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# ESTIMATION OF PEDESTRIAN SAFETY AT INTERSECTIONS USING SIMULATION AND SURROGATE SAFETY MEASURES

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ESTIMATION OF PEDESTRIAN SAFETY AT INTERSECTIONS THROUGH  
SIMULATION AND SURROGATE SAFETY MEASURES

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DISSERTATION

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A dissertation submitted in partial fulfillment of the  
requirements for the degree of Doctor of Philosophy in the  
College of Engineering  
at the University of Kentucky

By

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Lexington, Kentucky

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## ABSTRACT OF DISSERTATION

### ESTIMATION OF PEDESTRIAN SAFETY AT INTERSECTIONS USING SIMULATION AND SURROGATE SAFETY MEASURES

With the number of vehicles increasing in the system every day, many statewide policies across the United States aim to increase the use of non-motorized transportation modes. This could have safety implications because the interaction between motorists and non-motorists could increase and potentially increasing pedestrian-vehicle crashes. Few models that predict the number of pedestrian crashes are not sensitive to site-specific conditions or intersection designs that may influence pedestrian crashes. Moreover, traditional statistical modeling techniques rely extensively on the sparsely available pedestrian crash database.

This study focused on overcoming these limitations by developing models that quantify potential interactions between pedestrians and vehicles at various intersection designs using as surrogate safety measure the time to conflict. Several variables that capture volumes, intersection geometry, and operational performance were evaluated for developing pedestrian-vehicle conflict models for different intersection designs. Linear regression models were found to be best fit and potential conflict models were developed for signalized, unsignalized and roundabout intersections. Volume transformations were applied to signalized and unsignalized conditions to develop statistical models for unconventional intersections.

The pedestrian-vehicle conflicting volumes, the number of lanes that pedestrians are exposed to vehicles, the percentage of turning vehicles, and the intersection conflict location (major or minor approach) were found to be significant predictors for estimating pedestrian safety at signalized and unsignalized intersections. For roundabouts, the pedestrian-vehicle conflicting

volumes, the number of lanes that pedestrians have to cross, and the intersection conflict location (major or minor approach) were found to be significant predictors. Signalized intersection models were used for bowtie and median U-turn intersections using appropriate volume transformations. The combination of signalized intersection models for the intersection area and two-way unsignalized intersection models for the ramp area of the jughandle intersections were utilized with appropriate volume transformations. These models can be used to compare alternative intersection designs and provide designers and planners with a surrogate measure of pedestrian safety level for each intersection design examined.

**KEYWORDS:** Intersection Safety, Conflict Prediction Model, Pedestrians, Non-motorists, Unconventional Intersection Transformations

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# CHAPTER 1 INTRODUCTION

## 1.1 Background and Problem Statement

Everybody is a pedestrian at some point of time in a day depending on individual activity, mode choice or travel pattern. Although the length and duration of the role as a pedestrian vary, it is imperative to consider the needs and safety of pedestrians with equal importance to other road users. Between 1982 and 2006, the population in the United States had increased by 28.4% (U.S. Census Bureau, 2009) whereas the number of motor vehicle drivers had increased by 36.2% (FARS, National Highway Traffic Safety Administration, 2009). This increase in number of drivers has consequently increased the number of vehicles per 1000 people from 800.30 in 2000 to 841.67 vehicles in 2008 (Energy, 2010). These statistics implicate the dominance of automobiles in the United States and the raise in exposure level for potential conflicts with other road users such as with pedestrians. This exposure level is important since the rate of infrastructure development is unable to cope up with the rising demands which create a problem to efficiently and safely segregate road users. As a consequence of the increasing number of vehicles, the interaction between pedestrian and vehicle increase, especially at intersections since they compete to use a common space at the same time. According to the Fatality Analysis Reporting System (FARS) maintained by the FHWA about 4092 pedestrians were killed in 2009 which accounts for over 12% of all roadway fatalities of 33,808 in the United States (FARS, Fatality Analysis Reporting System Encyclopedia by National Highway

Traffic Safety Administration Website, 2010). According to FARS database, this percentage of pedestrian crashes has been consistent for over a decade.

It should also be noted that 72% of all pedestrian crashes occurred in urban areas and over 24% of them were at intersections. Nearly two pedestrians died in vehicle crashes per 100,000 persons. In some states like the District of Columbia, Maryland, New Jersey and New York pedestrian fatalities accounted of more than 20% of their state fatalities (FARS, 2009). The National Bicycling and Walking Study reported that fear for safety in traffic is one of the frequent concerns for non-motorists (Chang, 2008) since the risk of injury as a pedestrian is about four times more than that as a car driver (Elvik, 2009). These numbers underscore the seriousness of the pedestrian traffic safety problem.

Intersections are designed to facilitate and provide opportunities for traffic to move in different directions. Intersections need to allocate space and proportion time to various traffic movements and their objective is to achieve this in an efficient and safe manner. Conflicts occur when the paths of road users cross each other and this is especially the case at intersections. Traditionally, intersections have been defined and designed with due considerations to vehicles. The high frequency of pedestrian crashes however indicates that there is an increased need to protect pedestrians from crashes with motor vehicles and therefore reduce their risk on roadways. One of the objectives of traffic engineers and city planners is “access management” that aims to manage vehicular mobility and accessibility and enhance efficient travel to various destinations. Most of the performance measures and the functional classification of roadways

are based on mobility of motorists. Lately there has been strong advocacy towards livability and pedestrian friendly communities that encourage walking and promote healthier lifestyle (Lawrence Frank & Co., 2005). This creates a challenge to engineers and planners to strike a balance between motorist's mobility and non-motorist's safety.

Generally, it takes several years of crash data to analyze the underlying trend and understand the factors affecting it. Attempts to quantify pedestrian safety levels in a similar manner to that of motorists in terms of crash prediction models have been limited to due to lack of good and reliable crash records. Undercounting and non-reporting of injuries also add to the limitations of the data quality and availability. On the other hand, exposure data such as vehicle miles traveled is not available for pedestrians. The only means for deriving pedestrian exposure measures are obtained through estimates of the National Household Travel Survey conducted once in six to eight years (NHTS, 2010). To overcome the lack of historical crash and exposure data, a surrogate approach has been developed called "conflict analysis". Traffic conflicts have been used as a measure of the potential for crashes. Traffic conflict is defined as "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remained unchanged" (Amundsen & Hyden, 1977). The conflict analysis aims to study conflicts between vehicles or in this case vehicle- pedestrians, instead of waiting for actual crashes to occur. Due to lack of reliable pedestrian-vehicle crash records or adequate sample size, this approach can substitute actual crash

numbers to develop a surrogate measure of safety. The current developments in technology and advanced software allow now to simulate road conditions and analyze them in a controlled environment instead of collecting field data which is expensive and time consuming.

Technological developments in simulation allow users to study actual road conditions and determine the effects of their designs on safety and operational performance. In this case, a surrogate approach to quantify potential crashes has been developed for vehicular crashes as an alternative to crash prediction models using historical crash data. This research extends this procedure to develop generalized models for pedestrian crashes and covers conventional and unconventional intersections. Conventional designs include four legged traditional intersections and unconventional intersections include roundabout and indirect left turn treatments at intersections identified by FHWA. These include jug handle, median-turn, continuous flow intersection, and superstreet (Rodegerdts, et al., 2004).

Intersections are designed to serve various requirements of the vehicular traffic such as to regulate conflicting flows to improve safety and to provide appropriate signal phasing to reduce delays. This exposes pedestrians to various potential hazards such as large vehicular volumes, high approach speeds, multilane environments and complex signal phasing. The advantages provided to motorists should not be a disadvantage to pedestrians hence, quantification of potential hazards such as pedestrian-vehicle conflicts is necessary to initiate the



first step towards designing roadways that accommodate the needs of all road users.

Federal and local agencies have emphasized the need and importance of adopting “Smart Growth” policies that encourages alternative modes of transportation such as walking and biking to reduce various problems such as congestion, environmental pollution and health (Lawrence Frank & Co., 2005). When multiple users tend to occupy the common road space, conflicts are bound to happen. There is a need to quantify this conflict between pedestrians and vehicles at intersections so appropriate measures can be adopted to avoid the potential conflicts that could result into an actual crash. This study provides a step towards this purpose by understanding and estimating the risk for pedestrians from vehicles at various at grade intersections.

## **1.2 Study Objective**

Estimation of pedestrian safety is the primary objective of this study. However, the limited number of pedestrian-vehicle crashes does not allow for observing an intersection to determine the issues leading to a crash and allow for a robust statistical prediction model. Alternatively, observing potential pedestrian-vehicle conflicts based on “conflict” theory at an intersection it is subjective and it requires highly trained professionals for long observation periods. To overcome these problems, conflicts were analyzed in a controlled environment, such as micro-simulation models, and have been successfully adopted and validated in

various studies conducted on interaction of motorist (Gettman, Pu, Sayed, & Shelby, 2008). Recently, a few research efforts were conducted to incorporate the Surrogate Safety Assessment Model (SSAM) in developing potential crash prediction models for motorists but no attempt was made to quantify potential pedestrian-vehicle conflicts using SSAM. Simulation software such as VISSIM can now micro-simulate pedestrian flows and record their trajectories along with vehicle movements for time step as low as one second. This created an opportunity to analyze pedestrian-vehicle conflicts and apply the surrogate safety assessment procedure to generate potential pedestrian-vehicle conflict models. Thus, the primary effort of this research was to develop simulation models that reflect typical conventional and unconventional intersections incorporating pedestrian traffic and apply SSAM to quantify the potential pedestrian-vehicle conflicts. This approach will assist traffic engineers in identifying the potential risk that pedestrians face at a specific intersection. Such models can be a stepping step towards planning a facility or assess the safety performance of a facility with pedestrian viewpoint.

The following is an outline of this document that addresses these objectives:

- Chapter 2, presents a thorough review of the literature related to this research;
- Chapter 3, describes the methodology utilized in this process;
- Chapter 4, presents the statistical modeling and a synthesis of the results;

- Chapter 5, provides a summary of the research, the conclusions drawn based on the results, and recommendations for future consideration.

## CHAPTER 2 LITERATURE REVIEW

The first step undertaken was to conduct a thorough literature review to understand two main aspects of pedestrian safety: traditional practices adopted to quantify pedestrian safety and evolution of conflict analysis technique to quantify pedestrian safety. The Transportation Research Information Services (TRIS) Database was utilized to identify appropriate past work. This step describes the current practice to estimate pedestrian safety, identify key questions, and define areas where the current research could contribute to the knowledge base. First, various traffic and intersection characteristics that affect pedestrian safety were reviewed and then various approaches adopted to quantify pedestrian safety were documented in this section. Finally, literature on different intersection designs considered in this study was reviewed.

### 2.1 Contributing Factors

Many studies have determined the effect of various intersection and traffic characteristics that impact pedestrian safety based on the available crash numbers, police report and field observations. Harwood et al. (2008) conducted a comprehensive review on various intersection characteristics that affect pedestrian safety and listed various parameters that included pedestrian volume, vehicular volume, crossing width, presence of raised pedestrian crosswalks, crosswalk markings, crosswalk illumination, median refuge islands, raised intersections, bus stop location, pedestrian-related signing, pedestrian signal

type, pedestrian signal timing, right-turn-on-red and one-way streets. Specific parameters significant to this research include pedestrian and vehicle volumes and traffic signal parameters. Zegeer, Opeila, and Cynecki (1985) analyzed pedestrian crashes at 1,297 signalized intersections in 15 cities and found that the volume of pedestrians crossing at an intersection was the most influential variable in explaining the variation in pedestrian crashes. The study observed that the frequency of pedestrian crashes increased with increasing pedestrian volume and a similar relationship was also concluded by Brude and Larsson (1993) and Lyon and Persaud (2002).

The second most influential variable in the literature was found to be approaching vehicular volume, which was documented by all three studies mentioned above. The relationship between vehicular turn volume and pedestrian crashes was studied by Lyon and Persaud (2002) and Leden (2002) and both studies concluded that left turning vehicular volumes had a positive relationship to the pedestrian crashes, i.e. higher volumes resulted in more crashes. Robertson and Carter (1984) reported that the presence of pedestrian signal itself did not have any significance on the pedestrian crashes but the signal timing scheme had a positive relationship to reduced pedestrian crashes. Another study by Zegeer, Opiela, and Cynecki (1982) also found that intersections with exclusive signal phases adjusted for pedestrians had fewer pedestrian crashes. Another aspect of turn traffic is the Right turn on Red (RTOR) which was studied by Preusser et al. (1982) and examined sites in four states – New York State, Wisconsin, New Orleans and Ohio. The study

concluded that there was a small effect of increasing pedestrian-right turn vehicle crashes when RTOR was permitted.

## **2.2 Estimating Pedestrian Safety**

Quantifying pedestrian safety is equally important to defining contributing factors to pedestrian crashes. Most traditional analyses of traffic safety measures relied on observed accident data which were either collected or estimated. For estimation purposes, different types of statistical approaches have been adopted in various studies such as before-after comparisons of collected data and anticipatory estimation studies based on safety assessments. Another approach for estimating pedestrian safety that has recently gained popularity is the conflict analysis technique which is mainly due to developments and the ability of micro-simulation software.

A review of predictive models indicates that the most common form of statistical models adopted are generalized linear model (GLM) and negative binomial regression model. The typical characteristic of GLM approach is that it does not require the variable to be normally distributed. Hauer, Ng and Lovell (1988) adopted the GLM approach to describe the relationship between accident frequency and traffic flows at intersections. Their model used constants specific to the intersection type, posted speed and location, and used traffic volumes (AADTs) as explanatory variables. Another study by Sayed and Rodriguez (Sayed & Rodriguez, 1999) developed an adaptive accident prediction model for

estimating safety at unsignalized urban intersections using the GLM approach. The study estimated model parameters an error structure of Poisson distribution and calculated a suitable dispersion parameter based on Pearson's  $\lambda^2$  distribution, the number of observations, and the number of model parameters. The study aimed at identifying and ranking accident-prone locations, developing critical accident frequency curves, and evaluating before-and-after studies.

Poisson's distribution generally assumes a certain degree of variability in the dataset but since accidents are discrete random events, over dispersion is usually a common occurrence. Over dispersion is the condition where greater variability exists between the observed response and predicted value in a dataset than predicted by a statistical model. If over dispersion is present in a dataset, the estimated standard errors and test statistics overall goodness-of-fit will be distorted and adjustments should be made. To negotiate this variability, negative binomial distribution was adopted in many studies including Lyon and Persaud (2002), Leden (2002) and Zeeger et al. (2005). These studies adopted a general functional form:  $N_{ped} = \exp(\beta_0 + \beta_1 ADT + \beta_2 PedVol + \beta_3 X_3 \dots \beta_n X_n)$  where, ADT was the Average Daily Traffic, PedVol was the pedestrian volume,  $N_{ped}$  was the expected number of pedestrian crashes and X represented other variables such as proportion of left-turn volume, number of lanes, speed limit, presence/absence of a crosswalk, and presence/absence of a median. These studies concluded that an increase in total traffic and pedestrian volumes led to higher pedestrian crashes but the relationship between pedestrian volumes and pedestrian crashes was non-linear. Although the base model was similar in these

three studies, the Lyon and Persaud (2002) and Leden (2002) studies focused mainly on pedestrian and vehicle volumes whereas Zegeer et al. (1985) included other site characteristics and found positive correlation between median type, number lanes, and marked/unmarked crosswalks with pedestrian crashes. However it should be noted that the development of these models was dependent on the limited available frequency of pedestrian crashes and it required a large sample of sites for model development. The magnitude of minimum required sample size was reflected in many studies such as Lyon and Persaud (2002) study that utilized 122 intersections in the three-leg STOP-controlled group and compiled 11 years of data at these locations.

Shankar et al. (2003) evaluated Poisson-gamma and zero-inflated Poisson distribution (ZIP) models for predicting crashes involving pedestrians on urban or suburban roads in Washington. Pedestrian crashes are sporadic events hence a dataset would generally have excessive zeros. The ZIP models were applied to capture the “excess” zeroes that are predominant in most crash datasets and the model is believed to provide an improved fit to data compared to Poisson and Negative Binomial (NB) regression models. The study found that average daily traffic, traffic signal spacing, illumination, network design variables, social policy variables, and presence of center-turn lanes have a statistically significant effect on pedestrian crash probabilities.

Another prediction methodology developed by Harwood (2008) included base models for three- and four-leg signalized intersections, and Accident Modification Factors (AMF). This approach improves earlier methods in that it



contains a base model which was fixed for nominal conditions and then the effect of individual geometric design or traffic control features is accounted using AMF according to site characteristics. Even though specific site characteristics are considered, the AMFs are the results of previous studies and limited historical datasets and therefore they are not comprehensive. However, the advantage of these predictive models is that they can be readily applied to conventional intersections with minimum data but on the other hand the primary weakness is the limitation of the availability of crash data to generate a good model that can explain the observed variation.

Traditionally, the crash data is the ultimate measure of safety for engineers. If a location presents excessive number of crashes, it could attract the attention of safety engineers to investigate the site and identify possible features and parameters contributing to the crashes. In the case of pedestrian crashes, this approach would not likely work due to infrequent occurrence and an observer will have to wait a long period of time to collect enough data to be utilized. Additionally, there always exist concerns regarding the usefulness and reliability of available dataset since it has been speculated that datasets may not be adequate due to various reasons such as budget constraints, data gathering techniques, observation errors and data being biased and other limitations (Parker Jr. & Zegeer, 1989).

These reasons created the need to develop and utilize complementary methods to measure safety such as the “Conflict” Analysis. The concept was conceived by Perkins and Harris (1968) who defined conflict as a condition when

the driver takes evasive action to avoid a potential collision. This approach required observing and recording unsafe interactions between vehicles which is determined by the use of evasive action to avoid a potential collision. This theory became popular and was utilized in various studies that sought different ways to establish relationships between potential conflicts and actual crash. The user manual for the US conflict technique (Parker Jr. & Zegeer, 1989) lists possible evasive actions in all traffic situations that could be used by conflict observers to record when conducting a conflict analysis. However, this approach was debated by many studies including Chin and Quek (1997) who mentioned that the term “evasive” was subjective and that an action could be an outcome of a precautionary measure or due to differing driving techniques adopted by drivers. But Amundsen and Hyden (1977) deviated from the base definition and excluded the term “evasive” action and defined conflict as, “an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remained unchanged”. The definition however did not elaborate on the “observable” situation which again was debated upon by Chin and Quek (1997). The theory later evolved with the ability to quantify conflicts using the time and distance relationships. In general terms, traffic conflict was defined as when two or more vehicles tend to occupy the same space at the same time. In early 1970s and 1980s this measure was defined as the user risk for vehicles taking into account the roadway condition and the traffic environment.

Conflict techniques were primarily adopted as a tool to assess the safety of a roadway. The most widely used conflict analysis measure was “Time to Conflict” (TTC). Hayward (1972) defined TTC as “*The time required for two vehicles to collide if they continue at their present speed and on the same path*”. Based on 43 observations, he found that the minimum value of TTC was 1 sec for vehicle to vehicle and 1.5 seconds for vehicle to bicyclists. Hayward explained the TTC using a time-space diagram and inferred that if two vehicles were not on a collision path then the value of TTC would be infinite since they would not collide. On the other hand, if two vehicles were on a collision path and the speed and directions of both vehicles remained unchanged, then the value of TTC would be zero indicating that there would be a collision. According to Hyden (1987) conflicts could be considered dangerous by fixed TTC below 1.5 sec or a speed-dependent TTC.

Van Der Horst (1990) also studied conflicts between car-car, car-bicyclist and car-pedestrian and found that the median minimum time to conflict for all cases was close to 1.5 seconds. Several other measures of conflict were adopted (Allen et al., 1978, Gettman, Pu, Sayed, & Shelby, 2008) such as:

- Gap time which is the time difference between the arrival times of the vehicles at the point of crossing if no evasive actions were taken;
- Post Encroachment Time (PET), the time lapse between the end of encroachment of a vehicle on a collision point and the time that the other vehicle actually arrives at that point;

- Encroachment Time (ET), the as the time duration during which the turning of a vehicle infringes the right-of-way of the second vehicle;
- Initially Attempted Post Encroachment Time (IAPE), the time lapse between the commencement of an encroachment by a turning vehicle plus the expected time for the other vehicle to reach a common conflict point;
- Proportion of Stopping Distance (PSD), the ratio of the remaining distance to the potential point of collision and the acceptable minimum stopping distance; and
- Deceleration Rate (DR), which is the highest rate at which a vehicle must decelerate to avoid a collision.

Chin et al. (1991) recorded the ramp area of an expressway and utilized video recording to analyze the conflict data (TTC) to investigate the expressway on-ramp merging process. The study found that the inverse of TTC explained the conflict severity better than TTC. From the mixed Weibull distribution, the study estimated the average probability of near accident per merge at the merging section. Even though many studies acknowledged the potential of utilizing conflict analysis in estimating safety, it faced criticism for many reasons including observation errors, subjected to limited area, expensive and time consuming (Kim & Sul, 2009).

The inadequacies of “manual” conflict analysis procedures were overcome by micro-simulation methodology which could simulate the user defined

characteristics of vehicles, pedestrians and other components of roadway environment and record the behavior of each component at every time step. Traditionally, traffic simulation was primarily utilized to assess the operational efficiency of a roadway but with the advancement of simulation technology the application was extended for traffic safety analysis. A study conducted by Garber and Liu (2007) evaluated the impact of different truck-lane restriction strategies on highway safety performance through the implementation of simulation. They utilized TTC as the safety measure that was collected from Paramics models for analysis. Three types of conflicts data were reported that included lane-changing conflicts, merging conflicts, and rear-end conflicts. The study successfully depicted the utilization of simulation software in conflict analysis by identifying the impact of different restriction strategies, geometric factors as well as traffic factors on highway safety performance.

Sayed and Zein (1999) utilized conflict technique to develop a predictive model relating the number of conflicts to traffic volumes and accidents from 92 intersections. The study established conflict frequency and severity standards in the form of an Intersection conflict index that compared relative conflict risk among different intersections. The study found both that the conflicts and accidents followed a Poisson distribution and the model was found to be statistically significant which explained 70% to 77% of the variation between accidents and conflicts at signalized junctions. Fazio and Roupail (1990) adopted conflict technique and analyzed lane change and rear-end conflicts for traffic performance evaluation of weaving sections. Integrated Transportation

Simulation (INTRAS) model was utilized to record the number of conflicts and they concluded that conflict rates were more effective than speeds as a measure of effectiveness (MOEs) for the analysis of weaving sections. Further study by Fazio et al., (1993) related the simulated conflicts of 10 weaving sites on Interstate 294 with the real crash rates and found a 74% correlation between lane change conflicts and the police reported angle/sideswipe accident rates. The study also found 95% correlation between rear end conflict rates and actual rear end crash rates, for eight ramps of moderate lengths.

Gettman et al., (2008) conducted an extensive research on application of conflict technique and developed a computer program called “Surrogate Safety Assessment Model” (SSAM) which identifies potential conflicts. The surrogate measures proposed in the study include minimum TTC during the conflict event, minimum PET during the conflict event, maximum speed of the two vehicles (MaxS), maximum difference in the speed of the two vehicles during the conflict event (DeltaS), initial DR of the reacting vehicle and location of the starting and ending points of the conflict event. The study conducted theoretical validations, field validations and sensitivity analysis. While conducting the theoretical validation, the study utilized SSAM to assess the relative safety of a pair of intersection designs and found that under equivalent traffic conditions the software could statistically differentiate the total number of conflicts, the number of conflicts by type (i.e., crossing, lane-change, or rear-end), and conflict severity indicators. For the field test, the SSAM outputs were compared with available crash records for 83 intersections. The analysis showed that the simulation-

based intersection conflicts data provided by SSAM were significantly correlated with the field crash data, with certain exceptions such as path-crossing maneuvers, which were under-represented in the simulation. A sensitivity analysis was conducted to compare four simulation systems: AIMSUN, Paramics, TEXAS, and VISSIM and found that each simulation system exhibit modeling inaccuracies that lead SSAM to identify different conflict numbers. The study found that intersections modeled in VISSIM exhibited the least number of total conflicts whereas TEXAS had the highest total conflicts. The difference in number of conflicts was attributed to the driver behavior model which in TEXAS includes active conflict avoidance whereas other simulations employ reactive driver behavior modeling. Since a reactive driver behavior model was required to assess the potential of a conflict, VISSIM was chosen as the simulation environment for this study.

### **2.3 Unconventional Intersections**

Unconventional intersections have emerged in recent years that overcome the shortcomings of traditional four-legged intersections in terms of increasing capacity, reducing delays and reducing conflict points. The unconventional intersection designs considered in this study include median U-turn, bowtie, superstreet and jug handle design. Hummer (2003) evaluated the advantages and disadvantages of these unconventional intersections. Median U-turn designs improve the efficiency of the system by eliminating left-turn movements from the

major street at the intersection and instead provide U-turn crossovers at the downstream of the intersection to accommodate left turn movements as shown in Figure 1. Median U-turn design increase intersection capacity which reduces overall travel time across a section. Since it eliminates the left turn movement,



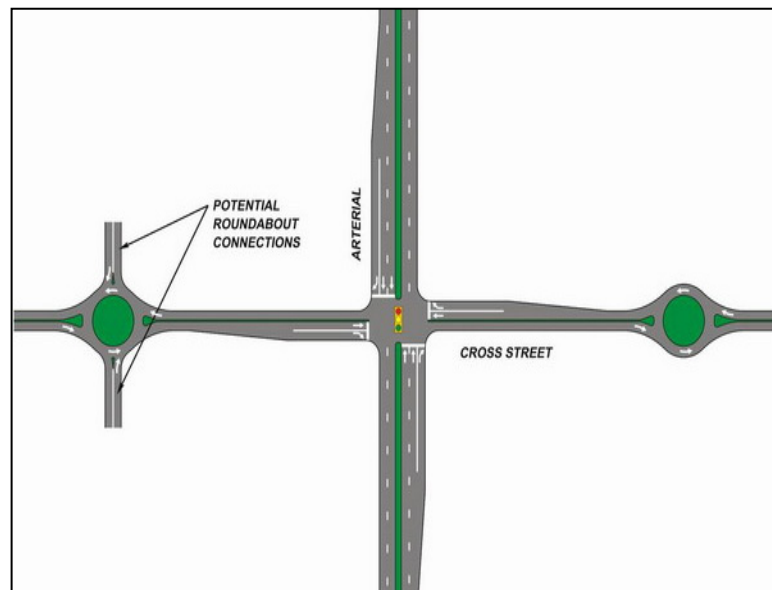
**Figure 1 Typical median U-turn intersection (UMD, 2004)**

there is no left-turn “waiting” traffic at the intersection to be accommodated requiring extra green time and thus allow for enhanced progression. Such intersections also pose fewer threats to pedestrians since there are fewer conflict points. However, the left turn movement experiences higher delays and travel distance because of longer maneuver and the design requires wider right-of-way.

The bowtie design is based on the same principle of eliminating left turn movement from the approaches of the major street and uses roundabouts on the



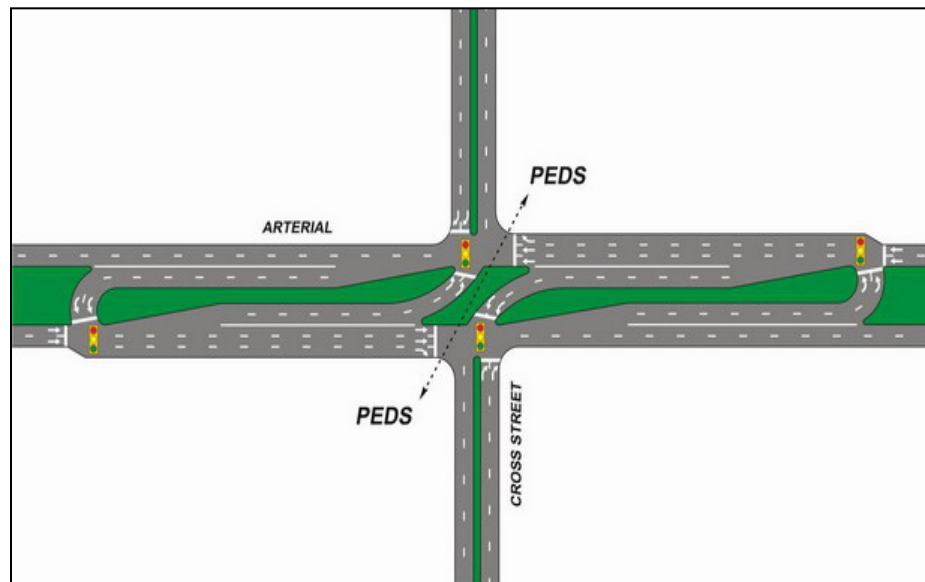
cross street to accommodate left turns (Figure 2). This design also was developed to increase capacity and enhance major street progression since there is no left turn movement at the intersection. However, the minor street capacity is reduced and the left turn and U-turn movements experience increased delays.



**Figure 2 Typical bowtie intersection (UMD, 2004)**

Another intersection design that prohibits left-turn movement is the superstreet which also prohibits through movements from side street approaches. This design requires the traffic from the minor street to turn right onto the major street and then make a U-turn maneuver after the appropriate location (Figure 3). Left turns from the main road approaches are executed in a manner similar to left turns at conventional intersections. The advantages of this design are the development of perfect two-way progression, safer than other designs, and increased intersection capacity (Hummer, 2003). However, this

design requires wider right-of-way as compared to conventional intersection, median U-turn and bowtie intersection, increases pedestrian crossing time and does not work well with increased minor street traffic.



**Figure 3 Typical superstreet intersection (UMD, 2004)**

Another design considered in this study is the jug handle design which also eliminates left turns from the major street and redirects them on the minor street before or after the intersection (Figure 4). The minor street remains as conventional minor street approach. The advantages of this intersection design are reduced delays on major street, reduced conflict points and increased capacity. However, the left turn experience increased delays, minor street experiences increased volume hence increased delays, the pedestrians have to cross ramps and the increased distance may be detrimental for bicyclists.



**Figure 4 Typical jug handle intersection (UMD, 2004)**

## **2.4 Summary and Research Needs**

Various parameters that affect pedestrian safety at roadways have been identified by previous studies. Traditional approaches to estimate pedestrian safety largely depend upon scarcely available crash data to develop prediction models. This is a major limitation, since pedestrian-vehicle conflicts are relatively rare and random events that do not provide an analyst with a desired sample size. The traffic conflict technique has evolved over the past decades and has been implemented in various scenarios for examining safety issues. The technique has been acknowledged by many studies as an important approach that can identify potential conflicts effectively.

The importance of traffic volumes in determining pedestrian crashes has been noted in various studies reviewed here. It is therefore essential to consider

this in the development of a crash prediction model. From previous studies it is evident that conflict analysis has been mainly utilized in vehicle to vehicle interaction and has not been implemented in pedestrian-vehicle conflicts. This is most likely due to lack of sufficient data to allow for robust analysis. However, recent software improvements have helped in simulating conflicts and thus use the conflict analysis technique as an alternative procedure to overcome this problem. Advanced software for simulation and additional support by surrogate safety measures makes it possible to investigate pedestrian-vehicle interactions at a microscopic level and develop potential conflict models. The simulation software VISSIM, for pedestrian modeling has been developed and validated over the past years. On the other hand surrogate safety models have been applied only to determine vehicle to vehicle potential conflict. No past work has identified the applicability of surrogate safety assessment to analyze pedestrian-vehicle conflicts nor the safety implications of unconventional intersection on pedestrian safety have been explored, which forms the foundation for this research.

## CHAPTER 3 METHODOLOGY

### 3.1 Intersection Modeling and Traffic Simulation

VISSIM (“VerkehrInStädten- SIMulationsmodell”; German for “Traffic in cities - simulation model”) version 5.30 was utilized to model all the intersection for this study (PTV, 2011). The primary reason to select VISSIM as the modeling software is its flexibility to model complex geometric configurations and ability to provide an option for user defined operational and driver behavior parameters. The general process of model development includes designing the network geometry, modeling traffic parameters, placing routing decisions and reduced speed areas for turn movements, assigning priority for movements in conflict areas and designing signals.

Generic models were developed using typical intersection characteristics. The flexible features in VISSIM assisted in easy coding of all conventional as well as unconventional intersections. “Links” represented roadways that are connected using “connectors” reflecting the appropriate lane configuration. All intersections were modeled with crosswalks and each approach had stop lines placed 4-ft away from crosswalks as suggested in the FHWA Manual on Uniform Traffic Control Devices (MUTCD, 2003). The approach length of each intersection was modeled at a minimum length of 1,500 feet for sufficient queue storage. The different lane configurations that were considered in this study are summarized in Table 1.

**Table 1 Intersections lane configurations**

Intersection Type	Number of Lanes		
	Major	Minor	Total Combinations
Unsignalized (TWSC/ AWSC)	1/2	1/2	4
Signalized	1/2/3	1/2/3	6
Roundabout	1/2	1/2	2
Median U-turn	2	2	1
Bowtie	2	1	1
Superstreet	3	2	1
Jug handle (Forward)	2	2	1

Next, various input parameters were carefully determined which included traffic composition, driver behavior and vehicular and pedestrian volumes. Traffic mainly comprised of vehicles and pedestrians. Simulated vehicular traffic comprised of passenger cars only since according to the United States Bureau of Transit Statistics, majority (about 73.4%) of the automobiles in the United States are passenger cars (BTS, 2011). Approximately one in four drivers operate their vehicle at a speed higher than the posted speed limit and hence varying speed profiles were incorporated in the simulation (Royal, 2003). To account for this variation, 75% of the vehicles traveled at the speed limit of 35mph, 18% of the vehicles exceeded the speed limit by 10 mph and 7% by 15mph. At all turning movements, vehicles targeted a speed of 15mph using the modeling feature of reduced speed areas. Similarly, to simulate average and fast moving pedestrians, 80% of pedestrians were assumed to walk at 3.5 feet per second and 20% at 4 feet per second. The preloaded Wiedemann 74-car following model

was selected in VISSIM for vehicle behavior, and default driving behavior parameters were adopted (Wiedemann, 1974). Other default base data parameters including acceleration and deceleration functions of vehicles were utilized.

Pedestrians were modeled as vehicles with personalized characteristics. Pedestrians were modeled with an average width of 1.65 feet and unique speed profiles were developed that included pedestrians walking at 3.5- and 4-feet per second. Crosswalks were modeled using Link property that were managed to allow pedestrians to follow each other as well as to overtake if required, within the same link. Further, to account for different exposure level, a range of traffic volumes was considered for each intersection model. Traffic signal warrants were used as a reference to develop the volume combinations for each intersection type. The Manual on Uniform Traffic Control Devices (MUTCD, 2003) lists specific warrants (Warrants 1, 2 and 3) that recommend signalization of an intersection based on major and minor street volumes. With these volumes as benchmark, volumes along the major and minor streets were defined to account for minimum and maximum intersection capacities.

The following sections define the simulation parameters used for each intersection considered in the simulation and identify the combinations evaluated.

### 3.1.1 Unsignalized Intersections

An exploratory analysis was conducted on unsignalized intersections (all-way and two-way stop controlled) which were evaluated by examining volume, left turn percentage, right turn percentage, pedestrian volumes and number of approach lanes.

- Volumes along the major road ranged between 200 vehicles per hour (vph) to 800 vph per approach. The upper threshold of 800 vph volume was evaluated since any number higher would warrant consideration of signal installation based on Warrant 3 of the MUTCD (2003).
- Volumes along the minor road ranged between 100 vph to 300 vph per approach. The 300 vph volume, in combination with the major road upper threshold of 800 vph, reflects an upper threshold of capacity for a single approach combination of unsignalized intersection. Any combination beyond would warrant consideration of signal installation based on MUTCD Warrant 3 (2003). Volumes were increased in 100 vph increments.
- Left turn and right turn percentages ranged from 10 to 30 percent. This reflects a full range of anticipated turn volumes up to 150 left turning vehicles, which would be at or near capacity for a left turn movement at unsignalized intersections (KTC, 2006). Turn percentages were increased in 10 percent increments.



- Number of lanes evaluated was one or two lanes per approach.  
Unsignalized operations with three or more lanes are not recommended due to safety concerns.
- Three pedestrian volumes were evaluated including 75, 100 and 125 pedestrians per approach.

Table 2 summarizes these criteria and value ranges. A full factorial design for this set of parameters required 216 simulations for all-way stop controlled (AWSC) intersections. Another 216 scenarios were used for two-way stop controlled (TWSC) intersections.

**Table 2 Unsignalized intersection simulation design matrix**

Parameter	Design values ranges			
	I	N	Increment	Total combinations
Major/minor street volumes (vph)	200/100	800/300	200/ 100	12
Turn percentage	10	30	10	3
Pedestrian volume (ped/hr)	75	125	25	3
Number of lanes	1	2	1	2

### 3.1.2 Signalized Intersections

Signalized intersections were evaluated similarly by examining traffic volume, left turn percentage, right turn percentage, pedestrian volumes and number of approach lanes.

- Volumes along the major road ranged between 250 vph to 1000 vph per approach. The 1,000 vph volume exceeded the requirements of Warrant 3 specification of MUTCD to consider signalization at an intersection. Volumes were increased in 250 vph increments.
- Volumes along the minor road ranged between 200 vph to 600 vph per approach. The 600 vph volume, in combination with the major road upper threshold of 1,000 vph, exceeds the upper threshold of capacity for any combination of a signalized intersection as depicted in Figure 4c-3 of MUTCD (2003) (Figure 5). Volumes were increased in 200 vph increments.

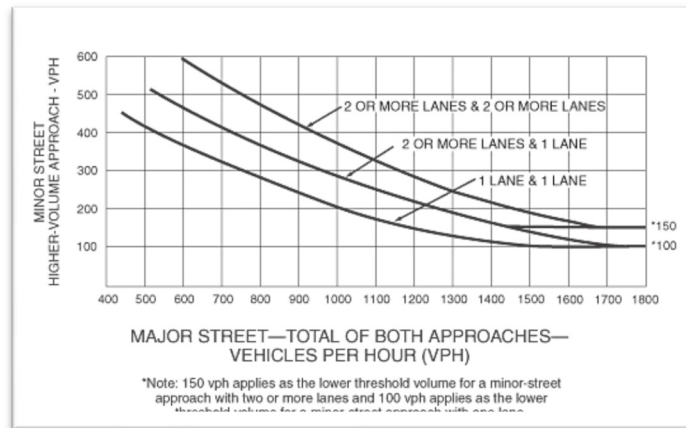


Figure 5 Warrant 3, peak hour, figure 4c-3 MUTCD (2003)

- Left turn and right turn percentages ranged from 5 to 15 percent. This reflected a full range of anticipated turn volumes up to 150 left turning vehicles per lane, which was at or near capacity for a left turn movement for one approach (KTC, 2006). Greater turn volumes would warrant an exclusive turn lane and protected phase (Koonce, et al., 2008) in which case there would be no pedestrian-vehicle interaction and hence no potential conflict to quantify. Turn percentages were increased in 5 percent increments.
- Three lane combinations were evaluated: one, two and three lanes per approach.
- Three pedestrian volumes were evaluated including 75, 100 and 125 pedestrians per approach.

Table 3 summarizes these criteria and value ranges. A full factorial design for this set of parameters required 324 simulations.

**Table 3** Signalized intersection simulation design matrix

Parameter	Design values ranges			
	i	N	Increment	Total combinations
Major/minor street volumes (vph)	250/200	1,000/600	250/ 200	12
Turn percentage	10	30	10	3
Pedestrian volume (ped/hr)	75	125	25	3
Number of lanes	1	3	1	6

### 3.1.3 Roundabouts

Roundabouts were evaluated similar to signalized intersections by examining traffic volume, left turn percentage, right turn percentage, pedestrian volumes and number of approach lanes.

- Volumes along the major road ranged between 250 vph to 1,000 vph per approach. While there is no warrant recommended for roundabout, similar volume combination as signalized intersection was examined. The 1,000 vph volume was considered as an upper threshold of capacity. Volumes were increased in 250 vph increments.
- Similarly, volumes along the minor road ranged between 200 vph to 600 vph per approach. The 600 vph volume, in combination with the major road upper threshold of 1,000 vph, was considered to reflect an upper threshold of capacity for a single-lane approach of roundabout. Volumes were increased in 200 vph increments.
- Left turn and right turn percentages ranged from 5 to 15 percent. This reflected a full range of anticipated turn volumes up to 150 left turning vehicles which was at or near capacity for a left turn movement for one approach. Turn percentages were increased in 5 percent increments.
- Two lane combinations were evaluated: one and two lanes per approach.

- Three pedestrian volumes were evaluated including 75, 100 and 125 pedestrians per approach.

Table 4 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 216 simulations.

**Table 4 Roundabout simulation design matrix**

Parameter	Design values ranges			Total combinations
	i	N	Increment	
Major/minor street volumes (vph)	250/200	1000/600	250/ 200	12
Turn percentage	5	15	5	3
Pedestrian volume (ped/hr)	75	125	25	3
Number of lanes	1	2	1	2

### 3.1.4 Unconventional Intersections

Test cases were analyzed for each unconventional intersection type and it was determined that selective transformations for signalized and unsignalized conditions could be applied to estimate pedestrian safety at unconventional intersections. For median U-turns, the appropriate signalized intersection model will be used, since the main intersection will remain signalized and thus retain the same conflict patterns. However, appropriate volume transformations were needed to reflect the changes. Assuming East-West direction as the mainline, the volumes were transformed as shown in Table 5.

**Table 5 Volume transformations for median U-turn**

Actual Movement	Transformation for Conflicting Volume Calculations
West bound right turn	West bound right turn + East bound left turn
East bound right turn	East bound right turn + West bound left turn
North bound right turn	North bound right turn + North bound left turn
South bound right turn	South bound right turn + South bound left turn
North bound left turn	0
South bound left turn	0
East bound left turn	0
West bound left turn	0

Bowtie intersections were analyzed similar to median U-turn design and the signalized intersection models are proposed with the volume transformations for the conflict pattern as shown below.

**Table 6 Volume Transformation for Bowtie**

Actual Movement	Transformation for Conflicting Volume Calculations
West bound right turn	West bound right turn + West bound left turn
East bound right turn	East bound right turn + East bound left turn
North bound right turn	North bound right turn + South bound left turn
South bound right turn	South bound right turn + North bound left turn
North bound left turn	0
South bound left turn	0
East bound left turn	0
West bound left turn	0

For jug handle Intersections, the focus was concentrated into two areas: the intersection region and the ramp area. For the intersection region, conflicts will be present from vehicles turning from the minor street onto the major and therefore the intersection region conflicts were equivalent to conflicts from minor street approach in signalized intersections. The ramp area accommodates the turning vehicles from the major street and serves as a minor street on a TWSC intersection and hence the minor street potential conflict model from TWSC was adopted. Superstreet and continuous flow intersections provide pedestrian phases which eliminate potential conflicts between vehicles and pedestrians and hence not documented in the pedestrian conflict section.

### **3.2 Other Modeling Parameters**

For realistic modeling, additional features available in VISSIM were utilized, such as the reduced speed area and priority rules. For all models, the reduced speed areas were specifically used in turn region (connectors) and circulating lanes for roundabouts. Reduced speed areas were included specifically for faster vehicles that could reduce their speed in order to reach a slower speed at the beginning of the reduced speed area using the gradual deceleration process. The other important feature that VISSIM offers is the “priority rules”. Priority rules are effective in designing unsignalized conditions. Vehicles on a single link (lane) can interact with each other based on certain parameters such as headway and lateral distance. Priority rules assist vehicles in recognizing the right-of-way for vehicles on other links. Priority rules were utilized to model unsignalized conditions to yield to other vehicles when required. It was also used to reflect the

permitted left turn phase in a signalized intersection where the left turning vehicle yields to opposite through traffic. To reflect the right-of-way for pedestrians, conflict areas were utilized so vehicles yielded to pedestrians at all intersections.

In addition to priority rules, the “Conflict Areas” parameter in VISSIM helps in modeling signalized intersections realistically. Conflict areas assist in most of the cases in determining the right-of-way between conflicting elements. For each area which is conflicting with different flows, VISSIM provides the ability to select which of the conflicting links has right of way.

An actuated signal controller was used with four seconds yellow and one second all-red intervals for all signalized intersections. Left-turn movements were assigned permissive phases. For all the models, East-West approaches were considered major and North-South as minor. Other microscopic characteristics such as speed profiles, vehicle-type characteristics and compositions along with driver behavior parameters were reviewed to reflect the practical condition in roadway.

### **3.3 Surrogate Safety Parameters**

VISSIM has the ability to record the movement of each individual vehicle and pedestrian with all of their associated attributes such as acceleration, direction, and speed and export it to a trajectory file for further analysis. This trajectory file is used as input in the SSAM software for analyzing potential conflicts. The SSAM software splits the study into several grids of 15m X 15m grids for



analysis. On each grid, it records the characteristics of every element in the study area such as the location, speed, acceleration, direction of travel and deceleration parameters of vehicles and pedestrians. Once it determines the characteristics of every element, it projects the path of all vehicles and pedestrians and calculates the distance between adjacent entities in the study area. Based on the surrogate safety measure, the Time-to-collision (TTC), it analyzes if a vehicle is in close proximity to a pedestrian. If the determined value of TTC between the pedestrian and vehicle was less than the critical value of 1.5 sec then the SSAM identifies it as a dangerous situation and reports it as a potential conflict. For every run, the SSAM recorded individual conflicts that were exported in comma separated value (csv) file which was post processed in Microsoft Excel. The calculation of time of conflict is depicted in Figure 6.

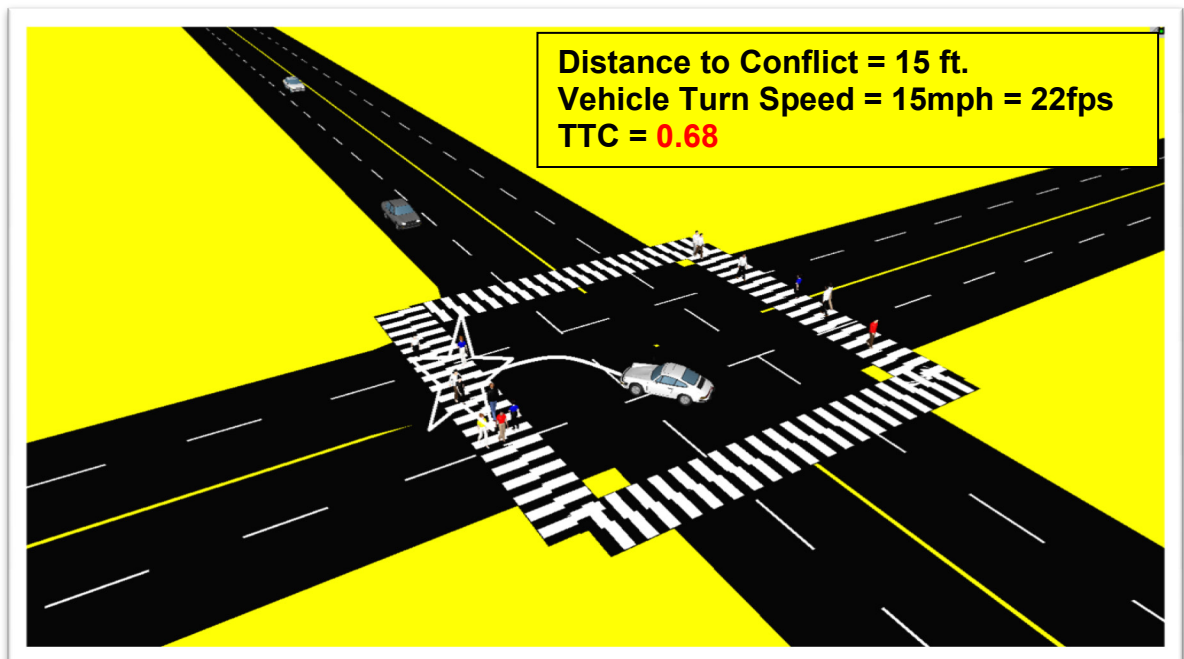


Figure 6 Example of time to conflict calculation

### 3.4 Post Processing Procedure

Extensive data handling was required since each file contained large number of conflict data which was processed to identify a conflict by intersection type and then refine the conflicts by number of approaches. First, to identify pedestrian only conflicts, the filter tool in excel as well as SQL queries in Microsoft Access were utilized. SSAM records several parameters of conflicts including width of the conflicting elements. Since pedestrians were assigned a fixed width of 1.64 feet (or 1m), any conflicts with pedestrians could be filtered using the width data from the output. Once filtered, the first link and second link data of the output was utilized to identify and match it with VISSIM model to determine if the conflict occurred at major or minor approach. This task was achieved by processing data using SQL in Microsoft Access.

## CHAPTER 4 STATISTICAL MODELING

This research was structured to address a various questions related to pedestrian safety at intersections. The primary analysis question was, “What are the safety effects of conflicting pedestrian-vehicle volumes on potential conflicts?” Several other analysis questions needed to be answered as well, including: What traffic and roadway characteristics have a significant effect on potential pedestrian-vehicle conflicts? Specifically, how are potential conflicts affected by traffic volume, pedestrian volume, number of lanes, turning percentages, approach types, i.e. major or minor streets.

The Statistical Package for the Social Sciences (SPSS) was utilized to conduct different statistical analyses and to answers these questions by developing models and analyzing coefficient of individual parameters in the prediction models. For each intersection type, two general modeling approaches were undertaken. The first deals with evaluating the effect of conflicting volumes along with other variables on potential pedestrian-vehicle conflicts for the entire intersection. It should be noted here that the conflicting volume is the product of the number of vehicles conflicting with the number of pedestrians at each intersection area. In the case of unsignalized intersections and roundabouts, the conflicting volume was equivalent to the approach and turning vehicular volume conflicting with the pedestrian crossing a conflicting leg of the intersection. For signalized intersection, it was equivalent to the turning vehicles conflicting with pedestrians at the adjacent leg of the intersection. The second approach was to

evaluate the effect of the location of the conflict, i.e. whether it occurred along the major or the minor road. In both approaches various variables examined as predictors including the conflicting volume, the number of lanes by approach, the percent of turns, and the approach volume. Several other variables were evaluated but were not statistically significant which included the signal timing parameters for signalized intersections and the crossing length variable that was equivalent to the number of lanes variables and hence eliminated.

Modeling technique was initialized with generalized linear modeling with varying the link function type. Models of general linear regression, Poisson and negative binomial type are evaluated. Overall the results indicated that the Poisson or negative binomial models are not appropriate, based on the ratio of the Deviance to degrees of freedom that was less than 1 indicating an under-dispersed response variable (i.e. there is less randomness than anticipated or too many cases with no conflicts in the data). The proposed model is a linear regression model and other variation of this model such as exponential function was evaluated.

#### **4.1 Unsignalized Intersections**

Individual potential conflict analyses were conducted for AWSC and TWSC intersections because of the differences in traffic flow patterns and interaction of vehicles with pedestrians. It was observed that the pedestrian-vehicle conflicts at intersections were affected by the arrival and departure patterns of vehicles, pedestrian and vehicular volumes and the length of crossing distance for

pedestrians. In general, at AWSC intersections vehicles approach intersections, stop and then go on a “first come first serve” priority basis. Therefore, there is no specific arrival and departure pattern or platoon formation which creates a random conflict pattern. Three different models were analyzed.

First, the pedestrian-vehicle conflicts for the entire intersection were evaluated. For AWSC intersections, a linear regression model was found significant at the 5% level with  $R^2$  values of 0.56. The significant variables included in the model were the conflicting volume, the percent of turns and number of lanes (Table 6). Similarly for the TWSC intersections, the regression model including the same variables was found significant with  $R^2$  of 0.85 (Table 6).

The analysis for evaluating the effect of the conflict occurrence along the major or the minor road also indicated significant prediction models for AWSC and TWSC intersections. The AWSC model had an  $R^2$  value of 0.41 with predictors as percent of turns, conflicting volume, number of lanes, and location of conflict (Table 7). The TWSC had a higher  $R^2$  (0.60) and the variables included the turn percent, conflicting volume and conflict location.

**Table 7 Unsignalized intersection models**

Model	Variable	AWSC		TWSC	
		Parameter	P value	Parameter	P value
Intersection	Intercept	-2.364	0.00	-3.012	0.00
	Turn percentage	0.092	0.00	0.164	0.00
	Conflict volume	0.084	0/00	0.126	0.00
	Number of lanes	0.867	0/00	0.266	0.00
Approach	Intercept	-0.474	0.00	-0.417	0.00
	Turn percentage	0.046	0.00	0.082	0.00
	Conflict volume	0.064	0/00	0.096	0.00
	Approach	-0.869	0.00	-0.915	0.00
	Number of lanes	0.434	0.00	NA	

The model for the entire intersection has positive coefficients for the variables considered implying that conflicts increase when each of the variables is increased. The first variable in the intersection model found statistically significant was the turning percentage of vehicular volume which quantifies the possible interaction between vehicles and pedestrians. The positive coefficient indicates that when there is an increase in percentage of turns, i.e. a large number of vehicles making turns at an intersection, there is greater potential for a conflict to occur within the pedestrian-vehicle common space at any given time. The coefficient of the conflicting volume variable similarly indicates the proportional increase in potential conflicts at intersections, since higher conflicting volumes could result in more conflicts. Additionally, the exposure area, which is defined here in terms of number of lanes that a pedestrian has to walk to cross an intersection, is also a significant indicator of increased potential conflicts at an intersection. This is anticipated, since exposure time increases

with wider crosswalks resulting in longer time required to cross the street and hence increasing the conflict probability.

Many intersections have unsymmetrical layout, i.e. different number of lanes for the major and minor street approaches. The “approach” model was developed based on separate major and minor approach conflicts and targeted to address these unsymmetrical intersections. Three variables in the “approach” model had positive coefficient that included turn percent, conflicting volume and number of lanes indicating that they had positive correlation with the potential conflicts. The coefficient of approach variable was found to be negative (-8.69 for AWSC and -9.15 for TWSC) indicating that more conflicts occur along the minor street crosswalks than along the major street. It should be noted that the approach variable has a binary value of one for the major and zero for the minor street. This is anticipated, since the major approach usually has higher vehicular volume than the minor approach resulting in increased potential vehicle-pedestrian conflicts along the minor street crosswalks. Conversely, the minor approach with lower volume has lower potential conflicts with pedestrians crossing the major approach.

## 4.2 Signalized Intersections

A similar approach was adopted for signalized intersections. First, the pedestrian-vehicle conflicts for the entire intersection were evaluated. The first variable introduced was the conflicting volume which was significant but had a  $R^2$  value of 0.34. Then the number of lanes was also tested along with the

conflicting volume and the resulting model was significant with a  $R^2$  of 0.50. Turn percent was also added and was found to be significant but did not contribute to the overall strength of the model hence was not included in the final model (Table 7).

The analysis for evaluating the effect of the conflict occurrence along the major or the minor road also indicated significant prediction models for signalized intersections. The model had an  $R^2$  value of 0.24 with predictors as conflicting volume, number of lanes, and location of conflict. With addition of turn percent in the model the  $R^2$  value of the model raises marginally to 0.25 (Table 8).

Further, a transformation of the approach model was evaluated. Each approach was evaluated with the exponential function of conflicts and the resulting model was found to be significant with a  $R^2$  value of 0.30 with predictors being the conflicting volume, approach type and number of approach lanes (Table 8). Introduction of turn percent to the model raises the  $R^2$  value to 0.32. This model has statistically significant variables and results in slightly higher coefficient of determination. Since most scenarios including unsymmetrical intersection layout conditions could be determined using this model, the exponential function transformation of the approach model is proposed as the final prediction model (Table 8).



**Table 8 Signalized intersection models**

Model	Variable	Parameter	P value
Intersection	Intercept	-3.22	0.00
	Conflict volume*	0.06	0/00
	Number of lanes	2.38	0/00
Approach	Intercept	0.21	0.00
	Conflict volume*	0.05	0/00
	Approach	-2.17	0.00
	Number of lanes	0.58	0.00
	Turn percent	0.09	0/00
Approach (exp. Conflicts)	Intercept	-0.48	0.00
	Conflict volume*	0.008	0/00
	Approach	-1.16	0/00
	Number of lanes	0.53	0/00
	Turn percent	0.03	0/00

\*Conflicting Volume in 1,000

The first model developed was for the entire intersection which showed similar trends and coefficient as the unsignalized intersection models. The positive coefficients of the variables indicate an increase in conflicts with increasing values of the variables. The number of vehicles conflicting with the number of pedestrians was the first significant variable in the intersection model. The second significant variable was the length of the crosswalk that the pedestrians need to cross which determines the exposure distance and time.

The second model developed was by approach which could be beneficial in application for unsymmetrical conditions. The model has a positive coefficient for conflicting volume, turn percent and number of lanes indicating that the potential for a conflict between pedestrian and vehicles increases when these parameters increase. The coefficient of approach is negative (-1.02) indicating again that more conflicts are anticipated along the minor street crosswalks than the major.

The third model, which utilizes an exponential transformation of the conflicts used in the approach model, indicates that the exponential function of potential conflicts also has positive correlation between conflicting volume, number of lanes and turn percentage. This model was analyzed and presented since the coefficient of determination ( $R^2 = 0.32$ ) was comparatively higher than the generic approach model which means that there would be more confidence in interpreting the potential conflicts using this model. Hence, this model is proposed for use because it can be applicable for all types of signalized intersections with varying major and minor lane configurations.

### **4.3 Roundabouts**

Following the previous methodologies, first the pedestrian-vehicle conflicts for the entire intersection were evaluated. The first variable introduced was the conflicting volume which was significant with  $R^2$  value of 0.62. Then the number of lanes was added to the model along with the conflicting volume and the resulting model was significant with a  $R^2$  of 0.71. Turn percent was also tested but was not found to be significant (Table 9).

The analysis for evaluating the effect of the conflict occurrence along the major or the minor road also indicated significant prediction models for roundabouts. The model had an  $R^2$  value of 0.72 with predictors as conflicting volume, number of lanes, and location of conflict (Table 9). The other variables considered was the percent turn but was not found to be significant.

Similar to signalized intersection, a transformation of the first approach was attempted for roundabouts. The entire intersection was evaluated with the exponential function of conflicts and the resulting model was found to be significant with a  $R^2$  value of 0.73 with predictors being the conflicting volume and number of approach lanes (Table 9). Since the previous model includes the location of conflict, that is proposed as the final model since it could be easily extended for unsymmetrical intersection designs.

**Table 9 Roundabout models**

Model	Variable	Parameter	P value
Intersection	Intercept	-2.38	0.00
	Conflict volume*	0.15	0/00
	Number of lanes	-1.86	0/00
Approach	Intercept	2.21	0.00
	Conflict volume*	0.10	0/00
	Approach	-4.86	0.00
Intersection (exp. Conflicts)	Number of lanes	0.93	0.00
	Intercept	0.48	0.00
	Conflict volume*	0.02	0/00
	Number of lanes	0.26	0/00

\*Conflicting Volume in 10,000

The three models developed are similar to the signalized intersection models. All variables in all three models are significant and have positive coefficients indicating that they are directly proportional to potential conflicts. Interestingly, the number of lanes for roundabouts is negative indicating that there is a negative correlation between the potential conflicts and number of lanes at roundabouts. For this reason further analysis was conducted and development of approach model and exponential function model revealed opposite trend, that is the number of lanes was significantly related to potential

conflicts and was directly proportional. For this reason, the intersection models are not considered in the final proposal. Since the approach model has a versatile applicability to unsymmetrical intersection layouts, the approach model is proposed for final application.

#### **4.4 Unconventional Intersections**

Most unconventional intersections considered in this study evolved from simple conventional signalized intersections. The characteristic layout of each unconventional intersection is some sort of an extension of conventional signalized intersection. As a result, transformations from signalized intersections were adopted in the potential conflict model development for unconventional intersections. The median U-turn (MUT) intersection could be considered as a signalized intersection with simple volume input transformation as noted in Table 5. It was therefore determined that median u-turn intersection design reflects similar conflict patterns as signalized intersection with conflicting volumes as previously determined. Similar pattern was also evident for the bowtie intersection and hence the signalized intersection models are proposed.

For the jug handle intersection design, two different areas need to be considered: the intersection region and the ramp area. For the intersection region, conflicts exist only at major leg of the intersection from minor approach vehicles. Hence, the potential conflict model from the signalized intersection minor street approach is adopted. For the ramp area, the ramp vehicles have to yield to the minor street traffic replicating a TWSC intersection and therefore they

can be assumed to behave as the minor approach of a TWSC intersection. Hence, the potential conflict model from TWSC was adopted with the coefficient of the approach being zero, since there is potential of conflicts are to occur at the minor street only. Superstreet and continuous flow intersections provide exclusive pedestrian phases which eliminate potential conflicts between vehicles and pedestrians and hence not documented in the pedestrian conflict section. For all unconventional intersection designs, approach models are proposed since it could be applicable to determine potential conflicts for unsymmetrical intersection layouts.

**Table 10 Coefficient of unconventional intersection statistical model by approach lane**

Intersection	Variable	Parameter	P value
MUT	Intercept	-0.48	0.00
	Conflict volume*	0.008	0/00
	Approach	-1.16	0/00
	Number of lanes	0.53	0/00
	Turn percent	0.03	0/00
Bowtie	Intercept	-0.48	0.00
	Conflict volume*	0.008	0/00
	Approach	-1.16	0/00
	Number of lanes	0.53	0/00
	Turn percent	0.03	0/00
Jug handle Ramp	Intercept	-0.417	0.00
	Turn percent	0.082	0.00
	Conflict volume**	0.096	0.00
	Approach	0	0.00
	Number of lanes	NA	
Jug handle Intersection	Intercept	-0.48	0.00
	Conflict volume*	0.008	0/00
	Approach	-1.16	0/00
	Number of lanes	0.53	0/00
	Turn percent	0.03	0/00

\*Conflicting Volume in 1,000

\*\*Conflicting Volume in 10,000

#### 4.5 Application

An analytical tool was developed as a result of this study that calculates potential conflicts at different intersection types. Table 10 shows an example of its application that can be used to evaluate alternative intersection designs with respect to potential pedestrian safety. For this test case, an intersection with two lanes on the major street and one lane on the minor street is considered with a traffic volume of 800 vph along major and 400 vph along minor approaches. The turning volumes are assumed to be 30% for both left and right turning vehicles at all approaches. A pedestrian volume of 100 pedestrians per hour crossing each major leg and each minor leg of the intersection were considered. The tool first determines the conflicting volume based on the vehicular and pedestrian volumes and then calculates the potential conflicts per hour for the intersection.

**Table 11 Example of application**

Intersection Type	Conflicting Volume		Potential Conflicts (hourly)		
	Major	Minor	Major	Minor	Total
AWSC	272,000	208,000	2.21	2.67	4.88
TWSC	272,000	208,000	3.74	4.04	7.78
Signalized	48,000	96,000	1.19	5.57	6.76
Roundabout	272,000	208,000	1.00	5.22	6.22
MUT	48,000	96,000	1.19	5.57	6.76
Bowtie	24,000	96,000	0.98	5.57	6.56
Jug handle	96,000	48,000	2.96	2.69	5.65

Table 10 shows the potential conflicts for all intersection types to be considered for a particular scenario. However, engineering judgment is required

along with this tool to select the appropriate design. From the table above, the AWSC has the lower number of potential conflicts than signalized intersection, however according to MUTCD Warrant 3, having a vehicular volume of 800 vph on the major street and 400 along the minor street warrants a signal installation. As a result, the AWSC and TWSC designs cannot be considered for further analysis. The remaining designs could be considered but with further evaluations such as benefit to cost analysis and land availability for unconventional intersections. The location of the intersection based on type of roadway (arterial, collector, etc.) could be used in determining the appropriate design. For urban scenarios, a roundabout could be preferred since it promotes reduced speeds. Where land is scarce, the conventional signalized design could be preferable. If mobility and efficiency of a system is of high priority and land acquisition is feasible, a jug handle intersection could be considered which in this case had the lowest number of potential conflicts. For each scenario, operational measures of effectiveness must be modeled and evaluated based on local conditions to determine the operational performance of the designs. Such an analysis would assist in determining which design could also address mobility issues in conjunction with the pedestrian safety concerns. The combination of safety and operational analysis could justify an intersection design for safe and efficient operation.

#### **4.6 Limitations of statistical modeling**

This study is a novel approach to quantify pedestrian safety and hence the models developed in this study have certain limitations in practical applications. The volume range of pedestrian and vehicles considered in this study were mostly based on the MUTCD warrants on signal installations. Additionally, high pedestrian volumes were considered to develop the potential conflict model in order to allow for meaningful numbers of conflicts. Even in this case, several cases had very few conflicts and this has created highly variable observations. As a result the model could be applicable only for the volume range specified in Tables 2, 3 and 4. Volumes below or above the specified range specified in these table may not be appropriately extrapolated since they were not specifically considered in the modeling process.

The models developed in VISSIM assumed typical intersection characteristics. Several other geometric and operational conditions such as intersection offsets or additional turning lanes have not been incorporated in this study and hence not applicable. Default driving and pedestrian walking characteristics in VISSIM were assumed which may vary by location across the country. The driver aggressiveness may vary with hour of the day and location which is not captured by the model. The effect of various signal timing schemes including the effect of right-turn-on-red has not been incorporated in the models. The model assumes that pedestrian cross the road only at the assigned pedestrian zebra crossing and they promptly obey the flashing “do not walk” sign which may not happen in real world scenario and hence there may be more potential for a crash than represented from the model.



The models for the unconventional intersections are the transformations from the signalized intersections. However very few unconventional intersections exist when compared to traditional intersections and as a result, driver unfamiliarity with those intersection types may exhibit varying behavior which in turn may affect the potential conflicts with pedestrians.

The models are recommended for preliminary evaluation purposes only since they are the initial attempt to adopt the surrogate safety measure for pedestrian safety. It should be noted again that these models are not an actual crash prediction model and the relationship between potential conflicts to actual pedestrian-vehicle crashes has not been quantified.

## CHAPTER 5 CONCLUSIONS

### 5.1 Findings and Recommendations

There is little previous work that has developed prediction models for pedestrian-vehicle conflicts as the literature review indicated. These problems are due to lack of data, required time to collect such data, and issues of reliability of available data when pedestrian crashes are considered. It is therefore important to seek other means for evaluating pedestrian safety. One such approach is that of conflict analysis where simulation can be used to develop possible conflict estimates for pedestrian-vehicle interactions. This study provides a first attempt in quantifying pedestrian-vehicle conflicts for different intersection types and thus allowing a relative comparison between various designs with respect to pedestrian safety level attained at each design.

The study describes an analytical process to quantify pedestrian safety using a conflict analysis technique combining simulation and surrogate safety model. Potential pedestrian conflict prediction models have been successfully developed for unsignalized, signalized and roundabout intersections. Additionally, transformations were developed to extend this methodology for unconventional intersections. The models developed can predict either the total number of conflicts for the entire intersection or for each intersection approach. It should be emphasized though that this study has developed a potential conflict-prediction model and not a traditional crash prediction model. The aim was to quantify the exposure which is the amount of “contact” with potentially dangerous

elements (vehicle) and not the “risk” which is defined as the probability of “contact” per unit exposure. Since the applicability of approach would be useful in most scenarios, approach models are finally recommended for all intersection types.

For all models suggested, the coefficients have positive signs indicating that they are directly proportional to potential conflicts. The only exception to this is the approach variable which has a negative sign indicating that more conflicts are expected along the minor street crossings due to typically higher turning volumes from the major street. The low  $R^2$  values observed for some models are indicative of the variability of the data that could be attributed to the few potential conflicts in the models even when large numbers of pedestrian volumes were used.

The conflict prediction model could be a useful tool in comparing intersection designs or evaluating alternative intersection designs with regards to pedestrian safety. Reliable and ample crash data are hard to collect and hence the models developed here could be used as substitutes and estimate conflicts as safety surrogate measures. The conflict prediction model could also be used to determine conflict resolution needs such as intersection treatments or traffic control options, although detailed investigation and engineering judgment as shown the application example will be required to support the final decisions. However, these models can assist in identifying the relative safety effectiveness between alternative designs for an intersection. This approach can provide both

planners and engineers the ability to evaluate their proposed planning and design treatments from pedestrian safety viewpoint.

Instead of waiting for certain number of crashes to occur in order to develop a significant prediction model that predicts future crashes, this work presents a preliminary effort towards the application of surrogate safety measures to quantify potential conflicts. This process could provide insight on pedestrian safety and compare intersection designs and could be used in addition to or instead of accident data when required. However, there are limitations of the models presented here regarding their applicability and use which on the other hand creates an opportunity for further research. The models are developed for typical intersections and the effect of varying intersection characteristics, such as offsets, medians, and left or right turn channelization, could be investigated. Preloaded driving behavior algorithms have been adopted for all simulations but they may practically vary by location (urban vs. rural) and hence the effect of gap acceptance and yielding behavior could be analyzed. Further, the effect of varying speed limits could potentially affect conflicts and development of new signal timing plans such as the recently popular leading pedestrian interval could affect the potential conflict that needs to be studied. The models developed do not account the severity or intensity of the conflicts which could be investigated using the TTC and other surrogate safety measures.

## 5.2 Future Research

The work presented here points to the need for a greater exploration of pedestrian safety. It initiates a novel perspective of utilizing safety indicators as potential conflict predictors. The models developed in this study focused on estimating safety but further research could be conducted to relate measures of effectiveness with potential conflicts, which can extend this methodology for both operational evaluation as well as safety evaluation purposes. Further, unconventional intersections such as median U-turn, jug handle, and superstreet have been used as alternative intersection designs and their safety implications on pedestrians could be evaluated using the methodology presented in this paper.

This study evaluated various lane combinations but several other geometric and operational conditions such as intersection offsets or additional turning lanes could be investigated. In addition, the effect of various signal timing schemes such as the recently popular leading pedestrian interval on potential conflicts needs to be evaluated. In recent years, various other unconventional intersections have been proposed and developed but their safety implications on pedestrian safety have not been investigated. The approach mentioned in this paper could be extended to innovative designs.

The literature on safety measures based on micro-simulation indicated that VISSIM was the most frequently used micro-simulation tool. However, there is no agreement about the suitability and applicability of any one simulation program, since each program exhibits its strengths and weaknesses and hence

sensitivity analysis is proposed for future research to analyze different simulation software. Validation of these models will be required although the available pedestrian crash data will be scarce and unreliable.

Typical intersection and default driving behaviors were adopted in this study. However, driving characteristics and intersection characteristics (such as signal timing) vary widely across the country. Identifying these varying characteristics and including them in the model could enhance its applicability in a generalized form. Since statistical modeling process is a “memoryless” process, i.e. the statistical models predict potential conflicts based on input parameters consistently, incorporating localized intersection treatments such as medians or signal timing plans (leading pedestrian interval) could make the models sensitive to changes at an intersection.

With the advancement of portable electronic devices and social media, “driver distraction” research has gained attention of researchers in recent years. The effect of using electronic devices on driver attention and driving behavior and also on the yielding behavior of motorists to pedestrians could be investigated. Quantification of such behavior and incorporating it in a model could make its more practical and representative of real life situation.

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