2013

DEVELOPMENT OF A DESIGN BASED INTERSECTION SAFETY PERFORMANCE EVALUATION TOOL

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Recommended Citation
Kirk, Adam J., "DEVELOPMENT OF A DESIGN BASED INTERSECTION SAFETY PERFORMANCE EVALUATION TOOL" (2013). *Theses and Dissertations--Civil Engineering*. 17.
https://uknowledge.uky.edu/ce_etds/17

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DEVELOPMENT OF A DESIGN BASED INTERSECTION SAFETY PERFORMANCE EVALUATION TOOL

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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ABSTRACT OF DISSERTATION

DEVELOPMENT OF A DESIGN BASED INTERSECTION SAFETY PERFORMANCE EVALUATION TOOL

The purpose of this research is to develop an intersection safety evaluation tool that is capable of assisting designers and planners in the assessment of alternative intersection designs. A conflict exposure model utilizing design hour volumes, intersection configuration and traffic control measures is proposed to achieve this goal. This approach makes use of data typically available for preliminary intersection design. The research goes beyond existing safety performance models which only examine non-directional average daily traffic (ADT) or practices which only account for the geometric and lane configuration of an intersection, such as conflict point analysis.

Conflict prediction models are developed for left-turn angle, right-turn, rear end and sideswipe crashes. These models were developed through the analysis of over 1000 simulation scenarios evaluating a full range of approach and turning volumes, lane configurations and traffic control strategies. The quantifiable metrics provided can be used to inform and improve alternative intersection selection processes by differentiating between alternatives based on a surrogate safety performance. This research may be used in screening of intersection alternatives to select the most beneficial design based on objective safety performance metrics.

KEYWORDS: Intersections, Safety, Highway Design, Performance Evaluation, Microsimulation

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DEVELOPMENT OF A DESIGN BASED INTERSECTION SAFETY PERFORMANCE EVALUATION TOOL

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November 4, 2013
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1 INTRODUCTION

Current intersection safety models do not provide adequate resolution for use in the planning or design stages of intersections as it relates to the selection of alternative configurations. Previous research has identified 13 distinct alternative intersection designs, but no systematic process has been identified, which can quantifiably compare these alternatives (1). Furthermore, most guidelines identify the need for comparative studies but do not identify the factors or methods that one should apply in determining the optimal design. It is reasonable then, to conclude that operational and safety problems may arise as suboptimal designs are selected.

The purpose of this research is to develop an intersection safety performance evaluation tool that is capable of assisting highway design professionals in the assessment of alternative intersection designs. A conflict exposure model is proposed to achieve this goal using data typically available during preliminary intersection design stages, such as design hour volumes, intersection configuration and traffic control measures. The analysis presented in this report has produced models which predict disaggregated conflicts by type, e.g. sideswipe, rear-end, and angle for signal controlled intersection designs. The models developed here can be used in screening alternative designs in the planning and preliminary design stages of signalized intersection projects to select the most appropriate design based on objective safety performance metrics.

A majority of safety prediction models use the Average Daily Traffic (ADT) as the independent variable to predict crash rates (2). However, for roadway design projects ADT is a constant and not affected by design choices. Therefore, these models differentiate safety benefits of alternative designs. Conflict point analysis has also been used to discern safety differences in designs (3). This approach is strictly dependent on geometry rather than roadway use or traffic volumes and is therefore not representative of the actual exposure at intersections. A method is needed to identify the crash exposure that is dependent upon traffic patterns and volumes at the intersection as they relate to the intersection configuration. This will allow for a more complete safety model, which can directly feed the planning and design process for intersection type evaluation and selection.

In order to limit the scope of the project while still providing a meaningful design tool, the crash models will be developed for a focused range of alternatives and limited sample of potential crash types. The models presented pertain only to intersections alternatives controlled by traffic signal control (6 of 13 alternatives identified) and account only for crashes resulting from permitted movements at the intersection. Conflicts which require vehicles to disregard a traffic control device, such as right angle crashes resulting from running a red light, or head-on crashes from crossing the double yellow line, are not analyzed or included in the model. These types of crashes are often the result of site specific geometry and/or significant human factors and are also not the product of the intersection design.

Analysis of 2009 Kentucky crash data was conducted to identify potential crash types for inclusion in the final models. This analysis examined the frequency of manner of collision codes and directional analysis codes within the Kentucky Crash database. Based on this analysis, angle and rear end collisions account for over 71 percent of intersection crashes. Due to the numerous types of angle crashes, e.g., left-through, through-through, right-through etc., directional analysis data for these crash types was also examined. The most prevalent angle crashes involved 1) one vehicle turning left (39%) and 2) two vehicles traveling through the intersection (35%). As through-through crashes require at least one vehicle to disregard a red indication, these will not be included in the analysis; however, angle crashes resulting from permitted left turn movements and right-turn movements will be included. The next most prevalent crash types are sideswipe crashes and single vehicle crashes, each representing an additional 8 percent of intersection crashes. As the intent of this study is not to identify human factors as they relate to crashes, but rather to identify vehicle-vehicle interactions as a result of intersection control and lane configuration, single vehicle crashes will not be included in this study.

Therefore, this analysis will analyze crashes resulting from 1) permitted turn movements, such as left-turn movements crossing opposing traffic 2) permitted right-turn movements, such as right turns on red, 3) traffic control operations, such as rear end crashes during red indications, and 3) approach maneuvers, such as sideswipe crashes resulting from lane changes.

It should be noted from the outset, that the study will not provide an estimate of anticipated crashes, or their severity level, but will provide a quantifiable safety metric for comparative safety analysis of potential intersection design alternatives.

2 LITERATURE REVIEW

A literature review was conducted to identify prior or current work regarding intersection safety evaluation to determine factors influencing intersection safety performance. The review also includes the identification of the primary crash patterns at intersections for inclusion in the model.

Previous research on the safety performance of intersections has focused on identifying contributing factors to intersection related crashes as well as the development of crash prediction models. Most of the past work in developing prediction models for estimating safety has been focused in utilizing historic crash data and attempting to relate crashes to various intersection features and factors. Another approach towards intersection safety focuses on the ability to predict the safety performance at an intersection aiming to evaluate and compre alternative design options. For this purpose, models are developed based on different types of intersection control and features. The ultimate goal of this literature review is to 1) identify previous intersection crash prediction models and 2) identify intersection design parameters that affect intersection crash rates. Factors which can be manipulated by the designer are of primary concern as the identification of these can lead to improved intersection designs. In 2008, intersection crashes accounted for 26.3 percent of all crashes on Kentucky's roadways (4). Furthermore, they accounted for 28.0 percent of all injury crashes, indicating a both a high prevalence and a high severity compared to other facilities. A review of the Kentucky Crash Database indicates that angle and rear-end crashes account for the largest proportion of intersection injury crashes each representing approximately 20 percent of fatal and injury crashes.

Intersections also serve as a critical component in accommodating the flow of traffic on the roadway network, as they allocate right of way between converging vehicles. Due to this convergence of traffic, the capacity of intersections is significant lower than unconstrained roadways. As such intersections frequently serve as the operational and safety choke point of roadway systems (1, 5). To address these demands, a number of new intersection designs have been introduced to improve intersection operations and safety. These alternatives to conventional signal and stop controlled intersections include the median U-turn design (used in Michigan extensively for years), the jug-handle design (used in New Jersey), and the continuous flow intersection (used in New York and Maryland). The use of roundabouts is also increasing in the US and research has shown that they can improve both the operational and safety levels of intersections. In total, 13 different intersection alternatives were identified for consideration in previous research and are listed below (1):

1. Signalized
2. Roundabout
3. All-way stop
4. Two-way stop
5. Unsignalized inside left-turn
6. Median U-turn signalized

7. Median U-turn unsignalized
8. Superstreet, unsignalized
9. Superstreet, signalized
10. Continuous flow intersection
11. Continuous green ‘T’
12. Jug-handle
13. Bowtie

In addition to the 13 intersection alternatives, over 12,000 different lane configuration are possible for a 4-leg intersection (1). These lane configurations include multiple approach lanes, left and right-turn combinations for each approach, plus special lane configurations required by select designs such as jug-handles and median U-turns.

The American Association of State Highway Transportation Officials’ (AASHTO) Policy on Geometric Design of Highways and Streets contains only minimal guidance for the design of these intersection alternatives (6). Recent research by Stamatiadis and Kirk developed processes for objectively evaluating operational performance of alternative designs; however, research on safety performance is limited and does not provide sensitivity to lane configuration, control or other design variations (1).

Various parameters have been shown to have an influence on crash rates at intersections including the ADT approaching an intersection, sight distances, intersection alignment, roadway and shoulder width and other traffic and environmental factors. McDonald conducted a study on two-way stop controlled intersections at divided highways and represented crashes per year as a function of major and minor road incoming daily traffic (7). Bared and Lum concluded that sight distances are shorter at high-crash intersections (8). Bauer and Harwood reviewed crash reports at urban intersections and concluded that geometric features of an intersection were cause for only 5 to 14% of all crashes, with the major influencing factoring being traffic demand (9). Pickering and Grimmer considered crashes at 3-legged intersections of 2-lane roads and developed a Poisson model with mean number of crashes per unit time related to ADT (10).

Another concept considered for estimating safety at intersections is that of “conflict points” or the number of points where vehicular paths at an intersection cross. Many statistical comparisons have documented the effect of conflict points for different types of intersection on crash rates. Jug-handle intersections are a typical example of a design that reduces the conflicting maneuvers at intersections by reducing the number of conflict points. Jagannathan et al. conducted a study to compare jug-handle to conventional intersection designs considering 44 New Jersey jug-handle intersections and 50 conventional intersections (11). Each conventional intersection was screened to assure similarity and uniformity of data sets and traffic characteristics to the jug-handle intersections. The analysis concluded that the differences in the distributions of severity and collision types between the two groups of intersections were significant. The paper concluded that conventional intersections had higher overall crashes and more head-on and left-turn accidents but relatively fewer rear-end crashes than jug-handle intersections.

Wadhwa and Thompson conducted a study on the relative safety of alternative intersection designs aimed at relating intersection safety to number of conflict points, conflict types, and intersection geometry (12). Three types of intersections were considered: T-junctions, cross intersections and roundabouts. The study, based on crash data analysis for the intersections in Townsville region in Australia, concluded that the type of control had a significant effect on the severity of crash and fatalities. The study found that the proportion of total crashes increased with increases in the number of conflict points. Based on the examined intersections, the number of fatalities per 1,000 crashes was 6.32, 5.83 and 1.46 for T-intersection, cross intersection and roundabouts respectively. The study also concluded that the level of safety is disproportional to the number of approaches and conflict points.

Another model was developed by Lu et al. utilized conflict points to determine the level of service safety for heterogeneous traffic flow in unsignalized intersections (13). The study emphasized the importance of field survey activities and acquiring existing conditions and traffic demand at the facility site to determine the level-of-safety service of a facility. The model was based on site characteristics such as geometrics, traffic conditions, roadway and environmental conditions, conflict points, and other site related conditions. The model quantified the safety performance of intersections as on a scale of A through F, similar to Level of Service definitions with each level having a defined performance range; “A” being the best scenario. Model parameters were designated as major factors, such as conflict points, minor factors (geometrics, traffic signs, traffic markings, pavement and lighting) and traffic factors which were established as the approaching traffic volume. Models were developed based on expert surveys and focus group discussion methods since crash data were unavailable for the study. The general form of the model was adjusted for ideal conditions that include intersection geometric characteristics, traffic signs, traffic markings, pavement conditions, and lighting conditions. Adjustment factors were used to reflect the potential safety performance under prevailing conditions to quantify the level-of-safety service. The study concluded by validating the model on fifteen un-signalized intersections from different areas that cover all six levels-of-safety service.

Dadic et al. conducted a study that aimed at increasing the overall capacity and safety of intersections by identifying and eliminating “unnecessary conflicts” (14). This study extended its review of conflict points to examine criss-crossing flow on upstream segments of intersections. Formulae were developed to determine the number of criss-crossing points between traffic flow in an intersection, dependent upon the number of access points, flow directions, and organization of flow through intersection. The study concluded that the avoidance of unnecessary criss-crossing on approach roadways reduces the amount of conflicts and increases the safety and capacity of intersections.

In addition to the use of conflict points, other parameters have been considered when developing predictive models. Bauer and Harwood developed statistical models to relate crash and geometric elements for at-grade intersections, traffic control features, and traffic volumes (9). Regression analysis was used as a screening tool to identify specific dependent variables (geometric design, traffic control) that could be considered for further analysis. Preliminary results indicated that the variables of geometric design, traffic control, and traffic volume variables explained 19 to 37% of the variation in intersection accidents. The traffic volume factor (ADT) showed the most statistical influence on crash rate and it was shown that the traffic volume factor decreased the influence of intersection geometry on crash rates. Therefore to investigate the influence of geometric design elements only, ADT was treated as an independent variable. According to the analysis, geometric design features of intersections accounted for small portion of variability but the individual effect on safety were statistically significant, which included presence of turn lanes, provision of channelization for free right-turns, number of lanes on major road, average lane width on major road, presence of median on major road, outside shoulder width on major road and access control on major road.

The Federal Highway Administration developed the *Interactive Highway Safety Design Model* (IHSDM) to predict the safety performance of rural two-lane highways. Various calibration procedures were developed for different jurisdictions. Harwood et al. documented the development of the IHSDM and presented a calibration procedure for the Crash Prediction Module (CPM) (15). The prediction algorithm consists of a base model that is then modified through the application of Accident Modification Factors (AMF). Three different models were developed for three-leg intersections with one-way stop control, four-leg intersections with two-way control, and four-leg signalized intersections. The algorithm includes a base model which utilizes on pre-defined functions, and is then modified with the AMFs and local calibration facotrs. The models predict crash frequency, severity distribution, and crash type distribution. The base model and the AMFs vary for each type of intersection based on ADT, sight distance, number of driveways and signal details. A calibration factor is obtained by dividing the total number of accidents for the sample by the sum of the predicted accidents from the original base model. The model for the new jurisdiction is the original base model multiplied by the calibration factor.

Wong et al. conducted a study to evaluate the associations between crashes, geometric design, traffic characteristics, road environment, and traffic control at signalized intersections in Hong Kong, controlling for the influence of exposure (16). Crash records, traffic surveys and signal timing details of 262 intersections were incorporated in the model that was based on Poisson regression to determine the safety performance of signalized intersections. It was observed that “killed and severe injury” crashes were rare incidents that were unlikely to be affected by the ADT.

An investigation by Vogt on rural intersections controlling various factors, including the number of approach legs, control type (signalized or stop-controlled), the number of approach lanes (four and two), alignment, the use of channelization, the angle of intersection, left-turn and truck percentages, and speed limits (17). The study developed numerical models that indicated almost all variables were statistically significant; and specifically for injury crashes intersection angle and minor road posted speeds were identified as significant.

Highway Safety Manual

The Highway Safety Manual (HSM), released in 2010 by the Transportation Research board, is the culmination of 9 individual research projects issued through the National Cooperative Highway Research Program (NCHRP), and previous research efforts (2). The purpose of the HSM is “to provide quantitative information for decision making,” based on safety performance of roadway facilities throughout the entire project development process. As such the HSM presents the current state of “knowledge, techniques and methodologies” to estimate safety performance and has the stated purpose of calculating “the effect of various design alternatives on crash frequency and severity.” However, review of the practice with regards to intersection alternative selection, demonstrates that the techniques and variables considered by the Highway Safety Manual do not allow full consideration of variables and alternatives evaluated by engineers during the design phase of a project.

The HSM methodology is based on developing predictive crash models for a given “period, traffic volume and constant geometric design characteristics of the roadway.” Chapters 10, 11 and 12 outline the methodologies for Rural Two-lane Roads, Rural Multilane Highways and Urban and Suburban Arterials, respectively. The predictive methodology calculates a base crash model that is predicated on the (ADT for the major and minor streets (2).

The base models are modified through the application of Crash Modification Factors (CMFs) presented in Chapter 14 “Intersections,” to reflect alternative designs. CMFs are developed independently for Urban, Suburban and Rural applications as well as 3-leg and 4-leg intersections. The following CMFs are included in the predictive methods for intersections, by the indicated roadway type (2).

- **Rural Two-Lane Roads**
    - Intersection Skew Angle (3-Leg and 4-Leg Two-Way Stop Controlled Intersections (TWSC); 4-Leg Signalized)
    - Intersection Left-turn Lanes (3-leg and 4-leg; Signalized and TWSC)
    - Intersection Right-turn Lanes (3-leg and 4-leg; Signalized and TWSC)
- **Rural Multilane Highways**
    - Intersection Skew Angle (3-Leg and 4-Leg)
    - Intersection Left-turn Lanes (3-leg and 4-leg; TWSC)

    - Intersection Right-turn Lanes (3-leg and 4-leg; TWSC)
    - Lighting
- **Urban and Suburban Arterials**
    - Intersection Left-turn Lanes (3-leg and 4-leg; Signalized and TWSC)
    - Intersection Right-turn Lanes (3-leg and 4-leg; Signalized and TWSC)
    - Red Light Running Cameras
    - Right-turn on Red (RTOR) Prohibition
    - Left-turn Phasing

Of the 5 CMFs outlined above, only the presence of a left or right-turn lane has the potential to influence alternative intersection designs and this only addresses lane configuration as opposed to intersection design type. Intersection skew is an effect of the site geometry and Red Light Running Cameras, RTOR Prohibition and Left-turn Phasing are operational decisions that may be applied to all signalized alternatives. While the left and right-turn lane CMFs can help quantify the safety performance of adding turn lanes, they are only included in the model as the number of approaches with left-turn lanes. The models do not account for the volume and/or demand associated with left-turn approach demand and therefore cannot assist the designer in determining the appropriate location of the turn lanes. Furthermore, turn lanes are only evaluated for two-way stop control and signalized intersections; lane configuration is not a safety factor for all-way stop control, roundabouts, or other alternatives.

The HSM also provides additional CMFs relating to alternative intersection designs (2). These are summarized in Table 1, which is extracted from the Highway Safety Manual. Examining the table, the HSM can evaluate five intersection alternatives, “Offset ‘T’ intersections, Roundabouts, All-way Stop Control, Two-Way Stop Controlled and Signalized intersections. However, the methods used to develop the CMFs do not allow for evaluation across alternatives. For instance an All-Way Stop Control intersection can only be compared to a modern roundabout. As the CMFs modify intersection total crash rates, these cannot be applied across categories due to the variation in crash type distributions.

Table 1: Intersection Related Safety Treatment Summary (2)

		Urban				Suburban				Rural			
		Stop		Signal		Stop		Signal		Stop		Signal	
HSM Section	**Treatment**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**	**Minor Road**	**All-Way**	**3-Leg**	**4-Leg**
14.4.2.1	Convert four-leg intersection to two three-leg intersections	✓	—	—	—	—	—	—	—	—	—	—	—
14.4.2.2	Convert signalized intersection to a modern roundabout	N/A	N/A	✓	✓	N/A	N/A	✓	✓	N/A	N/A	✓	✓
14.4.2.3	Convert stop-controlled intersection to a modern roundabout	✓	✓	N/A	N/A	✓	✓	N/A	N/A	✓	✓	N/A	N/A
14.4.2.4	Convert minor-road stop control to all-way stop control	✓	—	—	—	—	—	—	—	✓	—	—	—
14.4.2.5	Remove unwarranted signal on one-way streets (i.e., convert from signal to stop control on one-way street)	—	—	✓	✓	—	—	—	—	—	—	—	—
14.4.2.6	Convert stop control to signal control	✓	T	N/A	N/A	—	—	N/A	N/A	✓	—	N/A	N/A

NOTE: ✓ = Indicates that a CMF is available for this treatment.
T = Indicates that a CMF is not available but a trend regarding the potential change in crashes or user behavior is known and presented in Appendix A.
— = Indicates that a CMF is not available and a trend is not known.
N/A = Indicates that the treatment is not applicable to the corresponding setting.

While the methodologies presented in the HSM provide for analysis of general intersection patterns, they do not provide the detailed analysis required for the evaluation of intersection alternative designs, including intersection type in conjunction with lane configuration. Furthermore, the absence of approach specific CMFs do not provide the intersection designer with improved information as to where the specified improvements should be made.

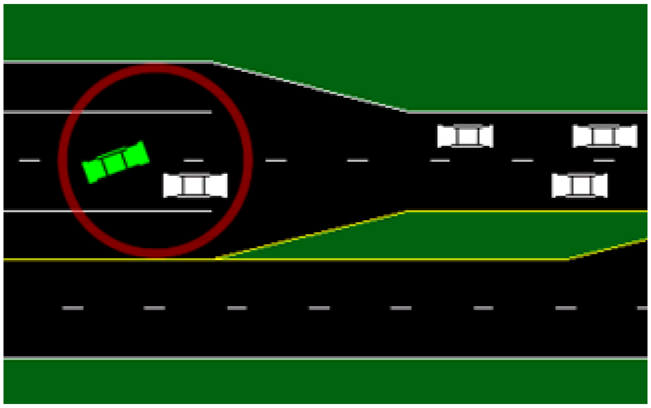
Safety Surrogate Assessment Model (SSAM)

A major limitation of the HSM approach is that it is based on the analysis of existing crash patterns. Crashes are known to be random events with a limited sample size. Crashes are also influenced by site specific factors, such as sight distance approach grades, etc. as well as temporal effects, such as weather, and varying traffic demand (18). All of these influencing factors can introduce variability into crash patterns at individual sites that cannot be accounted with the predictive models. In order to address some of the shortcomings of cross-sectional studies, safety surrogate measures have been developed to provide assessments of safety performance.

One such method is the Safety Surrogate Assessment Model (SSAM) developed by the Federal Highway Administration through contract with Siemens Energy & Automation, Inc. SSAM uses the concept of traffic conflicts to evaluate the existing or anticipated safety performance of an intersection (19). Traffic conflicts have been studied since the late 1960s, most notably documented in NCHRP Report 219, to provide a reliable and inexpensive tool to be used to “diagnose safety and operational deficiencies…within a short period of time (20).” Conflict studies traditionally utilize personnel trained to identify and record conflicts observed at an intersection. SSAM was developed to automate conflict analysis with the application of simulated operational programs.

SSAM models roadway facilities through a microsimulation program, such as VISSIM, AIMSUN, Paramics and TEXAS, which use specific lane configuration and operational control strategies in conjunction with measured and/or anticipated traffic volumes. These models produce a trajectory file (TRJ), which tracks the position of each simulated vehicle with respect to simulation time. SSAM then processes the vehicle trajectories, to identify ‘conflicting’ trajectories. A conflict is a scenario where two road users may crash if one does not alter its course as shown in Figure 1 (19).

Figure 1: Conflict Definition



The SSAM team conducted a field validation of procedures and results studying 83 four-leg signalized intersections. SSAM models were developed for the PM peak hour of operation at each site. Estimated conflicts determined from SSAM were then compared to actual crash rates at the intersections. Conflicts estimated by SSAM were shown to be significantly correlated with the historical crash data. A regression model relating conflicts to the annual crashes was shown to have an *R*-squared value of 0.41, indicating that the modeled peak hour conflicts could explain 41 percent of the variability in the year-long crash history dataset (19).

Several studies have used SSAM for the evaluation of alternative facility designs since its introduction in 2008 over a broad range of facility types. Most applicable to this research, researchers at North Caroline State University (NCSU) have successfully used VISSIM/SSAM to develop conflict models to evaluate roundabout slip lanes. These models were then validated using field data for ten single lane roundabouts in Carmel, IN. The research team concluded that the "results demonstrate the usefulness of SSAM analysis for… developing an empirical relationship between simulated conflicts and field observed crashes (21)."

Wang et al. developed a conflict detection model based on micro-simulation of motorized and non-motorized vehicles (22). The model was specifically developed for heterogeneous traffic in developing countries, where non-motorized vehicles did not have a separate lane. Using the models, the team was able to increase the capacity and safety of the study intersections.

Another study by Dijkstra et al. evaluated the effectiveness of microsimulation conflict models and found the total number of conflicts at intersections to be correlated with the total number of observed crashes at the intersection (23). However, the study also found "considerable differences" between conflict types and crash type distribution. Most notably, the number of rear end conflicts was seen to be overly represented, likely, because the models calculate conflicts between a moving vehicle and one standing still (stopped at a red light). It is also noted that the models cannot provide estimates of crashes resulting from disregarding traffic control, such as running a red light. While these crashes are relatively rare they have a high incidence of injury associated with them.

Conclusions

The literature reviewed here indicates that, the design and operation of intersections is a critical component of the roadway system. Intersection design is both improved and complicated by the introduction of a growing number of intersection design alternatives, and a myriad of lane configurations that can be used to optimize simultaneously operations, safety and economic viability of intersection designs.

A total of 13 different intersection designs and over 12,000 different lane configurations were identified by Kirk and Stamatiadis as feasible at-grade intersection designs (1). The sheer number of available alternatives limits the usefulness of traditional evaluation and comparative analysis methods. Furthermore, while research shows discernible safety performance of intersection alternatives, such as jug-handle designs (11), existing safety models have not been developed to allow for a comprehensive evaluation of alternatives and do not take into account design factors that may be manipulated by the designer to modify design performance, such as lane configuration, left-turn treatments etc.

Various research efforts have attempted to quantify the safety of intersections either by evaluating the past number of crashes or by predicting the risk involved based on several models that are a function of variety of parameters. Researchers have attempted to quantify safety performance based on intersection design elements such as sight distance, angle of intersection, median width, number of driveways and lane width, and traffic characteristics, such as approach speed, and traffic composition. Accident modification factors based on design elements such as these form the basis for the IHSDM and the proposed Highway Safety Manual. However, most elements identified and studied are independent of intersection type and do not provide meaningful input into alternative intersection design selection.

In order to provide meaningful input into intersection type selection, exposure estimates for specific turning movement volume combinations must be made. This allows for the differentiation of performance among different turn treatment options. Significant research has shown a relationship between intersection crash rates and traffic volumes. This underscores the need for exposure estimates in the form of volume to be used in estimating the likelihood another vehicle will be hit. These studies focus exclusively on ADT and do not account for the varied crash exposure resulting from directional movements (i.e., turning movements). A relationship between turn treatments and intersection safety performance is evident through studies of conflict points; however, no research was identified which has developed a model capable of predicting safety performance based on both volume measures and conflict points at an intersection.

The ultimate goal of this dissertation is to assist in the safety evaluation of alternative signalized intersection designs. Studies by Lu and Wang show that this evaluation is possible, but these models focus on unsignalized intersections and multi-modal impacts. Dadic developed a level of safety rating system showing the value of a comprehensive model, but lacked a robust crash data source to develop empirical models.

As shown by the NCSU research team application of the Safety Surrogate Assessment Model can be used to develop relationships between conflicts and traffic volume and lane configuration inputs. However, the NCSU research may be expanded by developing a model or models that may serve to encompass a fuller range of alternatives to allow for evaluation and comparison of not only lane configurations but alternative intersection designs as well.

From this review, it is evident that a surrogate crash metric, accounting for both lane configuration and traffic volume data is needed to adequately assess the safety tradeoffs across a full range of design alternatives. The application of the Safety Surrogate Assessment Model appears promising as it can provide 1) validated results that correlate with historical crash experience and 2) addresses the variability inherent in historical crash analysis so that an improved empirical model may be developed.

3 METHODOLOGY

Conflict exposure estimates were developed by analyzing observed conflict patterns within simulated traffic scenarios over a wide range of potentially influencing variables. Regression analysis was then used to develop a numerical model representing the likelihood of conflict with regard to the independent variables. Multiple scenarios were simulated using VISSIM. Conflicts were then identified through application of the Safety Surrogate Analysis Model. SSAM is a tool developed by the Federal Highway Administration which analyzes vehicle trajectory output from the VISSIM micro-simulation model. SSAM identifies "conflicts" between vehicles, which are defined as instances of near misses between two vehicles and is capable of categorizing the conflicts as either rear-end, crossing angle and lane changing (sideswipe) crashes. The primary analysis is then concentrated on developing the crash exposure relationship as a function of volumes and lane configuration. This approach was chosen over the collection of field data due to the ability to remove extraneous or site-specific causal factors from the evaluation. As such, underlying relationships between the intersection configuration and safety performance can be more readily identified. This is possible as an entire range of traffic conditions can be evaluated over a greater range of potential configurations.

Microsimulation Analysis

The first analytical task was to develop VISSIM and SSAM models for each crash type. Left-turn, rear end and sideswipe models were developed independently to eliminate interference from other intersection movements. A range of feasible traffic volumes was evaluated to ensure all movements operate under capacity, so that congestion related crash patterns are separated from other factors in the dataset. In addition to multiple volume scenarios, various lane configurations and traffic control strategies were also evaluated. The full range of analysis scenarios and variables evaluated are summarized below.

3.1.1 Left-turn Angle Conflicts

This analysis evaluates angle conflicts resulting from left-turning vehicles and opposing through vehicles on the same street reflective of permitted left-turn operations at a signalized intersection. Independent variables evaluated for these conflicts are left-turn volume, opposing through volume, the number of opposing through lanes and capacity as indicated by the percent green time for the given movement at a traffic signal. All scenarios will assume a single left-turn lane, as this is the only configuration allowed to accommodate permitted left-turn movements.

- Left-turn volumes range from 0 to 280 vehicles per hour. This represents a typical range of left-turn volumes, as the recommended threshold for protected left-turn movements is 300 vehicles per hour (24). Volumes will be increased in 40 vehicle per hour increments.
- Through volumes range between 400 vehicles per hour per lane to 2,000 vehicles per hour per lane. The 2,000 vphpl volume reflects an upper

threshold of saturation flow for a single lane (25). Volumes will be increased in 400 vehicles per hour increments.

- Number of opposing lanes are evaluated as one or two lanes. Permitted turns across three opposing lanes are not permitted at signalized intersections (26).
- Percent of green time is evaluated as 100 percent (reflective of uncontrolled movements), 70 percent (reflective of major street operations) and 35 percent (minor street operations). (Note: other models used a 60 percent and 40 percent green time split; however, the 70/35 split was used for left turn conflicts to increase differentiation between conflicts results).

The evaluation matrix shown in Table 2 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 240 simulations, assuming a single run for each parameter combination.

Table 2: Left-turn Angle Simulation Design Matrix

Parameter	**Design Values Ranges**			
	i	**n**	**increment**	**Total Combinations**
Left-turn Volume (vph)	0	280	40	8
Opposing Through Volume (vphpl)	400	2,000	400	5
Number of lanes	1	2	1	2
Traffic Control	*Parameter Values*			3
	Signal (100% green time)	Signal (70% green time)	Signal (35% green time)	

3.1.2 Right-turn Angle Conflicts

This analysis evaluates angle conflicts resulting from right-turning vehicles on the minor street reflective of permissive turns at a two-way stop controlled intersection or a right-turn on red operations at signalized intersections. Independent variables evaluated for these conflicts are right-turn volume and through volume on the major street, as wlel as one and two lanes on the major street. The varying lane configuration allows for approaching vehicles on the major street to change lanes to avoid potential crashes.

- Total volume on the minor street range from 50 vehicles per hour to 450 vph, which is reflective of the upper threshold of unsignalized operations as defined by the traffic signal warrants (24). Minor street volumes are increased in 100 vehicle per hour increments.
- Through volumes range between 200 vehicles per hour per lane to 1,000 vehicles per hour per lane. Volumes are increased in 400 vehicles per hour increments.
- Number of lanes are evaluated as one or two lanes on the major street. The unsignalized approach has a single lane as permitted turns from dual lanes are not recommended.

The evaluation matrix shown in Table 3 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 30 simulations, assuming a single run for each parameter combination.

Table 3: Right Turn Angle Simulation Design Matrix

Parameter	**Design Values Ranges**			
	i	**n**	**increment**	**Total Combinations**
Right-turn Volume	50	450	100	5
Approach Through Volume	200	1,000	400	3
Major Street Number of lanes	1	2	1	2

3.1.3 Rear End Conflicts

The independent variable of approach volume, left-turn percentage, presence of left-turn lanes, right-turn percentage, presence of right-turn lane are evaluated for the impact on rear end conflicts. As rear end conflicts are not dependent on interactions between lanes, the number of crashes is calculated per lane and therefore only a single lane alternative be evaluated. Capacity is evaluated as indicated by the percent green time for the given movement at a traffic signal.

- Volumes range between 200 vehicles per hour per lane to 1,000 vehicles per hour per lane.. Volumes are increased in 400 vehicles per hour increments.
- Left-turn and right-turn percentages range from zero (0) to thirty (30) percent. Turn percentages are increased in 10 percent increments.
- Each scenario be evaluated both with and without a right and left-turn lane.
- Percent of green time is evaluated as 100 percent (reflective of uncontrolled movements), 60 percent (reflective of major street

operations) and 40 percent (minor street operations). In addition, all combinations are evaluated as a stop condition to include minor street operations at 2-way stops and all-way stop control.

The evaluation matrix shown in Table 4 summarizes these criteria and value ranges. A full factorial design for this set of parameters requires 576 simulations, assuming a single run for each parameter combination.

Table 4: Rear End Simulation Design Matrix

Parameter	Design Values Ranges			
	i	n	increment	Total Combinations
Volume per lane	200	1,000	400	3
Left-turn Percentage	0	30	10	4
Right-turn Percentage	0	30	10	4
Left-turn Lane	0	1	1	2
Right-turn Lane	0	1	1	2
Traffic Control	*Parameter Values*			
	Signal (100% greentime)	Signal (60% greentime)	Signal (40% greentime)	3

3.1.4 *Sideswipe (Lane Change) Conflicts*

Sideswipe conflicts are evaluated against the independent variables of approach volume, Left-turn percentage, right-turn percentage, number of lanes and maneuvering length.

- Volumes range between 200 vehicles per hour per lane to 1000 vehicles per hour per lane. Volumes are increased in 400 vehicles per hour increments.
- Left-turn and right-turn percentages range from zero (0) to thirty (30) percent. Turn percentages are increased in 5 percent increments.
- Number of lanes are evaluated as both two and four lanes per approach
- Three separate maneuvering lengths are evaluated including 660 feet, 1,320 feet and 2,640 feet, reflective of 1/8 mile, ¼ mile and ½ mile signal spacing, which are typical of urban and suburban environments.

The evaluation matrix shown in Table 5 summarizes these criteria and value ranges. A full factorial design for this set of parameters requires 288 simulations, assuming a single run for each parameter combination.

Table 5: Sideswipe Simulation Design Matrix

Parameter	**Design Values Ranges**			
	i	**n**	**increment**	**Total Combinations**
Volume per lane	200	1,000	400	3
Left-turn Percentage	0	30	10	4
Right-turn Percentage	0	30	10	4
Number of Lanes	2	4	2	2
Maneuvering Length	*Parameter Values*			3
	1/8 mile	¼ mile	½ mile	

Safety Surrogate Assessment Model

VISSIM microsimulation software was used to produce vehicle trajectory files for each scenario developed. The resulting files for each of the conflict scenarios were processed by the SSAM program to determine the resulting conflicts. For all analysis scenarios only those conflict types matching the primary conflict type were used in the development of the models, (e.g., rear end conflicts, lane change conflicts or angle conflicts). Conflicts for each crash type were evaluated and a database was developed, which matched the independent evaluation variables described above with the number of conflicts observed.

Default SSAM parameters including 1.5 second time to collision and 5.0 second post encroachment time were used in the analysis. For the left-turn angle crashes, the TTC was increased to 2.0 seconds in order to increase the capture rate of conflicts for this underrepresented conflict type. These values were determined by performing a sensitivity analysis to maximize the number of conflicts observed for left turn maneuvers.

Statistical Analysis

Regression models were developed using the SPSS statistical software to determine the influence and significance of the independent variables consider in the analysis (27). In addition to the independent variables, several other variable transformations were also examined. The step-wise regression approach was used to narrow the list of significant variables and develop the final models. The basic premise for the development of the combinations examined was to pair an exposure estimate (volume or other combinations of volume with variables such as number of lanes or green percent of cycle) with the number of conflicts in the traffic stream. Finally, linear, log, exponential and polynomial models were considered to determine the best fit to the data. The full range of independent variables evaluated for inclusion in each of the models is summarized in each crash type in the following section. All models have been evaluated for colinearity of variables and have a variance inflation factor (VIF) less than 2, indicating that there is not significant multi-colinearity among the variables (28). Parameters of all models also have an associated p-statistic less than 0.01, indicating statistical significance of the parameter included in the final model.

For each conflict type considered, three regression models were developed. The first model uses only the root, or base, independent variables discussed above. This model is used to establish the baseline R^2 value for comparison of the additional explanatory power of the other models and derived variables. A second model was then developed using a stepwise selection process of all a) root variables, b) multiplicative (or inverse multiplicative) interactions between all root variables and c) select variables developed based on prior known interactions of operational parameters. In instances where neither model provided adequate explanatory power, a third model was developed using multiple derived variables to capture the full interaction among all of the variables.

As an example, the first model would have a structure as

$y = a_0 + a_1x + a_2y + a_3z;$

where x, y and z are the independent variables, a_0 is the model constant, and a_1, a_2, a_3 are the variable coefficients.

The second model is chosen from the three root variables (x, y, z) and the six multiplicative variables summarized below.

1) x^2 2) xy   3) xz   4) y^2 5)yz   6) z^2

The final model may have a structure similar to that shown below depending performance of the individual derived variables.

$$y = a_0 + a_1x^2 + a_2\, yz + a_3y$$

Variables for the second model were chosen through a stepwise selection process using a probability of F equal to 0.05 for entry and 0.10 for removal of the variable from the model. This indicates that there is a 95 percent probability that the selected parameter is significant so that it may be included in the model and a less than a 90 percent probability prior to its removal from the model.

4 RESULTS

The sections below summarize the statistical analysis results for the Left-turn Angle Conflicts, Right-turn Angle Conflicts, Rear End Conflicts and Sideswipe Conflicts. The goodness of fit for all models evaluated and discussion of the variable parameters and coefficients are presented with a discussion of the significance of each variable. Each of the final models is presented and discussed below.

Left-turn Conflicts

As identified above, four independent variables were evaluated to model conflicts related to left-turning vehicles from a primary street. These variables are:

- Left-turn Volume (LT)
- Opposing Through Volume (Thru)
- Number of Opposing Lanes (Lanes)
- Percent of Green Time (Green)

It should be noted that the left turn and through volumes were measured downstream of the signal to ensure that the models reflected vehicular flow, as opposed to vehicular demand, for scenarios where all demand was not able to travel through the intersection.

The initial model developed based on these root variables provided an adjusted R^2 value of 0.24. All variables except for the constant had a p-value less than 0.05 indicating a 95 percent probability that the variable is significantly correlated with left-turn conflicts. Table 6 summarizes the SPSS output for the model.

Table 6: Left-turn Conflicts Model 1

Parameters		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.219	.658		-.333	.740
	LT	.003	.001	.124	2.185	.030
	Thru	.001	.000	.273	4.792	.000
	Lanes	-1.515	.263	-.328	-5.760	.000
	Green	.022	.005	.248	4.357	.000

These data indicate that left-turn volume and opposing through volume are positively correlated with increasing left-turn conflicts, as would be expected. However, the number of opposing lanes is negatively correlated with left-turn conflicts, indicating that the model shows a decrease in left-turn crashes as the number of lanes crossed increases. This finding is in conflict with observed crash patterns, which show an increase in left-turn conflicts as the number of opposing lanes increases.

Furthermore, a positive correlation is shown between the percent of green time and left-turn conflicts. This is counterintuitive as it is expected that left-turn conflicts would increase as the capacity (or time available) to make a left-turn decreases, increasing the likelihood that smaller gaps in the traffic stream would be accepted.

Overall, the low R^2 value for the model indicates that the root variables alone do not provide ample explanatory power of the left-turn conflicts. A second model was developed capable of examining first order multiplicative interactions between the variables. Variables derived from first order interactions are summarized below. A new variable termed the Conflicting Volume (CV), which is the cross-product of the left turn demand and opposing through volume, was also included as a singular variable and also used to derive multiplicative variables.

The second model considered the following variables:

- LT
- Thru
- Lanes
- Green
- CV
- LT x LT
- LT x Thru
- LT x Lanes
- LT x Green
- LT x CV
- Thru x Thru
- Thru x Lanes
- Thru x Green
- Thru x CV
- Lanes x Lanes
- Lanes x Green*
- Green x Green
- Green X CV
- CV x CV

The second model had an adjusted R^2 value of 0.503. The model contained five variables, including Thru*Green, Lanes*Green, Thru*Lanes, Lanes*Lanes, Thru, Green. Table 7 summarizes the result of the SPSS output.

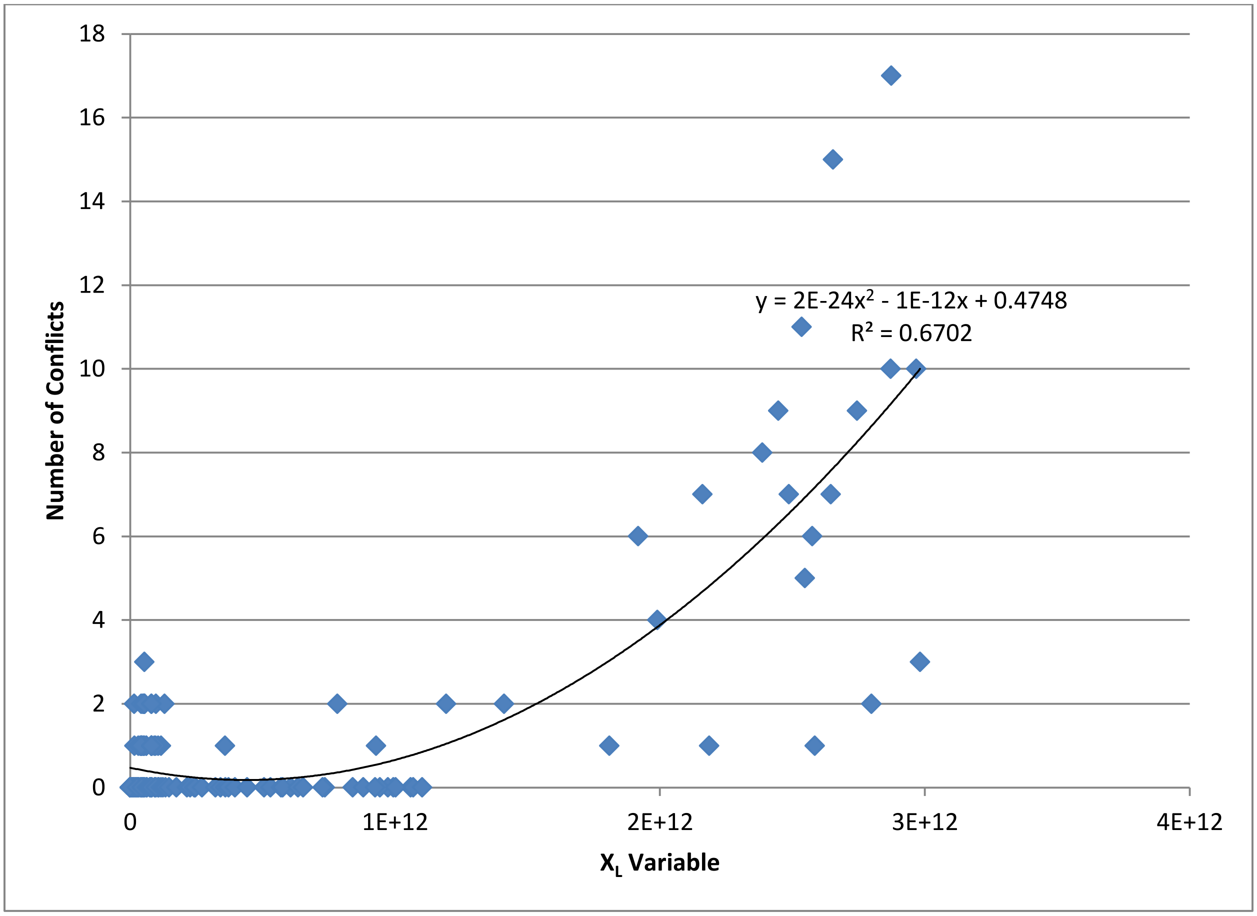
Table 7: Left-turn Conflicts Model 2

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
6	(Constant)	-2.841	.934		-3.041	.003
	Thru*Green	3.215E-5	.000	.770	4.072	.000
	Lanes*Green	-.046	.009	-1.087	-5.406	.000
	Thru*Lanes	-.003	.000	-1.493	-6.815	.000
	Lanes*Lanes	1.612	.247	1.037	6.522	.000
	Thru	.004	.001	.867	3.703	.000
	Green	.044	.015	.499	2.934	.004

Due to the poor prediction power of the model additional parameters were developed that had the ability to capture the full interaction among the variables and increase the explanatory power of the model. For the third model a single variable was developed which included all of the primary factors identified in the first models. This included left-turn volume, through volume, percent of green time and number of opposing through lanes. A multiplicative model was sought between left-turns, through volume and percent green time, as these variables all showed positive correlation with left-turn conflicts. The number of lanes, however, showed an inverse relationship with conflicts and an inverse multiplicative model was chosen. Finally, an iterative approach was used to select variable powers, which led to the use of squared values for through volume and percent green time, while the number of lanes utilized a power of three. The final variable termed X_L derived is provided in the equation below. Figure 2 shows a plot of the variable X_L and the number of left-turn conflicts. Evaluation of the plot indicates a parabolic trend indicative of a polynomial fit.

$$X_L = (\text{Left-turn}) \times (\text{Thru}^2) \times (\text{Green}^2) / (\text{Lanes}^3)$$

Figure 2: Variable 'X_L' versus Left-turn Conflicts



Analysis in SPSS for the 'X_L' variable was also conducted. Two analyses were conducted, the first with a linear equation and the second with a polynomial function. These models were shown to have an adjusted R^2 value of 0.58 and

0.67, respectively. Use of the X_L^2 variable alone provides an R^2 value of 0.66. The SPSS output is summarized in Table 8.

Table 8: SPSS Output Summary Left-turn Variable ‘X’

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	.092	.111		.822	.412
	XL	2.472E-12	.000	.760	17.722	.000
2	(Constant)	.319	.095		3.369	.001
	X_L2	1.020E-24	.000	.812	21.106	.000
3	(Constant)	.475	.110		4.334	.000
	XL2	1.518E-24	.000	1.208	8.031	.000
	XL	-1.331E-12	.000	-.409	-2.720	.007

The derived variable was then entered into the list of variables above and stepwise regression was used to develop a more robust model. The final model had an adjusted R^2 value of 0.70. In addition to the variable ‘X_L’ and ‘X_L^{2}’ two other derived variables were selected including 1) through volume (thru) x conflicting volume (CV), and 2) number of lanes (Lanes) x conflicting volume (CV). A summary of the model coefficients is provided in Table 9.

Table 9: Left-turn Conflicts Model 3

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
6	(Constant)	.426	.133		3.217	.001
	XL2	1.329E-24	.000	1.058	7.070	.000
	Thru*CV	2.629E-9	.000	.402	5.304	.000
	Lanes*CV	-2.474E-6	.000	-.310	-4.151	.000
	XL	-1.120E-12	.000	-.344	-2.335	.020

The added complexity to the model resulting from the introduction of two variables in addition to the variable X_L provides only a 3 percent increase in the explanatory power of the model over the singular variable X_L. Therefore, it is recommended that a singular polynomial model using the derived variable X_L be used to describe the left-turn conflict potential for intersections. A potential criticism of the polynomial model is that the model form itself forces a positive conflict value at 0 values. Therefore, a practical minimum value of X_L equal to 4.3×10^{11} is proposed for the equation. This threshold approximately equates to a signalized intersection with 100 left turn vehicles and 1000 through vehicles. Below this value, conflicts can be assumed to be 0.

Examining the X_L variable, the conflicting volume, which is the product of the left-turn volume and the opposing through volume, is present in the equation. The cross-product of the left-turn and through volume is a standard factor used in the determination of the capacity and safety of permitted left-turns at signalized intersections (29). The inclusion of the squared term for the opposing through volume may be indicative of a more significant influence on through volume as opposed to left-turn volume than current practice assumes.

It is evident from the model that the number of conflicts is inversely proportional to the number of opposing lanes. This is somewhat counterintuitive as the prevailing belief is that performing a left-turn across a single lane is safer than turning left across two or more lanes due to the increased time of exposure of the turning vehicle. Review of the literature however, indicates that the number of lanes plays little or no role in the anticipate crash rate. This prediction is similar to crash trends shown in New York State which tracks left-turn crashes by facility type and shows the same crash rate for 2-lane and 4-lane facilities (0.01 crashes per million entering vehicles) (30).

When examining the capacity constraints of left turn maneuvers from a major street, this result becomes clearer. Capacity of left turn movements are controlled by the number of gaps, or time between advancing vehicles, in the traffic stream large enough to allow a vehicle to turn left. For left turns from a major street a driver needs, on average, a 4.1 second gap between vehicles to safely perform a left turn maneuver (25). The number and size of gaps in a traffic stream can be described by a negative exponential distribution. Based on this distribution a probability function can be derived to determine the probability of gaps being greater than the critical gap as shown in equation 1 below (31).

Eq. 1. $P(h \geq t) = e^{-t/T}$

Where: h = vehicle headway

t = critical gap/headway

T = average vehicular headway

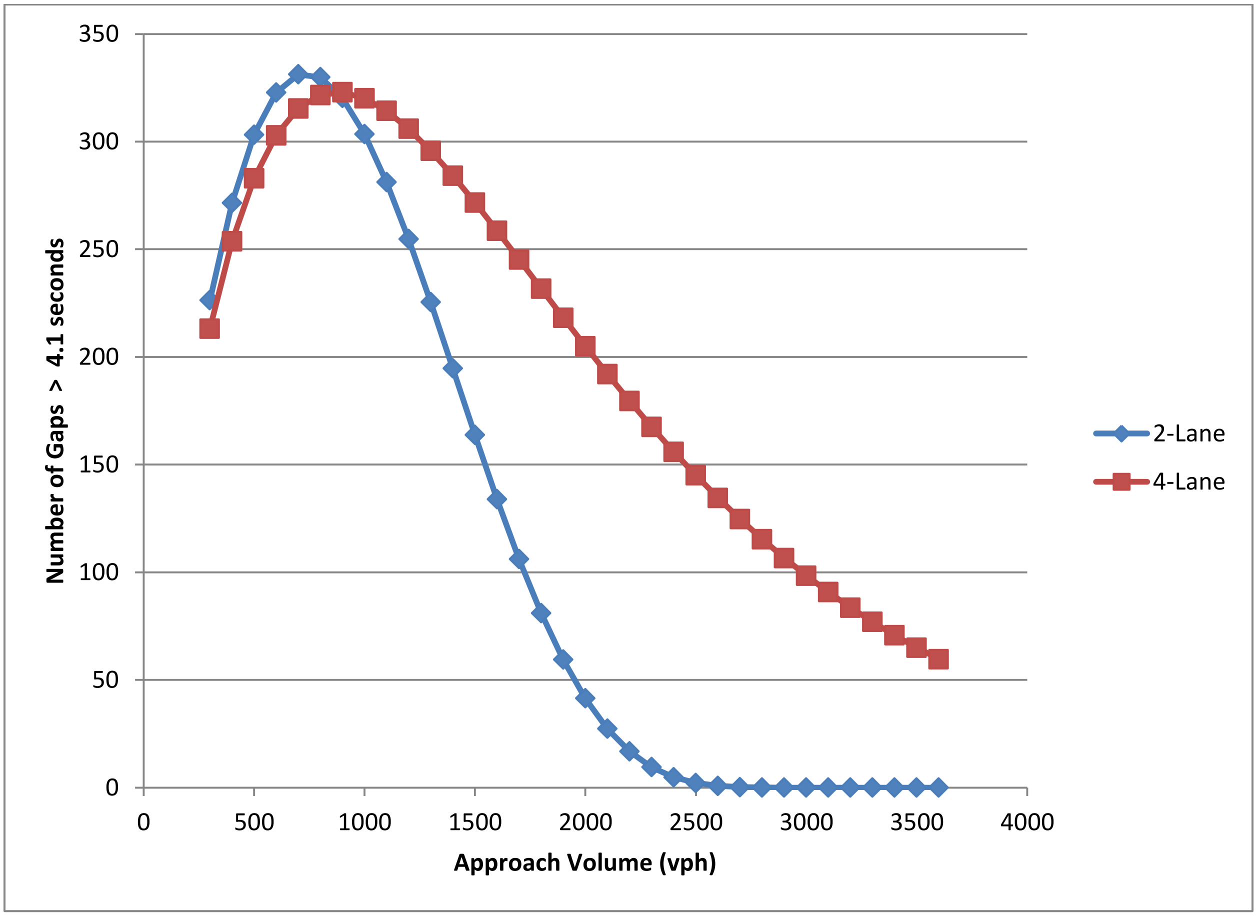
The problem with this distribution model is that it assumes drivers use the full range of gaps, i.e., it can predict vehicles follow each other with a gap as small as 0.1 seconds. Under constrained traffic conditions, drivers typically follow with a minimum gap to allow for increased safety. In these situations, a shifted negative exponential distribution is more appropriate as given by equation 2 below.

Eq. 2. $P(h>t) = e \wedge -((t- \tau)/T-\tau)$

Where: $\tau =$ shift of curve (i.e., minimum headway)

When examining gaps across traffic streams in multiple lanes, it can be seen that vehicles can travel with zero (0) or very small gaps, predicted by equation, as vehicles may travel side-by-side. When traffic only has one lane to travel, such as on a two-lane roadway, the shifted distribution given in equation 2 is more appropriate. Plotting these two distributions across a range of feasible volumes, reveals that for multi-lane facilities, there are significantly more gaps of adequate size to accommodate left turn vehicles, Figure 4. As the number and size of gaps increases in the traffic stream it is then reasonable to conclude that there would be less exposure to a conflict with other traffic when more lanes are present, as predicted by the proposed model.

Figure 4: Gap Distribution for two-lane and four-lane roadway



One factor in left turn angle crashes that is not accommodated by the model is the effect of human factors on crash patterns. Multi-lane facilities present a high demand on the driver requiring the driver to judge available gaps in two separate streams of traffic. VISSIM essentially assumes perfect knowledge and judgment on the part of the driver and thus crashes resulting from these crashes are not represented. As these extenuating circumstances are not accounted for in the conflict models, the models may underrepresent conflicts on multi-lane facilities.

Finally, the percent of green time (Green) indicates that conflicts increase as the additional capacity is added to the movement, which again is counterintuitive. It would be reasonable to assume that as capacity increases, the number of safe gaps in the traffic stream and the ability to safely perform the maneuver would increase. However, the model shows that conflicts are greatest at unsignalized intersections, which effectively have 100 percent green time. The increased safety of left-turns at signalized intersections may be the result of increased gaps in the traffic stream introduced by the signal operations. Furthermore, lost time in the through movement, or yellow time, may be used to move vehicles through the intersection in the absence of opposing traffic. Longer green times brought about by longer percent green times may also encourage vehicles to accept smaller gaps in the traffic stream instead of completing the movement at the end of the signal phase.

While this model does not provide explanatory power as high as the models for other conflict types, the inclusion of all evaluation parameters provides a meaningful input into the design process to start providing a differentiation between different design alternatives and the findings are consistent with other practice and crash experiences.

Right-turn Angle Conflicts

Three independent variables were evaluated to model conflicts related to permitted right-turn angle conflicts. These variables are:

- Right-turn Volume (RT)
- Opposing through volume (Thru)
- Number of Lanes (Lanes)

The initial model developed based on these root variables provided an adjusted R^2 value of 0.46. The only value that had a p-value less than 0.05 was the volume of right-turning vehicles. The number of lanes, opposing through volume and constant had p-values of 0.14, 0.23 and 0.97, respectively. Table 10 summarizes the SPSS output for the model.

Table 10: Right-turn Conflicts Model 1

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.230	6.393		.036	.972
	Thru	-.005	.004	-.190	-1.231	.229
	RT	.043	.011	.715	3.883	.001
	Lanes	4.075	2.656	.260	1.534	.137

These data indicate that right-turn volume and the number of lanes are positively correlated with increasing right angle conflicts. While the right-turn volume is expected to positively correlate with conflicts, increased right-turn conflicts as the number of lanes increases is counterintuitive. This is due to the fact that right-turns typically turn only into the rightmost lane and increasing the number of lanes would decrease the opposing volume in the turning lane.

Furthermore, the high p-value and low coefficient (-0.005) associated with the through volume further supports the notion that the volume of traffic in the opposing lane is not a good indicator of right-turn conflicts.

Overall, the adjusted R^2 value for the model (0.46) indicates that the root variables do not provide acceptable explanatory power for right angle conflicts. Therefore, in order to increase the explanatory power of the model, a second model was developed examining first order multiplicative interactions between the variables. Variables derived from first order interactions are listed below. In addition to the five first order multiplicative variables, a sixth multiplicative variable- the product of all three root variables –was also included in the model.

The second model considered the following derived variables:

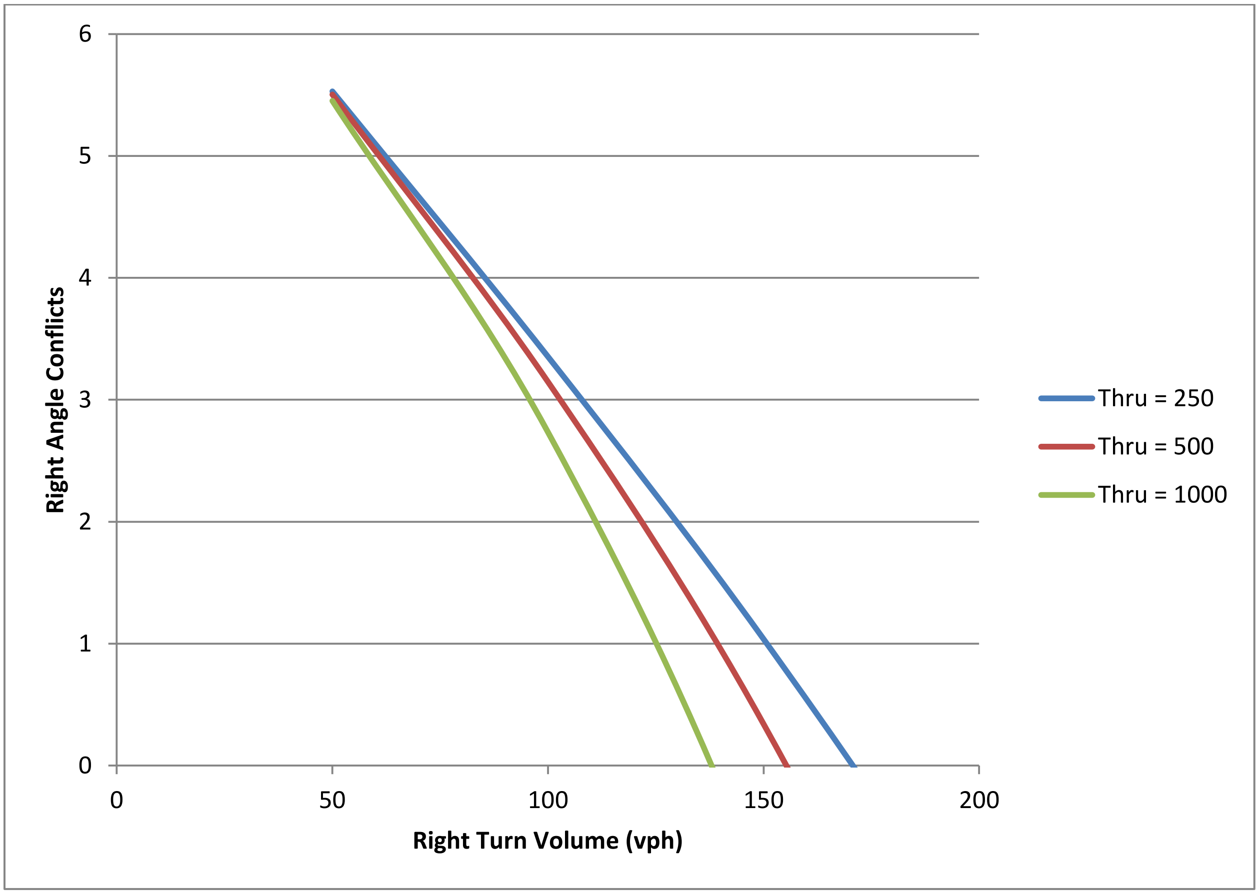
- RT
- Thru
- Lanes
- RT*RT
- RT*Thru
- RT*Lanes
- Thru*Thru
- Thru*Lanes
- Lanes*Lanes
- Thru*RT*Ln

The second model utilizing the first order multiplicative interactions of the variables provided an adjusted R^2 value of 0.85. The final model included the right-turn volume, square of the right-turn volume and the product of the thru and right-turn volumes. All variables had a p-value of less than 0.01. Table 11 summarizes this model and Figure 5 provides a graphical representation of the final model with right-turn angle conflicts by right-turn volume for three different thru volume combinations.

Table 11: Right-turn Conflicts Model 2

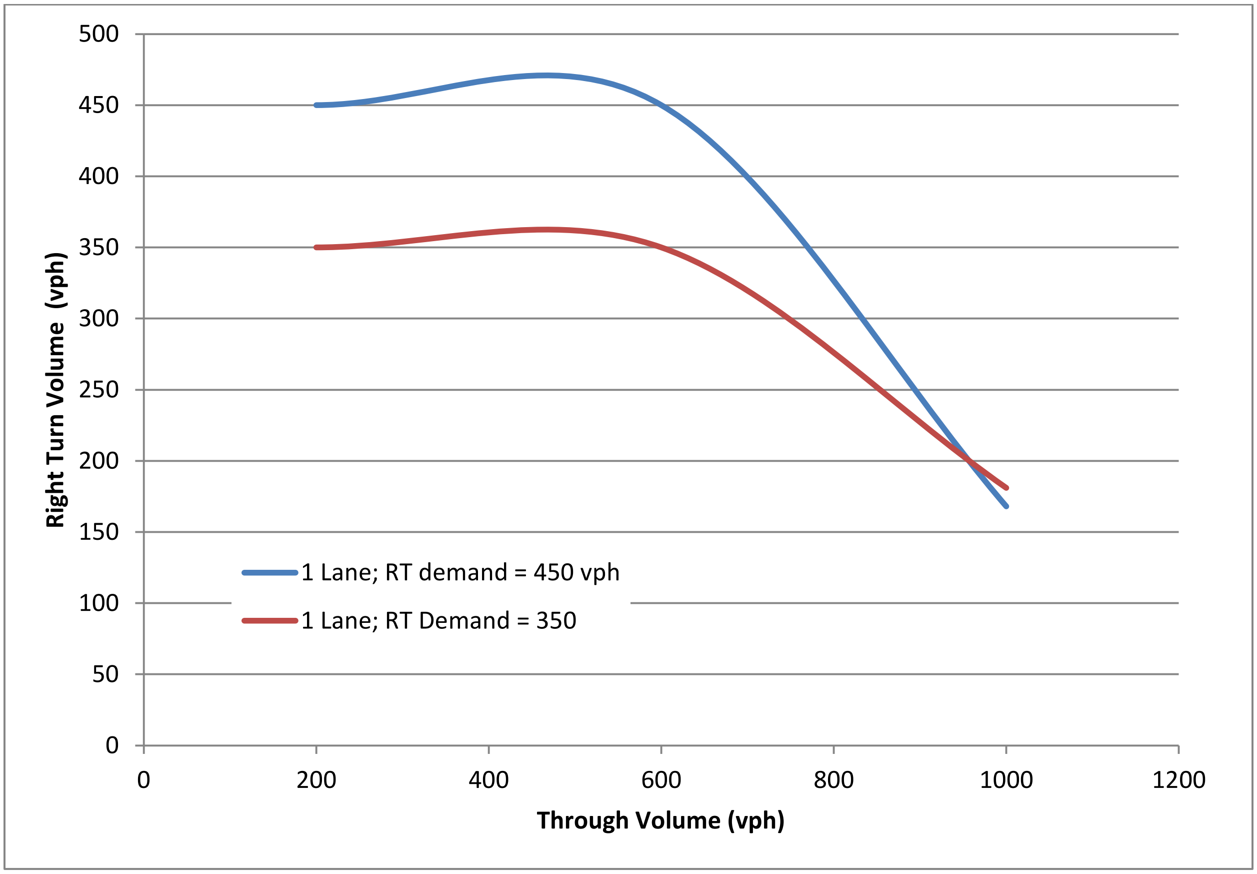
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
3	(Constant)	7.720	1.059		7.293	.000
	Rt*Rt	.000034	.000	2.395	8.569	.000
	Thru*RT	-8.261E-10	.000	-1.151	-8.391	.000
	RT	-.045	.014	-.750	-3.281	.003

Figure 5: Right-turn Conflicts by Right-turn Volume



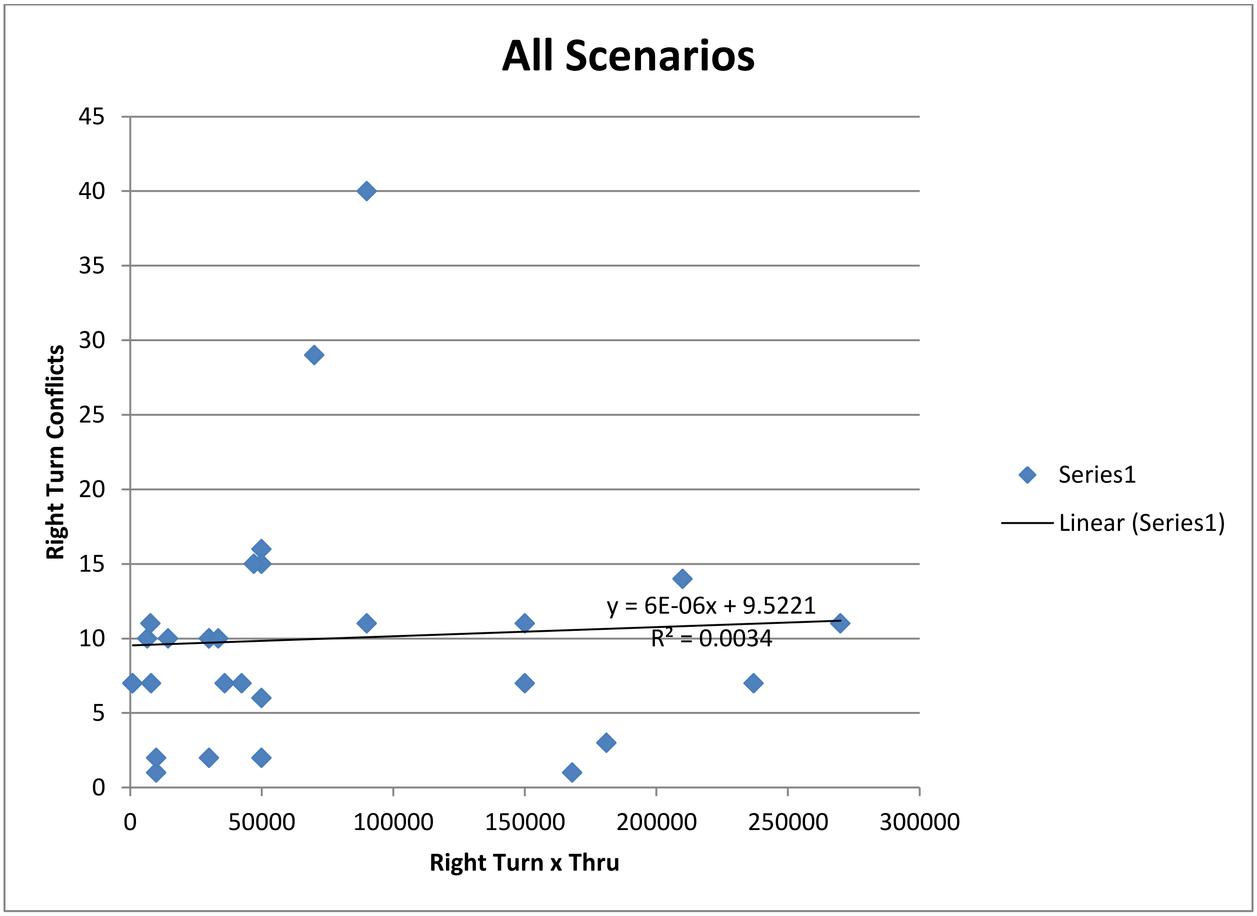
One surprising result of the model is that the variable RT*Thru has a negative coefficient indicating a decreasing trend with an increase in the variable. As identified earlier in the first model, the right-turn volume showed a definite positive correlation while the through volume showed a negative correlation. The negative correlation associated with this variable is likely due to the overrepresentation of the negative correlation with the through volumes, as the through volumes are higher than the simulated right-turn volumes. As this trend is counterintuitive, evaluation of the effect of through volumes on the capacity of the right-turn was evaluated. Figure 6 shows a plot of the right-turn volume passing through the intersection in relation to the through movements. The data shows that especially for the high through volumes, right-turn capacity is constrained limiting the amount of right-turn traffic and thus limiting the exposure to right-turn angle crashes. This effect may also explain the positive correlation of the number of lanes with increased right-turn conflicts, as the increased number of lanes increases the capacity of the right-turn movements and thus increases the opportunity for a right-turn angle conflict. As this model essentially represents the effect of capacity constraint on the right turn conflicts, it does not achieve the goal of the study to establish the relationship between conflict exposure and traffic demand and intersection configurations.

Figure 6: Right-turn Volume by Through Volume



In order to develop a more appropriate measure the relationship between conflicts and the product of Right Turn and Through Volume was evaluated as shown in Figure 7. Examining the plot and a linear trend line, there is no discernable trend within the data points.

Figure 7: Right-turn Conflicts by Right Turn Volume x Through Volume



Data were then evaluated independently for the 1 lane and 2 lane scenarios, as shown in Figures 8 and 9, respectively. As can be seen in Figure 8, strong relationships exist based on the right turn volume with low opposing through traffic, but conflicts dramatically reduce as the volume increases, as a result of the capacity constraint. However, when examining two-lane data, Figure 9, any trend is lost. For through volumes of 600 and 1000 vph, there is a decrease in conflicts as right turn traffic increases, while a positive trend is shown for through volumes of 200 vph.

Figure 8: Right-turn Conflicts by Right Turn Volume x Through Volume (1 Lane)

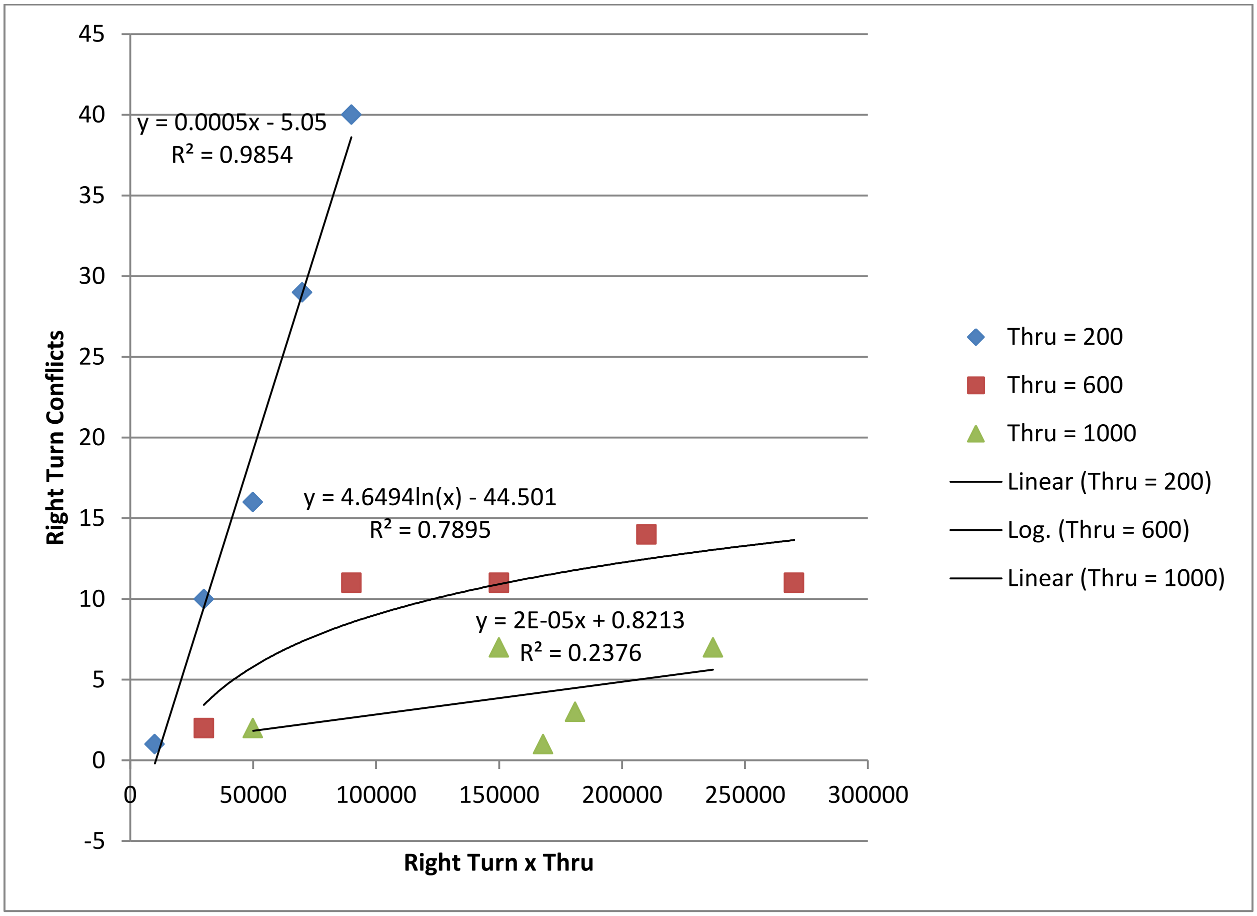
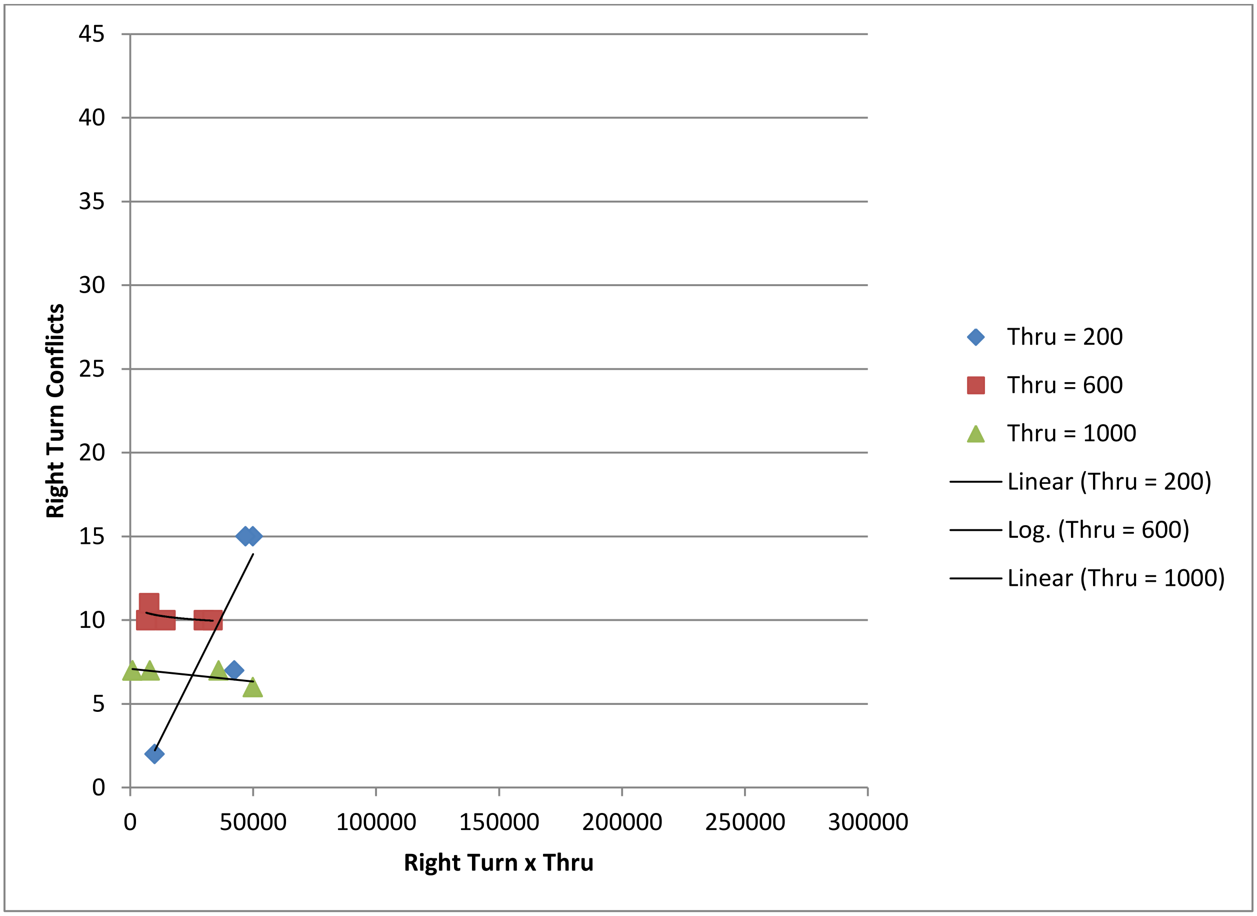


Figure 9: Right-turn Conflicts by Right Turn Volume x Through Volume (2 Lane)



The data presented above, indicate that the methodology fails to provide a reasonable trend to define a relationship for right turn conflicts. Most notable is the inverse relationship shown between opposing through volume and the number of conflicts. This decreasing trend is evident even at relatively low volumes of through traffic (i.e., 600 vph), which should not be a capacity constrained conditions. The absence of a credible trend may point toward improper driver behavior for right turning vehicles within the simulation model to accurately reflect driver decision making. Therefore, no model is recommended to represent right turning conflicts.   While this does provide a limitation to the overall project, the absence of a right turn conflict model does not significantly alter the value of the overall research as the final signalized model would be representative of operations that do not allow “right turns on red.”

Rear End Conflicts

As identified above, four independent variables were evaluated to model conflicts related to rear end vehicles at a signalized intersection. These variables are:

- Right-turn Volume
- Left-turn Volume (LT)
- Through Volume (Thru)
- Percent of Green Time (Green)

The initial model developed based on these root variables provided an adjusted R^2 value of 0.791. All variables except for the constant had a p-value less than 0.01 indicating a 99 percent probability that the variable is significantly correlated with rear end conflicts. Table 12 summarizes the SPSS output for the model.

Table 12: Rear End Conflicts Model 1

Model		Unstandardized Coefficients		Standardized Coefficients	T	Sig.
		B	Std. Error	Beta		
1	(Constant)	33.053	5.005		6.604	.000
	Green	-.547	.060	-.473	-9.188	.000
	RT	.053	.016	.174	3.278	.002
	LT	.154	.016	.507	9.530	.000
	Thru	.046	.006	.415	7.853	.000

These data indicate that left-turn, through and right-turn volume are positively correlated with increasing rear end conflicts, as would be expected. Additionally, in examining the standardized coefficients it is seen that for the range of values evaluated, the left-turn volume has the largest influence on rear end conflicts (0.507, compared to 0.415 (through) and 0.174 (right)). Additionally, a negative correlation is shown for percent green time, indicating a decrease in rear end conflicts with increasing intersection capacity; again this trend is consistent with anticipated results

Overall, the adjusted R^2 value for the model indicates that the root variables do provide acceptable explanatory power for rear end conflicts. However, in order to increase the explanatory power of the model, a second model was developed capable of examining first order multiplicative interactions between the variables. Variables derived from first order interactions are listed below.

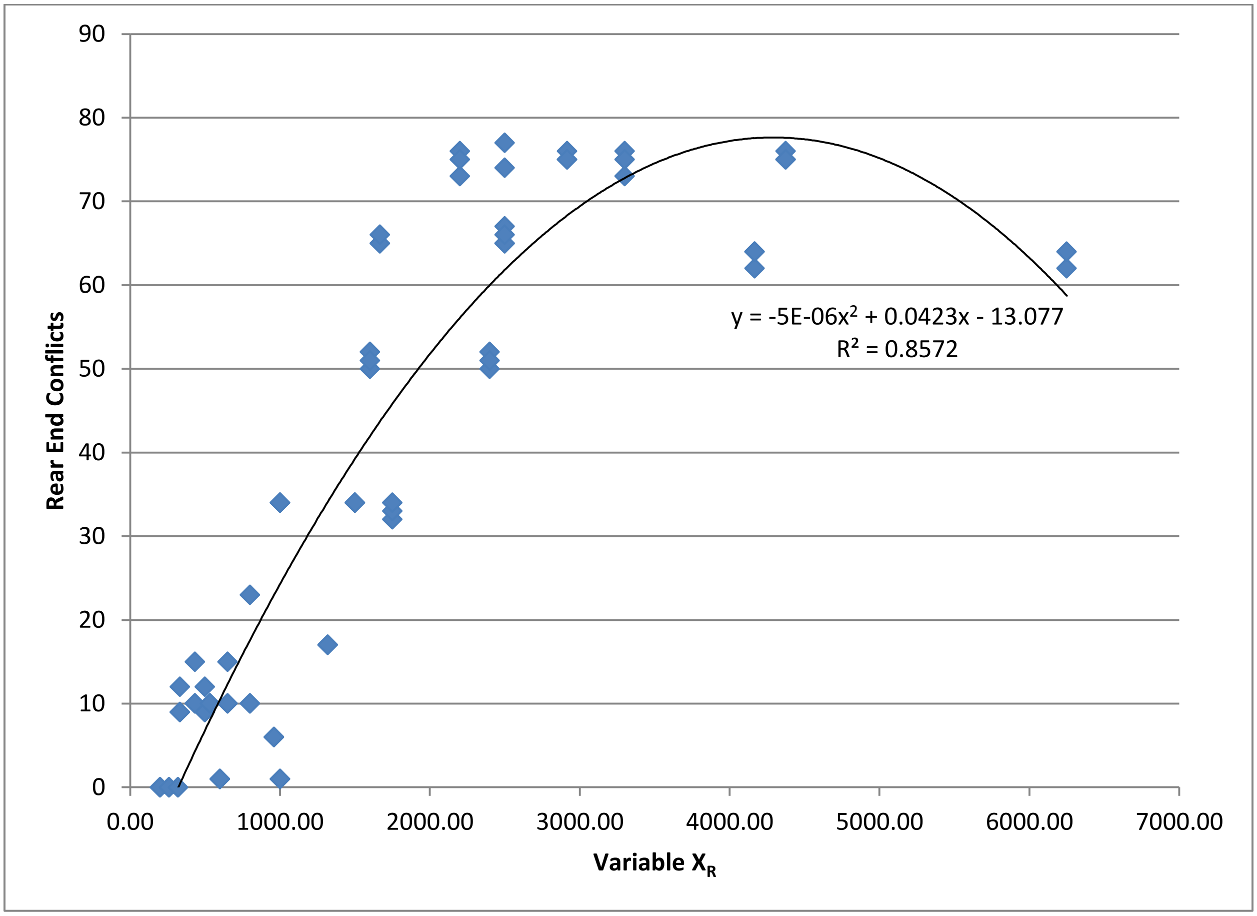
The second model considered the following variables:

- RT
- LT
- Thru
- Green
- RT*RT
- RT*LT
- RT*Thru
- RT*Green
- LT*LT
- LT*Thru
- LT*Green
- Thru*Thru
- Thru*Green
- Green*Green

The literature review also indicated a high correlation of rear end crashes with congestion, so a measure of congestion based on intersection critical volume was also developed. The congestion variable identified as variable 'X_R' calculates the critical volume (through and right-turn traffic plus left-turn traffic) and divides it by the available green time. The final variable derived is provided in the equation below. Figure 10 shows a plot of the variable X_R and the number of rear end conflicts. Evaluation of the plot indicates a parabolic trend indicative of a polynomial fit. Above a value of 4000, the graph can be shown to fall off and curve downward, indicative of oversaturated and congested conditions that may free vehicular movement.

$$X_R = (\text{Through Volume} + \text{Right-turn} + \text{Left-turn}) / (\text{Green})$$

Figure 10: Variable ‘X_R’ versus Rear End Conflicts



Analysis in SPSS for the ‘X_R’ variable was also conducted. Three analyses were conducted, the first with a linear equation, the second using the square of the X_R variable and the third a 2nd degree polynomial function. These models were shown to have an adjusted R^2 value of 0.67, 0.38 and 0.85, respectively. The SPSS output is summarized in Table 13.

Table 13: SPSS Output Summary Variable ‘X_R’

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	5.645	2.920		1.933	.057
	XR	.017	.001	.819	12.607	.000
1	(Constant)	22.802	2.992		7.620	.000
	XR^2	2.412E-6	.000	.624	7.061	.000
1	(Constant)	-13.077	2.690		-4.862	.000
	XR^2	-4.925E-6	.000	-1.275	-10.024	.000
	XR	.042	.003	2.019	15.871	.000

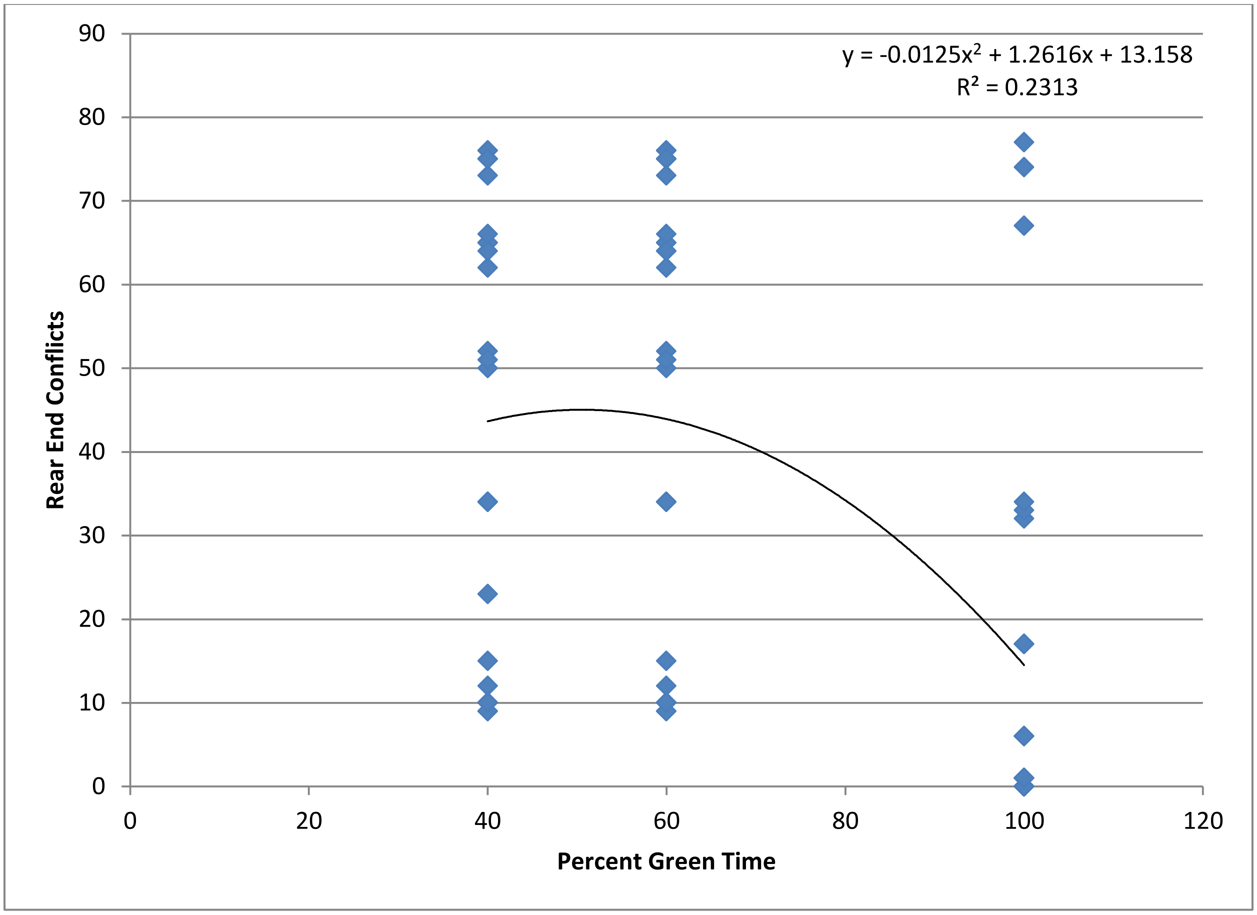
The derived variable ‘X_R’ was then entered into the full list of multiplicative variables above and stepwise regression was used to develop a robust model. This model had an adjusted R^2 value of 0.90. In addition to the ‘X_R’ and ‘X_R^2’ variables the percent green time (Green) and its squared value (Green^2) was shown to be significant predictors of rear end crashes. All variables had a p-value of less than 0.01 indicating a 99 percent confidence that the variables are correlated with the occurrence of rear end conflicts. A summary of the model coefficients is provided in Table 14.

Table 14: Rear End Conflicts Model 2

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
4	(Constant)	-60.643	13.296		-4.561	.000
	XR	.040	.002	1.909	17.695	.000
	XR^2	-4.635E-6	.000	-1.200	-11.249	.000
	Green^2	-.014	.003	-1.683	-4.806	.000
	Green	1.778	.406	1.539	4.376	.000

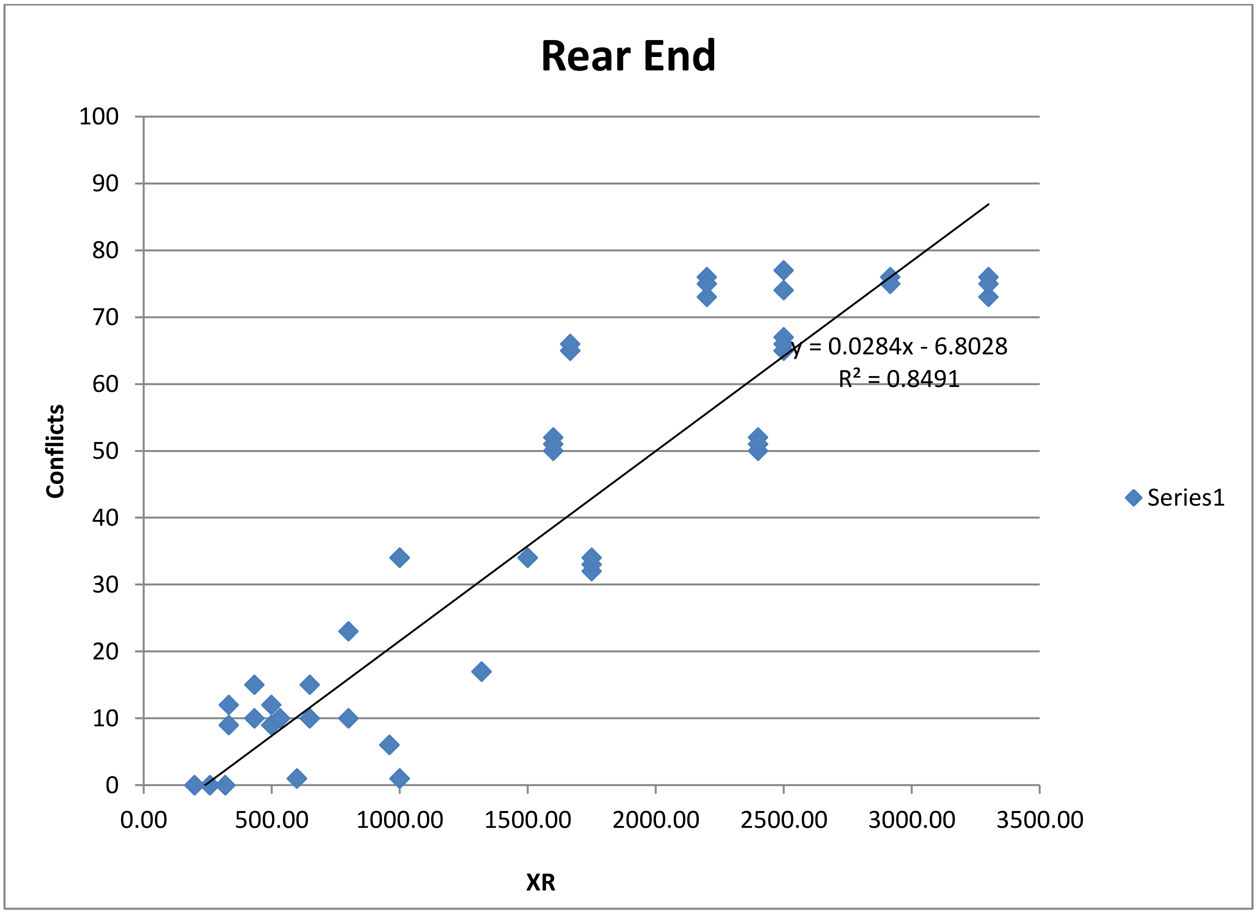
Examining the standardized coefficients, both the variable X_R and percent green time, equally contribute to the number of rear end conflicts. Figure 11 shows a plot of rear end conflicts by the percent of green time, which indicates a sharp decrease in rear end conflicts as the percent of green time increases. However, it is observed that there is little difference between the 40 percent green time and the 60 percent green time. This may be indicative of other factors influencing rear end conflicts other than the percent of green time that is captured in the variable. A potential factor that should be further examined would be the cycle length, which affects the number of cycles (and thus stops) experienced at the signal. While the 100 percent green time simulations were run with an underlying 90 second cycle, it would be the same as having a single cycle per hour. These two variables show that the number of rear end conflicts is dependent upon 1) the amount of congestion present at the intersection as evidence by the influence of X_R, but rear ends may also result from the very presence of the signalized intersection and the forced stops in the traffic stream required by red lights.

Figure 11: Rear End Conflicts by Percent Green Time.



While this model does increase the explanatory power of the model with the inclusion of the Percent Green Time variable, examination of Figure 11 above, does not show that significant of a trend with the green time variable. Furthermore, the additional complexity of the model for a 0.05 increase in R2 may be more indicative of overfitting the model and not representative of an actual improvement in the predictive power of the model. Therefore, it is recommended that only the X_R variable as shown in Figure 10 be used. One potential problem with this model, as identified previously, the upper end of data points, with X_R variable > 4000, reflect oversaturated conditions. Therefore, the oversaturated data points were excluded from the data set and a new model developed. The final recommended model is shown in Figure 12. As the model still utilizes a negative intercept, a practical minimum value of X_R equal 234 is proposed for the equation; below this value, conflicts can be assumed to be 0. This model provide an R^2 value of 0.85.

Figure 12: Rear End Conflicts by Variable X_R (Recommended Model).



Sideswipe (Lane Change) Conflicts

As indicated above, five independent variables were evaluated to model conflicts related to sideswipe conflicts at signalized intersections. These variables are:

- Right-turn Volume (RT)
- Left-turn Volume (LT)
- Total Approach Volume (App)
- Number of Lanes (Lanes)
- Upstream maneuvering distance (Dist)

The initial model developed based on these root variables provided an adjusted R^2 value of 0.76. All variables except for the right-turn volume had a p-value less than 0.01 indicating a 99 percent probability that the variable is significantly correlated with rear end conflicts; the right-turn volume had a p-value of 0.086. Table 15 summarizes the SPSS output for the model. This model used the natural log of the number of sideswipe conflicts, as opposed to the direct count of conflicts due to an improved fit of the model.

Table 15: Sideswipe Conflicts Model 1

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-.575	.183		-3.141	.002
	App	.001	.008	.598	12.543	.000
	RT	.00044	.025	.072	1.726	.086
	LT	.00181	.025	.299	7.127	.000
	DIST	-.000428	.117	-.129	-3.644	.000
	Lanes	.237	.039	.216	6.131	.000

These data indicate that all variables are positively correlated with increasing sideswipe conflicts, as would be expected. The only exception is that of the upstream maneuvering distance which shows a negative correlation. The negative correlation for the upstream maneuvering distance is expected as increasing the distance over which a lane change maneuver can be made would increase the time needed to make the maneuver. Additionally, examining the standardized coefficients it is seen that the total approach volume has the largest influence on sideswipe conflicts (0.598), indicating the total congestion may be more indicative of sideswipe potential than the number of lane change maneuver required by turning vehicles.

Overall, the adjusted R^2 value for the model (0.76) indicates that the root variables provide acceptable explanatory power for sideswipe conflicts. However, in order to increase the explanatory power of the model, a second model was developed capable of examining first order multiplicative interactions between the variables. Variables derived from first order interactions are listed below.

The second model considered the following derived variables:

- RT
- LT
- App
- Lanes
- Dist
- RT*RT
- RT*LT
- RT*App
- RT*Lanes
- RT/Dist
- LT*LT
- LT*App
- LT*Lanes
- LT/Dist
- App*App
- App*Lanes
- App/Dist
- Lanes*Lanes
- Lanes/Dist
- Dist*Dist

The second model utilizing the first order multiplicative interactions of the variables provided an adjusted R^2 value of 0.762. In addition to the constant, the model contains thirteen other variables. Table 16 summarizes this model. Despite this increased complexity, the model provided no increase in the explanatory power (R^2) of the model.

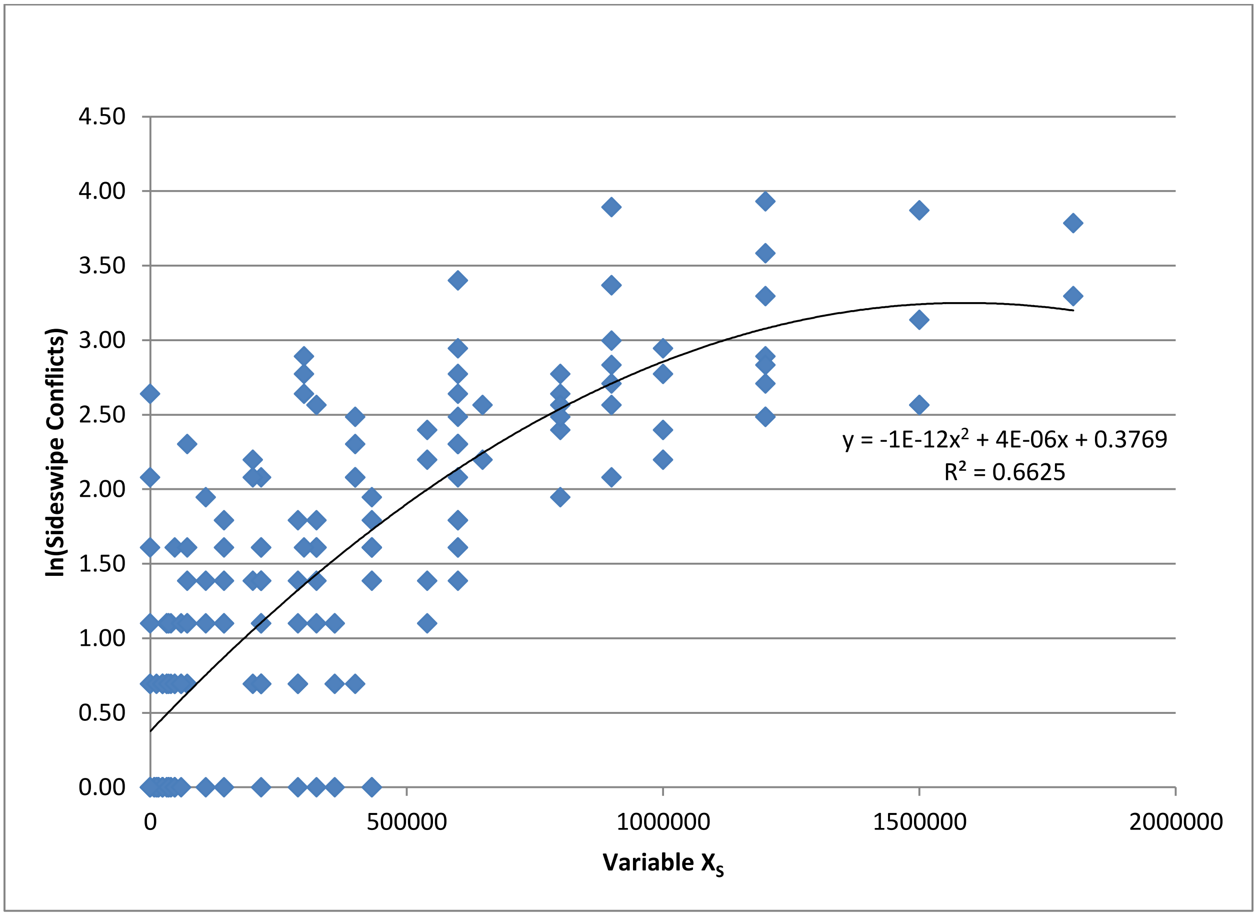
Table 16: Sideswipe Conflicts Model 2

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
13	(Constant)	5.315	1.651		3.219	.002
	LT*Lanes	.009	.002	.581	4.186	.000
	Flow*Flow	4.064E-6	.000	.730	2.944	.004
	Flow	-.013	.003	-.945	-3.786	.000
	Flow*Lanes	.002	.001	.666	3.954	.000
	RT/Dist	15.081	3.856	.387	3.911	.000
	LT*LT	2.318E-5	.000	.267	1.818	.071
	LT	-.034	.012	-.688	-2.876	.005
	Lanes*Lanes	-.292	.109	-.197	-2.674	.008
	Flow*LT	1.573E-5	.000	.645	2.528	.012
	RT*Lanes	-.004	.002	-.250	-2.110	.036
	RT*RT	4.633E-5	.000	.535	3.634	.000
	Flow*RT	-1.534E-5	.000	-.629	-3.013	.003
	LT/Dist	-9.055	4.075	-.232	-2.222	.028

In an attempt to increase the explanatory power of the model and come closer to identifying a singular explanatory variable, as was done for the other models, a new variable was derived. The primary concept in developing the derived variable was to provide an estimate of the exposure of lane changing vehicles. For instance, if 20 vehicles were changing lanes from the right lane to the left lane (as if to make a left-turn), the derived exposure would be the product of 20 times the number of vehicles in the left lane. In order to derive this variable, it was assumed that traffic was equally distributed across all lanes, e.g., if 120 vehicles were turning left on a three lane roadway, 40 left-turning vehicles would be in each lane. Those vehicles in the rightmost lane would be required to cross two lanes of traffic, those in the center lane would be required to cross one lane and those in the left lane would not have to change lanes. An equation was derived to calculate this value (termed 'X_S') for multiple lane configurations, which is presented below. Figure 13 shows the relationship between the lane change exposure variable s and the natural log (ln) of the lane change conflicts.

$$X_S = (\text{Lanes} - 1)(\text{Left-turns} + \text{Right-turns})(\text{Total Approach Volume}) / \text{Lanes}$$

Figure 13: Sideswipe Variable by Lane Change Exposure (X_S)



Analysis in SPSS for the ‘X_S’ variable was also conducted. Three analyses were conducted, the first with a linear equation, the second using the square of the X_S variable and the third a 2nd degree polynomial function. These models were shown to have an adjusted R^2 value of 0.62, 0.43 and 0.66, respectively. The SPSS output is summarized in Table 17.

Table 17: SPSS Output Summary Variable ‘X_S’

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	.565	.065		8.666	.000
	XS	2.163E-6	.000	.787	17.607	.000
2	(Constant)	.950	.067		14.116	.000
	XS^2	1.321E-12	.000	.659	12.082	.000
3	(Constant)	.377	.073		5.183	.000
	XS	3.617E-6	.000	1.317	11.298	.000
	XS^2	-1.139E-12	.000	-.568	-4.875	.000

Including the derived variable in the full list of multiplicative variables did not increase the R^2 value of the model. As can be seen from the presented models, the first model based on the root variables [Right-turn Volume (RT); Left-turn Volume (LT); Total Approach Volume (App); Number of Lanes (Lanes); Upstream maneuvering distance (Dist)] had the highest adjusted R^2 value and provided the simplest and most easily applied model. There is an inherent advantage in selecting a model with a singular composite variable (as was derived for the left-turn model), in that the numeric model will not provide non-zero estimates when necessary exposure elements, such as turning volumes, are not present. However, the presence of sideswipe conflicts predicted by this model is not dependent on any singular value, as lane changes can result from any traffic in the system when more than a single lane is present. Therefore, the first model presented in Table 15 is recommended as the final prediction model for determining sideswipe crashes at signalized intersections.

Summary

The conflicts obtained through the SSAM analysis showed trends between conflict occurrence and the variables examined. The final models all have an R^2 value greater than 0.67 with the rear end having the highest R^2 value of 0.90. R^2 is a measure of the goodness of fit of the model and a measure of the data variability explained by the numerical model. This high level of fit demonstrates that the models developed here can explain a majority of the variability seen in the conflict distributions. The resulting three prediction models are summarized in equations 1 through 3.

Eq. 1. Left Turn Angle Conflicts = = $2E\text{-}24X_L^2 - 1E\text{-}12\ X_L + 0.4748$

Where: $X_L = \dfrac{\text{(Left-turn) x (Through Volume)}^2 \text{ x (Percent Green)}^2}{\text{(Number of Lanes)}^3}$

Eq. 2. Rear End Conflicts = $0.0284X_R - 6.8028$

Where: X_R = (Through Volume + Right-turn + Left-turn) / (Percent Green)

Eq. 3. Sideswipe Conflicts = $0.001X_1 + 0.00044X_2 + 0.00181X_3 -0.000428{*}X_4 + 0.237X_5$

Where: X_1 = Approach Volume

X_2 = Right Turn Volume

X_3 = Left Turn Volume

X_4 = Maneuvering Distance

X_5 = Number of Lanes

5 MODEL CALIBRATION

The models developed and discussed above provide a quantifiable method to independently estimate left-turn, rear end, sideswipe and right-turn conflicts. While these models are a step toward developing a well-rounded (complete) intersection safety model, the research performed by Dijkstra et al showed that the distribution of conflict types predicted by simulated conflict models did not relate to the distribution observed in crash histories (23). As a result, these models can be used to estimate a decrease in left-turn crashes between a traditional signalized intersection and a jug-handle intersection, and can show a corresponding increase in rear end conflicts. However, a decrease in left-turn conflicts by 1 is not necessarily equivalent to a 1 conflict increase in rear ends, which represents a shortcoming of the models presented above.

In order to address this issue a calibration effort was undertaken to correct for the unequal distribution of conflicts in relation to crashes. The multi-vehicle crash distribution at signalized intersections as presented by the Highway Safety Manual was used as the baseline for average distributions of actual crash types. A conflict calibration factor was then derived as the quotient of the average crash distribution and the distribution of average conflicts observed in the scenarios evaluated above. Table 18 presents these values.

Table 18: Conflict Calibration Factor Determination

Conflict Type	Observed Conflicts		Average Crash Distribution	Conflict Calibration Factor
	Average Conflicts	Percent Distribution		
Rear End	33.91	67%	48%	0.72
Right Angle	9.97	20%	12%	0.61
Left-turn	0.97	2%	12%	6.28
Sideswipe	5.94	12%	3%	0.26
Other	N/A	N/A	25%	N/A
Total	50.79	100%	100%	

Final conflicts can be then be determined by 1) determining the predicted number of conflicts from the models presented above and 2) multiplying by the resultant conflicts by the calibration factor presented in Table 18 above.

Example Application

An example is provided here to demonstrate the potential application of the models presented above to compare alternative intersection designs. This example compares 4 different types of intersection designs identified below and shown in Figures 14 through 17.

1. Signalized Intersection (1-Lane Major Street Approach)
2. Signalized Intersection (2-Lane Major Street Approach)
3. Jughandle (2-Lane Major Street Approach)
4. Median U-Turn (2-Lane Major Street Approach)

Figure 14: Signalized Intersection (1-Lane Major Street Approach)

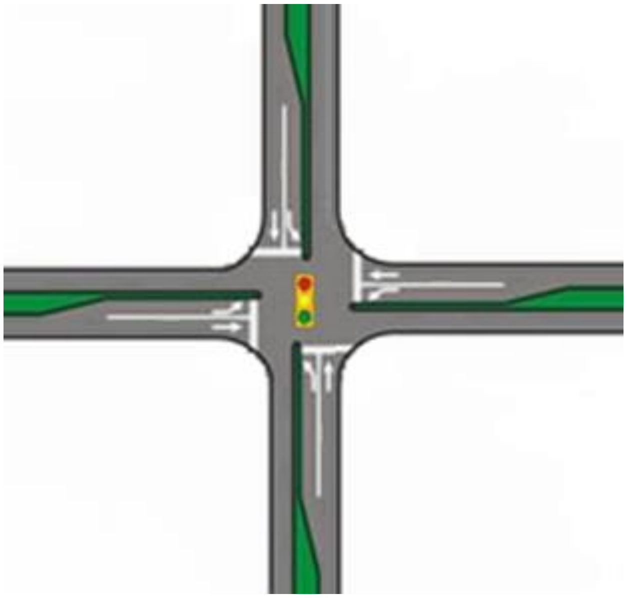
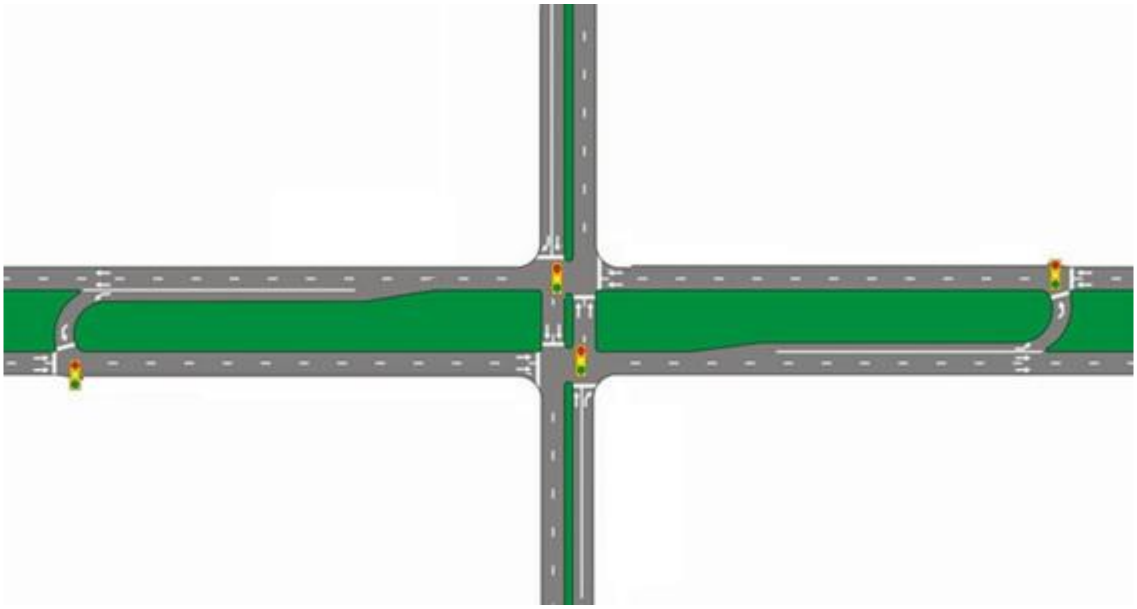


Figure 15: Signalized Intersection (2-Lane Major Street Approach)

Figure 16: Jughandle (2-Lane Major Street Approach)

Figure 17: Median U-Turn (2-Lane Major Street Approach)



The alternatives were evaluated against 3 different volume scenarios, reflective of intersections having an average daily traffic (ADT) range of 15,000 vehicles per day (vpd), 25,000 vpd and 30,000. Volume scenarios assumed 10 percent of traffic arrived during the peak hour, with a 60/40 volume distribution between major and minor streets and a 60/40 directional split on each street. Final turning volumes for each of the three scenarios are shown in Figures 18, 19, and 20.

Figure 18: Example Volume Scenario 1 (15,000 ADT)

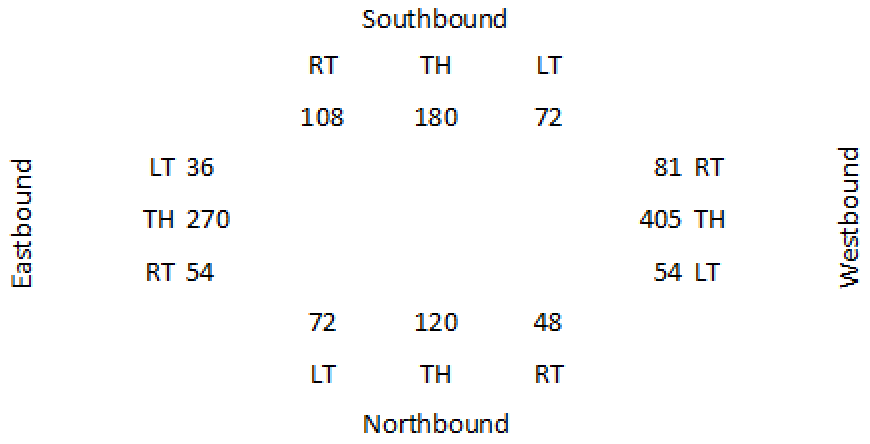


Figure 19: Example Volume Scenario 2 (25,000 ADT)

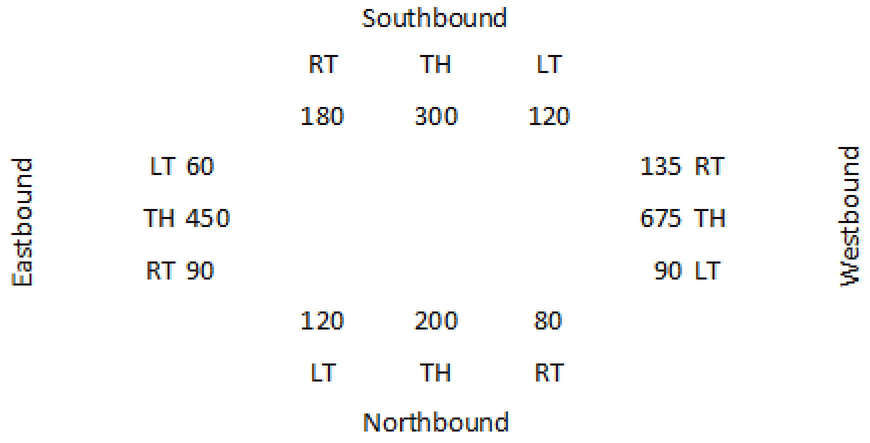
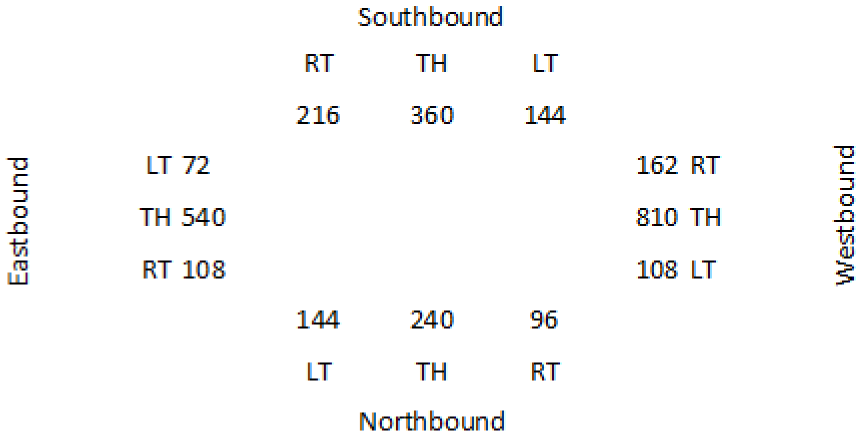


Figure 20: Example Volume Scenario 1 (30,000 ADT)



The models were then applied to estimate the number of conflicts associated with each intersection and volume combination. Conflicts are estimated by approach for each individual conflict type. As an example the following is presented to determine the number of left turn angle, rear end and sideswipe conflicts for the eastbound approach of Alternative 1; Volume Scenario 1. (Calculation results for all alternatives and volume scenarios are contained in Appendix B).

Example: Left Turn Angle Conflicts (Alternative 1; Volume Scenario 2; Eastbound Approach

Left Turn Angle Conflicts = 3E-12 X_L

Where: X_L = (Left-turn) x (Thru^2) x (Green^2) / (Lanes^3)

$X_L = (60) \times (810^2) \times (60^2) / (1^3) = 1.42E11$

Left Turn Angle Conflicts = 0.43

Rear End Conflicts = $0.0249X_R$

Where: X_R = (Through Volume + Right-turn + Left-turn) / (Green)

XR = (60+450+90) / 0.6 = 1000

Eastbound Rear End Conflicts = 24.9

Sideswipe Conflicts = $0.001X_1 + 0.00044X_2 + 0.00181X_3 -0.000428*X_4 + 0.237X_5$

Where: X_1 = Approach Volume = 600

X_2 = Right Turn Volume = 90

X_3 = Left Turn Volume = 60

X_4 = Maneuvering Distance = 300

X_5 = Number of Lanes = 1

Eastbound sideswipe crashes = 0.8

Using the above methods, conflicts were determined for each approach, under each of the 21 volume and intersection type scenarios. In addition, these scenarios were simulated and the processed through SSAM. The results of the analysis of the 15,000 vpd, 25,000 and 30,000 analyses are summarized in Table 19. Appendix A contains the full calculations for each scenario.

Table 19: Alternative Design Conflict Comparison

Alternative	Volume Scenario (ADT)	CROSSING		LANE CHANGE		REAR END		**TOTAL**	
		Model	SSAM	Model	SSAM	Model	SSAM	**Model**	**SSAM**
Signalized Intersection (1-Lane Major Street Approach)	15,000	0.19	0	1.1	1	58.0	109	**59.3**	**110**
Signalized Intersection (2-Lane Major Street Approach)		0.11	0	3.1	6	30.8	73	**34.0**	**79**
Jughandle (2-Lane Major Street Approach)		0.05	0	2.5	5	37.2	89	**39.7**	**94**
Median U-Turn (2-Lane Major Street Approach)		0.00	0	1.9	5	41.9	95	**43.8**	**100**
Signalized Intersection (1-Lane Major Street Approach)	25,000	0.89	2	4.0	5	114.8	326	**119.7**	**333**
Signalized Intersection (2-Lane Major Street Approach)		0.53	0	4.5	12	87.6	206	**92.7**	**218**
Jughandle (2-Lane Major Street Approach)		0.25	1	3.9	7	98.2	253	**102.4**	**261**
Median U-Turn (2-Lane Major Street Approach)		0.00	0	3.3	11	106.0	242	**109.3**	**253**
Signalized Intersection (1-Lane Major Street Approach)	30,000	1.53	6	5.0	32	143.2	514	**149.7**	**552**
Signalized Intersection (2-Lane Major Street Approach)		0.92	0	5.3	19	116.0	327	**122.2**	**346**
Jughandle (2-Lane Major Street Approach)		0.43	4	4.7	13	128.8	623	**133.8**	**640**
Median U-Turn (2-Lane Major Street Approach)		0.00	0	4.0	18	138.1	359	**142.1**	**377**

The right column in Table 19 summarizes the total number of crashes predicted by the model and observed by SSAM. As can be seen, under the three volume scenarios examined, the models are consistent in identifying the expected rank order of intersection alternatives in comparison with the SSAM results. Furthermore, the relative differences between the model predictions and the SSAM results are consistent, with the model following similar trends as SSAM. The only exception to this is the discrepancies between the Jughandle design for the 30,000 ADT scenario. For this scenario, the SSAM was observed to identify considerably more rear end crashes than the predicted by the model or observed for the other alternatives. Review of the VISSIM simulation results, indicate the considerable back-ups were created for this scenario which resulted in undue congestion at the intersection. This congestion was determined to be due to inadequate signal timing, rather than a lack of capacity at the intersection.

It is noted that the proposed models show a lower number of total conflicts than the SSAM models. However, this is to be expected as the proposed models only account for conflicts resulting from 3 distinct potential conflict points and does not represent the full spectrum of potential crashes, capable of being observed in SSAM. However, the ultimate decision that could be derived from the models is consistent.

6 CONCLUSIONS

Summary

Review of existing crash patterns shows that the intersection crashes account for over 25 percent of all crashes and represent major choke points of roadway networks (1,4,5). In order to address this critical aspect of our roadway system, over 13 different intersection designs have been developed including jug-handles, superstreets and median U-turn designs. The literature review conducted as part of this research has shown that there is a lack of research tools that allow a roadway designer or planner the ability to compare safety performance of all available intersection types so that the most beneficial design may be selected. This research has developed surrogate safety models that can be used to evaluate the safety performance of signalized intersections, covering 6 of the 13 intersection alternatives identified.

Current approaches to intersection safety models do not provide the sensitivity to differentiate between various types of signalized intersection control. Furthermore, the reliance on before/after crash analysis of existing intersections does not allow for application beyond the existing intersection types. While research shows discernible safety performance of intersection alternatives, such as jug-handle designs (11), existing safety models have not been developed to allow for a comprehensive evaluation of alternatives and do not take into account design factors that may be manipulated by the designer to modify design performance, such as lane configuration, left-turn treatments etc.

This research aims to fill this void by developing a comprehensive safety surrogate model for signalized intersections. Application of the Safety Surrogate Assessment Model (SSAM) developed by the FHWA was used to develop conflict models to serve as a surrogate exposure metric for intersection safety. While simulated conflicts from SSAM have been shown to correlate with actual crash patterns (19,21,22), no research has applied SSAM without the need to develop individual simulation models for every alternative considered.

This research evaluated four different types of conflicts including angle conflicts resulting from permitted left and right-turns, rear end conflicts and sideswipe or lane change conflicts. Over 1000 simulations using various lane configurations and volume combinations were performed. Trajectory output from the models was processed by SSAM to evaluate conflicts for each model. Finally, linear regression models were developed based on the model parameters evaluated to develop relationships between estimated conflicts and volume and lane configuration conditions.

This analysis produced three separate models, summarized below, that can be used to estimate potential conflicts for specific intersection configuration and volume scenarios. Analysis conducted for the right turn angle conflicts was inconclusive and did not provide a reasonable relationship that could be readily applied.

Eq. 1. Left Turn Angle Conflicts = = $2E\text{-}24X_L^2 - 1E\text{-}12\ X_L + 0.4748$

Where: $X_L = \frac{\text{(Left-turn) x (Through Volume)}^2 \text{ x (Percent Green)}^2}{\text{(Number of Lanes)}^3}$

Eq. 2. Rear End Conflicts = $0.0284X_R - 6.8028$

Where: X_R = (Through Volume + Right-turn + Left-turn) / (Percent Green)

Eq. 3. Sideswipe Conflicts = $0.001X_1 + 0.00044X_2 + 0.00181X_3 -0.000428{*}X_4 + 0.237X_5$

Where: X_1 = Approach Volume

X_2 = Right Turn Volume

X_3 = Left Turn Volume

X_4 = Maneuvering Distance

X_5 = Number of Lanes

While the models developed provide a broad range of conditions that may be evaluated, there are limitations to their application. For instance, left-turn conflicts only represent conflicts resulting from permitted left-turns and do not accommodate protected/permitted or protected only operations. Similarly right-turn conflicts only model conflicts resulting from right-turns on red when right-turning vehicles are permitted movements. All conflicts also deal only with unsaturated conditions and do not address congested operations such as priority reversal conditions, where a queued through vehicle gives way to turning traffic, that frequently contribute to crashes. The use of simulation in developing the conflict models also may limit the application of the models, as it does not account for human factor elements that are typically present, such as cognitive demands on judging gaps in traffic streams to turn left across two or more lanes.

In addition, conflict calibration factors have been developed that allow the type specific conflicts to be used in tradeoff analysis of multiple intersection configurations and modifications to travel patterns.

The research goes beyond existing safety performance models which only examine non-directional average daily traffic (ADT) or practices which only account for the geometric and lane configuration of an intersection, such as in conflict point analysis. The models developed here can be used in screening alternative designs in the planning and preliminary design stages of roadway and intersection projects to select the most appropriate intersection design based on objective safety performance metrics.

Future Research

The models presented above are statistically significant by accounting for much of the variability identified in the datasets and indicate significant potential for further development and application of this approach. However, further efforts are needed to expand the scope and impact of this this research.

Most notable is the fact that the models presented above estimate conflicts only for signalized intersection alternatives, covering only 6 of the 13 intersection alternatives identified. Future work should look to extend these methodologies to unsignalized operations so that a comprehensive surrogate model can be used to evaluate potential intersection designs across the whole range of alternatives. Some of the models developed, such as the left-turn and right-turn angle conflicts can be readily applied to unsignalized intersections, but other operations such as those at roundabouts and stop controlled approaches should be evaluated as well. Development of such models would allow for quantitative assessment and comparison of safety performance so that intersection safety and performance can be optimized.

As clearly demonstrated in the development of the right-turn angle conflicts, some of the models are reflective of not only exposure but capacity constraints as well. Additional refinement of simulation scenarios would provide an identification of the point at which the capacity constraint becomes the major influencing factor and provide increased refinement of the exposure effects prior to reaching that point. This future research should increase the number of simulation runs, and utilize smaller volume steps between the ranges for all volumes.

The models are also representative only of permitted maneuvers at intersections and cannot account for crashes resulting from disregarding of traffic control devices, such as red light running which presents significant risk associated with right angle crashes. These types of crashes are not possible at other intersection types such as roundabouts and hence this probability should be accounted for to provide a complete view of alternative tradeoffs. While micro-simulation conflict models are not capable of capturing this occurrence, research should be conducted to identify calibration or additional factors that can account for this possibility. As was demonstrated by the need for calibration factors within the conflict models, methods should be sought which can combine conflict analysis and historical crash trends to provide a complete picture of safety impacts associated with intersection designs and performance.

Another area of future efforts should address normalization of the various models, to allow for comparisons between different conflict types. While this research does provide a rudimentary calibration factor, it is based on the limited number of simulations provided in this research. Future research should examine calibration factors based on comparison of simulated conflicts and actual field crash histories.

While this research provides a proof of concept that a surrogate safety model can be developed that can differentiate between intersection alternatives based on lane configuration and traffic demand, it should be validated against real world crash histories. As the models are intended to differentiate between alternatives for a singular intersection, validation could be performed using before/after studies where innovative or alternative control strategies have been implemented. Once these areas are addressed, an interface to easily apply the models should be developed. Current application requires manual manipulation of turning volumes and calculation of the various factors which limits the application of the exposure models to a limited number of alternatives. The development of an application that can streamline the objective modeling process based on typical design inputs would increase the utility and ultimate application of the methods.

APPENDIX A

Example Calculations

Table A-1: Left Turn Conflicts

Alternative 1					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	486	324	288	168	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	3.06E+10	2.04E+10	9.56E+09	3.25E+09	
Conflicts	**0.09**	**0.06**	**0.03**	**0.01**	0.19
25000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	
Through Volume	810	540	480	280	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	1.42E+11	9.45E+10	4.42E+10	1.51E+10	
Conflicts	**0.43**	**0.28**	**0.13**	**0.05**	0.89
30000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	972	648	576	336	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	2.45E+11	1.63E+11	7.64E+10	2.60E+10	
Conflicts	**0.73**	**0.49**	**0.23**	**0.08**	1.53
Alternative 2					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	486	324	288	168	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	2.00	2.00	1.00	1.00	
XL	1.53E+10	1.02E+10	9.56E+09	3.25E+09	
Conflicts	**0.05**	**0.03**	**0.03**	**0.01**	0.11
25000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	

Through Volume	810	540	480	280	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	2.00	2.00	1.00	1.00	
XL	7.09E+10	4.72E+10	4.42E+10	1.51E+10	
Conflicts	**0.21**	**0.14**	**0.13**	**0.05**	0.53
30000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	972	648	576	336	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	2.00	2.00	1.00	1.00	
XL	1.22E+11	8.16E+10	7.64E+10	2.60E+10	
Conflicts	**0.37**	**0.24**	**0.23**	**0.08**	0.92
Alternative 3					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	72	72	
Through Volume	522	378	324	222	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	0.00E+00	0.00E+00	1.21E+10	5.68E+09	
Conflicts	**0.00**	**0.00**	**0.04**	**0.02**	0.05
25000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	120	120	
Through Volume	870	630	540	370	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	0.00E+00	0.00E+00	5.60E+10	2.63E+10	
Conflicts	**0.00**	**0.00**	**0.17**	**0.08**	0.25
30000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	144	144	
Through Volume	1044	756	648	444	
Percent Green	100.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	0.00E+00	0.00E+00	9.67E+10	4.54E+10	
Conflicts	**0.00**	**0.00**	**0.29**	**0.14**	0.43

Alternative 4

15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	0	0	
Through Volume	594	450	288	168	
Percent Green	100.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Conflicts	**0.00**	**0.00**	**0.00**	**0.00**	0.00
25000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	0	0	
Through Volume	990	750	480	280	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Conflicts	**0.00**	**0.00**	**0.00**	**0.00**	0.00
30000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	0	0	
Through Volume	1188	900	576	336	
Percent Green	60.00	60.00	40.00	40.00	
Lanes	1.00	1.00	1.00	1.00	
XL	0.00E+00	0.00E+00	0.00E+00	0.00E+00	
Conflicts	**0.00**	**0.00**	**0.00**	**0.00**	0.00

Table A-2: Rear End Conflicts

Alternative 1

15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	270	405	120	180	
Right Turn Volume	54	81	48	108	
Percent Green	0.60	0.60	0.40	0.40	
XR	600	900	600	900	
Conflicts	14.9	22.4	14.9	22.4	74.7
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	
Through Volume	450	675	200	300	
Right Turn Volume	90	135	80	180	
Percent Green	0.60	0.60	0.40	0.40	
XR	1000	1500	1000	1500	
Conflicts	24.9	37.4	24.9	37.4	124.5
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	540	810	240	360	
Right Turn Volume	108	162	96	216	
Percent Green	0.60	0.60	0.40	0.40	
XR	1200	1800	1200	1800	
Conflicts	29.9	44.8	29.9	44.8	149.4

Alternative 2

15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	270	405	120	180	
Right Turn Volume	54	81	48	108	
Percent Green	0.60	0.60	0.40	0.40	
XR	600	900	600	900	
Conflicts	14.9	22.4	14.9	22.4	74.7
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	

Through Volume	450	675	200	300	
Right Turn Volume	90	135	80	180	
Percent Green	0.60	0.60	0.40	0.40	
XR	1000	1500	1000	1500	
Conflicts	24.9	37.4	24.9	37.4	124.5
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	540	810	240	360	
Right Turn Volume	108	162	96	216	
Percent Green	0.60	0.60	0.40	0.40	
XR	1200	1800	1200	1800	
Conflicts	29.9	44.8	29.9	44.8	149.4
Alternative 3					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	270	405	156	234	
Right Turn Volume	54	81	48	108	
Percent Green	0.60	0.60	0.40	0.40	
XR	600	900	690	1035	
Conflicts	14.9	22.4	17.2	25.8	80.3
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	
Through Volume	450	675	260	390	
Right Turn Volume	90	135	80	180	
Percent Green	0.60	0.60	0.40	0.40	
XR	1000	1500	1150	1725	
Conflicts	24.9	37.4	28.6	43.0	133.8
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	540	810	312	468	
Right Turn Volume	108	162	96	216	
Percent Green	0.60	0.60	0.40	0.40	
XR	1200	1800	1380	2070	
Conflicts	29.9	44.8	34.4	51.5	160.6

Alternative 4

15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	324	441	120	180	
Right Turn Volume	126	153	48	108	
Percent Green	0.60	0.60	0.40	0.40	
XR	810	1080	600	900	
Conflicts	20.2	26.9	14.9	22.4	84.4
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	
Through Volume	660	855	200	300	
Right Turn Volume	90	135	80	180	
Percent Green	0.60	0.60	0.40	0.40	
XR	1350	1800	1000	1500	
Conflicts	33.6	44.8	24.9	37.4	140.7
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	792	1026	240	360	
Right Turn Volume	108	162	96	216	
Percent Green	0.60	0.60	0.40	0.40	
XR	1620	2160	1200	1800	
Conflicts	40.3	53.8	29.9	44.8	168.8

Table A-3: Sideswipe Conflicts

Alternative 1					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	270	405	120	180	
Right Turn Volume	54	81	48	108	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	2	2	
Conflicts	0.2	0.4	0.2	0.3	1.1
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	
Through Volume	450	675	200	300	
Right Turn Volume	90	135	80	180	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	2	2	
Conflicts	0.8	1.2	0.7	1.0	3.6
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	540	810	240	360	
Right Turn Volume	108	162	96	216	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	2	2	
Conflicts	0.9	1.4	0.8	1.2	4.4
Alternative 2					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	36	54	72	72	
Through Volume	306	405	120	180	
Right Turn Volume	54	81	48	108	
Distance	300.00	300.00	300.00	300.00	
Lanes	3	3	3	3	
Conflicts	0.7	0.9	0.6	0.8	3.1
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	60	90	120	120	

Through Volume	450	675	200	300	
Right Turn Volume	90	135	80	180	
Distance	300.00	300.00	300.00	300.00	
Lanes	3	3	3	3	
Conflicts	1.0	1.4	0.9	1.2	4.5
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	72	108	144	144	
Through Volume	540	810	240	360	
Right Turn Volume	108	162	96	216	
Distance	300.00	300.00	300.00	300.00	
Lanes	3	3	3	3	
Conflicts	1.2	1.7	1.1	1.4	5.3
Alternative 3					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	72	72	
Through Volume	306	459	156	234	
Right Turn Volume	54	81	48	108	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	3	3	
Conflicts	0.4	0.6	0.7	0.9	2.5
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	120	120	
Through Volume	510	765	272	390	
Right Turn Volume	90	135	80	180	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	3	3	
Conflicts	0.6	1.0	1.0	1.3	3.9
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume			144	144	
Through Volume	612	918	312	478	
Right Turn Volume	108	162	96	216	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	3	3	
Conflicts	0.8	1.2	1.1	1.5	4.7

Alternative 4					
15000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	0	0	
Through Volume	378	531	120	180	
Right Turn Volume	54	81	120	180	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	2	2	
Conflicts	0.4	0.7	0.3	0.5	1.9
25,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	0	0	
Through Volume	630	885	200	300	
Right Turn Volume	90	135	200	300	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	2	2	
Conflicts	0.8	1.1	0.6	0.9	3.3
35,000 ADT	EB	WB	NB	SB	Total
Left Turn Volume	0	0	0	0	
Through Volume	756	1062	240	360	
Right Turn Volume	108	162	240	360	
Distance	300.00	300.00	300.00	300.00	
Lanes	2	2	2	2	
Conflicts	0.9	1.3	0.7	1.0	4.0

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