @ 88th Avenue - View 3

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Wed Nov. 24,2010	9:33 AM	5:33 PM	**10:00 AM**	**4:00 PM**	**6**

This view shows the center of the intersection, focused mainly on the south and west regions. The main movements observed are south bound through, north bound left turn, east bound through, and west bound left turn vehicles. While a number of other vehicles are also visible in this angle, they are not tracked in this view. The six conflicts seen in this view are as follows:

-South bound through rear end

-East bound through rear end

-West bound left turn rear end

-North bound left turn rear end

-East bound left turn vs. West bound through opposing

-North bound left turn vs. South bound through opposing

Figure 5.8 Sample image from View 4

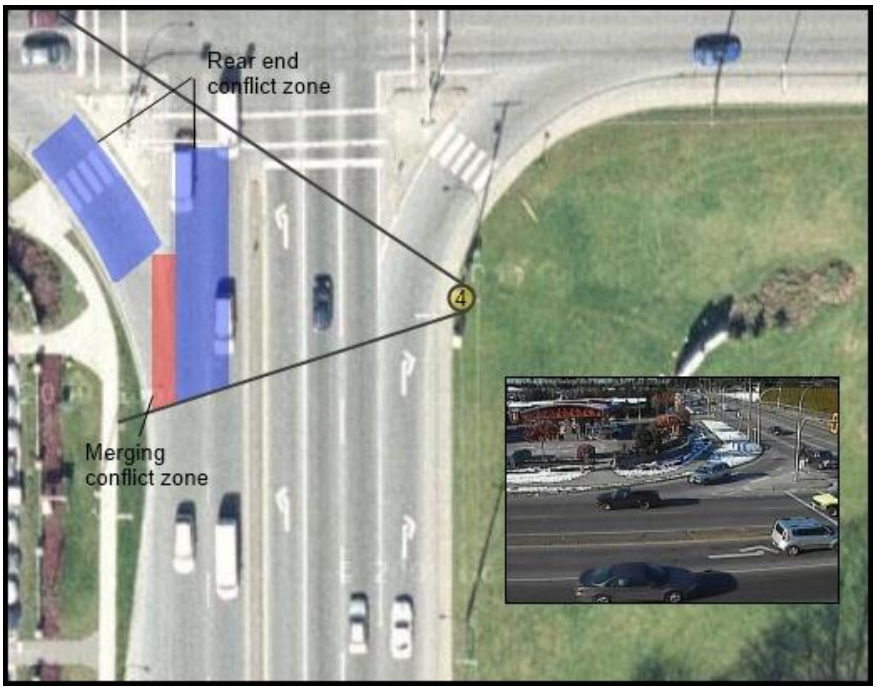


Table 5.4 King George Boulevard @ 88th Avenue - View 4

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Tue Nov. 23, 2010	9:33 AM	5:33 PM	**10:00 AM**	**4:00 PM**	**6**

This view shows the area immediately south of the intersection, with the camera pointed westwards. The main movements observed in the scene are the south bound through and east bound right turning vehicles. Although north bound through vehicles are also visible at the bottom of the screen, these vehicles are not considered in this view and are excluded from the tracking. Three conflicts are considered in this view:

-East bound right turn rear end

-South bound through rear end

-East bound right turn vs. South bound through merge

5.3.2 152nd Street at 104th Avenue

Figure 5.9 Sample image from View 1

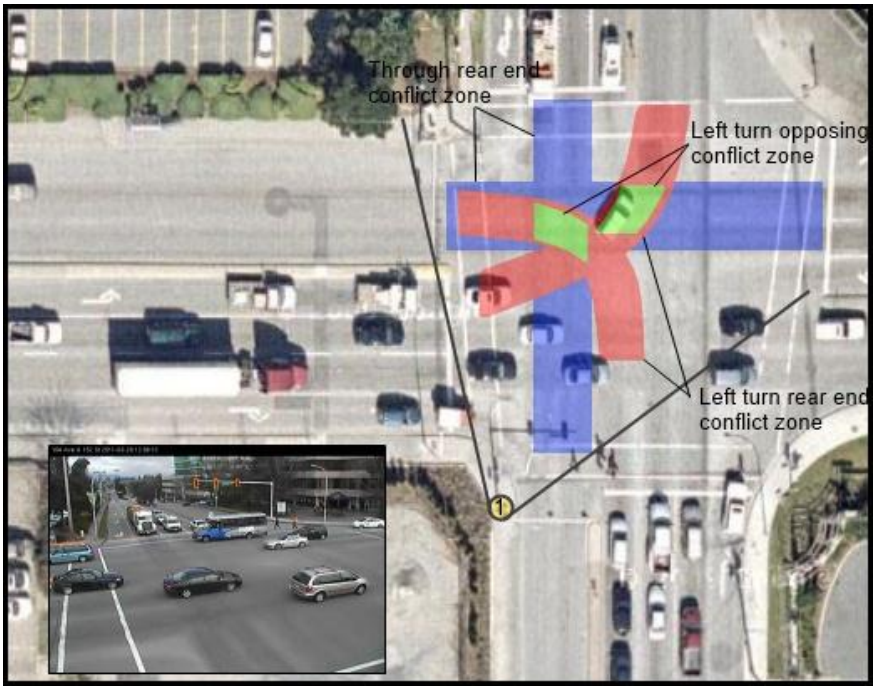


Table 5.5 152nd Street @ 104th Avenue - View 1

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time
Mon Mar. 28, 2011	9:04 AM	5:04 PM	**10:00 AM**	**4:00 PM**	**6**

This view shows the centre of the intersection, but is focused mainly on the north and west regions. The main movements observed in this view are south bound through, north bound left turn, east bound left turn and west bound through. A number of other movements can also be seen in this view, but are excluded from tracking. The conflict types considered in this view are as follows:

-North bound left turn rear end

-South bound through rear end

-East bound left turn rear end

-West bound through rear end

-North bound left turn vs. South bound through opposing

-East bound left turn vs. West bound through opposing

Figure 5.10 Sample image from View 2

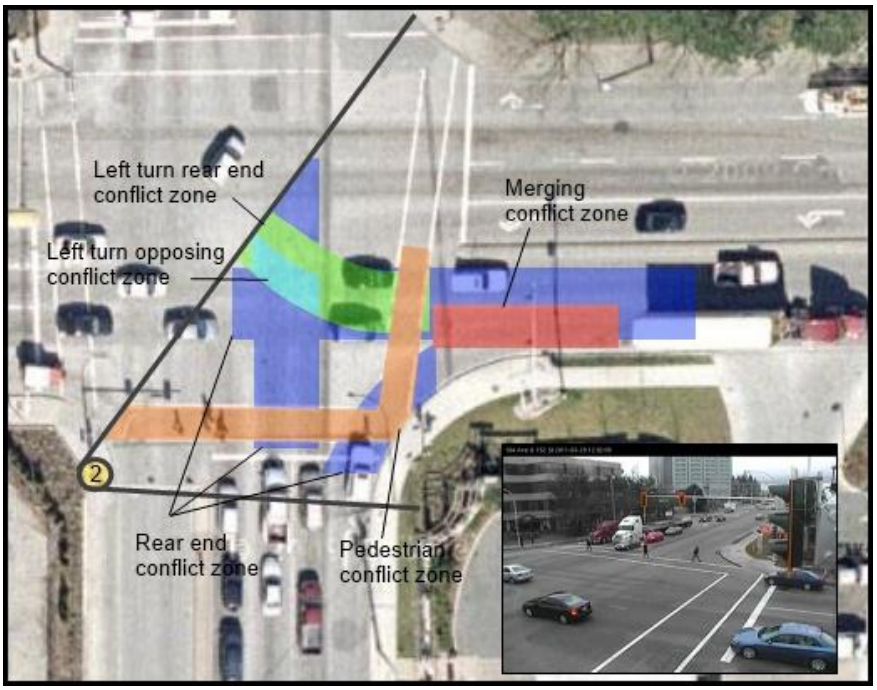


Table 5.6 152nd Street @ 104th Avenue - View 2

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Tue Mar. 29, 2011	9:02 AM	5:02 PM	**10:00 AM**	**4:00 PM**	**6**

This view shows the centre of the intersection, but is focused mainly on the south and east regions. The main movements observed in this view are north bound through, south bound left turn, west bound left turn, east bound through, and pedestrians in both the east and south crosswalks. A number of other movements can also be seen in this view, but are excluded from tracking. The conflict types considered in this view are as follows:

-South bound left turn rear end

-North bound through rear end

-West bound left turn rear end

-East bound through rear end

-South bound left turn vs. North bound through opposing

-West bound left turn vs. East bound through opposing

-East approach pedestrians

-South approach pedestrians

Figure 5.11 Sample image from View 3

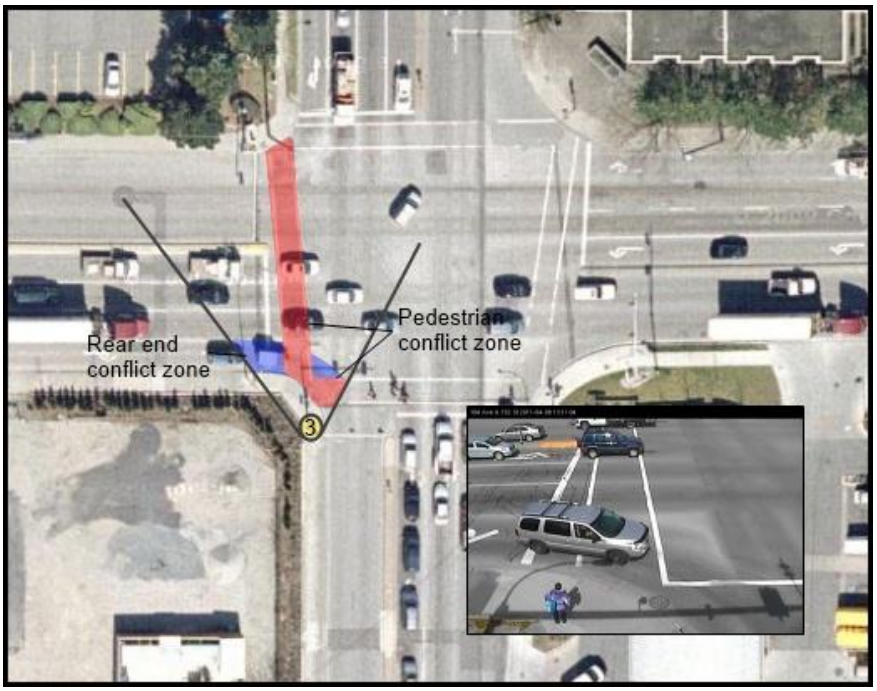


Table 5.7 152nd Street @ 104th Avenue - View 3

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Fri Apr. 8, 2011	9:10 AM	4:10 PM	**10:00 AM**	**4:00 PM**	**6**

This view shows the western most region of the intersection, with the camera pointed northwards. The main movements observed in the scene are the south bound through and east bound through, and right-turning vehicles, as well as pedestrians in the west crosswalk. Although other vehicles are also visible at the bottom of the screen, these vehicles were not considered in this view and are excluded from the tracking. Three conflicts are considered in this view:

-East bound right turn rear end

-East bound right turn vs. South bound through merge

-West approach pedestrians

5.3.3 Data collection shortcomings

Since a single camera is used at each intersection, there are some difficulties in collecting reliable video data. The main concern is the immobility of the cameras which are set up by the City of Surrey to monitor traffic from the most advantageous angle. The problem encountered with this camera placement is that road users in the furthest corner opposite the camera are difficult to track. As such, this study represents only an analysis of half of each intersection. While it may have been possible to detect conflicts between some road users at the opposite side, reliability is deemed to be too low to base on these results any definite conclusions.

Furthermore, since the video cameras are controlled by the City of Surrey Traffic Operations Department, data collection is subject to their schedules. The biggest shortcoming here is that their regular hours of operation do not start until 9:00am, which means that no video can be recorded before 9:00am, with a useful start time of 10:00am. This start time misses the morning peak period at both intersections and leaves out a valuable time frame for data collection. Although this omission was unfortunate, it has not severely impacted the research findings.

5.4 Results and analysis

The following sections describe the results obtained from the automated conflict analysis. Unlike past studies employing the same automated safety analysis for before and after safety evaluations, here there is no benchmark against which to compare the number of conflicts. In the diagnostic context, the goal is to determine which conflict types and road users are over-represented. The indication of an over-represented conflict type is derived by comparing the frequency and severity of all conflict types. As the proceeding analysis demonstrates, a pattern of conflict types emerges from the vast database of interactions. In addition to the location of each interaction (conflict point), the trajectory, speed and acceleration of the road users involved is also available.

Once a specific region, road user or conflict type is identified, a safety expert can review this information for all events, to determine whether some consistent behaviour is to blame for the conflicts. The reviewer can also access video segments for each conflict of interest. From this, conflicts can be reviewed to yield further insight into the causes of safety issues.

For the conflict types identified as being most problematic, short video segments containing the conflict are generated. This provides a permanent record of each event that can be stored for future reference. In this study, the researchers reviewed a substantial number of video segments for the conflict types that occurred most often. In each case, there are multiple causes for conflicts, but consistent trends are identified. Sections 5.4.1 and 5.4.3 present the conflict types and frequencies for King George Boulevard at 88th Avenue and 152nd Street at 104th Avenue. For each intersection, the most frequent conflict types are analyzed to determine the most likely cause. These sections detail the results of this analysis and the significance of these findings is discussed later.

5.4.1 King George Boulevard at 88th Avenue

This intersection analysis encompasses all conflicts within the intersection, as well as at the south and east approaches. Due to the height and location of the camera, neither the west nor north approach movements can be analyzed. Further discussion of this shortcoming can be found in the recommendations section.

Table 5.8 King George Boulevard at 88th Avenue conflict breakdown

ID #	Conflict Type	Low	Mid	High	**Total**
1	West bound left turn rear end	124	72	31	**227**
2	North bound right turn merging	101	50	76	**227**
3	North bound through rear end	101	65	42	**208**
4	South bound through rear end (Scene3)	54	98	50	**202**
5	West bound through rear end	135	30	6	**171**
6	East bound through rear end (Scene4)	95	38	33	**166**
7	East bound through rear end (Scene1)	138	19	3	**160**
8	West bound left turn opposing	59	61	33	**153**
9	South bound through rear end (Scene3)	50	71	19	**140**
10	North bound right turn rear end	103	12	23	**138**
11	East bound left turn opposing	19	59	54	**132**
12	East bound left turn rear end	59	37	26	**122**
13	North bound left turn rear end	32	59	21	**112**
14	South bound left turn rear end	52	38	22	**112**
15	North bound left turn opposing	20	34	52	**106**
16	South bound left turn opposing	45	45	15	**105**
17	East bound right turn merging	16	13	14	**43**
18	North bound right turn pedestrian	8	8	25	**41**
19	East bound right turn rear end	3	7	6	**16**

Figure 5.12 Location of all conflicts with denoted severities

Figure 5.13 Total conflict frequency distribution

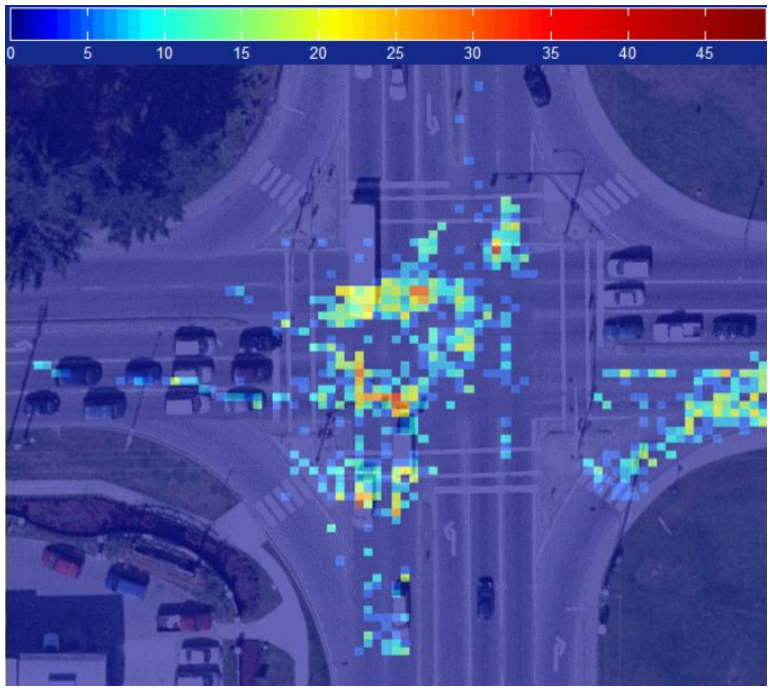


Table 5.8 shows a breakdown of the number of conflicts by type and severity. The top conflict types are as follows:

-Westbound left turn rear end

-Northbound right turn merging

-Northbound through rear end

Figure 5.12 and 5.13 show a visual representation of the conflict points of all detected events. The colouring of each point in

Figure corresponds to the severity level previously noted, while the coloured sections in Figure represent the total number of conflicts per square meter. Even without prior knowledge of the types of conflicts, the clustering evident in east, center and the east approach of the intersection. Knowing which types of events are occurring most frequently, a reviewer can focus their efforts on counteracting specific problems. Looking at the list of the three problem conflict types, the characteristics of any one event can be ascertained.

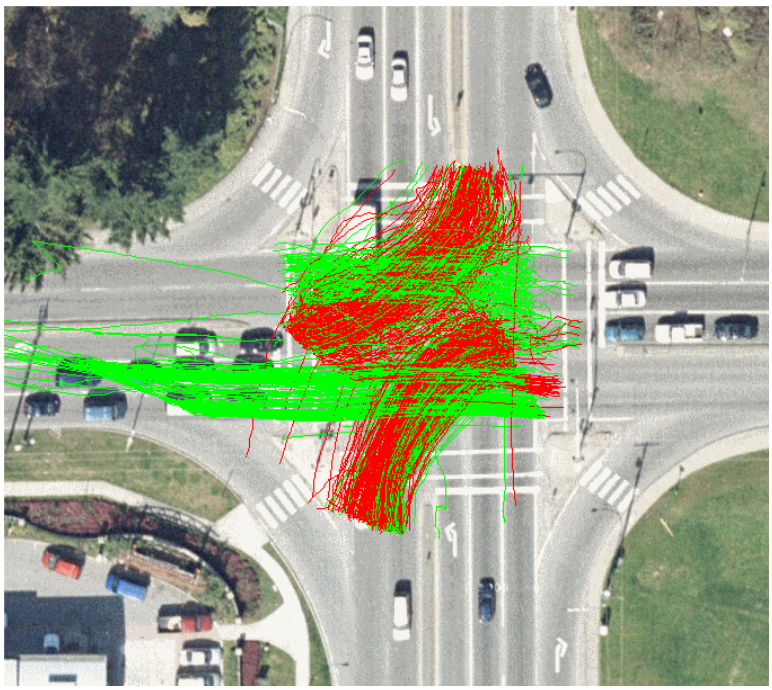
5.4.2 Conflict analysis

5.4.2.1 Eastbound and westbound left turn conflicts

Reviewing the events of this type, a pattern emerges pointing to the behaviour of the left turning vehicles. The geometry of the intersection is such that left turning vehicles are able to see the opposing through vehicles from a sufficient distance. Many of the conflicts are then a product of the conscious decision making of the left turning vehicle. The two prevalent observable trends are as follows:

Figure 5.15 Conflict points with left turning conflicts highlighted

Figure 5.16 Trajectories of vehicles involved in left turning conflicts



5.4.2.1.1 Poor gap acceptance

Left turning vehicles are often seen turning without a sufficient gap between successive through vehicles. The left turning vehicles also exhibit impatient behaviour by inching further and further into the intersection while waiting to turn. Both observations indicate driver frustration towards long delay times that result in poor decision making.

5.4.2.1.2 Late phase left turns

Left turning vehicles are also seen turning frequently at the end of the protected and permissive phases. Conflicts occur in both cases with opposing vehicles that are given their own right of way. At the end of the leading protected phase, late-turning vehicles impede opposing through vehicles and cause right angle conflicts and increased delays. Vehicles that turn at the end of the green phase create similar problems with the perpendicular traffic flow. The latter scenario also makes vehicles more susceptible to dangerous conflicts with opposing through vehicles who are also attempting to clear the intersection.

5.4.2.2 Northbound through conflicts

Although the posted speed limit is 60 km/h, vehicles travelling northbound through the intersection are able to reach higher speeds because the nearest intersection is over three-quarters of a kilometer away. While not as inherently dangerous as right angle events, rear end events at high speeds can cause damage and injuries, and result in severe traffic delays. The following trends are repeatedly observed to lead to rear end conflicts with northbound vehicles:

Figure 5.17 Conflict points with north bound through rear end conflicts highlighted

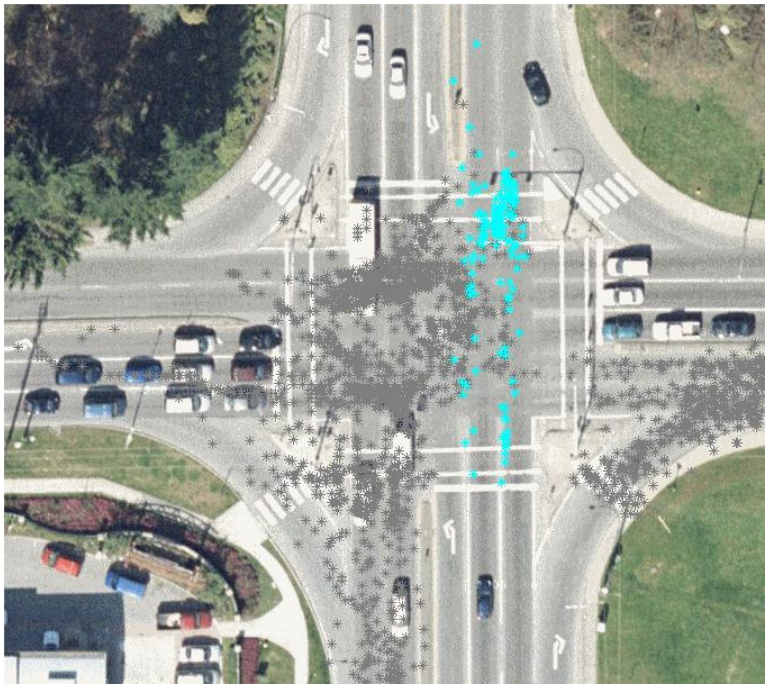
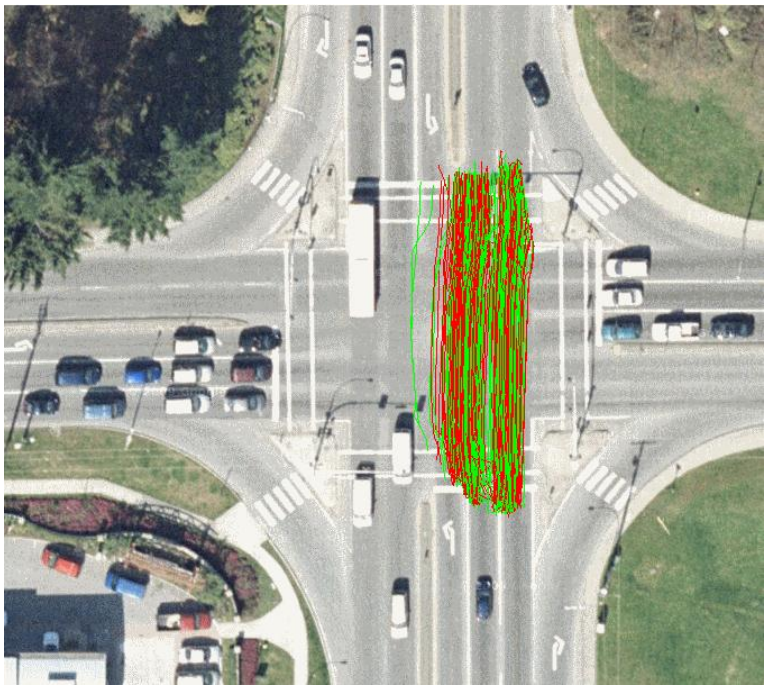


Figure 5.18 Trajectories of vehicles involved in northbound through rear end conflicts



5.4.2.2.1 Insufficient headways

Towards the end of their green phase, north bound through vehicles trying to clear the intersection accelerate and result in conflicts with other north bound through vehicles. As vehicles often accelerate in anticipation of a phase change, these conflicts may stem from vehicles responding to the upstream advanced warning flasher. In an attempt to clear the intersection, drivers increase the potential for a rear end collision with the vehicle in front of them.

5.4.2.2.2 Downstream obstructions

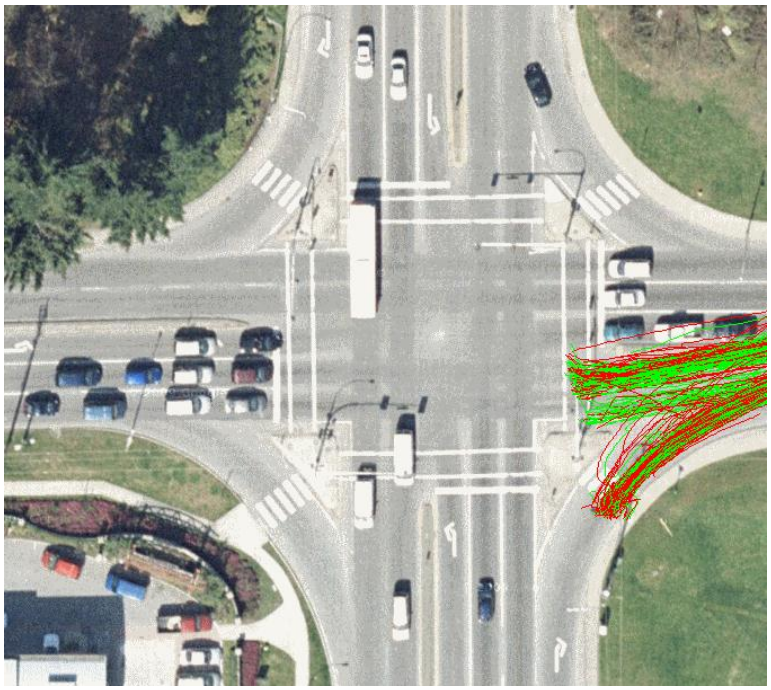
More serious rear end conflicts are observed when buses or improperly merging vehicles impede northbound traffic downstream of the intersection. Many suburban drivers are not accustomed to following and yielding to buses that may need to re-enter traffic.

5.4.2.3 Northbound right turn merge

The right turn merging conflicts at this intersection often occur as a result of a driver's perception of right of way. In this case, there is no continuous lane for right turning vehicles, and some drivers do not realize until they are well into the turn. The behaviour was observed to consistently lead to conflicts:

Figure 5.18 Conflict points with north bound right turn merging conflicts highlighted

Figure 5.19 Trajectories of vehicles involved in northbound right turn merging conflicts



5.4.2.3.1 High right turn speed

A designated right turning lane extends 85m upstream of the intersection and allows right turning vehicles to bypass queued north bound traffic. Many vehicles involved in merging conflicts travel at a high speed into the turn and are forced to come to an abrupt stop. Drivers appear to expect a merging lane and often inadvertently enter the main traffic flow.

As previously mentioned, the north and west intersection approaches, as well as the west and south bound right turning lanes are not captured in the safety analysis. While a brief visual analysis of the video does not indicate any obvious issues in these areas, in the interest of thoroughness, they should be included in a full review.

5.4.3 152nd Street at 104th Avenue

With the camera directed at the center, west and south approaches of the intersection, the safety analysis of this intersection includes both vehicle and pedestrian conflicts. Some conflict types are detected in multiple camera angles but only the conflicts from the view which best displayed it are used. Due to the height and location of the camera, conflicts in the northeast corner of the intersection and the northern crosswalk are not tracked.

Table 5.9 shows a breakdown of the number of conflicts by type, severity and exposure. North bound left turning rear ends, west approach pedestrians and east bound through rear ends are the most frequent conflict types. Figure is a visual representation of the corresponding conflict points, with the severities highlighted in red, yellow and orange. The clustering of conflict types shown in

Figure further illustrates the over-representation of the identified conflicts. Knowing which types of conflicts are occurring most frequently assists in the efforts of the reviewers who must analyze the specific problems. As with the previous intersection, video data of the identified conflicts is reviewed so that further conclusions can be drawn.

Table 5.9 152nd Street at 104th Avenue conflict breakdown

ID #	Conflict Type	Low	Mid	High	**Total**
1	North bound left turn rear end	175	87	21	**283**
2	East bound right turn pedestrian	66	70	102	**238**
3	East bound through rear end	159	38	39	**236**
4	West bound through rear end	104	53	19	**176**
5	East bound right turn read end	96	39	18	**153**
6	West bound left turn rear end	99	28	12	**139**
7	East bound right turn merging	61	55	4	**120**
8	West bound right turn rear end	33	38	43	**114**
9	East bound left turn rear end	65	36	9	**110**
10	North bound right turn rear end	37	43	20	**100**
11	South bound through rear end	41	34	22	**97**
12	East bound left turn opposing	39	49	18	**97**
13	West bound left turn opposing	24	36	35	**95**
14	East bound left turn merging	30	44	19	**93**
15	North bound through rear end	39	27	17	**83**
16	South bound left turn rear end	27	38	13	**78**
17	North bound left turn opposing	6	17	51	**74**

18	South bound right turn pedestrian	12	10	37	**59**
19	North bound right turn pedestrian	18	27	13	**58**
20	South bound right turn rear end	16	13	26	**55**
21	North bound right turn merging	23	12	15	**50**
ID #	Conflict Type	Low	Mid	High	**Total**
22	North bound left turn merging	16	16	17	**49**
23	North bound left turn pedestrian	4	11	27	**42**
24	West bound left turn merging	8	12	13	**33**
25	West bound right turn merging	4	11	3	**18**
26	South bound left turn opposing	5	6	4	**16**
27	East bound through pedestrian	1	7	7	**15**
28	West bound left turn pedestrian	6	1	3	**10**
29	South bound through pedestrian	3	2	2	**7**
30	South bound left turn pedestrian	0	2	2	**4**

Figure 5.20 Location of all conflicts with denoted severities

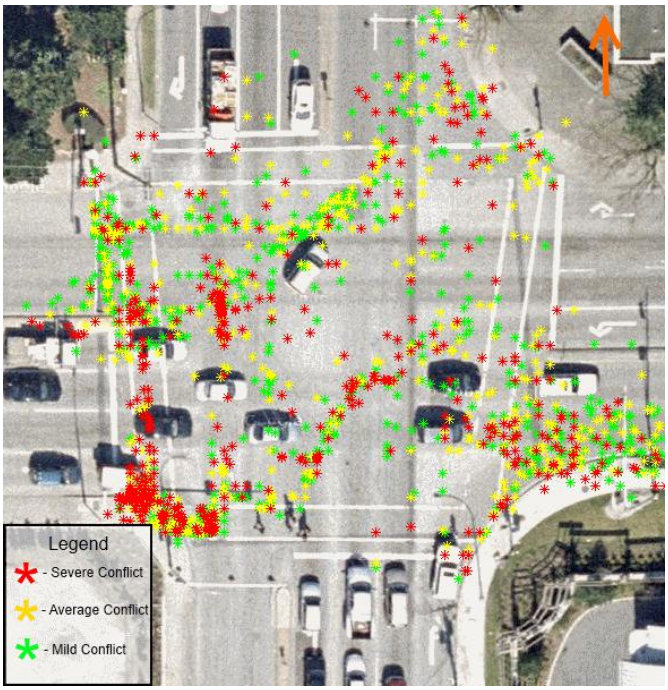
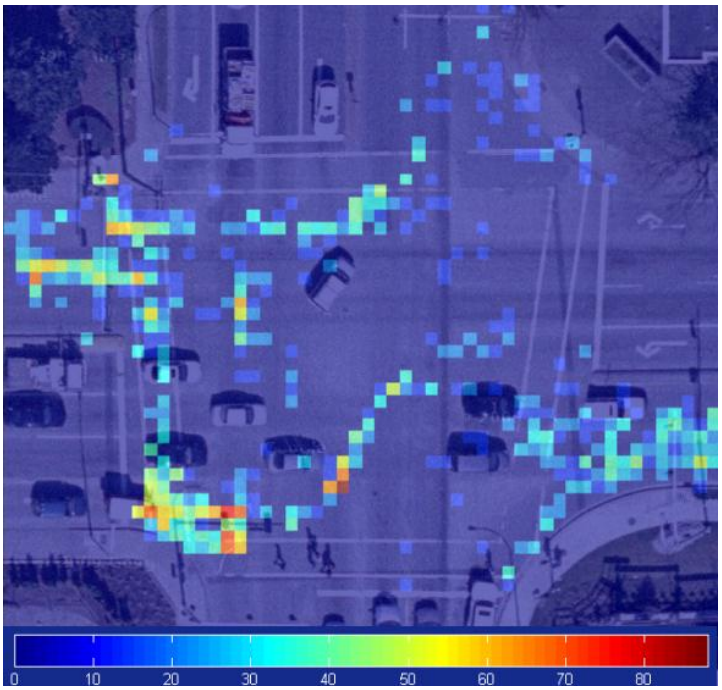


Figure 5.21 Total conflict frequency distribution



5.4.3.1 West approach pedestrians

Pedestrians crossing in the west approach are involved in frequent conflicts with vehicles. Most notably, eastbound right turning vehicles have a very high occurrence of severe conflicts. South bound right turning and north bound left turning vehicle also have a number of conflicts with these same pedestrians. Each of these movements can legally be undertaken during the pedestrian walk phase, provided the pedestrians are given the right of way. All of the pedestrian conflicts occur because vehicles ignore the pedestrian right of way, or pedestrians enter the crosswalk after the walk phase. The following are the prevailing trends seen to lead to most of the pedestrian conflicts:

Figure 5.22 Trajectories of vehicles and pedestrians involved in conflicts

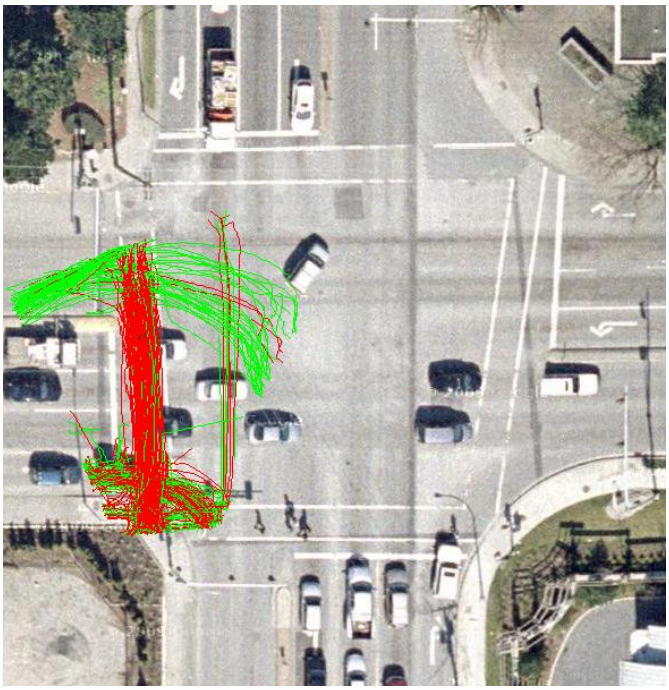
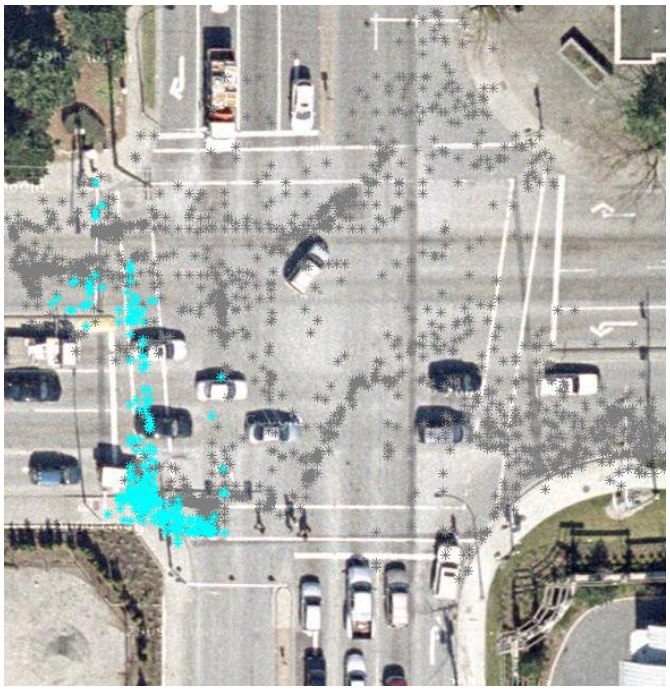


Figure 5.23 Conflict points with west crosswalk pedestrian conflicts highlighted



5.4.3.1.1 East bound right turning vehicles

Many conflicts occur where southbound pedestrians are obscured from view from these vehicles, with conflicts resulting near the southwest corner of the intersection. Eastbound right turning vehicles and north bound pedestrians also frequently interact at the curb where pedestrians first step into the crosswalk.

5.4.3.1.2 Northbound left turning vehicles

Although less frequent than right turning pedestrian conflicts, left turning pedestrian interactions produce a number of severe conflicts. As left turning vehicles have few available gaps, they often make their turn without first checking for clearance. A number of instances also occur when pedestrians enter the crosswalk near the end of the phase and conflict with late left turning vehicles.

5.4.3.2 Northbound left turn rear ends

The clustering of conflicts in the northwest corner of the intersection is a by-product of a number of different movements converging in a single location. The type of conflicts to occur are both right turn merging and through and left turn rear end events. The most frequent of these events occurs between north bound left turning vehicles. The issues that result in these events are caused by both the turning vehicles, as well as the actions of the surrounding vehicles.

Figure 5.24 Conflict points with north bound left turn rear end conflicts highlighted

Figure 5.25 Trajectories of vehicles involved in northbound left turning rear end conflicts

5.4.3.2.1 Bus stop/right turning vehicles

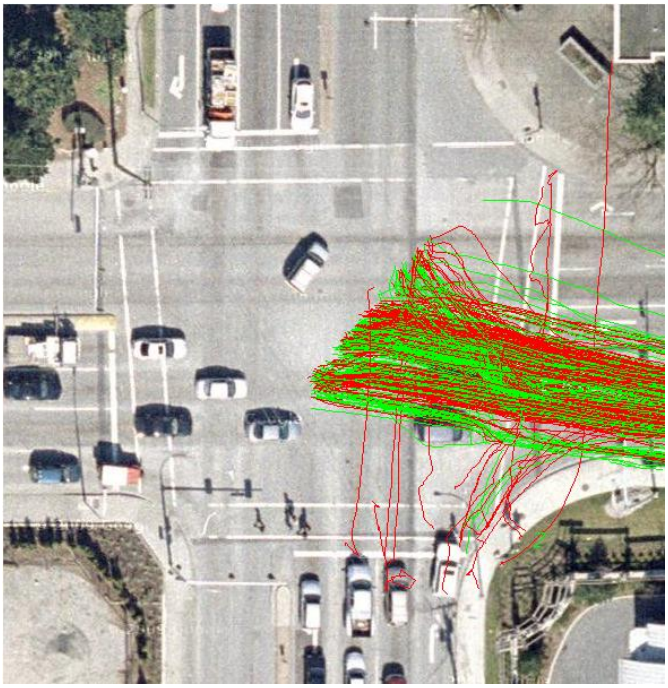
A common cause of conflicts is interaction between south bound right turning vehicles and north bound left turning vehicles. Although there is sufficient space for each vehicle to end their movement in the nearest lane, turning vehicles often encroach into the far lane. Whether this behaviour actually occurs, many drivers hedge their movements based on a conservative driving approach when a possible interaction may occur. By avoiding the merging conflict, turning vehicles cause conflict with following vehicles that may not be aware of the turning vehicle.

The downstream bus stop adjacent to west bound 104th Avenue also creates a number of conflicts. The bus stop is only 30m downstream of the intersection but stopped buses protrude very near to the intersection. Similar to the above situation, left turning drivers are able to turn without interacting with a stopped bus, but many drivers decelerate regardless. The result is another situation in which following left turning vehicles often have a rear end conflict with the forward vehicle.

5.4.3.3 Eastbound through rear ends

Figure 5.26 Conflict points with eastbound through rear end conflicts highlighted

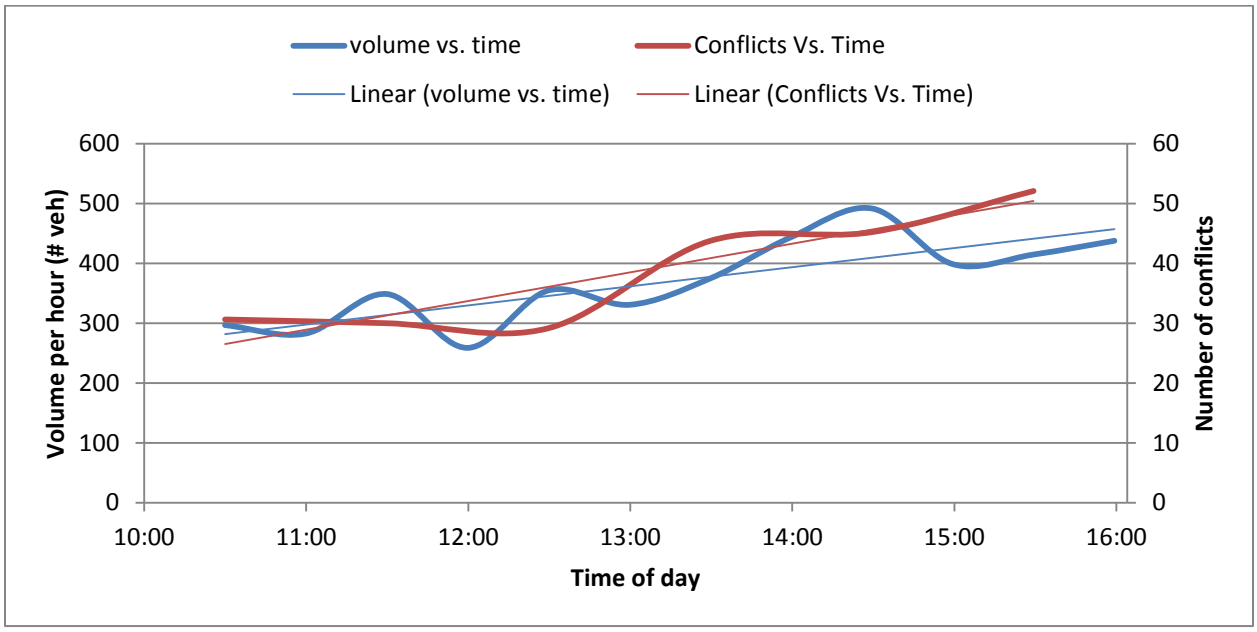
Figure 5.27 Trajectories of vehicles involved in eastbound through rear end conflicts



5.4.3.3.1 High speed/downstream driveways and traffic lights

The area immediately east of the intersection has a number of driveways with entering and exiting vehicles. As 104th Avenue leads to the Trans-Canada Highway, vehicles travelling east often drive well above the posted speed limit. A significant number of conflicts occur when vehicles turning right into a downstream driveway temporarily obstruct the flow of through traffic. The rate of deceleration required creates a substantial number of rear end conflicts at the exit of the intersection. During peak hours, traffic waiting to enter the highway can spill back nearly to the intersection. Vehicles coming from uncongested upstream areas must reduce speed quickly and in doing so cause rear end conflicts. Figure shows how closely related conflicts are to volumes for this movement and further implicates congestion as a main causal factor. A red light camera is currently in operation capturing the eastbound through direction and may also contribute to drivers feeling the need to quickly clear the intersection.

Figure 5.28 Plot of eastbound through volume and conflicts



5.5 Recommendations

5.5.1 King George Boulevard @ 88th Ave

5.5.1.1 Left turn conflicts

Typically when a signalized intersection experiences collision problems involving left turning vehicles, the solution is to provide additional protection (more green time) for the left turn phase. At this intersection, however, the cycle length is at the maximum length recommended by the City of Surrey. Any additional left turn green time will negatively affect the level of service of other traffic movements. An alternative solution is to provide a more advantageous geometry for left turning vehicles and disincentives for drivers to turn after their green phase. By creating an offset for each opposing left turn bay, a driver's sight line is improved, allowing them to make safer left turns. Alternatively, using red light cameras to deter end of phase left turns may change a drivers' behaviour and reduce the incidence of red light running.

A more drastic change would require the modification of the left turn signal phase from protected-permissive, to protected only. Protected left turns significantly reduce right angle turning interactions that are typically the most dangerous types of conflicts. Although generally implemented when left turning vehicles must cross three opposing lanes of traffic, the high collision frequency at King George Boulevard at 88th Avenue and the concentration of conflicts detected from these movements may be cause for special attention. While traffic flow may be marginally decreased, a protected only phase could well be accommodated within the current cycle length.

Further investigation of left turn countermeasures will provide a better indication of the best fit for this intersection. Comparing the daily signal schedule to the number of conflicts over time will show the concentration of conflicts occurring during phase changes. If the concentration changes over time, signal operations can be altered only during those periods that require attention. Simulations and comparison sites should then be used to determine whether safety benefits accrued from protected left turns can justify

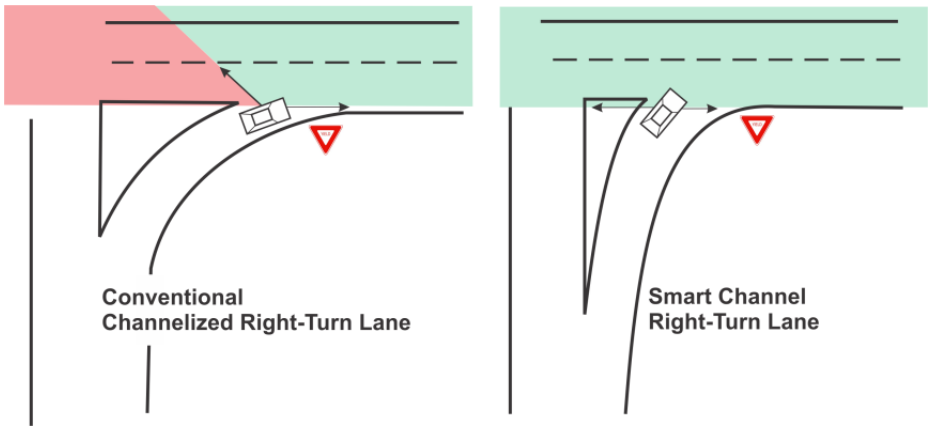
the decreased level of service. Further study should also be conducted to determine whether red light cameras can significantly decrease aggressiveness in left turning behaviour.

5.5.1.2 Northbound right turn merging

The solution for mitigating the northbound right turn merging conflicts is reducing the speed at which the right turns are made. While the northbound right turn lane allows drivers to safely and efficiently exit the through stream, many fail to decelerate to an adequate turning or stopping speed. The simplest solution is to implement additional signage to warn drivers of an impending merge point with no merging lane. The yield sign posted on the shoulder of the right turn lane is clearly visible, although many drivers appear not to take notice until they are nearly in the path of the conflicting traffic. An advanced warning sign would warn drivers that there is no continuous lane upon exit of the right turn.

A stronger speed deterrent is physically or lawfully requiring drivers to reduce their approach speed into right turns. Changing the yield sign to a stop sign, along with an appropriate warning, will force drivers to come to a complete stop and take a more conscious stock of the oncoming vehicles. Alternatively, by reducing the turning radius, drivers must navigate their right turns more carefully, to reduce the risk of sweeping merge conflicts. Past studies have shown that the design shown in Figure make drivers less susceptible to merging conflicts (Autey et al. 2011). The re-alignment requires drivers to approach the turn at nearly a right angle, so as to better see the conflicting vehicles.

Figure 5.29 Right turn realignment to reduce vehicle speed (Autey et al. 2011)



Using the intersection traffic monitoring camera, typical speeds of vehicles approaching the northbound right turn can be tracked. Based on this information, the design can be created to reduce the turning radius of the right turn. If typical speeds are higher than recommended, additional signs can be used to create a reduced speed zone in the right turn lane. Neither the signage nor the realignment treatments are costly and can also reduce rear end and pedestrian conflicts in the right turn as well.

5.5.1.3 Northbound through rear ends

Most of the northbound through rear end conflicts occur as a result of speed and aggressive driving. When drivers attempt to clear an intersection near the end of their phase, they increase the potential for conflict significantly. One of the most important factors in limiting these conflicts is to curb the aggression in approaching movements. Using a red light camera serves as a strong deterrent for drivers to enter the intersection on an amber or red light. Also, while it is in place as a safety measure, removing or updating the advance warning flasher on the approach may be useful as well. Past studies have shown the benefits of advance warning flashers to be inconclusive (Sayed et al. 1999), and in practice, many drivers see the warning as an indication to drive faster.

Another facet to improve the north bound through movement is to improve the conditions downstream of the intersection. Some of the most severe conflicts are observed when buses are stopped at the bus stop parked just north of the intersection. Moving the bus stop further downstream helps alleviate some of these conflicts and at only a marginal cost to pedestrians. Also, similar to the issue with the northbound right turning vehicles, westbound right turning vehicles occasionally encroach into the through vehicle path. Incorporating clearer signage for the turning vehicles should improve their adherence to the yielding conditions. This would potentially reduce another significant portion of the northbound through conflicts, as through vehicles would not be forced to evade stray turning vehicles.

5.5.2 152nd Street @ 104th Avenue

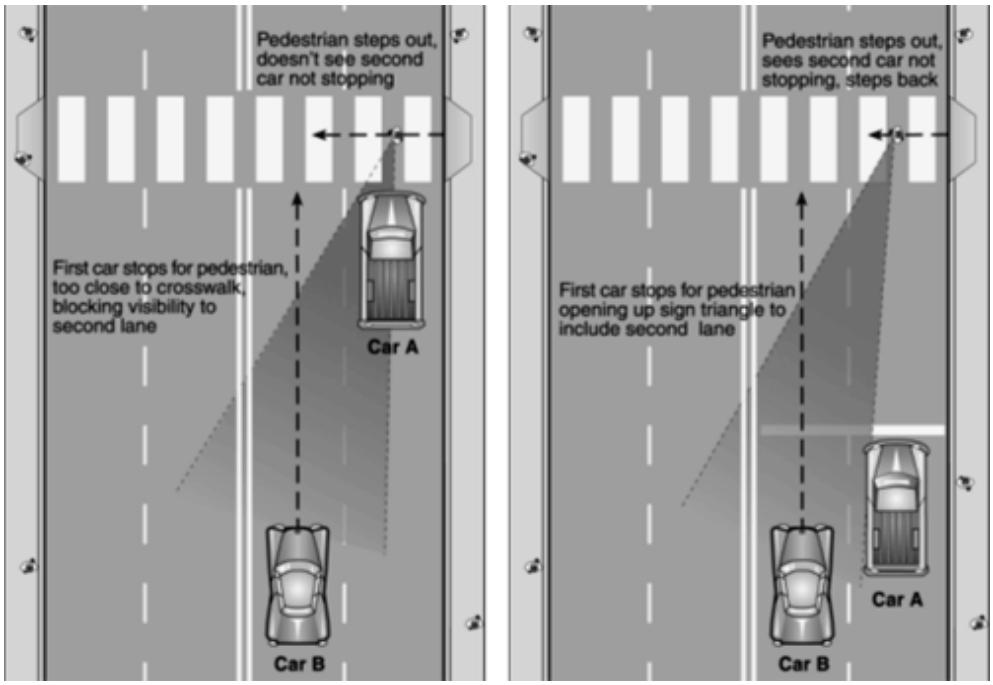
5.5.2.1 West approach pedestrians

Pedestrian conflicts in this region occur due to the non-compliance and the inattentiveness of both pedestrians and drivers. The goal in this situation is to protect the pedestrian and ensure they are visible and the drivers remain alert so that pedestrians can cross the street in their allotted phase. Installing countdown timers to compliment the walk/flash do not walk sign gives some of the responsibility to the pedestrian to ensure they cross only when enough time is available. This will reduce conflicts between end of phase northbound left turning vehicles and pedestrians who inadvertently start to cross late in the phase. A countdown timer would be most effective if used with an automated pedestrian detection system, as the use of push-button pedestrian signal actuators is low at a four-way stop controlled intersection.

Once pedestrians are in the crosswalk, drivers who may pose a potential threat should be aware of their presence. Inattentive drivers can be notified of a pedestrians in the crosswalk much the same as a midblock flashing pedestrian crossing. If drivers are made aware that they must yield the right of way, many conflicts that occur as the pedestrians step off the curb can be avoided. Since right turning vehicles pose the most imminent danger to pedestrians, they should also have the best vantage point from which to

see them. For eastbound vehicles, this can be accomplished by staggering the stop bar so that the left turning vehicles are furthest back (Figure). This would allow right turning vehicles to observe both southbound through vehicles and pedestrians without first having to encroach into the cross walk. For southbound right turning vehicles, the vegetation on the northwest corner may obstruct the sight of the driver. Opening a larger clearing on the corner will minimize the conflicts that occur as pedestrians step off the north side curb.

Figure 5.30 Demonstrated effect of having vehicles stop further back of the intersection (City of Ottawa 2010)



As the data indicates, the most persistent pedestrian conflicts occur between right turning vehicles and pedestrians near the curb. If the intersection remains hazardous to pedestrians, even after the recommended treatments are installed, it may be prudent to restrict right turning movements on red lights. Although typically reserved for busy urban intersections, and depending on the time of day or whether the pedestrian signal has been activated, restrictions may be warranted here. Further investigation should be made into the level of service decrease with restricted right turns on red and the ability of the drivers to adapt to changing signals.

5.5.2.2 Eastbound through rear ends

Similar to the northbound through rear ends at King George Boulevard at 88th Avenue, many of these conflicts are a result of excessive speed. When through vehicles are presented with congestion, or a turning vehicle at the exit of the intersection, they must take evasive action to avoid a collision. In reviewing the conflicts, the most common cause of this is vehicles turning into driveways immediately east of the intersection. To eliminate these conflicts, the driveways should be relocated further downstream or to minor streets.

Travelling east on 104th also leads from a less congested area into one that can see heavy volume during peak hours. Due to the queues leading to the Trans-Canada highway, vehicles are often required to dramatically reduce speed after crossing the intersection. Improved signage could be useful to warn drivers of the sudden change. Either a static or active sign would be effective in warning drivers to expect slowed conditions ahead. While this is not a dramatic treatment, it should change driver expectation and make them more cautious about their speed.

5.5.2.3 Northbound left turn rear ends

The northbound left turn rear end conflicts are symptomatic of a number of issues. The most common and severe conflicts occur when both a northbound left turn and southbound right turn are being made simultaneously. Though this can legally be done, left turning vehicles are often unsure of continuing into the exiting lane for fear of a sideswipe collision. As a result, when multiple vehicles are turning left in succession, subsequent vehicles are forced to avoid a collision with the leading left turn vehicle. To alleviate this issue, the left turn bay for the eastbound direction should be staggered backwards (which is also a recommendation for pedestrian conflicts). This will allow northbound left turning vehicles to make left turns with a smaller radius and reduce the likelihood of interacting with southbound right turning vehicles.

A similar situation also occurs when a bus stops at the bus stop just west of the intersection. Left turning vehicles have enough room to complete their manoeuvre but are hesitant to do so. Frequent situations are observed where a bus is stopped, and a southbound vehicle is beginning a right turn. In conjunction with the above lane realignment, the bus stop here should be relocated further downstream as this will ensure there is sufficient room for both right and left turning vehicles.

5.6 Diagnosis findings presentation

In November 2011, the findings of the previous section were presented to the City of Surrey Traffic Operations Department as potential improvements to their safety shortcomings. The recommendations made are based on prevailing traffic engineering solutions to typical safety issues. As this study focused on two well-studied locations, the safety concerns identified at both locations are not foreign to the Traffic Operations Department. Although there is little difference in the type of countermeasures recommended, the benefits of a process that provides objective reasoning was recognized.

6 City of Surrey Post-Treatment Safety Analysis

This section presents an observational before and after study that uses the same automated traffic conflict technique used for diagnosis. The basis for this type of before and after study comes from previous work done at UBC (Ismail et al. 2010; Sayed et al. 2012). The goal of this work is to quantify the impact off a safety treatment implemented in response to a deficiency identified in previous sections of this thesis. As this study is for demonstrative purposes only, a single conflict type is chosen for review.

6.1 Background

As part of a road safety program, the City of Surrey committed to implement several countermeasures at the 152nd Street at 104th Avenue intersection. These treatments affected several facets of the intersection and included re-alignment of lane markings and crosswalks as well as new traffic signal and right-of-way operation. One specific area identified for treatment was the west approach pedestrian crosswalk. As part of their improvements, the City of Surrey implemented two recommendations specified in this thesis (previously submitted as a report to the City of Surrey Traffic Operations Department), with regards to these movements. As such, this location was targeted as a suitable target for post-treatment review.

6.1.1 Observational before and after studies

Traditional before and after studies are implemented in much the same way as are blackspot studies. Once an intersection has been targeted as a problem location, a countermeasure is applied in order to prevent what is deemed to be causing the safety problems. After implementation, the collision data of a location will be collected as per normal procedure. Once a sufficient period of time has passed, the post-treatment data is compared with the pre-treatment data to determine the effectiveness of the countermeasure. In this procedure, an attempt is made to isolate the true effect of the countermeasure by controlling for outside factors such as volume change and regression to the mean. This procedure is detailed in Section 2.7 of this thesis.

The main problem with the standard review method is the time required to accurately measure the effectiveness of a treatment. Though the statistical analysis methods provide an accurate quantification of the effects but a two or three year time gap means that by the time a review is conducted it usually has little impact. Traffic engineers strive to improve driving conditions, but inadequate review processes mean that countermeasures can be recommended without an understanding of their true effectiveness. As treatments often require significant capital expenditure, traffic authorities have a vested interest to ensure their decisions are as efficient as possible. What is required, then, is a more efficient means of accurately reviewing the practical value of a safety treatment.

To accomplish this, previous studies have advocated and successfully used the automated traffic conflict technique for review. The process for a traffic conflict technique before and after study follows the same reasoning as a traditional before and after study with the main benefit of shorter data collection time in both periods. In this study, the automated traffic conflict technique before and after study is not only used to review the effectiveness of the applied treatments but is also used by proxy the ability of the previously presented diagnosis methodology to identify specific deficiencies and suggest focused treatments.

6.1.2 Intersection geometry changes

The changes made to the pedestrian right-of-way are highlighted in Figure andFigure as follows:

A. Dual drop down to allow more direct pedestrian movement
B. Cross-walk shifted west to allow more clearance from third lane southbound through vehicles
C. Cross-walk realigned to be perpendicular to traffic, providing improved sightlines

6.1.2.1 Treatment A: dual drop pedestrian ramps

This addition provides more clearly defined paths for pedestrians and, in particular, those with baby strollers or with disabilities. It is not fully clear from the image, but this improvement gives separate ramps for pedestrians using the west and south crosswalks. While more convenient, this also makes the intentions of a pedestrian clearer to drivers as they are able to face their direction of travel.

Figure 6.1 Highlighted changes to pedestrian crossing ramps from (a) single drop to (b) dual drop

(a) (b)

6.1.2.2 Treatment B: west crosswalk re-positioning

This treatment was implemented in response to changing the right-most southbound lane from a turning lane only into a shared through and turn lane. Moving the lane further west protects pedestrians from high speed, southbound through vehicles that may deviate from their lane in error. As this treatment is in response to a new condition, no improvement over the pre-treatment period can clearly be attributed to it.

Figure 6.2 Changes to west pedestrian crosswalk re-positioned and re-aligned and from (a) before to (b) after with approximate before markings denoted

(a) (b)

6.1.2.3 Treatment C: west crosswalk re-alignment

The crosswalk re-alignment is the most significant improvement to the pedestrian right-of-way geometry as it shifts their north origin to a more visible position. As noted in the diagnosis portion of the study, the most common conflict at the intersection is between eastbound right turning vehicles and southbound pedestrians. Upon further review, a clear cause of this is an obstructed view of crossing pedestrians by the

turning vehicles. With the improvement, when vehicles are stopped at the stop bar in the right-most eastbound lane, they are now at a right angle to the crosswalk and have a better view of the crosswalk.

6.1.3 Signal operation changes

In addition to geometric changes, two signal changes were implemented, both affecting the west approach pedestrians. Examples of the two changes are depicted in Figure andFigure , as follows:

D. Protected only turns for northbound left turning vehicles
E. Pedestrian countdown timer to inform pedestrians of the time remaining to complete their crossing

6.1.3.1 Treatment D: protected only northbound left turns

The change from protected-permissive to protected only northbound left turns is another measure of response to the additional through lane of southbound traffic. The City of Surrey has a policy in place where any left turn movement at an intersection that must cross three lanes of oncoming traffic will have a protected only left turn phase. This change has a residual effect on west approach pedestrians, as a number of conflicts are recorded in the before period between these road users. The protected only phase effectively eliminates these conflicts which occur frequently towards the end of the green phase. In the after period, any event involving these road users would have to result from non-compliance by one or the other.

Figure 6.3 Protected only left turn signal and signage

6.1.3.2 Treatment E: pedestrian countdown indicator

The pedestrian countdown timer gives a clear indication to the pedestrians about the amount of time they have remaining to reach their destination. This addition to the pedestrian signal is becoming the new standard as it removes the need for pedestrians to interpret the meaning of the flashing do not walk sign. The pedestrian countdown timer is recommended as a countermeasure in the diagnosis section of this study mainly as a way to reduce end of phase conflicts between pedestrians and northbound left turning vehicles. As the above noted protected left turn phase removes these conflicts, the countdown timer is now redundant for this purpose. The indicator is still beneficial however, and can help prevent pedestrians, especially the elderly, from being trapped in the crosswalk after the phase is over.

Figure 6.4 Sample of pedestrian signal with countdown indicator

6.2 Data collection

While the actual time required for substantial results has not been definitively identified, previous studies use two eight hour days in both before and after periods. The main constraint for a sufficient time period is the ability to capture enough conflicts in both the before and after periods to confidently identify a change. As the previous study focuses on a location in a more rural part of British Columbia with lower conflict frequency, the same time period is considered to be sufficient for this particular study.

6.2.1 Before period

Although the problems associated with the before period are already defined in the diagnosis section, a new set of data is analyzed, in order to conduct a fair comparison. The video footage is a part of the originally collected video at 152nd Street at 104th Avenue that was to be used as diagnosis footage. The specific angle focuses only on the west approach pedestrian crosswalk and was deemed too narrow a focus area for the original study. Details of the before period data collection and conflict zones captured are given in Table 6.1 and Figure 6.5.

Figure 6.5 Sample image from before video footage

Table 6.1 Before period data collection summary

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Wed. Mar. 16, 2011	9:27 AM	5:27 PM	**9:27 AM**	**5:27 PM**	**8**
Tue. Apr. 5, 2011	9:58 AM	5:58 PM	**9:58 AM**	**5:58 PM**	**8**

6.2.2 After period

The data collection for the after period was conducted with the intention of capturing only the west approach crosswalk. A concerted effort is made to replicate as nearly as possible the view from the before study. Since the signal mast on which the camera is mounted has been moved, the view is not identical to that of the before period. Despite this difference, the tracking quality and ability to identify conflicts is not materially different, is that the comparison of data is fair. Details of the after period data collection and conflict zones captured are given in Table 6.2 and Figure 6.6, respectively. Although it was noted that the northbound left turning vehicles could no longer legally conflict with pedestrians, they are still tracked for consistency.

Figure 6.6 Sample image from after video footage

Table 6.2 After period data collection summary

Recording date	Recording start time	Recording end time	Used start time	Used end time	Total time (hours)
Tue. May. 15, 2012	8:15 AM	4:15 PM	**8:15 AM**	**4:15 PM**	**8**
Tue. Apr. 5, 2011	7:00 AM	3:00 PM	**7:00 AM**	**3:00 PM**	**8**

6.3 Analysis and results

This section presents the findings of comparison between the before and after periods. The study is a simplified version of previous before and after studies which maintains the main underlying principles. Most significantly, the reduction in conflicts presented below is calculated without the use of a control location.

Previous studies recommend using control sites to account for confounding factors, but the simple nature of this study makes the use of one unnecessary. Since so many changes have been implemented at the study location, it is difficult to isolate any one contributing factor. To account for volume change,

exposure is included as a normalizing value for each of the four study days. As the before and after portions of the study are both in typical data collection periods, no other significant volume correction is applied. The results provided below still show irrefutable proof of reduced conflicts and improved safety, even though the confounding factor control is missing.

6.3.1 Exposure

As noted, the normalized value applied to the conflict results is volume correction and this measure is applied to account for expected variation in volume on a daily basis. The procedure for including a measure of exposure is given in Equation 6.1 below. The idea behind the controlling measure is to include volumes of both movements involved in a given conflict type. The resulting value itself provides no useful measure but is a simple way to account for the density of each movement. The real maximum number of conflicts or collisions is controlled by the number of vehicles in the lesser volume of the two movements. This measure neglects the conflicting movement, however, which is an obvious necessity for the conflict to occur.

$$E_{i,j} = \sqrt{{V_i}^2 + V_j^2} \tag{6.1}$$

Where:

$\mathrm{E_{i,j}} = \text{Exposure Factor}$

$\mathrm{V_i} = \text{Volume of Conflicting Movement i}$

$\mathrm{V_j} = \text{Volume of Conflicting Movement j}$

6.3.2 Comparison

Table 6.3 below compares the results between the before and after study periods. As can be seen, there is a clear reduction in the number of conflicts recorded over the two days in the after period. The most

obvious decrease is in the occurrence of left turning conflicts, which are almost completely mitigated in the after period. Both the conflicts with eastbound and southbound right turning vehicles are also reduced in the after period, indicating a tentative success of the remaining countermeasures.

Table 6.3 Comparison of conflict frequency by type

	Pedestrian conflicts per hour					
	EB-RT		SB-RT		NB-LT	
Day	1	2	1	2	1	2
Before	25.7	20.75	11.8	10.75	7.33	7.9
After	18.3	15.8	3.7	1.4	0.6	0
% Change	-27%		-77%		-96%	

6.3.3 Data significance

While the reduction in each type and the total number of conflicts indicates the positive performance of the countermeasures, this before and after study is by no means definitive proof of success. The author recognizes the relatively small size of the study as well as the lack of control for confounding factors. Regardless of these shortcomings, however, the methodology used provides an end point for the automated diagnosis study. When applied correctly, the before and after study is a logical conclusion to the diagnosis procedure that can be used to confirm the correct identification of countermeasures.

7 Conclusions

This study demonstrates the ability to use automated conflict detection to diagnose safety deficiencies at intersections. The traffic conflict technique is recommended for safety studies as it overcomes deficiencies of collision data gathering. Conflicts occur more frequently than collisions so that data can be gathered over a short period of time with no bias due to under-reporting. The traffic conflict technique is criticized as it relies on human detection of events. This introduces subjectivity into the data collection process that may vary between surveyors. Furthermore, it is difficult for observers to provide objective measures of events, as it requires the ability to calculate speeds and distances in real time.

The automation of the conflict detection improves upon the manual technique by removing human detection. Video data is collected on location and then returned in-office to be encoded and analyzed. The conflict detection system works by first tracking road users in the video footage by using a feature-based detection algorithm. Features are then grouped together based on a probabilistic framework as a complete road user. Using a set of learned, 'prototype' movements, the projected trajectories of all road users are compared to see if a conflict can be measured. This process is repeated for each frame (1/30 second) of the video data from which a database of different conflict types and severities is determined.

A proof of concept study was undertaken on a short segment of available data prior to embarking on a full-sized study. This study analyzes a 45 minute segment of video recorded at an intersection in downtown Vancouver, British Columbia. The intersection experiences high pedestrian volumes and is identified by the city of Vancouver as consistently having a safety problem. The analyzed video is used to determine where the majority of conflicts occur, as well as the road users most commonly involved in the conflicts. Furthermore, as a part of this study, a manual observer is employed to determine the accuracy of the automated tracking algorithm and its conflict detection proficiency.

In this short period of time, consistent trends of conflicts were observed and possible causes are identified. The concentration of conflict points give a clear indication of the main safety deficient areas

while the trajectories and behaviour of the road users involved provide potential reasoning for the conflicts. The manual review of the tracking algorithm shows that it is possible to track 100% of road users even though there are instances when some vehicles or pedestrians are given multiple tracks. Although this has an effect on volume counts, it does not play a major factor in altering the conflict detection. Finally, the review shows the ability of the conflict detection procedure to identify a sufficient number of conflicts detected by a trained safety professional. Based on the results of this study, the researchers are confident that a broader study can be undertaken.

For the full study, two intersections in Surrey, British Columbia are selected based on the frequency and severity of collisions occurring from 2005 to 2008. King George Boulevard at 88th Avenue is selected because of its high vehicle-vehicle collision frequency, while 152nd Street at 104th Avenue is selected because of its high vehicle-pedestrian collision frequency. Video data from each intersection is collected with a pivoting traffic monitoring camera provided by the City of Surrey Traffic Operations Department. A total of seven different views are recorded, each of which provide a vantage of specific conflict types. For each view, six hours of data are analyzed, from which various conflicts are objectively identified by type, location and severity. The three most frequent conflict types are isolated at each intersection as follows:

King George Boulevard at 88th Avenue

- East and westbound left turn rear end and opposing
- Northbound right turn merging
- Northbound through rear end

152nd Street at 104th Avenue

- West crosswalk pedestrian
- Eastbound through rear end

- Northbound left turn rear end

Short video clips containing each conflict are automatically generated, and serve as a permanent record for review. For each of the six conflict types noted above, the video clips and characteristics of involved road users are further analyzed to determine the most likely cause. In all cases, road user speed and trajectories along with visual inspection of events demonstrated repeated trends that lead to conflicts. It is assumed that the causes of conflicts are the same contributing reasons for the over-represented collision types at the intersections. Using this assumption and available literature, countermeasures are recommended in an attempt to reduce collisions corresponding to the identified conflicts.

After the results of the diagnosis study are presented to the City of Surrey, they are independently implementing a number of safety improvements at the intersection of 152nd Street at 104th Avenue. The motivation to apply these treatments likely does not come from the recommendations in this study alone, although two of the main recommendations contained herein are applied in some form. Of the several changes made to the intersection, five are aimed at improving the safety for the west approach pedestrians. These changes provide an opportunity to retroactively test the effectiveness of the safety treatment. This review is also seen as a measure of the procedure by which the recommendations are identified in the diagnostic study.

A before and after study is conducted to test the effectiveness of the improvements made to the west approach pedestrian crosswalk. Two eight hour days of data are analyzed for both the before and after periods. The number of conflicts for each day is corrected for the volume exposure to be fairly compared. Previous before and after studies advocate the use of a control site to account for confounding factors but limited data availability and the presence of several uncontrollable variables means that the use of one will provide only marginally better results. The comparison between before and after data shows a clear decrease in the frequency of conflicts in all types of conflicts between vehicles and pedestrians. The

results of the before and after study not only demonstrate the effectiveness of the countermeasures, but also the process by which they are recommended.

The automated conflict technique can provide an efficient and objective safety analysis for any location. The analysis technique is still in development with some questions that remain to be answered about the relationship between conflicts and collisions. The mechanics of both are similar, but a quantifiable correlation should be defined between the occurrences of each. This will aid the reviewers to further exploit the vast amounts of conflict data and to provide a much needed supplement to collision data. Future research should focus on identifying this link as well as on the creation of a conflict database, against which study locations can be compared. As conflict data becomes more understood, the method described in this study can provide a truly proactive approach to traffic safety engineering.

Bibliography

The World Bank. (2002). Retrieved December 20, 2011, from Roads and Highways: Road Safety: http://www.worldbank.org/transport/roads/safety.htm#developing

ADOT. (2009). *ADOT Traffic Engineering Policies, Guidelines and Procedures.* Arizona Department of Transportation.

Amundsen, F., & Hyden, C. (1977). Proceedings of the First Workshop on Traffic Conflicts.

Archer, J. (2004). Methods for the Assessment and Prediction of Traffic Safety at Urban Intersections and Their Application in Micro-Simulation Modeling. Division of Transport and Logistics, Royal Institue of Technology.

Atev, S., Arumugam, H., Masoud, O., Janardan, R., & Papanikolopoulos, N. (2005). A Vision-Based Approach to Collision Prediction at Traffic Intersections. *IEEE Transactions on Intelligent Transportation Systems*, 416-424.

Autey, J., Sayed, T., & Zaki, M. (2011). Safety evaluation of right-turn smart channels using automated traffic conflict analysis. *Accident Analysis and Prevention*, 120-130.

BCMOTI. (2008). *Collision Modification Factors For British Columbia.* Engineering Branch Ministry of Transportation & Infrastructure.

Brown, G. (1994). Traffic Conflicts for Road User Safety Studies. *Canadian Journal of Civil Engineering*, 1-15.

Campbell, B. (1992). Safety Versus Mobility. *IATSS Research, 16*(2).

Federal Highway Administration. (1981). *Highway Safety Evaluation - Procedural Guide.* Federal Highway Administration.

Glauz, W., & Migletz, D. (1984). The TRaffic Conflict Technique of the United States of America. *NATO ASI Series*, 41-58.

Guo, F., Klauer, S., McGill, M., & Dingus, T. (2010). *Evaluating the Relationship Between Near-Crashes and Crashes: Can Near-Crashes Serve as a Surrogate Safety Metric for Crashes?* Blacksburg: US Department of Transportation National Highway Traffic Safety Administration.

Hauer. (2005). The Road Ahead. *Journal of Transportation Engineering, ASCE*, 333-339.

Hauer, E. (1996). Identification of Sites with Promise. *Transportation Research Record: Journal of the Transportation Research Board*.

Hauer, E., Kononov, J., Allery, B., & Griffith, M. (2002). Screening the Road Network for Sites with Promise. *Transportation Research Record*.

Hayward, J. (1972). Near-Miss determination through use of a scale of danger. *Highway Research Record*, 24-34.

Hediyeh, H., Sayed, T., Zaki, M., & Ismail, K. (2012). Before-and-After Analysis of Pedestrian Crossing Speed Behavior at Scramble-Phase Signalized Intersections. *Transportation Research Record*.

Hyden, C. (1987). The Development of a Method for Traffic Safety Evaluation - The Swedish Traffic Conflicts Technique. *Bulletin 70*.

Ismail, K., Sayed, T., & Saunier, N. (2010). Automated Analysis of Pedestrian-Vehicle Conflicts: A Context for Before and After Studies. *Transportation Research Record: Journal of the Transportation Research Board*, 52-64.

Ismail, K., Sayed, T., & Saunier, N. (2010). Automated Analysis of Pedestrian–Vehicle Conflicts: Context for Before-and-After Studies. *Transportation Research Record: Journal of the Transportation Research Board*, 52-64.

Ismail, K., Sayed, T., Saunier, N., & Lim, C. (2009). Automated Analysis of Pedestrian-Vehicle Conflicts Using Video Data. *Transportation Research Record: Journal of the Transportation Research Board*, 44-54.

Kamijo, S., Matsushita, Y., Ikeuchi, K., & Sakauchi, M. (2000). Traffic Monitoring and Accident Detection at Intersections. *IEEE Transactions on Intelligent Transportation Systems*, 108-119.

Kanade, T., & Tomasi, C. (1991). *Detection and Tracking of Point Features.* Carnegie Mellon University Technical Report.

Kloeden, C., Mclean, A., Moore, V., & Ponte, G. (1997). *Travelling Speed and the Risk of Crash Involvement.* Adelaide: NHMRC Road Accident Research Unit.

Kononov, J., & Janson, B. (2002). Diagnostic Methodology for the Detection of Safety Problems at Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 51-56.

Kragh, B., Miller, T., & Reinert, K. (1986). Accident Costs for Highway Safety. *Public Roads*, 15-20.

Laureshyn, A., Svensson, A., & Hyden, C. (2010). Evaluation of Traffic Safety, Based on Micro-Level Behavioural Data: Theoretical Framework and First Implementation. *Elsevier*.

Li, S., Sayed, T., Zaki, M., Mori, G., Stefanus, F., & Khanlooa, B. (2012). Automating Collection of Pedestrian Data Using Computer-Vision Techniques. *Transportation Research Record: Journal of the Transportation Research Board*.

Li, S., Sayed, T., Zaki, M., Mori, G., Stefanus, F., Khanlooa, B., et al. (2012). Automatic Collection of Pedestrian Data Using Computer Vision Techniques. *Transportation Research Record*.

Mathers, C. D. (2005). *Updated projections of global mortality and burden of disease, 2002-2030: data sources, methods and results.* Worl Health Organization.

Maurin, B., Masoud, O., & Papanikolopulos, N. (2005). Tracking all traffic: computer vision algorithms for monitoring vehicles, individuals, and crowds. *Robotics & Automation Magazine*, 29-36.

Ministry of Public Works and Government Services. (2012). *Transport in Canada 2011.* Ottawa: Transport Canada.

Office of Energy Efficiency. (2008). *Canadian Vehicle Survey.* Ottawa: Natural Resources Canada.

Ottawa, C. o. (2010). *Pedestrian Intersection Safety Countermeasure Handbook.* Ottawa.

Parker, M., & Zeeger, C. (1989). *Traffic Conflict Techniques for Safety and Operations Observer's Manual.* McLean, Virginia: US Federal Highway Administration.

Parker, M., & Zeeger, C. (1989). *Traffic Conflict Techniques for Safety and Operations: Observer Manual.* McLean: Office of Implementation: Federal Highway Administration.

Perkins, S. R. (1967). *Traffic conflict characteristics; accident potential at intersections.* Warren, MI: General Motors Corporation.

Puccher, J., & Dijkstra, L. (2000). *Making Walking and Cycling Safer: Lessons from Europe.* New Brunswick, New Jersey: Rutgers University—Bloustein School.

Qin, X., & Ivan, J. (2001). ESTIMATING PEDESTRIAN EXPOSURE PREDICTION MODEL IN RURAL AREAS. *Transportation Research record*, 89-96.

Ramage-Morin, P. (2008). *Health Reports - Motor Vehicle Accident Deaths.* Ottawa: Statistics Canada - Health Information and Research.

Revesz, R. (1999). Environmental Regualtion, Cost Benefit Analysis, and the Discounting of Human Lives. *Columbia Law Review*.

Sayed, T., & de Leur, P. (2008). Collision Prediction Models for British Columbia. British Columbia Ministry of Transportation and Infrastructure.

Sayed, T., & Ho, G. (2000). *Analysis of Collision Prone Location and Selection of Countermeasures.* Vancouver: Insurance Corporation of British Columbia.

Sayed, T., & Saunier, N. (2007). Automated Analysis of Road Safety with Video Data. *Transportation Research Record: Journal of the Transportation Research Board*, 57-64.

Sayed, T., & Zein, S. (1999). Traffic Conflict Standards for Intersections. *22*.

Sayed, T., Abdelwahab, W., & Navin, F. (1995). Identifying Accident Prone Locations Using Fuzzy Pattern Recognition. *Journal of Transportation Engineering, ASCE*.

Sayed, T., Ismail, K., Zaki, M., & Autey, J. (2012). Feasibility of Computer Vision-Based Safety Evaluations: a Case Study of a Signalized Right-Turn Safety Treatment. *Transportation Research Record*.

Sayed, T., Vahidi, H., & Rodriguez, F. (1999). Advance Warning Flashers: Do They Improve Safety? *Transportation Research Record: Journal of the Transportation Research Board*, 30-38.

Svensson, A. (1986). Estimating Effects in Certain Before-and-after Studies. *Scandanavian Journal of Statistics*, 39-47.

Svensson, A. (1998). A Method for Analysing the Traffic Process in a Safety Perspective. *PhD Thesis*. Department of Traffic Planning and Engineering, Lund University.

Svensson, A., & Hyden, C. (2006). Estimating the Severity of Safety-Related Behaviour. *Accident Analysis and Prevention*, 379-385.

Tarko, A., Davis, G., Saunier, N., Sayed, T., & Washington, S. (2009). *Surrogate Measures of Safety.* White Paper ANB 20(3) Subcommittee on Surrogate Measures of Safety.

Vernez Moudon, A. (2001). *TARGETING PEDESTRIAN INFRASTRUCTURE IMPROVEMENTS: A Methodology to Assist Providers in Identifying Suburban Locations with Potential Increases in Pedestrian Travel.* Seattle: Washington State Transportation Center.