Research Report
KTC -12-04/SPR 380-09-1F

Improving Intersection Design Practices

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Kentucky Transportation Center

176 Oliver H. Raymond Building

Lexington, KY 40506-0281

(859) 257-4513

fax (859) 257-1815

www.ktc.uky.edu

Research Report
KTC-12-4 / SPR-09-380-1F

IMPROVING INTERSECTION DESIGN PRACTICES

Final Report

by

Nikiforos Stamatiadis
Professor

Adam Kirk
Research Engineer

Nithin Agarwal
Research Associate

and

Chris Jones
Research Assistant

Department of Civil Engineering
and
Kentucky Transportation Center
College of Engineering
University of Kentucky
Lexington, Kentucky

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16. Abstract The purpose of this report is to document the development of the Intersection Design Alternative Tool (IDAT) developed for the Kentucky Transportation Cabinet. IDAT provides an automated objective design and evaluation approach of 14 alternative intersection designs to assist in the conceptual design of at-grade intersections. The tool evaluates intersection operations, safety performance, bicycle/pedestrian accommodation and has the ability to assist access management implementation.			
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EXECUTIVE SUMMARY

Intersections are a critical component of the roadway system and frequently act as choke points on the transportation system. In addition, intersection crashes account for approximately 30 percent of all crashes in Kentucky (Kentucky State Police, 2007). As a critical component of the state transportation system, intersection design requires an objective methodology to identify the most appropriate solution that meets the purpose and need of the project as well as addresses site constraints. The current state of practice, while achieving great strides in improving the efficiency of Kentucky's roadway system, lacks a systematic, objective and well-defined approach to evaluating individual design alternatives.

The goal of this project is to improve intersection design practices by 1) expanding the scope of intersection design alternatives considered and 2) providing a structured and objective evaluation process to compare alternative design concepts. This is achieved through the development of the Intersection Design Alternative Tool (IDAT) that is capable of evaluating 14 alternative traffic control and intersection conceptual designs for a given location. IDAT evaluates intersection operations, safety performance, bicycle/pedestrian accommodation and the ability to assist access management implementation.

A major component of this effort was the development of methods to size different intersection designs. IDAT identifies the most efficient design (minimum number of lanes) that is capable of meeting a targeted level of operation. As such, the design team will be presented with several options, which meet the minimum operational requirements, allowing examination of other trade-offs such as right of way impacts, safety considerations etc. This approach will eliminate the need to compare different alternatives with varying performance levels across different types of traffic control measures.

The software developed as part the study is ready to be distributed for use to the practitioners. The software allows for the preliminary evaluation of all intersection designs considered and provides a basic method for comparing all of them at an equal level of operation. The software also provides a more robust safety evaluation method for at-grade intersections predicting the number of conflicts for vehicles and pedestrians for each design considered.

IDAT provides greater efficiency in the evaluation and design of intersection alternatives and can consider and address operational efficiency and safety for all at-grade intersection uses. This allows for a more appropriate and properly customized design for each intersection and avoids the use of "standard or typical" designs. Moreover, this approach provides a

properly justified and documented decision process that could become part of the design file for the project based on sound engineering judgment.

INTRODUCTION

Problem Statement

Intersections are a critical component of the roadway system and frequently act as choke points on the transportation system. In addition, intersection crashes account for approximately 30 percent of all crashes in Kentucky (Kentucky State Police, 2007). Intersection design is a balancing act of various elements and constraints to produce a solution that will address mobility, safety, environment, and financial aspects of the project. To achieve this balance, alternative strategies and options must be identified, developed, and evaluated in a systematic manner. Significant advances in transportation engineering have identified new traffic control measures and practices capable of further increasing the operational efficiency and safety of intersections. Understanding the effect and impacts of the various design factors and elements on the performance of each alternative is critical in the proper evaluation of alternatives and can have a significant influence on the final design of a project. As a critical component of the state transportation system, intersection design requires an objective methodology to identify the most appropriate solution that meets the purpose and need of the project as well as addresses site constraints. The current state of practice, while achieving great strides in improving the efficiency of Kentucky's roadway system, lacks a systematic, objective, and well-defined approach to evaluating individual design alternatives.

In addition to the complexity of intersection design, another concern is the ever-shrinking state transportation budget over the past few years. This trend requires the development of designs and solutions that are more efficient and practical in addressing project needs. It is therefore reasonable to assume that designs may need to be evaluated more critically and in a different manner than current practice. Reconsideration of current design and evaluation practices may be warranted to meet this new constraint.

Research Objectives and Approach

The goal of this project is to improve intersection design practices by 1) expanding the scope of intersection design alternatives considered and 2) providing a structured and objective evaluation process to compare alternative design concepts. This is anticipated to be achieved through the development of a screening tool that is capable of evaluating several alternative traffic control and intersection designs for a given location. The tool will be comprehensive in its evaluation incorporating critical criteria that must be addressed to achieve an appropriate and successful design.

A major component of this effort will be to develop methodologies capable of appropriately sizing the different intersection design alternatives. It is envisioned that the tool will identify the most efficient design (minimum number of lanes) that is capable of meeting a targeted level of operation. As such, the design team will be presented with several options, which meet the minimum operational requirements, allowing examination of other trade-offs such as right of way impacts, safety considerations, etc. This approach will eliminate the need to compare different alternatives with varying performance levels across different types of traffic control measures.

The outcome of the project will be to provide a greater efficiency in the evaluation and design of intersection alternatives; with the intent to achieve greater operational efficiency and improved safety performance at Kentucky's intersections. These methodologies can be incorporated into the Project Development Process, to consider and address operational efficiency and safety for all intersection uses. This will allow for a more appropriate and properly customized design for each intersection and avoid the use of "standard or typical" designs. Moreover, this approach will provide a properly justified and documented decision process that could become part of the design file for the project based on sound engineering judgment.

This project will be completed in two phases with the following activities within each phase:

Phase I

1. A review of literature on intersection design practices will be conducted to identify potential intersection alternatives, critical intersection design elements, and document similar efforts by others.
2. A validation of proposed screening methods will be performed to confirm and calibrate models used in the initial screening of alternatives.
3. An evaluation tool will be developed that incorporates the validated models allowing for simultaneous comparison of all feasible intersection design alternatives.

Phase II

1. A refinement of the evaluation tool will be performed focusing on the development of a quantitative safety component with vehicular and pedestrian modes.
2. A set of guidelines for use of the tool will be developed that could be used to train the Cabinet personnel.

Report Organization

This report documents the findings of the work completed in both phases of the project, including the literature review as well as the development of the evaluation tool. The literature review findings are presented in the following section, followed by the efforts undertaken to develop and validate a process for determining optimal intersection size for various traffic control alternatives. The efforts undertaken to create and validate a process for developing the models to be used in the evaluation tool regarding the safety components are presented next. The next section of the report presents the latest version of the evaluation tool and provides a guidance manual for its use.

LITERATURE REVIEW

Introduction

The literature review presented below is aimed at identifying four elements. The first was to identify alternative at-grade intersection designs that may be utilized in Kentucky. Second, factors affecting intersections and how they may be utilized during the design process were sought. Third, objective intersection design processes and methodologies were sought that direct the sizing and evaluation of design alternatives. Finally, safety issues as they relate to intersection design were identified, and approaches for predicting safety performance were documented. Each of these elements is discussed in detail in the following sections.

Alternative Intersection Designs

A number of alternative intersection designs have been used throughout the country that aim at improving intersection operation and safety. These alternatives to conventional intersections include the median U-turn design (used in Michigan extensively for years), the jughandle 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 United States, and research has shown that they improve both the operational and safety levels of intersections. The American Association of State Highway Transportation Officials (AASHTO) Policy on Geometric Design of Highways and Streets contains guidelines on the design of standard intersections and contains some guidance on the median U-turn, jughandle, and roundabout alternatives (AASHTO, 2004). However, this guidance is limited and lacks any specific guidance regarding when and how to use these alternatives

Despite the lack of guidance on the national level, some states provide guidance or information for alternative intersection design types. The Maryland State Highway Agency has developed the Unconventional Arterial Intersection Design tool that provides conceptual information and considerations for a wide range of alternative intersection designs (Maryland SHA, 2005). Twelve states have developed roundabout guides which address the planning, design and operations of roundabouts, primarily based on the FHWA Roundabout: An Informational Guide (FHWA, 2000). This guidance is presented and discussed below.

Unconventional Intersection Designs

The Maryland DOT has embarked on an effort to develop a tool that considers and evaluates unconventional intersections, which are considered as promoting efficiency of operations along arterials (Maryland SHA, 2005). The intersection options included in this tool

are divided based on the type of grade separation. At-grade intersections, which are the focus of this research effort, are presented below. A description of the alternative designs along with positive and negative aspects of their application is presented in Appendix A.

- Unsignalized inside left turn
- Median U-turn signalized
- Median U-turn unsignalized
- Superstreet, unsignalized
- Superstreet, signalized
- Continuous flow
- Continuous green T
- Jughandle
- Bowtie
- Modern roundabout
- Paired intersections

Roundabouts

Roundabouts are receiving more consideration when designing intersections. As noted above, 12 states have developed roundabout guides and 5 states have been identified as having a specific roundabout policy. Some states (such as New York and Virginia) recommend roundabouts as the preferred alternative in intersection design and control. Many of the state manuals reference the FHWA Roundabout: An Informational Guide (FHWA, 2000) in their intersection design guides for more information on roundabout use and design. A memorandum issued by FHWA also emphasized the need to consider roundabouts as an alternative design option on all federally-funded projects (FHWA, 2008). A list of states with roundabout guides and policies is provided in Appendix B.

The FHWA Guide addresses various roundabout design aspects including planning, policy, geometric design and operations. The Policy Section discusses when a roundabout could be implemented. Factors affecting roundabout installation include safety, vehicle delay, environmental factors, spatial requirements, operations and maintenance costs, traffic calming, aesthetics, multimodal considerations for pedestrians and bicyclists, and cost.

The state of Wisconsin produced a roundabout guide to determine when it is proper to control an intersection with a roundabout (Wisconsin DOT, 2008). This is a guide that promotes the use of roundabouts as viable alternatives for controlled intersections. Since there is limited publication in the US on roundabout implementation, the guide outlines a process that should be

followed on projects to evaluate what type of control device should be used. Roundabouts can be used in place of signalized or stop-controlled intersections depending on the design factors of the intersection. The factors to be considered include safety, operational analysis, construction cost, right-of-way, practical feasibility, operations and maintenance cost, environmental issues, and pedestrians and bicycles.

Florida DOT also has the Florida Roundabout Guide that is developed to address the design aspects of this intersection control type (Florida DOT, 2007b). The guide includes a section on justification of roundabout use as an alternative intersection control and identifies the factors to be analyzed and considered when comparing it to two-way stops, all-way stops and signal control. The guide also identified justification categories including traffic calming, safety improvements, special geometric conditions (five legs, high volumes, etc.), and signalization (roundabout delay compares favorably with signal).

Access Management

Another issue that could have an impact on intersection design is access management, since the presence of access points or driveways within the functional area of the intersection can “result in traffic-operation, safety and capacity problems” (Gluck et al 1999). A recent report identified a number of specific problems:

- Through traffic blocked by vehicles waiting to turn into a driveway
- Right or left turns into or out of a driveway (both on artery and crossroad) are blocked
- Driveway traffic is unable to enter left-turn lanes
- Stopped vehicles in left-turn lanes impact driveway exit movements
- Traffic entering an arterial road from the intersecting street or road has insufficient distance
- The weaving maneuvers for vehicles turning onto an artery and then immediately turning left into a driveway are too short
- Confusion and conflicts resulting from dual interpretation of right-turn signals (Gluck et al, 1999)

Intersection designs have also been developed to mitigate the impact of these access points. Most notably intersection designs that utilize a non-traversable median have been documented to reduce the potential for head-on crashes, speed differential, and left-turn conflicts with pedestrians and bicyclists. The Highway Capacity Manual also identifies benefits for operations and capacity, due to a reduced number of access points and the inclusion of non-traversable medians. However, like safety benefits, these impacts have only been quantified for

roadway sections and not in individual intersection applications. This gap in research precludes the ability to quantify the benefits of these treatments, however, the inclusion of these points within the discussion of intersection design can be provided to make the planner and designer aware of the potential benefits for designs that address access management issues.

Intersection Design Factors

In order to provide guidance on the design and evaluation of alternative intersection designs, it is critical to identify and understand the factors that affect them. This will facilitate the development of the proper design for the intersection based on its characteristics. Past research that evaluated and compared intersection design alternatives has concentrated on comparing travel time and delay of the alternatives. A few papers have provided collision frequencies and rates for some alternatives, especially roundabout and median U-turn designs. However, there is practically no literature providing guidance on elements to be considered when evaluating and comparing different design concepts, nor is guidance provided that identifies the conditions in which such alternative designs would be beneficial.

A recent effort by the Federal Highway Administration (FHWA) resulted in developing the *Signalized Intersections: Informational Guide* that provides the methods needed for evaluating the safety and operations of signalized intersections (2004). The guide provides a range of treatments that can be used ranging from low- to high-cost measures. Issues regarding geometric features of the intersection and operational techniques were identified and their effect on intersection design was discussed. However, pedestrian and bicycle traffic issues are not addressed in the guide. Although the guide focuses primarily on high-volume signalized intersections, many treatments are applicable for lower volume intersections as well.

In addition to published research, a review of design guides used by each state was undertaken to determine the factors considered in intersection design and how decisions regarding control type and size are reached. Of the 41 state transportation agencies reviewed only a few states have developed their own intersection design guidelines contained within a separate Intersection Design Manual or included within their roadway design manuals. All states reviewed have intersection design guidance that adhere to or follow the AASHTO guidance and Manual of Uniform Traffic Control Devices (MUTCD) for determining traffic control (mainly for signalization). Florida, Missouri, New Jersey, New York, Texas, and Washington all have intersection design guides that specifically identify factors to be considered in intersection design. These guides also provide additional information and do not simply reiterate the AASHTO guidance. Among the states reviewed, Florida and Texas have the most

comprehensive Intersection Design Guides. Appendix B contains a summary of intersection design guidance provided by all 41 states reviewed. It should be noted that nine states did not respond to the request for providing their design guide. These guides are summarized below.

Florida

The state of Florida has developed its own guide for intersection design. The Florida Department of Transportation (FDOT) published the Florida Intersection Design Guide in 2007 (Florida DOT, 2007a). This guide is intended to identify mandatory requirements and to provide guidelines for selecting a design when there are alternatives. Professionals who design intersections use the guide in order to determine the geometrics of the intersection as well as the control type.

In the introduction of the guide, the intersection design requirements and objectives are presented. These include the following:

- Safe and convenient operation for all road users, including cyclists and pedestrians
- Proper accessibility for pedestrians with special needs
- Adequate capacity for peak-hour demand on all movements
- Adequate maneuvering space for design vehicles
- Resolution of conflicts between competing movements
- Reasonable delineation of vehicle paths
- Adequate visibility of conflicting traffic
- Storage for normal queuing of vehicles
- Appropriate access management application
- Minimum delay and disutility to all road users
- Proper drainage of storm water
- Accommodation for all utilities, both above and below the ground
- Necessary regulatory, warning and informational messages for all road users
- Suitable advance warning of all hazards
- Uniformity of treatment with similar locations

These design requirements are based on Florida statutes as well as authoritative references that have been adopted by FDOT. Based on the objectives listed above, the factors

that FDOT considers important to intersection design are safety, accessibility, capacity, drainage, and utilities.

The guide also defines the data required for intersection design. This data confirms the factors that FDOT finds important to intersection design which focus mainly on safety and capacity. The following specific data items are required:

- Approach volumes, typically 24 hour volume summarized by 15 minute intervals
- Peak hour turning movement counts
- Existing geometrics
- Pedestrian and bicycle volumes, if applicable
- Distances to other intersections
- Crash history
- Institutional locations such as schools and hospitals
- Posted speed limits along the intersecting roads
- Physical and right of way features and limitations
- Site development features such as businesses and driveways
- Community considerations such as need for parking and landscape character

The guide addresses only roundabouts as an alternative intersection design and there is no discussion for any other alternative designs. FDOT has produced a separate roundabout design guide that provides design considerations for when to use a roundabout as well as the design characteristics of the roundabout, which is discussed in another section of the review (FDOT, 2007b).

Missouri

The Missouri DOT has developed a new Engineering Policy Guide that also includes a section on intersection design (Missouri DOT, 2008). The section identifies five basic elements for consideration in designing intersections along with specific items to be considered. These are as follows:

- Human Factors: Driving habits, ability of drivers to make decisions, driver expectancy, decision and reaction time, conformance to natural paths of movement, pedestrian use and habits, bicycle traffic use and habits
- Traffic and Safety Considerations: Design and actual capacities, design-hour turning movements, size and operating characteristics of vehicle, variety of movements

(diverging, merging, weaving, and crossing), vehicle speeds, transit involvement, crash experience, and bicycle and pedestrian movements

- Physical Elements: Character and use of abutting property, vertical alignments at the intersection, sight distance, angle of the intersection, conflict area, speed-change lanes, geometric design features, traffic control devices, lighting equipment, safety features, bicycle traffic, environmental factors, and cross walks
- Economic Factors: Cost of improvements, effects of controlling or limiting right-of-way on abutting residential or commercial properties where channelization restricts or prohibits vehicular movements, and energy consumption
- Functional Intersection Area: Perception-reaction distance, maneuver distance, and queue-storage distance

Design concepts for three- and four-leg intersections are presented for stop and yield control, traffic signal, and roundabouts. For each of these types, additional design guidance is provided relying on the AASHTO guide and the Missouri Access Management Guidelines. Finally, consideration of pedestrian and bicyclist needs are considered as part of intersection design, since they can affect efficient operation at intersections.

New Jersey

The state of New Jersey has an at-grade intersection design section in its Roadway Design Manual. This section discusses the design of intersections as well as the jughandle intersection, an alternative intersection design used primarily in New Jersey. The guide lists the major factors that affect the design of an intersection which include traffic, physical, economic, and human (New Jersey DOT, 2003). Additional information for each factor is presented to allow for proper identification of data needs and considerations and it includes the following:

- Traffic: Possible and practical capacities, turning movements, size and operating characteristics of vehicles, control of movements at points of intersection, vehicle speeds, bicycle and pedestrian movements, transit operations, and crash experience
- Physical: Topography, abutting land use, geometric features of the intersecting roadways, traffic control devices, and safety features
- Economic: Cost of improvements and the economic effect on abutting businesses where channelization restricts or prohibits certain vehicular movements within the intersection area

- Human: Driving habits, ability of drivers to make decisions, effect of surprise, decision and reaction times, and natural paths of movements must be considered

New York

The state of New York has a section on intersection design in the state Highway Design Manual. The section presents the design of intersections based on the AASHTO guidelines (New York DOT, 2006). The need to coordinate intersection design with the requirements and guidance provided in the manual for pedestrian and bicycle facilities is also noted. The section identifies circular (traffic circle, rotary, and roundabout), angular (three-leg, four-leg, and the multi-leg) and nontraditional (jughandle, super-street median crossover, median U-turn crossover, and continuous flow) intersections. Considerations for selecting an intersection layout include local conditions and right of way costs along with operational, which include design-hour volumes and predominant movements, types and mix of vehicles, pedestrians, and bicyclists, approach speeds, number of approaches, and safety needs. However, no additional discussion on how each of these could influence the selection is provided.

The state has an intersection policy where once roundabouts are determined to be a feasible alternative they are considered to be the preferred alternative due to the proven substantial safety benefits and other operational benefits. The manual recommends the use of the FHWA Roundabout Guide (FHWA, 2000) and has developed a web site for designers and users for providing information on design and use issues (New York DOT, 2009).

Texas

The Texas Transportation Institute (TTI) developed an Intersection Design Guide in 2006 for the Texas DOT (TxDOT). This Guide provides information on each of the design elements associated with an intersection and discusses related geometric and operational issues involved in urban intersection design. The project examined current design practices by TxDOT, cities, and consulting engineers to gain an understanding of current intersection design practices (Fitzpatrick et al, 2005). As part of the development of the guide, current factors associated with intersection designs were determined.

A number of factors were identified as contributing to the determination of the intersection type including the following:

- Functional class of intersecting streets
- Design level of traffic
- Number of intersecting legs

- Topography
- Access requirements
- Traffic volumes, patterns, and speeds
- All modes to be accommodated
- Availability of right of way
- Desired type of operation

The study also identified major goals of intersection design including:

- Consideration of all modes: bicycles, pedestrians, transit, and motor vehicles
- Reduction in the number of conflict points
- Controlling of relative (approach) speeds
- Coordination of intersection design and traffic controls
- Minimization of skew angle
- Avoidance of multiple and compound merging and diverging maneuvers
- Separation of conflict points
- Favoring of the predominant flow
- Segregation of non-homogeneous flows
- Consistency with local/neighborhood objectives

The study identified four major groups of factors to be considered when designing an intersection including the following:

- Human Factors: Driving habits, decision making ability of drivers, pedestrians, and bicyclists, expectancy of driver, pedestrian, and bicyclist, decision and reaction time of various users, and pedestrian and bicyclist use, ability, and habits
- Traffic Considerations: Design and actual capacities, design-hour turning movements, size and operating characteristics of vehicles, variety of movements (diverging, merging, weaving, turning, and crossing), vehicle speeds, crossing distance, signal complexity, transit presence, modal types and operations, crash experience, and bicycle and pedestrian movements
- Physical Elements: Character and use of abutting property, vertical alignments at the intersection, sight distance, intersection angle, speed-change lanes, geometric design features, traffic control devices, lighting and utilities, safety features, and pedestrian facilities (sidewalk, curb ramps, crosswalks)

- Economic Factors: Cost of improvements, effects of controlling or limiting rights of way (ROWs) on abutting properties, vehicular delay cost, pedestrian delay, air quality cost, functional intersection area, available right of way, and number of approach lanes and legs

Washington

The Washington Roadway Design Manual has a section on intersection design. The introduction of the manual states that “intersections are a critical part of highway design because of increased conflict potential. Traffic and driver characteristics, bicycle and pedestrian needs, physical features, and economics are considered during the design stage to develop channelization and traffic control to enhance safe and efficient multimodal traffic flow through intersections” (Washington State DOT, 2008).

For at-grade intersections, the manual states that there are seven factors that affect the intersection configuration at any given location. These factors are the number of intersecting legs, the topography, and the character of the intersecting roadways, the traffic volumes, patterns, speeds, and the desired type of operation.

A separate section dealing with roundabout design is included in the Roadway Design Manual. The section outlines design concepts and principles for roundabouts and identifies the steps to be taken for roundabout design using the same factors as above in the design process.

Summary

The review of 41 state DOTs indicated that some guidance is included in each state’s design manual presenting elements to be considered for intersection design. As noted above, all manuals adhere to the AASHTO guidance and several refer the reader to the information presented in Chapter 9 of the AASHTO policy (AASHTO, 2004). A few manuals mention alternative intersection designs but they do not provide any guidance as to when they could be considered as viable alternatives. Moreover, no manual provides specific guidance for selecting appropriate intersection design or control types; most manuals simply note that comparisons among alternatives should be performed. It is apparent that there is a lack of any tools that provide designers or planners with an estimate of appropriateness for different intersection designs.

Intersection Design Procedures

A basic problem in comparative analysis of intersection designs is ensuring that the alternatives examined all deliver a similar level of operational performance. For instance, a signalized intersection with two approach lanes on the major road may service the same volume as a single lane roundabout. It is therefore critical to correctly size each alternative based on targeted operational parameters. This will allow for full comparison of other design factors such as construction costs, right of way and environmental impacts. Capacity analysis software may be used for design and sizing, however, this requires an iterative process for each alternative to achieve the desired level of capacity. This approach may be time consuming and limit the range of alternatives to be considered.

An approach that could be used in developing and evaluating comparative alternatives is the Critical Lane Analysis. This method allows for the automation of the design process of signalized intersections by systematically linking traffic demand, geometric design and operational level of service. Critical Lane Analysis, as developed by Messer and Fambro (1977), uses the geometry of the intersection along with intersection traffic volumes as the basis for establishing a measure of potential performance and, by extent, of capacity. The critical lane analysis uses the volumes of the approaches for an intersection to estimate their distribution among the available lanes. Once volumes are apportioned to each of the lanes, phasing plans are developed that allow for the appropriate intersection movements. Critical volumes for each phase are determined based on certain rules and these volumes are summed to determine the total critical lane volume for the intersection. This sum can then be directly related to the level of service definition for signalized intersections (Table 1). This methodology establishes the capacity of the intersection based on the volume of conflicting flows for different phasing options and geometry.

Table 1 Level of service and maximum sum of critical lane volumes at signalized intersections

Level of Service	Traffic Flow Condition	Volume to Capacity Ratio	Critical Lane Volumes		
			Two-Phase	Three-Phase	Multiphase
A	Stable	<0.6	900	855	825
B	Stable	<0.7	1050	1000	965
C	Stable	<0.8	1200	1140	1100
D	Unstable	<0.85	1275	1200	1175
E	Capacity	<1.0	1500	1425	1375

Source: Messer and Fambro, 1977

Similar techniques (i.e. estimates of capacity) have been developed for unsignalized intersection designs as well. The Special Report 209 Highway Capacity Manual (1985)

provided intersection capacity estimates based solely on conflicting movements and reserve capacity while considering intersection geometry. The Level of Service designations for unsignalized intersections provided by the manual are summarized in Table 2.

Table 2 Level of Service criteria for unsignalized intersections

Reserve Capacity	Level of Service	Expected Delay to Minor Street Traffic
>400	A	Little or no delay
300-399	B	short traffic delays
200-299	C	Average traffic delays
100-199	D	Long traffic delays
0-99	E	Very long traffic delays
<0	F	*

Source: Special Report 209 Highway Capacity Manual, 1985

Finally, a recent report offered another consideration for estimating capacity for roundabouts (Rodgers et al, 2007). This report develops control delay models for single and multi-lane roundabouts using the critical lane methodology as shown in Equations 1 and 2, respectively.

$$c_{crit} = 1130 \text{ ext}(-0.0010 \times v_c) \text{ (Single Lane Roundabouts)} \quad (1)$$

$$c_{crit} = 1130 \text{ ext}(-0.0007 \times v_c) \text{ (Multi-Lane Roundabouts)} \quad (2)$$

Where: c_{crit} = entry capacity of critical lane (pcu/h)
 v_c = conflicting flow (pcu/h)

Intersection Safety Issues

Intersections are areas of potential conflict and safety of intersections has always been the subject of a large body of research. Various parameters have shown to have an influence on crash rates at intersections including the average daily traffic (ADT) approaching an intersection, sight distances, intersection alignment, roadway and shoulder width and other traffic and environmental factors. McDonald (1953) conducted a study on two-way stop-controlled intersections at divided highways and represented crashes per year in graphical form as a function of major and minor road incoming daily traffic. Bared and Lum (1992) concluded that sight distances are shorter at high-crash intersections. Bauer and Harwood (1996) reviewed crash reports at urban intersections and concluded that geometric features of an intersection were cause for only 5 to 14 percent of all crashes. Pickering and Grimmer (1986) considered crashes at three-legged intersections of two-lane roads and developed a Poisson model with

mean number of crashes per unit time related to ADT. Hauer et al. (1988) developed an approach creating a negative binomial model to correct the regression-to-mean bias in a study that reviewed signalized intersections in Toronto.

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. Bauer and Harwood (1996) developed statistical models to relate crash and geometric elements for at-grade intersections, traffic control features, and traffic volumes. The study indicated that the traffic volume factor (ADT) claimed most of the statistical influence on crash rate, and it was believed that the traffic volume factor decreased the influence of intersection geometry on crash rates while the geometry of an intersection did not prove statistically significant in predicting a crash. The paper concluded that negative binomial is most suited in modeling as the traditional approach of multiple regressions is inappropriate because crash rates were random discrete events and did not follow normal distribution. Traditional multiple regression models sometimes predict negative integers for crash frequencies and crash rates which is inappropriate because roadway segments cannot have fewer than zero crashes or crash rates and the negative binomial distribution accounts for the over dispersion effect.

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. (2000) documented the development of the IHSDM and presented a calibration procedure to the Crash Prediction Module (CPM). The prediction algorithm consists of a base model that is related to Accident Modification Factors (AMF). Three different models were developed for three-leg intersections with STOP control, four-leg intersections with STOP control, and four-leg signalized intersections. The basic structure of the algorithm includes a base model based on pre-defined functions and the AMF and calibration factors (to account for different demographics and roadway characteristics in each state in the US). The models predict accident frequency, and severity and type distribution. Empirical Bayes (EB) procedures are then provided to validate model predictions against site-specific accident history, if available. The base model and the AMF vary for each type of intersection based on ADT, sight distance, number of driveways and signal details. The EB approach is to combine the estimates from the accident prediction algorithm and site-specific accident history data. 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. Martinelli et al. (2009) conducted a study to report in the IHSDM calibration

procedure that was applied to the Arezzo province road network in order to evaluate the effective transferability of the IHSDM. Another study conducted by Sun et al. (2006) applied the HSM Calibration procedure to the Louisiana State road network. The calibration helped achieve a difference between actual and predicted number of accidents lower than 5 percent, against 30 percent without calibration.

Persaud et al. (2002) developed a crash prediction model for injury and damage-only crashes at three- and four-legged signalized and unsignalized intersections in Canada that relates crash risk and traffic attributes, including traffic volume. Various crash data from the study revealed the chronological changes in safety conditions and enabled a comparison of the safety performance of junction types across Vancouver and California that were recalibrated for Toronto using a procedure proposed for the application in the IHSDM (Harwood et al. 2000).

An investigation by Vogt (1999) 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. The study developed a negative binomial model that predicted crash counts. The model indicated that almost all variables were statistically significant and specifically for injury crashes that intersection angle and minor road posted speed were significant.

A review of the predictive models for pedestrian safety at intersections revealed that the most common form of statistical model developed also utilized a negative binomial regression. Several studies used the basic form of $N_{ped} = \exp(\beta_0 + \beta_1 ADT + \beta_2 Vol + \beta_3 X_3 + \dots \beta_n X_n)$ where, N_{ped} was the expected number of pedestrian crashes, ADT the average daily traffic, Vol is the pedestrian volume and X_i represented other variables such as proportion of left-turn volume, number of lanes, speed limit, presence of a crosswalk, and presence of a median (Lyon and Persaud, 2002; Leden, 2002; Zeeger et al., 2005). All models concluded that an increase in total traffic volumes and pedestrian volumes led to higher pedestrian crashes but the relationship between pedestrian volumes and pedestrian crashes was nonlinear. It should however be noted that the development of these models was dependent on the limited available frequency of pedestrian crashes and required a large sample of sites for development. The extent of the minimum required sample size was reflected in many studies. For example, Lyon and Persaud (2002) utilized 122 intersections in the three-leg STOP-controlled group and compiled 11 years of data at these locations while Zeeger et al. (2005) collected data from 2,000 locations.

Harwood et al. (2008) developed another prediction methodology for urban and suburban arterials for three- and four-leg signalized intersections that included base models and

AMF's. This approach utilizes a base model, which is fixed for nominal conditions and then estimates the effect of individual geometric design or traffic control features using AMF according to site characteristics. This approach was utilized in the predictive crash models presented by the Highway Safety Manual, which is considered to be the current state of the art in safety research (AASHTO, 2010). The base crash model is predicated on major street and minor street average daily traffic without regard to specific turning movements at the intersection. AMFs are provided for basic geometry including the presence of left or right turn lanes, left and right turn phasing and the presence of intersection lighting and red light running cameras (AASHTO, 2010). While the methodologies presented in the manual provide for analysis of general intersection patterns, they do not provide guidance required for intersection, or alternative evaluation. Moreover, the AMFs are based on expert panels and evaluation of previous studies that could be viewed as subjective. AMFs also require calibration to local conditions, which is another procedure that demands knowledge of historical crash data.

Another concept recently considered for estimating safety at intersections is that of "conflict points." Many statistical comparisons have documented the effect of conflict points for different types of intersections 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. (2006) conducted a study to compare jug-handle to conventional intersection designs considering 44 New Jersey jug-handle intersections and 50 conventional intersections. Each conventional intersection was screened to assure similarity and uniformity of data sets and traffic characteristics to the jug-handle intersections. An analysis of variance (ANOVA) between groups concluded that the differences in the distributions of severity and collision types between the two groups of intersections were significant. A negative binomial model was developed in which the independent variables were the major road Annual Average Daily Traffic (AADT), minor-road AADT, major road posted speed limit, minor road posted speed limit, number of lanes of the major road and minor road for each approach and median type. All variables were significant beyond the 95 percent confidence level. The paper concluded that conventional intersections had more head-on, left-turn, fatal-plus-injury, and property-damage-only accidents and relatively fewer rear-end accidents than jug-handle intersections. There were more than twice as many head-on collisions per million vehicle miles traveled at conventional intersections as at jug-handle intersections. Three different types of jug-handle intersections were considered: Forward, Forward-Reverse and Reverse-Reverse and concluded that Forward jug handles had the highest overall rate of crashes per million vehicle miles traveled, close to 1.3 to 1.4 times as many as the other two types and were statistically

significant. Reverse–reverse jug-handles have the lowest rate of angle crashes and left-turn crashes per million vehicle miles traveled because the ramps reduce the opportunity for crossing conflicts.

A study by Nambisan et al. (2007) evaluated six roundabouts in the Las Vegas metropolitan area and concluded that only minor and medium sized roundabouts were safer and more efficient than the conventional intersection, whereas major roundabouts with more than 20,000 ADT did not function significantly better than conventional intersections. Wadhwa and Thompson (2006) conducted a study on relative safety of alternative intersection designs that aimed at relating the intersection safety to number of conflict points, conflict types, and intersection geometry. Three types of intersections were considered: T-junctions, cross intersections and roundabouts. The study, based on crash data analysis for the intersections in the Townsville region in Australia, concluded that the type of control had a significant effect on the severity of crash and fatalities. The study also stated that roundabouts were the safest type of intersection control and that the proportion of crashes increased with increases in the number of conflict points. The study found that the number of fatalities per 1,000 crashes was 6.32, 5.83 and 1.46 for T-intersection, cross intersection and roundabouts respectively. Investigation on the traffic control used at the intersections showed that the proportion of fatal crashes per 1,000 crashes was 7.95, 5.87 and 4.27 fatalities for uncontrolled, un-signalized (signage) and signalized intersections, respectively. The study mentioned that the level of safety is disproportional to the number of approach and conflict points.

Traditionally, traffic conflicts are observed based on manual counting and estimation, which are time-consuming, labor-intensive and sometimes inaccurate. To overcome these deficiencies, simulation tools have been recently utilized for studying conflicts instead of field studies or video techniques largely due to their ability for automatic data collection mechanism. Recently, a Surrogate Safety Assessment Model (SSAM) has been developed to analyze the traffic conflicts generated from simulation tools (FHWA, 2008). The report also assessed and validated the SSAM outputs based on the data from simulation tools. Field validation tests were conducted to compare the conflicts derived from SSAM with crashes. Eighty-three four-leg signalized intersections in British Columbia and Canada were simulated using VISSIM and analyzed by SSAM. The significant correlations between predicted conflicts and real accidents were evaluated by several statistical tests including safety ranking by total incidents and incident types, regression model tests, identification of incident prone locations. Total conflicts and conflict types were separately used to determine intersection rankings. Regression models were developed to establish a relationship between average hourly conflict frequencies derived by

SSAM and the estimated average hourly crash frequencies. The results gave a correlation rate ($R=0.41$) between total conflicts and total crashes. They also mentioned, based on the comparison between conflicts and crashes, conflict-to-crash ratios may vary by different types.

Other Intersection Issues

An issue of concern in several of the studies has been the need for uniformity to allow for comparison of different (types) of intersection at different locations. This was mainly attributed to the intersection “influence area,” since each intersection type has different such areas. For example, the influence area for a signalized intersection will be different than that of median U-turn, since in the U-turn option a larger area will be impacted. Therefore, defining this area is critical if different intersection designs are to be compared for evaluating their safety performance. A review of various studies documented this variance in the influence area of an intersection and the differing opinions of various researchers. Lyon et al. (2005) reported collisions within a radius of 20 meters from the center of an intersection as intersection-related crashes. Harwood et al. (2002) considered all crashes within 250 ft of an intersection as intersection-related. Cottrell and Mu (2005) specified the influence area based on the stopping sight distance of about 500 ft for an average approach speed of 40 mph. They concluded that the crash risk was often overestimated, since only two of the 35 intersections they investigated had an influence area of 500 ft while others were in the range of only 100 ft. Jokschi and Kostyniuk (1998) selected a maximum influence zone of 350 ft and a minimum of 7 ft and stated that the influence zone was based on individual judgment and not based on specific functions.

Adbel-Aty et al. (2009) identified the influence area of an intersection using stopping sight distance criteria and conducted a study to propose a common method that could be adopted by state DOTs. For this purpose they investigated the influence of various other parameters, such as size of an intersection, length of left turn lane, through and left turning vehicle volumes and skewness on the upstream influence area. A survey was conducted of 26 states and two territories across the United States, of which 15 states acknowledged utilizing distance as a criterion to identify intersection related crashes and most of them used varying default distance values. Intersection approach geometric design data, traffic control and operational features, traffic volumes and crash data was collected for 177 regular four-legged signalized intersections for this study and changes were made appropriately to generate a consistent data. The study proposes an application of “varied influence areas” to analyze heterogeneous intersections and concludes that factors vary for internal as well as the approach areas and hence it is recommended to define influence areas in two ways: at-intersection and

intersection-related. According to this study, factors affecting internal areas are number of lanes of the near-side intersecting approach and the angle of intersection, and the factors affecting the approach influence areas are dependent upon approach through volume, speed limit, jurisdiction, number of right lanes and approach left-turn protection. The study states that the safety influence areas should be determined independently and then the estimated safety influence areas based on samples could be used for other intersections in the study area and therefore achieve a better consistency among various intersections across the United States.

Summary

The review revealed that there is not a significant amount of research on alternative intersection designs, factors that affect intersection design or design procedures. The limited guidance that is available is provided by state agencies that have developed their own intersection design guidelines.

A total of 11 alternative intersection designs were identified in addition to “traditional” signalized or stop-controlled intersections. The majority of these were only promoted by the Maryland State Highway Agency. Of interest is the fact that no state has developed a systematic process that compares these alternative designs. Most manuals identify the need for comparative studies but none identifies the factors that one should consider in weighing alternatives and determining the optimal design. Maryland is the only state that is in the process of developing such an approach but not much progress has been made since 2005 when the concept was initiated. The development of separate manuals for roundabouts by a few states is a step in the right direction for identifying and considering alternative intersection designs; however, these do not provide a means for comparison and may further segregate alternative designs from traditional or other alternative designs. The lack of any specific guidance on the national and state level regarding the specific use and implementation of alternative designs is likely to discourage engineers from considering one or more of the alternatives, even though they may be appropriate. It is reasonable to then conclude that unnecessary construction and operation costs, collisions, and delays may occur as such suboptimal designs are employed or retained.

The information from the states that had independent intersection design guidance showed that there are a few common design factors among states, which may be potential factors to be considered when designing intersections. These factors could be used in this research and provide the basis for evaluating design options and alternatives. The review indicates that the most frequently used factors are operational analysis and construction cost

(six of seven states with specific guidance). These two factors are considered controlling for designing and evaluating intersection options, since they define the operational and construction efficiency of the intersection. Safety and pedestrian and bicycle needs come second (five of seven states). In addition, issues relative to access management should be considered, since they have the potential to influence operations and safety at an intersection. It is therefore recommended that the preliminary analysis consider these five factors (i.e. operations, cost, safety, pedestrian and bicycle user needs, and access management) in the evaluation process.

The methods discussed for estimating intersection capacity present simple estimates based on intersection geometry and turning volumes. These methods, while not as refined as current micro simulation models and/or more complex macro models allow for direct linkage between intersection design and operation. Such simple models may allow for manipulation through computational models, which allow for the automation of preliminary designs to establish the basic geometry needed to achieve a desired intersection capacity. Even though the Critical Lane Analysis and unsignalized intersection Level of Service methods could be considered as outdated, they have served as the foundation for the newer calculating procedures used in the current version of the Highway Capacity Manual (2004). These approaches are viewed as a basic, fundamental process for evaluating intersection design alternatives. The focal point behind all these approaches is that they provide the potential for a common basis of comparison, i.e. volume to capacity ratios or unused capacity, which can be used in targeting design options and providing a common basis for comparisons.

Review of the previous literature and the state of the art practices in intersection crash models indicates a lack of guidance for intersection design and alternative design selection. The majority of variables examined are not sensitive to design inputs, such as number of lanes or left turn treatments. While conflict analysis does account for these scenarios, it does not account for the traffic patterns at the intersection and therefore cannot reflect the optimum solution for a given design hour volume. From this review, it is evident that a crash exposure metric, accounting for both geometric and traffic volume data, is needed in order to adequately assess the safety trade-offs of various design alternatives.

Various researches 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 type of intersection, such as point and tight diamond intersection, intersection design elements, such as sight distance, angle of intersection, median width, and lane width, and traffic characteristics, such as approach speed, and average daily traffic. The

interpretation and evaluation of safety has also been quantified using different approaches such as conflict point at an intersection and safety influence area of an intersection. Safety of intersection has also been studied according to size, such as major and minor intersection. The ultimate goal of these researches is to identify the influence of certain parameters that could have a positive or negative effect on the safety of conflicting vehicles and hence could be promoted or eliminated accordingly.

OPERATIONS COMPONENT

Intersection Types

The first consideration in the next stages of the project was to identify possible alternative designs to be integrated within the screening tool. The Maryland alternatives presented above formed the basis for the analysis. In order to complete the spectrum of choices, the traditional designs utilizing stop control (two-way and all-way) and traffic signals were included. Input from the Study Advisory Committee was sought at the September 26, 2008 meeting to determine the final list of intersection designs to be considered. These intersection types are listed below and further discussion of their operating characteristics and layout is provided in Appendix A.

- Signalized
- Roundabout
- All-way stop
- Two-way stop
- Unsignalized inside left turn
- Median U-turn signalized
- Median U-turn unsignalized
- Superstreet, unsignalized
- Superstreet, signalized
- Continuous flow
- Continuous green T
- Jughandle
- Bowtie
- Paired intersections

These intersections may be grouped in the two major categories of signalized or unsignalized control. However, most designs manipulate a traditional design through redirected or channelized turn movements in order to address problematic or heavy turning movements. For example, the median U-turn operates as a signalized intersection at its center, paired with two adjacent intersections to accommodate left-turning movements. Each alternative has advantages and disadvantages as well as differing turn movement arrangements that will optimize efficiency of each design. Furthermore, each alternative may also be manipulated to

accommodate a wide range of alternate lane configurations to meet the unique demands of each project.

The next effort concentrated on developing a method to measure the operational requirements for an intersection to operate at a desired level of delay, i.e. capacity. This effort focused on utilizing existing methods and approaches that could be used in estimating the number of lanes required for an intersection to operate at the desired capacity. The development of such a tool can then allow users to establish a basic comparison framework for screening preliminary intersection design alternatives without having to fully evaluate every possible alternative.

Currently, intersections are first designed and an evaluation of their operational characteristics follows to check if they meet the allowable standards in terms of control delays, capacity, and level of service. This study aims to use operational characteristics to help size and design the intersection, reversing the current process. This will allow for a preliminary evaluation of all possible designs, screening out those that would be considered less desirable or appropriate based on operational performance. Also, this approach will allow for a more even comparison of all alternatives, since all options will target the same operational level.

The use of the Critical Movement Analysis (CMA) was considered an appropriate approach for developing such size estimates for intersections. As noted in the previous section, this approach is the basis of the current versions of lane allocations and groupings in the current version of the Highway Capacity Manual and therefore, it was deemed appropriate for sizing intersections. The CMA can be used to develop the required size of an intersection given a target value of acceptable capacity. However, these methods are currently only applied to signalized intersections. Therefore, it was necessary to expand these methods to include stop-controlled intersections as well as yield control utilized at roundabout. The following sections discuss the CMA approach developed for each of these traffic control options.

Signalized Intersections

The CMA defines as critical volume for an intersection the sum of the critical volumes for each signal phase for that intersection. Critical volume is calculated by assigning volumes to the available lanes in the intersection. If turning bays are present, all turning volumes are assigned to the turning bays; else, the turning volumes are added to the through volumes in the through lanes. If left turns are added to through movements, left turn equivalents are used based on the opposite through traffic to estimate their impact (i.e. delay) on the through traffic. Once the volumes have been assigned to the lanes, the critical volume for each signal phase is

calculated. If the approach has protected left turns, the highest lane volume allowed to move in each phase is the critical volume. If the approach has a permitted left turn, the highest sum of through or right single lane and opposing left is used. The sum of the critical volumes for each phase is the total critical volume for the intersection.

Roundabouts

Approach and conflicting volume is used for roundabout design in order to primarily determine whether a two-lane roundabout is needed. It is the sum of the approach volume for a single approach plus the volume circulating in the roundabout, conflicting with the vehicles attempting to enter the roundabout. This volume is simple to calculate, as it is the volume for the given approach plus the through and left movements from the approach immediately to the left, plus the left movements from the approach opposite the given approach. For example, the approach and conflicting volume for the northbound approach is total northbound volume plus the through and left eastbound movements plus the left southbound movements.

Two-Way Stop Control

The critical approach volume is a term developed in this study to address the absence of any method that could be used to estimate a similar metric as the critical volume for signalized intersections or the approach and conflicting volumes for roundabouts. The basic assumption is that vehicles on the stop-controlled approaches must find appropriate gaps to complete their movements. In this case, through and left-turn movements on the stop-controlled approach are in conflict with the movements in both free-flow directions, (i.e. without stop signs) and their movement is controlled by the heaviest movement in both directions of the free-flow approaches. Right-turn movements from the stop-controlled approach must only find an acceptable gap in the through movements for the intersection leg to the left of the approach leg, as these are the only vehicles in the free-flow direction that could impede right turn movements. Rules were developed to calculate the approach critical volume and are as follows:

1. Assign volumes to the major approach lanes based on the presence of right or left turn bays. Assume a single through lane regardless of actual number of through lanes.
2. Assign volumes to the minor (stop-controlled) approach lanes based on the presence of right or left turning bays.
3. Determine the lane with the maximum volume for the stop-controlled approach.

4. Calculate the approach conflicting volume based on the maximum lane volume for the stop-controlled approach.
 - a. If the approach lane with the maximum volume is a right turn lane, approach critical volume equals the maximum between 1. Approach right turn volume plus conflicting non stop-controlled through movement and 2. Maximum volume in the through or left lane plus the maximum lane volume for either direction of the non stop-controlled approaches.
 - b. If the approach lane with the maximum volume is a through lane, the approach critical volume equals the approach through lane volume plus the maximum lane volume for either direction of the non stop-controlled approaches.
 - c. If the approach lane with the maximum volume is a left-turn lane, the approach critical volume equals the approach left lane volume plus the maximum lane volume for either direction of the non stop-controlled approaches.

The approach critical volume is based on the assumption that some movements can occur in the same gaps if left and right turn bays are present. For example, vehicles in left turn bays are able to complete their maneuver at the same time as through vehicles. If turn bays are not present, all vehicles will be in the same lane regardless of movements and thus, all movements in a single lane must be treated as through movements. In this case, the approach critical volume is the volume in the single lane plus the maximum free-flow single lane volume.

Free-flow approaches with more than one through lane are treated as having one lane because it is assumed that vehicles using the available lanes do not always drive side by side but rather approach the intersection at different times in each lane. In this case, the vehicle on the stop-controlled approach still conflicts with the total volume moving through the intersection and not simply a single lane volume.

Evaluation Approach

The concepts presented above have not been proven and the first step in this effort was to demonstrate the relationship between delays and intersection design and volumes based on CMA through simulation. Different scenarios of volumes, i.e. vehicles per hour (vph), were identified to be simulated and obtain estimates of control delays. These delays were then used in determining the relationship between traffic volumes and delays for each intersection control option evaluated. This study considered only four-leg intersections and the control types examined are two-way stop, all-way stop, signal, and roundabout. The Corridor Simulation

(CORSIM) software was chosen as the simulation software due to its microscopic nature and ability to simulate traffic conditions in various traffic control environments.

The first step of this work was to determine the different traffic volume scenarios to use in the simulation models. In the following, the east-west cardinal directions were considered the major street approaches, while the north-south directions were those of the minor street. A combination of different volumes and turning percentages were determined for the east/west direction and the north/south direction. Based on the street volumes, different turn percentages were used. The volumes were selected in a manner that they would be greater than the minimum volumes to satisfy the four-hour signalization warrant (MUTCD, 2000). The volume combinations used are shown in Table 3.

Table 3 Intersection approach volumes

Total Street Volume (vph)	Eastbound	Westbound
1,800	1,080	720
1,400	840	560
1,000	600	400
600	360	240
Total Street Volume (vph)	Northbound	Southbound
1,200	600	600
800	400	400
400	200	200
860	600	260
570	400	170
285	200	85

The east/west street used two different turning percentages. The first was 10 percent left turns and 10 percent right turns, and the second was 15 percent left turns and 15 percent right turns for each of the four different volumes. The turn percentages used for the north-South Street were not uniform and were based on the total northbound approach volume (Table 4).

Table 4 North-south turn percentages

Northbound Approach Volume (vph)	Left Turn (%)	Right Turn (%)
600	10	10
	20	30
400	10	10
	20	30
	30	60
200	30	60

A total of 96 different scenarios were created based on these approach volumes and turn percentages¹. For each of these scenarios, different calculations were needed to determine either the total critical volume for the all-way stop-controlled and signalized intersections, the approach and conflicting volumes for roundabouts, or a critical approach volume for two-way stop-controlled intersections. The process followed for each of the different traffic control options is described next.

Lane Configuration

Determining the lane configuration was a partially iterative process. Critical volume was used to determine the lane configuration for signal control intersections while approach and conflicting volume was used to determine the lane configuration for roundabouts. The lane configuration used for signal-controlled intersections was also used for two-way and all-way stop-controlled intersections.

The initial lane configuration for each scenario was single-lane approaches for all four legs. The next step involved the determination of turning bay requirements. For each approach, right turn bays were added if the right turning volume was greater than 100 vph. Similarly, left turn bays were added if the left turning volume was greater than 100 vph.

For the signal-controlled intersections, basic signal phasing rules were developed, and the timing was calculated based on critical volumes. To determine if a left-protected phase was required, the left turns for the approach were multiplied by the opposing through movements. If this value was greater than 50,000 vph, a protected left turn phase was used. If not, left turns were permitted during a single phase for that direction. For this study, the possible signal plans used were a two-phase, a three-phase, or a four-phase signal. There were two types of three-phase signal plans: a left-protected phase in the east/west direction or a left-protected phase in the north/south direction.

A spreadsheet was created which contained the total approach volume, volume for each movement, lane configuration, and signal phasing. A macro was created to calculate the critical volumes for each signal phase as well as the total critical volume for the intersection based on

¹ For the east/west direction, there are four volumes with two turning percentages for each volume. For the north/south direction, there are six total volumes, with three different northbound approach volumes, 600, 400, and 200, each used twice. For the 600 approach volume, there are two possible turning percentages. For the 400 approach volume, there are three different turning percentages. For the 200 approach volume, there is one turning percentage. $4*2*(2*2+3*2+1*2) = 96$

the rules for calculating critical volume. Initially, critical volume was calculated for the intersection with one through lane for each approach and the appropriate turn bays. If the total intersection critical volume was greater than 1,400 vph, a second through lane was added in the east/west direction and the approach and total critical volumes were recalculated. In this case, a new timing plan was also developed to represent the revised conditions.

For roundabouts, two lanes were used for the approach if the approach and conflicting volume was greater than 1100 vph. If any approach required two lanes, a two lane roundabout was used. If one direction of the approach required two lanes, the opposite direction of that approach also used two lanes.

Simulation Results

As noted above, each of the 96 volume scenarios for each of the four traffic control options were evaluated using CORSIM. Default values were used for all parameters that were not modified among the various runs. Control delay per vehicle was measured for each scenario and control type. The output processor for CORSIM was utilized to create a spreadsheet of the desired outputs. The multiple runs feature was used to run each simulation four times using a different random number (i.e. representing a different traffic volume arrival pattern). The output processor allowed for recording the results for each run as well as the average and standard deviation to a single spreadsheet for each approach. The average control delay value for each volume scenario and traffic control was recorded for each approach and calculated for the entire intersection.

For each type of control evaluated, either the corresponding key volume or total volume was used to determine the relationship between control delay and this volume metric. Regression analysis was used to determine the best fit for the data to correlate delays to the corresponding volume metric. For the signal-controlled and all-way stop-controlled intersections, critical volume was used as the predicting variable, while for the two-way stop-controlled intersection the approach critical volume was used and for the roundabout the approach and conflicting volume was utilized.

Signalized Intersections

The delay data was examined as a function of the total critical volume for the intersection. The results showed that there is a relationship between delay and critical volume confirming a priori expectations. The plot of the results in Figure 1 indicates that there is a sharp increase of delays as the total critical volume approaches 1,400 vph indicating that the

intersections approach capacity conditions and the current geometry and timing plans will lead to high delays. Obviously, the tradeoff for lower delays will be the reduction of the critical volume, which could be achieved with additional lanes or turning bays. However, this will lead to a wider intersection footprint and thus increase required right of way.

Figure 1 Signalized intersection delay and critical volume

All-Way Stop Control

The total intersection critical volume was also used for the all-way stop control. The data trend was similar to that observed for signalized intersections but the high delay increases occurred at approximately 1,200 vph (Figure 2).

Figure 2 All-way stop control intersection delay and critical volume

Two-Way Stop Control

For the two-way stop-controlled intersections, approach critical volume was plotted against the approach control delay per vehicle. This was deemed appropriate since there is no control delay for the main street due to the absence of any control. The use of the total intersection control delay would skew the data since only the stop-controlled approaches experience any delay. In this case, there are 192 data points, twice as many as there are for the signalized and all-way stop-controlled intersections, since there are two approaches used for each scenario, instead of one intersection. The data shows that the delay increases occur at approximately 900 vehicles approach volume (Figure 3).

Figure 3 Two-way stop control intersection delay and approach critical volume

Roundabouts

For the roundabouts, the data was divided based on the number of circulating lanes in the roundabout, i.e. single and double. The flow conditions for the roundabouts with two circulating lanes are much more complicated than the single lane roundabouts to develop a relationship between approach and conflicting volumes and delay due to the complicated interactions among entering and conflicting vehicles in each lane of the roundabout. There were 44 single lane roundabouts among the 96 scenarios tested. The delay for each approach was considered to determine its relationship to approach and conflicting volumes, since each approach has the opportunity to control the design of the roundabout. A total of 176 data points were used in this analysis. The data in Figure 4 shows that all delays were in general lower than any of the other controls, supporting a priori findings. In addition, at approximately 1,000 vehicles of approach and conflicting volume delays were increasing—another prior research finding that is supported by the data.

Figure 4 Roundabout approach delay and approach and conflicting volume

Statistical Analysis

A statistical analysis was performed for each of the four intersection controls to determine whether the relationship noted between the volume metrics used and the delay estimated was statistically significant. To test this significance, regression models were developed to examine the relationship of volume and delays. The tests were performed to determine whether the trends are random and whether the coefficients of the regression lines are different than zero. All tests indicate that the relationships are significant and all coefficients and intercepts were significantly different than zero. Therefore, it can be concluded that the volume metrics used for each intersection control are capable of capturing the changes in the delays and therefore they can be used as indicators of the capacity and level of operation of the intersection as a result of the traffic control used.

Based on this analysis the derived critical volume procedures were validated. The analysis also allowed for the determination of ultimate capacity for each of the traffic control options. Capacity was identified by significant deflection identified in the delay curve. These critical volume capacities can be used to establish the ultimate threshold for the targeted

performance values of each alternative design. As such, designs can be insured that they operate below capacity and at an acceptable level of service. Table 5 identifies the capacity threshold for each alternative. These values will be used in determining the appropriate intersection design in the tool to be developed.

Table 5 Critical volume capacity thresholds

Intersection Control	Volume (vph)
Signal	1,350
All-Way Stop	1,200
Two-Way Stop	1,000
Roundabout	1,000

Operations in Intersection Design Alternative Tool

The findings of the simulation efforts indicate that the various volume metrics for each intersection design are reasonable delay predictors. This relationship between delays and volume metrics was used to develop the minimum required lane configuration for a given intersection traffic control scheme while achieving a targeted level of capacity for a given set of traffic volumes. Design hour volumes can be used to estimate the minimum lane requirements for each intersection design assuming a level of operation at 90 percent of capacity.

SAFETY COMPONENT

Methodology

In order to develop the safety companion to the Intersection Design Alternative Tool (IDAT), micro-simulation was utilized to identify potential crash patterns for various vehicular and pedestrian traffic patterns and volumes. The primary objective of the approach was to develop a relationship between the lane configuration and traffic volumes at an intersection with the crash exposure estimates provided by the SSAM. As noted above, SSAM is a software application that processes vehicle trajectory data from micro-simulation models such as VISSIM to identify potential conflicts. The crash exposure relationship can be expressed as a function of volumes (V) and geometry (G) or $f(V,G)$. Defining this function was the primary effort of the analysis. Two distinct approaches were developed to address the vehicular and pedestrian safety issues and are presented in the following sections.

Vehicular Safety

Prediction models for each specific crash were deemed appropriate in order to evaluate intersection safety and estimate the potential number of conflicts. This approach was deemed appropriate in order to eliminate interference of the various intersection movements and also allow for use of the models in all alternative designs utilized in the IDAT. Specific crash types were identified for use here as defined below:

- Signalized intersections: left-turn related, sideswipe, rear end and right-turn related. Other crashes such as right angle are not anticipated, since the presence of the signal would limit such crashes. Even though additional crash types could be present at a signalized intersection, SSAM cannot identify possible conflicts for those movements due to being considered protected movements.
- Unsignalized intersections: rear end for all-way stop control (AWSC) and rear end, right-turn related, left-turn related from the main street, and right angle for two-way stop control (TWSC). For AWSC, all movements are protected and only rear end conflicts are anticipated. The crossing maneuvers from the side street and the left turn from the main street are the only unprotected movements that could result in conflicts at TWSC intersections.
- Other intersections: a combination of the signalized and unsignalized conflicts will be used as required to determine the appropriate conflicts to be used for each alternative design.

VISSIM and SSAM models for each crash type were first developed. A range of feasible traffic volumes was evaluated to ensure that all movements operate under capacity, so that congestion related crash patterns will not affect the evaluation. In addition to multiple volume scenarios, various lane configurations were also evaluated for the rear end and sideswipe crashes. A total of 20 simulation scenarios were conducted for each crash type. This number of scenarios was chosen to allow for evaluation of a single independent variable, based on a general regression rule of thumb that there must be at least 20 times as many cases as independent variables (Garson, 2010). The scenarios for each crash type to be utilized in the simulations are presented in the following sections.

Left Turn Angle

Angle crashes resulting from left turning vehicles and opposing through vehicles on the same street, reflective of permitted left turn operations at a signalized intersection are included in this conflict type. These conflicts will be evaluated by examining 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 will range from 20 to 300 vph. This represents a typical range of left turn volumes, as the recommended threshold for protected left turn movements is 300 vph (Rodegerdts et al., 2004). Volumes will be increased in 40 vph increments.
- Through volumes will range between 200 vehicles per hour per lane (vphpl) to 1,000 vphpl. The 1,000 vphpl volume reflects an upper threshold of capacity for a single approach of a signalized intersection. Volumes will be increased in 400 vphpl increments.
- Number of lanes will be evaluated as one, two or three lanes, as this is representative of the majority of roadways.
- Percent of green time will be evaluated as 100 percent (reflective of uncontrolled movements), 60 percent (reflective of major street operations) and 40 percent (minor street operations).

Table 6 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 216 simulations, assuming a single run for each parameter combination.

Table 6 Left turn angle simulation design matrix

Parameter	Design Values Ranges			Total Combinations
	i	N	increment	
Left turn volume (vph)	20	300	40	8
Opposing through volume (vphpl)	200	1000	400	3
Number of lanes	1	3	1	3
<i>Parameter Values</i>				
Traffic control	Signal (100% green time)	Signal (60% green time)	Signal (40% green time)	3

Crossing Angle (TWSC)

Angle crashes resulting from left and through vehicles and through vehicles on the primary street, reflective of turn operations at a TWSC intersection are included in this conflict type. These crashes will be evaluated by examining left turn volume, through volumes and through volume on the major street, and the number of through lanes on the major street.

- Total volume on the minor street will range from 50 vph to 400 vph, which is reflective of the upper threshold of unsignalized operations as defined by the traffic signal warrants (FHWA, 2009). Minor street volumes will be increased in 100 vph increments.
- Left turn percentage will range from 0 to 50 percent. Left turn percent will be increased in 10 percent increments.
- Through volumes will range between 200 vphpl to 1,000 vphpl. The 1,000 vphpl volume reflects an upper threshold of capacity for a single approach of a signalized intersection. Volumes will be increased in 400 vphpl increments.
- Number of lanes will be evaluated as one or two lanes. Unsignalized operations with three or more lanes are not recommended due to safety concerns.

Table 7 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 180 simulations, assuming a single run for each parameter combination.

Table 7 Crossing angle simulation design matrix

Parameter	Design values ranges			Total combinations
	i	N	Increment	
Minor street volume (vph)	50	450	100	5
Left turn percentage	0	50	10	6
Opposing through volume (vphpl)	200	1000	400	3
Number of lanes	1	2	1	2

Rear End

Rear end crashes will be evaluated by examining volume, left turn percentage, presence of left turn lanes, right turn percentage, and presence of right turn lane. Based on exploratory analysis it appears that the number of crashes should be calculated per lane and therefore only a single lane alternative be evaluated. Capacity will also be evaluated as indicated by the percent green time for the given movement at a traffic signal.

- Volumes will range between 200 vphpl to 1,000 vphpl. The 1,000 vphpl volume reflects an upper threshold of capacity for a single approach of a signalized intersection. Volumes will be increased in 400 vphpl increments.
- Left turn and right turn percentages will range from zero to 30 percent. This reflects a full range of anticipated turn volumes up to 900 left turn vehicles, which would be at or near capacity for a left turn movement. Turn percentages will be increased in 10 percent increments.
- Each scenario will be evaluated both with and without a right and left turn lane.
- Percent of green time will be 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 will be evaluated as a stop condition to include minor street operations at two-way stops and all-way stop control.

Table 8 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 512 simulations, assuming a single run for each parameter combination.

Table 8 Rear end simulation design matrix

Parameter	Design values ranges			Total combinations
	I	N	Increment	
Volume per lane	200	1000	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
<i>Parameter Values</i>				
Traffic control	Signal (100% green time)	Signal (60% green time)	Signal (40% green time)	3

Sideswipe Crashes

Sideswipe crashes will be evaluated by examining volume, left turn percentage, right turn percentage, number of lanes, and maneuvering length.

- Volumes will range between 200 vphpl to 1,000 vphpl. The 1,000 vphpl volume reflects an upper threshold of capacity for a single approach of a signalized intersection. Volumes will be increased in 400 vphpl increments.
- Left turn and right turn percentages will range from zero to 30 percent. This reflects a full range of anticipated turn volumes up to 900 left turn vehicles, which would be at or near capacity for a left turn movement. Turn percentages will be increased in 5 percent increments.
- Number of lanes will be evaluated as a two lane pair and subsequently sideswipe crashes will be predicted based upon a per pair basis. As an example a two-lane roadway would have a single pair and a three lane section would have two two-lane pairs. Calculating crashes in this manner is consistent with the exploratory analysis conducted for rear end crashes.
- Three separate maneuvering lengths will be evaluated including 660 feet, 1320 feet and 2640 feet, reflective of 1/8 mile, 1/4 mile and 1/2 mile signal spacing, which are typical of urban and suburban environments.

Table 9 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 144 simulations, assuming a single run for each parameter combination.

Table 9 Sideswipe simulation design matrix

Parameter	Design values ranges			Total combinations
	I	N	Increment	
Volume per lane	200	1000	400	3
Left turn percentage	0	30	10	4
Right turn percentage	0	30	10	4
<i>Parameter Values</i>				
Maneuvering length	1/8 mile	¼ mile	½ mile	3

Pedestrian Safety

A slightly different approach was undertaken for simulating and estimating crash prediction models for pedestrians. In this case, specific intersection types were simulated to allow for developing the relationships between specific designs and vehicle-pedestrian interaction. This was required because the exposure was varied by each intersection design type as well as due to the need to consider all potential conflicts to pedestrians from vehicular flow patterns at the same time. For all scenarios examined, the traffic parameters included the volumes along the major and the minor streets and the pedestrian volumes. The turn percentages for the right and left turns were also varied to allow for identifying their effect on the potential presence of conflicts. Finally, the number of lanes per approach was varied to properly estimate their effect on conflict potential. It should be noted that the number of pedestrians simulated per approach is relatively high which was considered essential to allow for identifying an adequate number of conflicts in order to develop reliable prediction models. For each scenario examined, ten different random numbers were used to produce an average number of conflicts by scenario.

A range of traffic volumes was considered for each intersection model and signal warrants were used as a reference to develop the volume combinations for each intersection type based on the Manual on Uniform Traffic Control Devices (FHWA, 2009). In determining the upper thresholds for the combinations examined, typical conditions in Kentucky roadways were considered along with maintaining a non-congested condition at the intersection. The specific parameters for each intersection type considered and their ranges are discussed below.

Unsignalized Intersections:

Unsignalized intersections (TWSC and AWSC) were evaluated by examining volume, left turn percentage, right turn percentage, pedestrian volumes and number of approach lanes.

- Volumes along the major road ranged between 200 vph to 800 vph per approach and were increased in 200 vph increments.
- Volumes along the minor road ranged between 100 vph to 300 vph per approach and were increased in 100 vph increments.
- Left turn and right turn percentages ranged from 10 to 30 percent. This reflects a full range of anticipated turn volumes up to 150 left turn vehicles, which would be at or near capacity for a left turn movement at unsignalized intersections (KTC, 2006). Turn percentages were increased in 10 percent increments.
- Number of lanes evaluated was one or two lanes per approach. Unsignalized operations with three or more lanes are not recommended due to safety concerns.
- Three pedestrian volumes were evaluated including 75, 100 and 125 pedestrians per approach.

Table 10 summarizes these criteria and value ranges. A full factorial design for this set of parameters required 216 simulations for AWSC intersections. Another 216 scenarios were used for TWSC intersections.

Table 10 Unsignalized intersection simulation design matrix

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

Signalized Intersections

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

- Volumes along the major road ranged between 250 vph to 1000 vph per approach and were increased in 250 vph increments.
- Volumes along the minor road ranged between 200 vph to 600 vph per approach and were increased in 200 vph increments.
- Left turn and right turn percentages ranged from 5 to 15 percent. This reflected a full range of anticipated turn volumes up to 150 left turn vehicles per lane, which was at or near capacity for a left turn movement for one approach. Greater turn volumes would

warrant an exclusive turn lane and permitted phase in which case there would be no pedestrian-vehicle interaction and hence no potential conflict to quantify (KTC, 2006). Turn percentages were increased in 5 percent increments.

- Three lane combinations were evaluated - one, two and three lanes per approach.
- Three pedestrian volumes were evaluated including 75, 100 and 125 pedestrians per approach.

Table 11 summarizes these criteria and value ranges. A full factorial design for this set of parameters required 324 simulations.

Table 11 Signalized intersection simulation design matrix

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

Roundabouts

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

- Same volume and turn percentage as for the signalized intersections were applied to the roundabout analysis.
- Two lane combinations were evaluated - one and two lanes per approach.
- Three pedestrian volumes were evaluated including 75, 100 and 125 pedestrians per approach.

Table 12 summarizes these criteria and value ranges. A full factorial design for this set of parameters would require 216 simulations.

Table 12 Roundabout simulation design matrix

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

Conflict Analysis

The VISSIM software was used to produce vehicle trajectory files for each scenario developed. The resulting conflicts were determined through processing the trajectory files for each of the crash scenarios by SSAM. Default SSAM parameters including 1.5 seconds time to collision and 5.0 seconds post encroachment time were used in the analysis. For the purposes of this analysis, only those conflict types matching the primary conflict type were used in the development of the models. Conflicts for each model run were evaluated and a database developed which matched the independent evaluation variables described above with the number of conflicts observed.

Statistical models were then developed for each crash type through the Statistical Package for Social Sciences (SPSS). Regression models were evaluated where the dependent variable was the number of conflicts and the various design parameters were used as independent variables (i.e. predictors). Data transformations, such as X , X^2 , or X/Y , were used to determine the optimum independent variable for the regression equation. Regression models were developed using the SPSS statistical software to determine the influence and significance of the independent variables consider in the analysis. In addition to the independent variables, several other variable transformations were also examined. Linear, logarithmic and 2nd order polynomial equations were used to fit the regression and the best-fit model was chosen for each scenario. 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 lanes or green percent of cycle) with the number of conflict points in the traffic stream. Finally, linear, log, exponential and polynomial models were evaluated to determine the best fit to the data. The full range of independent variables evaluated for inclusion in each of the models is summarized below. All models have been evaluated for colinearity of variables and have a variance inflation factor (VIF) less than 2.0, indicating there is not significant multi-

colinearity among the variables (Heckert and Filliben, 2003). 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.

Research Findings

Vehicular Safety

The conflicts obtained through the SSAM analysis showed definite 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 0.84. 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 over 67 percent of the variability seen in the conflict distributions. Each of the final models is presented and discussed below.

Left Turn Conflict Analysis

As identified above, the analysis scenarios for left turn angle conflicts examined a range of design inputs. Based on these considerations, the following variables were evaluated for inclusion in the final model to predict the number of conflicts.

- Left-turn volume
- Opposing through volume
- Percent green time
- Number of opposing through lanes
- (Left turn volume) $\times$ (Opposing through volume)
- (Opposing through volume) $\times$ (Number of lanes)
- ((Opposing through volume) / (Number of lanes)) $^$ (Number of lanes)
- (Opposing through volume) $\times$ (Number of lanes) $\times$ (Left turn volume)

Left turn conflicts were best described by a linear function with three independent variables, presented in Equation 3.

$$\text{Conflicts} = 38.612 + 0.00007626(x_1) + 0.006(x_2) - 0.559(x_3) \quad (3)$$

Where: $x_1 = (\text{Left turn volume}) \times (\text{Opposing through volume})$

$x_2 = (\text{Opposing through volume}) \times (\text{Number of lanes})$

$x_3 = (\text{Percent of green time allocated to phase})$

This model produced an R^2 value of 0.73. Variables x_1 and x_2 directly link the volume to lane configurations, and conflict analysis providing a robust model that may be used to differentiate between different left turn treatments at intersections. The addition of the percent of green time also shows that the conflicts are a function of roadway capacity and as green time increases there can be expected a corresponding decrease in crashes. The results are also intuitive, since increase in volumes and number of lanes will result in more conflicts, while an increase in green time will result in a less congested environment and thus reduce left-turn related conflicts.

Rear End Conflict Analysis

As identified above the analysis scenarios for rear end conflicts examined a range of design inputs. The following variables were evaluated for inclusion in the final model to predict the number of conflicts.

- Approach volume
- Right turn volume
- Right turn percent
- Left turn volume
- Left turn percent
- Left turn lane presence
- Right turn lane presence
- Percent green time
- Cycles per hour
- (Volume) / (Cycles per hour)
- Number of gaps
- (Left turn volume) $\times$ (Through volume)
- Critical volume
- (Critical volume) / (Percent green time)

Rear end conflicts were best described by the polynomial function shown below in Equation 4.

$$\text{Conflicts} = -3.284 - 0.007(x^2) + 1.463(x) \quad (4)$$

Where: $x = (\text{Approach critical volume}) / (\text{Percent of green time allocated to phase})$

This model produced an R^2 value of 0.84. Critical volume provides a measure of both traffic demand and lane configuration. Furthermore, the inclusion of the percent of green time shows that conflicts are a function of roadway capacity and as green time increases, crashes are expected to decrease. It should be noted that this model was developed only analyzing single lane approaches, which may limit the applicability of the model.

Sideswipe Conflict Analysis

The following variables were evaluated for inclusion in the final model to predict the number of conflicts.

- Approach volume
- Left turn percent
- Right turn percent
- Upstream maneuvering length
- Left turn volume
- Right turn volume
- $[(\text{Left turn vol.}) / (\text{No. of lanes})] \times [(\text{Right turn vol.}) / (\text{No. of lanes})]$
- $(\text{Left turn volume}) \times (\text{Right turn volume})$
- $[(\text{Through volume} / \text{No. of lanes})] \times [(\text{Turning vol.}) / (\text{No. of lanes})]$
- $(\text{No. of lanes} - 1) \times (\text{Turn volume}) \times (\text{App. vol.}) / (\text{No. of lanes})$

Sideswipe conflicts were best described by a linear function with three independent variables, presented in Equation 5.

$$\text{Ln}(\text{Conflicts}) = 0.290 + 0.000001279(x_1) + 0.001(x_2) - 0.00004(x_3) \quad (5)$$

Where: $x_1 = (\text{No. of lanes} - 1) \times (\text{Turn volume}) \times (\text{App. vol.}) / (\text{No. of lanes})$

$x_2 =$ Approach volume

$x_3 =$ Upstream maneuvering distance

This model produced an R^2 value of 0.67. Variables x_1 and x_2 directly link the volume to lane configurations and conflict analysis providing a robust model that may be used to differentiate between intersection alternatives. The predicted decrease in conflicts as maneuvering distance increases is also consistent with expectations, i.e., longer maneuvering distances will reduce conflicts.

Right Angle Conflict Analysis

The following variables were evaluated for inclusion in the final model to predict the number of conflicts.

- Approach volume
- Left turn percent
- Right turn percent
- Upstream maneuvering length
- Left turn volume
- Right turn volume
- $[(\text{Left turn vol.}) / (\text{No. of lanes})] \times [(\text{Right turn vol.}) / (\text{No. of lanes})]$
- $(\text{Left turn volume}) \times (\text{Right turn volume})$
- $[(\text{Through volume} / \text{No. of lanes})] \times [(\text{Turning vol.}) / (\text{No. of lanes})]$
- $(\text{No. of lanes} - 1) \times (\text{Turn volume}) \times (\text{App. vol.}) / (\text{No. of lanes})$
- $(\text{Through volume}) \times (\text{Right Turn Volume.}) \times (\text{No. of lanes})$
- $(\text{Through volume}) \times (\text{No. of lanes})$

Right angle conflicts were best described by a three variable linear model function with independent variables, presented in Equation 6.

$$\text{Conflicts} = -0.632 + 0.095(x_1) + 0.0001(x_2) - 0.006(x_3) \quad (6)$$

Where: x_1 = Right Turn Volume

x_2 = $(\text{Through volume}) \times (\text{Right Turn Volume.}) \times (\text{No. of lanes})$

x_3 = $(\text{Through volume}) \times (\text{No. of lanes})$

This model produced an R^2 value of 0.80. Variables x_2 and x_3 directly link the volume to lane configurations and conflict analysis providing a robust model that may be used to differentiate between intersection alternatives.

Intersection Conflict Prediction Models

1. **AWSC.** These intersections predominantly exhibit rear end potential conflicts that were best described by an exponential function of entering volume as shown in Equation 7.

$$\text{Conflicts} = 4.48 * (e^{0.005X}) \quad (7)$$

Where: X = Conflicting volume = Left Volume * Opposing Thru

This model produced an R^2 value of 0.92. This univariate model explicitly linked the entering vehicular volume at an intersection to the overall rear end collisions at the AWSC. At AWSC intersections, vehicles stop-and-go successively and only one approach has the right-of-way at any given time which minimizes or eliminates crossings or sideswipe crashes. Hence the resulting potential conflict model for an AWSC intersection is composed of rear end conflicts.

2. **TWSC.** Conflicts at TWSC included both right angle and crossing conflicts that were best described by linear equations as shown in Equation 8:

$$\text{Conflicts} = [5.18 + (6.45 \cdot e^{-0.07})x_1] - [5366.22 - 981.66x_2 + 10.7x_3] \quad (8)$$

Where x_1 = Conflicting volume = (Approach Thru * Right turn²) / Lanes²

x_2 = Lanes

x_3 = Total Volume

The equation has two components (shown in brackets) where the first estimates right angle conflicts (R^2 0.59) and the second calculating crossing conflicts (R^2 0.71).

Variables x_1 , x_2 and x_3 link volumes and lane configurations to the overall conflicts providing a robust model to analyze varying lane configurations.

3. **Roundabouts.** At roundabouts vehicles continuously change trajectories and speed, and therefore the crossing and lane change conflicts were not segregated. Instead an overall conflict model for the intersection was developed with respect to the total intersection volume (Equation 9):

$$\text{Conflicts} = 0.57(e^{0.0039x}) \quad (9)$$

Where x = Total volume

This model has an R^2 value of 0.80.

4. **Signalized.** At signalized intersections, the total potential conflicts model developed includes four individual conflicts (including permitted left turn, lane changing, rear ends, and right angle) shown in Equation 10:

$$\begin{aligned} \text{Conflicts} = & [9(e^{-13})x_1 + 0.08] + [0.59*(x_2) + (0.07)*x_3 + 0.29*(x_4) - 0.13 * (x_5) + 0.22 * (x_6)] \\ & + [1.91*(x_7) - 1.2 * (x_7)^2 - 1.68*(x_8^2) + 1.54*(x_8)] + [5.18 + (6.45e^{-0.07})*x_9] \end{aligned} \quad (10)$$

Where: x_1 = (left)*(thru²)*(green time²)/(lanes³)

x_2 = Flow

x_3 = Right volume

x_4 = Left volume

x_5 = Upstream Weaving Distance

x_6 = Lanes

x_7 = Critical volume

x_8 = Green time

x_9 = Conflicting volume ((stop-controlled left turn + through) * (mainline approach volume))

The permitted left turn model had an R^2 value of 0.59. The sideswipe model had a R^2 value of 0.88. The rear end model had an R^2 value of 0.95 and the right angle crossing had an R^2 value of 0.59. The models used here are considering all potential parameters that could have an influence, including volumes, number of lanes, and signal parameters.

5. **Median U-turn.** Conflicts at median U-turn intersections are comprised of conflicts at the intersection along with the conflicts at the U-turn point including crossing and rear end conflicts (Equation 11):

$$\text{Conflicts} = [0.59x_1 + 0.07x_2 + 0.29x_3 - 0.13x_4 + 0.22x_5] + [1.91x_6 - 1.2(x_6)^2 - 1.68(x_7)^2 + 1.54x_7] + [5.18 + (6.45e^{-07})x_8] + [(4 * e^{-05}(x_9) - 1.02 + 5e^{-08}x_{10} + 0.03)]^2 \quad (11)$$

Where: x_1 = flow

x_2 = Right volume

x_3 = Left volume

x_4 = Distance

x_5 = Lanes

x_6 = Critical volume

x_7 = Green time

x_8 = Conflicting volume

x_9 = EB UTurn * WB Thru

x_{10} = Thru*thru*uturn

The U-turn crossing and rear end models had an R^2 value of 0.52 and 0.55 respectively.

6. **Jughandle.** The conflicts at a jughandle intersection consist of conflicts at the intersection area and the conflicts at the ramp region. Since left turns are permitted at the minor street approach of the intersection, the volume input is transformed to include the minor street left turn volumes only. The prediction of the conflicts at the ramp region is based on the TWSC model (Equation 12).

$$\begin{aligned} \text{Conflicts} = & [9(e^{-13})x_1 + 0.08] + [0.59*(x_2) + (0.07)*x_3 + 0.29*(x_4) - 0.13 * (x_5) + 0.22 * (x_6)] \\ & + [1.91*(x_7) - 1.2 * (x_7)^2 - 1.68*(x_8^2) + 1.54*(x_8)] + [5.18 + (6.45e^{-07})*x_9] + [5.18 + (6.45e^{-07})x_{10}] - [5366.22 - 981.66x_{11} + 10x_{12}] \end{aligned} \quad (12)$$

Where: $x_1 = (\text{left}) * (\text{thru}^2) * (\text{green time}^2) / (\text{lanes}^3)$

x_2 = Flow

x_3 = Right volume

x_4 = Left volume

x_5 = Upstream Weaving Distance

x_6 = Lanes

x_7 = Critical volume

x_8 = Green time

x_9 = Conflicting volume

x_{10} = Conflicting volume

x_{11} = Lanes

x_{12} = Total volume

7. **Bowtie.** The conflicts at a bowtie intersection consist of those at the intersection area as well as those at the two-roundabout intersections in the minor street (Equation 13):

$$\begin{aligned} \text{Conflicts} = & [0.59x_1 + 0.07x_2 + 0.29x_3 - 0.13x_4 + 0.22x_5] + [1.91x_6 - 1.2(x_6)^2 - 1.68(x_7)^2 + 1.54x_7] \\ & + [5.18 + (6.45e^{-07})x_8] + [2 * (0.57 * (e^{0.0039x_9}))] \end{aligned} \quad (13)$$

Where: x_1 = flow

x_2 = Right volume

x_3 = Left volume

x_4 = Distance

x_5 = Lanes

x_6 = Critical volume

x_7 = Green time

x_8 = Conflicting volume

x_9 = Total volume

Pedestrian Safety

For each intersection type the modeling approach undertaken was to develop a model that would allow for the distinguishing of potential pedestrian-vehicle conflicts by the location of the conflict, i.e. whether it occurred along the major or the minor road. The models considered several variables including conflicting volumes, number of lanes, percentage of left turns, and traffic and pedestrian volumes. The conflicting volume is defined in this study as the product of the number of vehicles conflicting with the number of pedestrians at each intersection area. In the case of unsignalized intersections and roundabouts, the conflicting volume was equivalent to the approach and turning vehicular volume conflicting with the pedestrian volume crossing a conflicting leg of the intersection. For the signalized intersections, it was equivalent to the turning vehicles conflicting with pedestrians at the adjacent leg of the intersection. Traffic and pedestrian volumes were considered only for models that did not include the conflicting volume to avoid using variables that are related and thus violate the assumption of independence among predictors. In general, the conflicting volumes were better predictors than the traffic and/or pedestrian volumes alone. General linear regression, exponential regression, Poisson and negative binomial models were evaluated. Overall the results indicated that the Poisson and negative binomial models are not appropriate, based on the ratio of the deviance to degrees of freedom that was less than 1.0 indicating an under-dispersed response variable (i.e. there is less randomness than anticipated or too many cases with no conflicts in the data).

As identified above the analysis scenarios for conflicts at all intersections considered a range of design inputs. Based on these considerations, the following variables were evaluated for inclusion in the final model to predict the number of conflicts.

- Approach vehicular volume
- Pedestrian volume
- Turn percent
- Number of lanes
- Location of conflict
- Conflict volume

Unsignalized Intersections

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

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

1. **AWSC.** Conflicts were best described by a linear function with four independent variables (Equation 14).

$$\text{Conflicts} = -0.47 + 0.06(x_1) + 0.05(x_2) - 0.87(x_3) + 0.43(x_4) \quad (14)$$

Where: x_1 = Conflict volume

x_2 = Turn percent

x_3 = Location of conflict

x_4 = Number of lanes

This model produced an R^2 value of 0.41. Variables x_1 , x_2 and x_4 directly link the pedestrian and vehicular volumes to lane configurations and conflict analysis providing a significant model that may be used to differentiate between different numbers of lanes at intersections. Moreover, variable x_3 allows for estimating conflicts separately for the main and minor street indicating that more conflicts are expected along the minor street. The addition of the number of lanes reflects the increased exposure of pedestrians due to wider streets. The results are also intuitive, since increase in volumes and number of lanes will result in more conflicts.

2. **TWSC.** Conflicts were best described by a linear function with three independent variables (Equation 15).

$$\text{Conflicts} = -0.42 + 0.10(x_1) + 0.08(x_2) - 0.92(x_3) \quad (15)$$

Where: x_1 = Conflict volume

x_2 = Turn percent

x_3 = Location of conflict

This model produced an R^2 value of 0.60. Variables x_1 and x_2 directly link the pedestrian and vehicular volumes to conflicts providing a robust model. Moreover, variable x_3 allows for estimating conflicts separately for the main and minor street indicating that more conflicts are expected along the minor street.

3. **Signalized Intersections.** The analysis for signalized intersections considered the same variables as those noted above and provided a significant prediction model. The model developed included four variables (Equation 16).

$$\text{Ln Conflicts} = -0.48 + 0.008(x_1) + 0.03(x_2) + 0.53(x_3) - 1.16(x_4) \quad (16)$$

Where: x_1 = Conflict volume

x_2 = Left turn percent

x_3 = Number of lanes

x_4 = Location of conflict

The model had an R^2 value of 0.32. Variables x_1 and x_2 directly linked the pedestrian and vehicular volumes to conflicts providing a significant model. Moreover, variables x_3 and x_4 allow for considering the effect of lane configurations on the safety of pedestrians, indicating that estimating conflicts separately for the main and minor street indicate that more conflicts are expected along the minor street.

5. **Roundabouts.** The analysis for developing a prediction model for roundabouts also produced a significant prediction model (Equation 17).

$$\text{Conflicts} = 2.21 + 0.1(x_1) - 4.86(x_2) + 0.93(x_3) \quad (17)$$

Where: x_1 = Conflict volume

x_2 =Location of conflict

x_3 =Number of lanes

This model produced an R^2 value of 0.71. Variables x_1 and x_2 directly link the pedestrian and vehicular volumes to lane configurations and conflict analysis providing a robust model that may be used to differentiate between different numbers of lanes at intersections. Moreover, variable x_3 allows for estimating conflicts separately for the main and minor street indicating that more conflicts are expected along the minor street. The addition of the number of lanes reflects the increased exposure of pedestrians due to wider streets. The results are also intuitive, since increase in volumes and number of lanes will result in more conflicts.

6. **Median U-Turn.** Potential pedestrian-vehicle conflicts at median U-turn intersections replicate the conflicts at conventional signalized intersections with volume transformations. Since left turns are prohibited at major and minor streets, the same volume transformations as applied for the vehicular models are used. The final model recommended for a median U-turn intersection is:

$$\text{Ln Conflicts} = -0.48 + 0.008(x_1) + 0.03(x_2) + 0.53(x_3) - 1.16(x_4) \quad (18)$$

Where: x_1 = Conflict volume
 x_2 = Left turn percent
 x_3 = Number of lanes
 x_4 = Location of conflict

7. **Bowtie.** Potential pedestrian vehicle conflicts at bowtie intersections replicate the conflicts at conventional signalized intersections with volume transformations. The final model recommended for bowtie intersection:

$$\text{Ln Conflicts} = -0.48 + 0.008(x_1) + 0.03(x_2) + 0.53(x_3) - 1.16(x_4) \quad (19)$$

Where: x_1 = Conflict volume
 x_2 = Left turn percent
 x_3 = Number of lanes
 x_4 = Location of conflict

8. **Jughandle.** Potential pedestrian vehicle conflicts at jughandle intersections were analyzed for intersection area and ramp area independently. The intersection area witnessed pedestrian conflicts at major approach from minor street vehicle traffic only. Since there are no turn movements for the major street at the intersection, there are no potential pedestrian conflicts from major street vehicular traffic. The turn traffic from the major approach exist using the ramp and join the minor street to turn left or right which conflict with the pedestrians at the end of the ramp. This section replicates the conflicts of minor approach of TWSC since the ramp traffic yields to all other traffic before making any maneuver.

$$\text{Ln Conflicts} = -0.48 + 0.008(x_1) + 0.03(x_2) + 0.53(x_3) - 1.16 (x_4) \quad (20)$$

Where: x_1 = Conflict volume
 x_2 = Left turn percent
 x_3 = Number of lanes
 x_4 = Location of conflict (0 for Minor)

Potential pedestrian vehicle conflict prediction model for the ramp area:

$$\text{Conflicts} = -0.42 + 0.10(x_1) + 0.08(x_2) - 0.92 (x_3) \quad (21)$$

Where: x_1 = Conflict volume

x_2 = Turn percent

x_3 = Location of conflict (0 for minor)

Safety in Intersection Design Alternative Tool

The prediction models developed indicate that the various volume and geometry metrics for each intersection design are reasonable predictors of conflicts. These models are used to predict the number of conflicts for each alternative. The predicted number of conflicts is used to develop the safety scores for each alternative as defined in the following section.

INTERSECTION DESIGN ALTERNATIVE TOOL

The review of state design manuals identified a set of potential factors to be considered when designing intersections. The information from the states that had additional guidance showed that there are a few common factors among all states. These common factors were used in this research and provided the basis for evaluating design options and alternatives. The review showed that the most frequently used factors are operational analysis, construction cost, safety, and pedestrian and bicycle needs. In addition, facilitation of access management was deemed an appropriate additional consideration since it has the potential to influence operations and safety at an intersection. Therefore, it was determined that the evaluation tool will utilize these five factors, i.e. operations, right of way requirements, safety, pedestrian and bicycle user needs, and access management.

Metrics for each of the evaluation factors were then determined. These metrics allow for quantification of the factors for each design and provide a means for evaluating and comparing all possible options. In addition, a weighted scoring approach was developed to provide a composite score that could be used in ranking the alternative designs. The metrics for each of the factors identified above are presented below.

Operations

The findings of the simulation efforts noted above indicate that the various volume metrics for each intersection design are reasonable predictors of the delay. This relationship between delays and volume metrics was used to develop the minimum required lane configuration for a given intersection traffic control scheme while achieving a targeted level of capacity once the traffic volumes are determined. Design hour volumes can be used to estimate the minimum lane requirements for each intersection design assuming a level of operation at 90 percent of capacity.

This approach allows for developing a comparison where all options will operate at similar levels. This also alleviates the problem of different levels for different design options and thus makes comparison among alternatives more difficult and often highly subjective. The tool provides a schematic diagram of the required number of lanes for each potential design and identifies whether the design is feasible and recommended.

All possible lane combinations of each approach are evaluated for each approach, except that a restriction is placed that both the major and minor streets have the same number of through lanes. Figure 5 shows the eight different approach combinations for a single through lane alternative. These eight approach configurations developed for the signalized intersections

served as the basis for the other intersection alternatives, which were modified to meet the unique demands of each of the differing designs.

Figure 5 Approach lane configurations

Each of the eight approach configurations were scored based on 1) the total number of lanes used in the design, and 2) the desirability of the configurations from an operational, safety and driver expectancy (i.e. commonality of design used) standpoint. Lane configurations were rated as follows:

- 1: 8 (Highest Score)
- 2: 6.5
- 3: 6.5
- 4: 5
- 5: 4
- 6: 2
- 7: 3
- 8: 1 (Lowest Score)

For feasible combinations (i.e., v/c is less than 0.90), a total intersection score was then developed as the sum of the individual approach scores. The combination with the highest score is then chosen as the preferred configuration for that alternative. For each alternative

design, a preferred configuration is developed for single-lane, two-lane and three-lane approaches on the major street.

Volume transformations were utilized for each of the innovative intersection designs along with decomposing them to appropriate signalized and unsignalized elements in order to estimate the lane requirements. For example, in the median U-turn (unsignalized) all left turning volume was added to the through movement and used the left turn at the U-turn location. The required number of lanes to serve the reconfigured volumes at the intersection produced the new configuration for the intersection, and a similar approach for an unsignalized intersection produced the requirements for the U-turn.

IDAT provides a multiple level screening analysis to allow the user to select the preferred alternative or alternatives to be carried forward for further analysis. All design alternatives that have been identified as feasible through the CMA process are carried forward and presented in the final output. This includes the identification of the highest scoring single lane, two-lane and three lane configurations for each alternative. If multiple approach lane configurations are feasible for a given alternative, those with a greater number of through lanes are identified as “Not Recommended” to identify that a configuration with a smaller footprint is feasible. The feasible alternatives are then evaluated using a weighted scoring scheme to assist in the final evaluation.

Right of Way

The size of the intersection becomes a critical determinant of suitability, since all alternatives are developed to operate at the same level of efficiency. The intersection sizing (number of lanes) is used to gauge the initial right of way requirements by developing a basic scoring method. While this method cannot provide precise estimates at the preliminary design stage due to topographic or other constraints on the site, it can provide a relative comparison between alternatives. The scoring method provides 5.0 points for an approach with a single lane. A point is deducted for each additional lane added and approaches with five or more lanes receive 0 points. A deduction of 0.5 is made for turn lanes (i.e., left or right auxiliary lanes), since they will likely be required only for a short length. The average score of all approaches for the design is used in the final scoring. An additional deduction of 1.0 point for median U-turn and 2.0 points for jughandle and bowtie designs is made overall due to the increased space requirements for this design. Even though intersection size may be disaggregated into components, including number of approach lanes, intersection number of

lanes, (including auxiliary lanes) and physical intersection area, such a detailed approach was not deemed appropriate for the anticipated level of use of the evaluation tool.

Safety

Intersection safety is measured through conflict prediction models based on the geometry of the intersection, traffic control and the volume of specific turn movements susceptible to potential crash types. Conflict models predict angle conflicts between through traffic and turning traffic, rear end conflicts and sideswipe or lane change conflicts on multi-lane approaches. All conflict types are summed providing a total number of conflicts for each specific alternative. This number of conflicts is then normalized on a scale of 0 to 5 (0 having the poorest performance, i.e., the highest number of conflicts, and 5 having the best performance or fewest conflicts) to allow for alternative scoring and weighting of various design factors. This approach allows for a safety metric sensitive to slight variations among the various design options. This level of sensitivity in the safety analysis, allows for the development of comparisons among the various intersection designs, based on the specific turning movements and constraints at the intersection.

Pedestrians

Intersection types also measure pedestrian intersection safety through conflict prediction models. Conflict models are based on the geometry of the intersection, the pedestrian volume, and the volume of specific turn movements susceptible to potential crash types. The prediction models provide a comparative safety analysis for estimating the effects of each design on pedestrian safety and allowing for the development of comparisons among the various intersection designs. Similar to vehicular safety, pedestrian conflicts are normalized on a scale of 0 to 5 as well.

Bicycle

The suitability to accommodate bicycles for each intersection type is based on the scoring developed by the SAC. As noted above, each intersection type was evaluated independently by the SAC and assigned a score based on the appropriateness of the design for bicyclists.

Access Management

Facilitation of access management by each design was also addressed in a similar manner as that of safety and pedestrian and bike appropriateness, i.e. by developing an appropriateness rating for each intersection type based on the potential of the design to assist in access management. Those intersection designs, which lend themselves to strong access management measures, such as median U-turns or roundabouts, were rated high, as they support restricted turning movements and can improve access management. Additionally, intersection designs which limit the number and length of turn lanes may also be more beneficial for dense access areas as they reduce the functional area of the intersection by permitting access points closer to the point of intersection.

Intersection Scoring

Based on the alternative design scores for each category, a composite score is developed for each intersection design that allows the designer to rank order the potential designs. The composite score is determined by applying a scoring weight to each of the criteria discussed above. The initial weights for each of the evaluation metrics used are considered equal, i.e. each variable accounts for 33 percent of the final score. The safety category includes three subcategories (vehicular, pedestrian and bicycle traffic) and each is weighed equally, i.e. 11 percent of the total score. These weights are adjustable by the user to reflect the relative importance of each category for a given intersection design.

A summary for all of the scores, i.e. ROW, safety, pedestrian/bike, and access management, is provided in Table 13. Figure 6 shows the final design tool and alternative scores.

Table 13 Intersection criteria scores

INTERSECTION ALTERNATIVE	ROW	Veh. Safety	Ped.	Bike	Access Mgmt
2-Way Stop Control	Based on Individual Performance (Range: 0-5)	Based on Individual Performance (Range: 0-5)	Based on Individual Performance (Range: 0-5)	2.5	1.0
4-Way Stop Control				5.0	1.5
Signalized Intersection (1 lanes)				3.5	2.5
Signalized Intersection (2 lanes)				3.0	3.0
Signalized Intersection (3 lanes)				2.0	3.0
Jughandle A EB (1 Lanes)				3.0	3.5
Jughandle A EB (2 Lanes)				2.5	4.0
Jughandle A EB (3 Lanes)				1.5	4.0
Jughandle A WB (1 Lanes)				3.0	3.5
Jughandle A WB (2 Lanes)				2.5	4.0
Jughandle A WB (3 Lanes)				1.5	4.0
Jughandle A EB-WB (1 Lanes)				3.0	3.5
Jughandle A EB-WB (2 Lanes)				2.5	4.0
Jughandle A EB-WB (3 Lanes)				1.5	4.0
Roundabout				4.0	5.0
Median U-Turn (Signalized) (1 Lanes)				2.5	5.0
Median U-Turn (Signalized) (2 Lanes)				2.0	5.0
Median U-Turn (Signalized) (3 Lanes)				1.5	5.0
Median U-Turn (Unsignalized)*				2.5	5.0
Superstreet (Signalized)				1.5	4.0
Superstreet (Unsignalized)				1.5	4.0
Inside Left Turn (Signalized) (NB 'T') (1 Lane)				1.0	3.5
Inside Left Turn (Signalized) (NB 'T') (2 Lane)				1.0	4.0
Inside Left Turn (Signalized) (NB 'T') (3 Lane)				0.5	4.0
Inside Left Turn (Signalized) (SB 'T') (1 Lane)				1.0	3.5
Inside Left Turn (Signalized) (SB 'T') (2 Lane)				1.0	4.0
Inside Left Turn (Signalized) (SB 'T') (3 Lane)				0.5	4.0
Inside Left Turn (Unsignalized) (NB 'T')				1.0	3.0
Inside Left Turn (Unsignalized) (SB 'T')				1.0	3.0
Bowtie (1 Lane)				2.5	5.0
Bowtie (2 Lane)				2.0	5.0
Bowtie (3 Lane)				1.5	5.0

INTERSECTION ALTERNATIVE	OPERATION EVALUATION	MINIMUM LANE CONFIGURATION						RDV	SAFETY				A.M.	SCORE
									Veh.	Ped.	Bike			
		NB	SB	EB	WB	EB U	WB U							
2-Way Stop Control*	Not Feasible							0	0	0	0	0	0	
4-Way Stop Control	Not Feasible							0	4.0	4.0	5.0	1.5	0	
Signalized Intersection (1 lanes)	Feasible							4.4	4.0	4.0	3.5	2.5	3.5	
Signalized Intersection (2 lanes)	Not Recommended							4.3	3.0	3.0	3.0	3.0	3.4	
Signalized Intersection (3 lanes)	Not Recommended							3.8	2.5	2.5	2.0	3.0	3	
Jughandle A EB (1 Lanes)	Feasible							2.4	3.0	2.5	3.0	3.5	2.9	
Jughandle A EB (2 Lanes)	Not Recommended							2.3	2.5	1.5	2.5	4.0	2.8	
Jughandle A EB (3 Lanes)	Not Recommended							1.8	2.0	1.5	1.5	4.0	2.4	
Jughandle A WB (1 Lanes)	Feasible							2.3	3.0	2.5	3.0	3.5	2.8	
Jughandle A WB (2 Lanes)	Not Recommended							2.3	2.5	1.5	2.5	4.0	2.8	
Jughandle A WB (3 Lanes)	Not Recommended							1.9	2.0	1.5	1.5	4.0	2.5	
Jughandle A EB-WB (1 Lanes)	Feasible							2.1	3.0	2.5	3.0	3.5	2.8	
Jughandle A EB-WB (2 Lanes)	Not Recommended							2.1	2.5	1.5	2.5	4.0	2.7	
Jughandle A EB-WB (3 Lanes)	Not Recommended							1.8	2.0	1.5	1.5	4.0	2.4	
Roundabout	Feasible							0	5.0	4.0	4.0	5.0	3.1	
Median U-Turn (Signalized) (1 Lanes)	Not Feasible							0	4.0	3.5	2.5	5.0	0	
Median U-Turn (Signalized) (2 Lanes)	Feasible							2.3	3.0	2.0	2.0	5.0	3.2	
Median U-Turn (Signalized) (3 Lanes)	Not Recommended							1.5	2.5	2.0	1.5	5.0	2.8	
Median U-Turn (Unsignalized)*	Not Feasible							0	4.0	2.5	2.5	5.0	0	
Superstreet (Signalized)	Feasible							1.9	3.5	2.5	1.5	4.0	2.8	
Superstreet (Unsignalized)	Not Feasible							0	3.5	1.5	1.5	4.0	0	
Inside Left Turn (Signalized) (NB 'T') (1 Lane)	Not Feasible							0	4.0	1.0	1.0	3.5	0	
Inside Left Turn (Signalized) (NB 'T') (2 Lane)	Not Feasible							0	3.0	1.0	1.0	4.0	0	
Inside Left Turn (Signalized) (NB 'T') (3 Lane)	Not Feasible							0	2.5	0.5	0.5	4.0	0	
Inside Left Turn (Signalized) (SB 'T') (1 Lane)	Not Feasible							0	4.0	1.0	1.0	3.5	0	
Inside Left Turn (Signalized) (SB 'T') (2 Lane)	Not Feasible							0	3.0	1.0	1.0	4.0	0	
Inside Left Turn (Signalized) (SB 'T') (3 Lane)	Not Feasible							0	2.5	0.5	0.5	4.0	0	
Inside Left Turn (Unsignalized) (NB 'T')*	Not Feasible							0	3.5	1.0	1.0	3.0	0	
Inside Left Turn (Unsignalized) (SB 'T')*	Not Feasible							0	3.5	1.0	1.0	3.0	0	
Bowtie (1 Lane)	Feasible							2.6	3.5	3.5	2.5	5.0	3.6	
Bowtie (2 Lane)	Not Recommended							2.3	2.5	2.5	2.0	5.0	3.2	
Bowtie (3 Lane)	Not Recommended							1.8	2.0	2.0	1.5	5.0	2.8	

Figure 6 Example IDAT output

Appendix C contains a full discussion of and user guide for the Intersection Design Analysis Tool developed by this effort. The tool is available on the KTC website at www.ktc.engr.uky.edu.

SUMMARY AND CONCLUSIONS

Intersections are a critical component of the roadway system and frequently act as choke points on the transportation system. Moreover, intersection crashes account for approximately 30 percent of all crashes in Kentucky (Kentucky State Police, 2007). As a critical component of the state transportation system, intersection design requires an objective methodology to identify the most appropriate solution that meets the purpose and need of the project as well as addresses site constraints. The current state of practice, while achieving great strides in improving the efficiency of Kentucky's roadway system, lacks a systematic, objective and well defined approach to evaluating individual design alternatives.

The outcome of this project improves intersection design practices by 1) expanding the scope of intersection design alternatives considered and 2) providing a structured and objective evaluation process to compare alternative design concepts. This is achieved through the development of the IDAT that is capable of evaluating 13 alternative traffic control and intersection conceptual designs for a given location. IDAT evaluates intersection operations, safety performance (vehicular and pedestrian), bicycle and pedestrian accommodation and the ability to assist access management implementation.

A major component of this effort was the development of methods to size different intersection designs. IDAT identifies the most efficient design (minimum number of lanes) that is capable of meeting a targeted level of operation. As such, the design team will be presented with several options, which meet the minimum operational requirements, allowing examination of other trade-offs such as right of way impacts, safety considerations, etc. This approach will eliminate the need to compare different alternatives with varying performance levels across different types of traffic control measures.

Simulation was utilized to initially determine the various volume metrics for each intersection design to be used as predictors of the delay. This relationship between delays and volume metrics was used to develop the minimum required lane configuration for a given intersection traffic control scheme while achieving a targeted level of capacity once the traffic volumes are determined. Design hour volumes can be used to estimate the minimum lane requirements for each intersection design assuming a level of operation at 90 percent of capacity. This approach allows for developing a comparison where all options will operate at similar levels.

Safety estimates were also developed for vehicle and vehicle-pedestrian conflicts that could allow for establishing the potential safety performance of the intersections considered. Safety performance of the intersection was quantified by estimating the potential conflicts for

each intersection design alternative evaluated for a given scenario. The models were developed by applying SSAM on a series of simulated scenarios for each design option. SSAM identifies potential conflicts that could result in a crash which can be then be linked to the geometric and traffic demand characteristics of the intersection. A variety of volume combinations were used for each scenario simulated and models were developed that allow the user to predict the number of potential conflicts for each design alternative for a given set of design volumes. Models for vehicular and vehicle-pedestrian conflicts were developed separately and incorporated in the IDAT for screening design alternatives and allowing for a complete and systematic approach for identifying appropriate intersection designs.

The tool developed here could be used in preliminary evaluations in order to determine the most appropriately sized options to be explored in greater detail. Detailed analysis of each recommended option is strongly recommended to accurately estimate the operation of each design. The comparisons of simple and complicated designs through the proposed tool are valid and allowable, since it only compares their potential operational level and safety implications at a common ground. The tool is capable of identifying simpler solutions that could address a situation without having to resort to expensive, multi-lane designs. The use of a targeted value, in this case v/c of 0.90, avoids comparing options with differing operational levels which could be more difficult to compare and often highly subjective. An additional benefit of the tool is the ability to relatively evaluate intersection designs with respect to safety performance through the use of potential conflict. This provides for a complete and systematic approach for identifying appropriate intersection designs.

IDAT allows for the identification of the optimal design through a preliminary evaluation and comparison of several intersection designs and provides a more robust safety comparison for the design considered through prediction of the number of conflicts for vehicles and pedestrians. These two metrics allow for an objective evaluation of the alternatives, since they are based on current operational capacity practices, safety prediction models, and size based on number of lanes. Therefore, the proposed tool clearly utilizes objective metrics and thus can provide an accurate list of feasible alternatives for further analysis and evaluation.

The software developed as part the study is ready to be distributed for use to the practitioners. The software allows for the preliminary evaluation of all intersection designs considered and provides a basic method for comparing all of them at an equal level of operation. The software also provides a more robust safety evaluation method for at-grade intersections predicting the number of conflicts for vehicles and pedestrians for each design considered.

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APPENDIX A
ALTERNATIVE INTERSECTION DESIGN SUMMARY

TRADITIONAL SIGNALIZED INTERSECTION

A traditional signalized intersection is the standard intersection treatment for mid to high volume at-grade intersections. KYTC currently maintains over 2500 traffic signal installations. The MUTCD maintains warrants for the use and implementation of traffic signal control.

Geometric Design

Signalized intersections can have three or more legs, though intersections with greater than four legs may be problematic due to design and operational considerations. Intersection angle is typically recommended between 75 and 115 degrees. Typically the number of through lanes on the roadway will be maintained through the intersection, with auxiliary left and/or right turn lanes added at the intersection as needed for capacity. Auxiliary through lanes may also be added to accommodate through traffic under special conditions.

Traffic Control

Control is provided by the use of a traffic control signal, which assigns right-of-way based on pre-timed patterns or on-demand when used in conjunction with vehicle detectors.

Considerations

- The traditional signalized intersection assumes that pedestrian phases will be provided to allow for crossing. However, no median islands are included to act as refuge for crossing wider designs.
- It is generally assumed that the greater the number of through lanes the greater vehicular and pedestrian safety risk due to increased potential for sideswipe crashes and the longer crossing distance for ped/bike.
- Signalized intersections are typically neutral in improving access management. Presence of turning lanes may affect access management.

Resources

Manual of Uniform Traffic Control Devices. Federal Highway Administration. Washington, D.C., 2009.

KYTC Highway Design Manual. KYTC Division of Design. Frankfort, KY.

http://transportation.ky.gov/design/designmanual/Design_Manual.html

ALL-WAY STOP-CONTROLLED INTERSECTION

All -way stop control requires that all approaches to an intersection come to a complete stop. All-way stop control is used where the volume of traffic on the intersecting roads is approximately equal. This intersection typically operates at lower capacity than other fully controlled designs, though it does provide a high level of safety if adequate sight distance and other geometric features are present.

Geometric Design

Stop-controlled intersections can have three or more legs, though intersections with greater than four legs may be problematic due to operational considerations. Stop control operates best with single lane approaches or at a minimum a single lane for each movement. Wide approaches having more than one through lane provide decreased visibility of the stop sign and can deter from drivers anticipation of the need to stop.

Traffic Control

Control is provided by the use of a stop sign (R1-1), which may be supplemented by advance warning signs and/or supplemental plaques.

Considerations

- All-way stop-controlled intersections may pose problems to drivers in understanding right of way but they also have slower speeds that may be compensatory.
- All-way stop-controlled intersections may pose access management problems in high volume conditions due to backups.

Resources

Manual of Uniform Traffic Control Devices. Federal Highway Administration. Washington,D.C., 2009.

KYTC Highway Design Manual. KYTC Division of Design. Frankfort, KY.

http://transportation.ky.gov/design/designmanual/Design_Manual.html

MULTI-WAY STOP-CONTROLLED INTERSECTION

Multi-way stop control provides stop control on minor approaches while allowing the major street to proceed uncontrolled. Multi-way stop control is used where the volume of traffic on the intersecting roads is low. This intersection typically can accommodate a high volume of traffic on the major street, but may experience higher delays and potential safety concerns for the minor approach.

Geometric Design

Stop-controlled intersections can have three or more legs, though intersections with greater than four legs may be problematic due to operational considerations. Stop control operates best with single lane approaches or at a minimum a single lane for each movement. Wide approaches have more than one through lane providing decreased visibility of the stop sign, and can deter from drivers anticipation of the need to stop.

Traffic Control

Control is provided by the use of a stop sign (R1-1), which may be supplemented by advance warning signs and/or supplemental plaques.

Considerations

- Multi-way stop control may pose problems to cross traffic (vehicular, bicycle, and pedestrian) due to large main street volumes.
- For pedestrians the absence of any median may cause additional concerns.
- Multi-way stop control may pose access management problems due to backups on the side street.

Resources

Manual of Uniform Traffic Control Devices. Federal Highway Administration. Washington, D.C., 2009.

KYTC Highway Design Manual. KYTC Division of Design. Frankfort, KY.

http://transportation.ky.gov/design/designmanual/Design_Manual.html

MODERN ROUNDABOUT

The modern roundabout is a circulatory at-grade intersection design that uses yield control on entry. Studies throughout the US and Kentucky demonstrate that when a roundabout is designed properly significant safety, operational, and cost benefits can be achieved over other types of intersection control. Research also substantiates that when improperly designed or implemented, roundabouts can experience higher crash rates, high operational delays, and increased costs.

Geometric Design

Roundabouts can have three or more legs, though intersections with greater than four legs may be problematic due to geometric design considerations. Roundabouts may be designed with a multiple approach and circulating lanes, which may be supplemented with auxiliary lanes at the intersection. Roundabout geometry is a primary controlling factor in both the operations and safety of the intersection, and is controlled by numerous factors such as entry deflection and entry angle and entry/exit path alignments.

Traffic Control

Control is provided by the use of a yield sign (R1-2) on the approach, providing uncontrolled movement for vehicles within the circulatory roadway.

Considerations

- Roundabout pedestrian crossings provide a median refuge and place pedestrians in front of approaching vehicles, though pedestrians may have trouble finding an appropriate time to cross the intersection. Travel distances are also typically longer.
- Bicycles are assumed to share the travel lanes with vehicles.
- Roundabouts can typically enhance access management by accommodating U-turns.
- Lack of driver education may be a problem temporarily.

Resources

Manual of Uniform Traffic Control Devices. Federal Highway Administration. Washington, D.C., 2009.

KYTC Highway Design Manual. KYTC Division of Design. Frankfort, KY.

http://transportation.ky.gov/design/designmanual/Design_Manual.html

MEDIAN U-TURN (SIGNALIZED)

The median U-turn design gains capacity by eliminating left-turns at the major intersection. Left turns use U-turn crossovers near the intersection. This intersection will have a larger footprint than other intersection designs due to the U-turn location on the major street and space needed to accommodate large U-turning vehicles.

Geometric Design

The Median U-turn design requires a wider median in which to make efficient U-turn movements for both autos and trucks. AASHTO

provides guidance on median requirements based on number of lanes and design vehicles.

Deciding the appropriate distance from a major crossroad intersection to the first U-turn crossover opportunity is a trade-off between providing a sufficient U-turn storage bay length (to minimize spillback potential) and keeping the left-turning path length short.

Traffic Control

The Median U-turn design greatly simplifies major intersection signal operations as direct left turn movements are prohibited at the major intersections, creating a simple two-phase plan.

Signing is particularly important for safe and efficient operations of the Median U-turn design. The most common and widely accepted signing is the "fishhook" design, used at the main intersections and at major crossover locations. Other regulatory signing requirements are similar to any conventional median highway.

Considerations

- Signalized median U-turn designs could provide pedestrian phase to facilitate crossing.
- For bicyclists, the extra length traveled may be detrimental and encourage them to act as pedestrians or use alternative means for crossing.
- The presence of median can enhance access management.
- Left turn traffic may experience longer travel distances and times.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Bared, J. Median U-Turn intersection Federal Highway Administration Publication FHWA-HRT-09-057. 2009.

MEDIAN U-TURN (UNSIGNALIZED)

An unsignalized median U-turn design operates the same as the signalized option discussed above, but does not provide for left or through movements from the minor street. The unsignalized option may be preferred at low-volume minor streets, which experience significant delays for through or left turning traffic.

Geometric Design

The Median U-turn design requires a wider median in which to make efficient U-turn movements for both autos and trucks. AASHTO provides guidance on median requirements based on number of lanes and design vehicles.

Deciding the appropriate distance from a major crossroad intersection to the first U-turn crossover opportunity is a trade-off between providing a sufficient U-turn storage bay length (to minimize spillback potential) and keeping the left-turning path length short.

Traffic Control

Under this design, both the right turns on the minor approaches and U-turn movements are controlled by stop signs. Signing is particularly important for safe and efficient operations of the Median U-turn design. The most common and widely accepted signing is the "fishhook" design, used at the main intersections and at major crossover locations. Other regulatory signing requirements are similar to any conventional median highway.

Considerations

- Unsignalized median U-turn designs could pose problems for pedestrians due to lack of pedestrian phase but the presence of the median may compensate for this.
- Pedestrians have to cross one direction at a time but traffic will not stop for them.
- For bicyclists, the extra length traveled may be detrimental and encourage them to act as pedestrians or use alternative means for crossing.
- The presence of median can enhance access management.
- Minor Street traffic may experience longer travel distances and times.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Bared, J. Median U-Turn intersection Federal Highway Administration Publication FHWA-HRT-09-057. 2009.

SUPERSTREET (SIGNALIZED)

The superstreet intersection is characterized by the prohibition of left-turn and through movements from side street approaches as permitted in conventional designs. Instead, the design accommodates these movements by requiring drivers to turn right onto the main road and then make a U-turn maneuver after the intersection. Left turns from the main road approaches are executed in a manner similar to left turns at conventional intersections

Geometric Design

Desirable minimum median widths between 40 and 60 ft. are typically needed to accommodate large trucks so that they do not encroach on curbs or shoulders. RCUT intersections with narrower medians need bulb-outs or loons at U-turn crossovers.

The spacing from the main intersection to the U-turn crossover varies in practice. The American Association of State Highway and Transportation Officials recommend a spacing of 400 to 600 ft.

Pedestrian crossings of the major road at the Superstreet intersection are usually accommodated on one diagonal path from one corner to the opposite corner (see 5).

Traffic Control

A conventional four-approach intersection essentially becomes two independent T-intersections. This independence allows each direction of the arterial to have independent signal control (including different cycle lengths, if desired) so that "perfect" progression can be achieved in both directions at any time at any intersection spacing.

Considerations

- Pedestrians can make safer but slower (two-stage) crossings of the arterial.
- For bicyclists, the extra length traveled may be detrimental and encourage them to act as pedestrians or use alternative means for crossing.
- The presence of median can enhance access management.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Bared, J. Restricted Crossing U-turn Intersection. Federal Highway Administration Publication FHWA-HRT-09-059. 2009.

SUPERSTREET (UNSIGNALIZED)

The unsignalized superstreet intersection operates the same as the signalized design discussed above. Application of the unsignalized superstreet design may be most beneficial when minor street volumes are low, but access control is needed along the major street.

Geometric Design

Desirable minimum median widths between 40 and 60 ft. are typically needed to accommodate large trucks so that they do not encroach on curbs or shoulders. RCUT intersections with narrower medians need bulb-outs or loons at U-turn crossovers.

The spacing from the main intersection to the U-turn crossover varies in practice. The American Association of State Highway and Transportation Officials recommend a spacing of 400 to 600 ft.

Pedestrian crossings of the major road at the RCUT intersection are usually accommodated on one diagonal path from one corner to the opposite corner.

Traffic Control

As with the unsignalized median U-turn design, the minor street and U-turn approaches are stop-controlled in addition to the left turn from the major street.

Considerations

- Unsignalized superstreet designs could pose problems for pedestrians due to lack of pedestrian phase but the presence of the median may compensate for this.
- Pedestrians have to cross one direction at a time but traffic will not stop for them.
- For bicyclists, the extra length traveled may be detrimental and encourage them to act as pedestrians or use alternative means for crossing which may be less safe than the intended design.
- The presence of median can enhance access management.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Bared, J. Restricted Crossing U-turn Intersection. Federal Highway Administration Publication FHWA-HRT-09-059. 2009.

INSIDE LEFT-TURN (SIGNALIZED)

The inside left turn or continuous green-T can only be used at T-intersections. The design provides free-flow operations in one direction on the arterial and can reduce the number of approach movements that need to stop to three by using free-flow right turn lanes on the arterial and cross streets and acceleration/merge lanes for left turn movements from the cross street.

Geometric Design

The primary consideration in the design is the merging of left turn traffic from the cross street into the free-flow lane. The length of the acceleration and merge length is dependent upon the speed of the facility and volume of progressing and merging traffic. Arterial right-of-way requirements for both CGT design variations are modest. A wider median is needed on the arterial in the merge-lane design to accommodate the merge and taper.

Traffic Control

The Continuous Green T-intersection is designed so that one direction of the main through-roadway does not have to stop. Arterial progression is more likely to be optimal (in the direction with signal control) when intersection demands for left turns to and from the T-approach are moderate to low.

The Continuous Green T-intersection is not conducive to pedestrian crossings, as pedestrians would have to cross a least two lanes of moving traffic without the aid of a signal. None of the Continuous Green T-intersections identified in a nationwide survey attempted to include provisions for pedestrian crossings.

Considerations

- Continuous green intersection designs could pose problems for pedestrians due to lack of any protection while crossing, other than the presence of the median.
- The presence of median can enhance access management but absence of U-turn accommodation may be detrimental.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Applied Technology and Traffic Analysis Program, Unconventional Arterial Intersection Design. Maryland State Highway Agency. 2004.

INSIDE LEFT-TURN (UNSIGNALIZED)

The unsignalized inside left turn can only be used at T-intersections and operates similarly to the signalized design option. This option can provide for efficient operations where left turn volumes do not meet traffic signal warrants, but adequate gaps on the major street do not accommodate left turns. This

This design can increase capacity by allowing traffic to only cross a single direction at a time.

Geometric Design

The primary consideration in the design is the merging of left turn traffic from the cross-street into the free-flow lane. The length of the acceleration and merge length is dependent upon the speed of the facility and volume of progressing and merging traffic. Arterial right-of-way requirements for both CGT design variations are modest. A wider median is needed on the arterial in the merge-lane design to accommodate the merge and taper.

Traffic Control

The inside left turn intersection is not conducive to pedestrian crossings, as pedestrians would have to cross a least two lanes of moving traffic without the aid of a signal.

Considerations

- Continuous green intersection designs could pose problems for pedestrians due to lack of any protection while crossing other than the presence of the median.
- The presence of median can enhance access management but absence of U-turn accommodation may be detrimental.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Applied Technology and Traffic Analysis Program, Unconventional Arterial Intersection Design. Maryland State Highway Agency. 2004.

JUGHANDLE

The jughandle design eliminates left turns from the major street by redirecting them either before or after the major intersection. The Jughandle ramps diverge from the right side of the arterial in advance of the intersection, removing the left turn movement from directly at the cross-street intersection. Arterial left turns are made at minor, stop-controlled intersections on the cross-street. Left turns from the cross-street remain as direct movements at the intersection.

Geometric Design

Right-of-way requirements along the arterial can be significantly less (10 to 20 feet) compared to a conventional median-divided roadway as the width requirements for median left turn pockets in both directions is eliminated; however, right-of-way requirements at the Jughandle intersections can be much greater.

Traffic Control

Intersections along the arterial often are controlled by two-phase signals; a third phase can be required for left turns from the cross street if the volume is heavy, but the Jughandle design always eliminates the direct left turn movement and signal phase on the arterial. Ramp terminals are typically stop-controlled for left turns and yield-controlled for channelized right turns.

Considerations

- Jughandle designs may pose problems for pedestrians due to the need to cross the uncontrolled jughandle movement downstream of the intersection.
- For bicycles, the longer distance to be traveled may become detrimental to the use of the design and encourage bicyclists to come with alternative crossings.
- A jughandle intersection may improve access management options along the main street but affect negatively the side street.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Applied Technology and Traffic Analysis Program, Unconventional Arterial Intersection Design. Maryland State Highway Agency. 2004.

BOWTIE

The Bowtie Intersection uses roundabouts on the cross street to accommodate left turns, instead of directional crossovers across a wide median. Left turns are prohibited at the main intersection, and the main intersection signal is reduced to a simple two-phase operation.

Geometric Design

The Bowtie Intersection was developed to overcome the wider arterial right-of-way requirements of other unconventional intersection design alternatives.

As per modern roundabout standards, the Bowtie Intersection roundabouts may have diameters between 90 and 300 feet, depending on speed, volume, number of approaches and the design vehicle. The distance from the roundabout to the main intersection may vary from 200 to 600 feet, with trade-offs between spillback potential and travel distance for left-turning vehicles.

Traffic Control

Intersections along the arterial are controlled by two-phase signals to control the right-turn and through movements on the major and minor approaches. At the roundabout vehicles yield upon entry to the roundabout; however, if the roundabout has only two entrances, the entry from the main intersection does not have to yield. The distances between the roundabouts and downstream signalized intersections should be great enough that potential queuing at the roundabout approaches does not spill back to the signalized intersection.

Considerations

- Bowtie designs could provide pedestrian phase to facilitate crossing.
- For bicyclists, the extra length traveled may be detrimental and encourage them to use alternative means for crossing.
- The potential for cross street traffic at the roundabouts may pose problems for vehicles.
- A bowtie intersection may improve access management options along the main street but negatively affect the side street.

Resources

American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets*, Washington, DC. 2004.

Applied Technology and Traffic Analysis Program, Unconventional Arterial Intersection Design. Maryland State Highway Agency. 2004.

APPENDIX B
STATE DOT INTERSECTION DESIGN GUIDANCE

Table B-1: State Intersection Design Guidance

State	Intersection Design Guidance
Alaska	Design policy follows the AASHTO Green Book. http://www.dot.state.ak.us/stwddes/dcsprecon/assets/pdf/preconhwy/ch11/chapter11.pdf
California	Design considerations identified as driver, vehicle, environment, pedestrian, bicyclist, capacity, accident data, preference to major movements, areas of conflict, and angle of intersection. http://www.dot.ca.gov/hq/oppd/hdm/pdf/chp0400.pdf
Colorado	Intersection design based on capacity analysis and Highway Capacity Manual, alignment and grade. http://www.dot.state.co.us/DesignSupport/Design%20Guide%2005/DG05%20Ch%2009%20Intersections.pdf
Connecticut	Traffic Control and Intersection Design Manual provides preliminary considerations for signal installations and the use of dual left turn lanes. http://www.ct.gov/dot/lib/dot/Documents/dpublications/Preliminary_Considerations.pdf
Delaware	Primary considerations are perception-reaction distance, maneuver distance, and queue storage distance. Project intersection design configurations are developed during the project development phase based upon capacity analysis, accident studies, pedestrian use, bicycle use and transit options. In addition, design-hour turning movements, size and operating characteristics of the predominant vehicles, types of movements that must be provided, vehicle speeds, and existing and proposed adjacent land-use are considered. MUTCD is used to warrant traffic control devices. http://www.deldot.gov/information/pubs_forms/manuals/road_design/pdf/07_intersections.pdf
Florida	A separate intersection design guide was developed including guidance for identifying requirements and providing guidelines for selecting a design when there are alternatives. MUTCD is used for signalization. http://www.dot.state.fl.us/rddesign/FIDG-Manual/FIDG2007.pdf

Table B-1: State Intersection Design Guidance (continued)

State	Intersection Design Guidance
Georgia	<p>Intersection size based on design speed, and storage requirements for turning lanes. Several basic parameters considered in determining the appropriate corner and control radii and length of median opening including: intersection angle, number and width of lanes, design vehicle turning path, clearances, encroachment into oncoming or opposing lanes, parking lanes, shoulders, and pedestrian needs.</p> <p>Signalization depends on existing and projected traffic volumes, including turning percentages. Must also conform to the GDOT's TOPPS 6785-1, Traffic Signals.</p> <p>http://wwwb.dot.ga.gov/dpm/desmanual/ch07/ch07.5.html http://wwwb.dot.ga.gov/dpm/desmanual/ch07/Ch07.1.html</p>
Idaho	<p>Uses the MUTCD to warrant traffic control and the Green Book for intersection design.</p> <p>http://itd.idaho.gov/manuals/Downloads/design.htm</p>
Illinois	<p>General design controls include intersection alignment, profiles, capacity analysis, design vehicles, pedestrian and bicycles, turning radii.</p> <p>http://www.dot.il.gov/blr/manuals/Chapter%2034.pdf</p>
Indiana	<p>General design controls for intersection design are design speed, intersection alignment, intersection profile, cross-section transition, vertical profile, capacity, level of service, and design vehicle.</p> <p>Conforms to the MUTCD for traffic control.</p> <p>http://www.in.gov/dot/div/contracts/design/mutcd/mutcd.html http://www.in.gov/dot/div/contracts/standards/dm/english/Part5Vol1/ECh46/ch46.htm</p>
Iowa	<p>Iowa DOT provides specific design procedures for unsignalized intersections on Rural Two-Lane roads. These procedures concentrate on providing minimum turning radii for the design vehicle. Individual guidance was not identified for multi-lane and urban roadways. The MUTCD is used to warrant traffic control devices.</p> <p>http://www.iowadot.gov/design/dmanual/06a-01.pdf</p>

Table B-1: State Intersection Design Guidance (continued)

State	Intersection Design Guidance
Kansas	<p><u>Intersection Control</u> Two-way stop control at intersections unless a traffic investigation and guidelines from the MUTCD indicate otherwise.</p> <p>New intersection primarily based on traffic volumes. Crash history is used for existing locations.</p> <p><u>Lane Configuration and Intersection Size</u> Peak hour turning movements are used to determine lane configuration, particularly when determining if auxiliary lanes are used.</p> <p>Right of way, utilities, funding are variables which may limit what can be done regarding lane configuration and intersection size.</p> <p><i>(Based on conversation with Brian Gower of the KDOT office of Design).</i></p>
Kentucky	<p>Several factors for intersection design are used including: character and use of the adjoining property, vertical alignments of the intersecting roadways, sight distance, angle of the intersection, conflict areas, traffic control devices, lighting equipment, environmental factors, and crosswalks.</p> <p>Three intersection types identified: three-leg, four-leg, and multi-leg. Central Office has final decision on when a traffic control device is warranted.</p> <p>http://transportation.ky.gov/design/designmanual/chapters/12Chapter%200900%20AS%20PRINTED%202006.pdf</p>
Louisiana	<p>Turning lanes are designed based on turning volumes, traffic volumes, reduced accident potential, and increased operational efficiency. MUTCD is used to warrant traffic control and a study must be done on intersection geometry and traffic flow.</p> <p>http://www.dotd.louisiana.gov/highways/project_devel/design/road_design/road_design_manual/Road_Design_Manual_(Full_Text).pdf</p>
Maryland	<p>Follows AASHTO Green Book. There is a traffic control guidance for signalization and other controls that follows MUTCD guidelines. Software has been produced that identifies and explains unconventional intersection designs.</p> <p>http://www.sha.maryland.gov/businesswithsha/bizStdsSpecs/desManualStdPub/publicationsonline/oos/TCDDM/default.asp</p> <p>http://attap.umd.edu/bbs/zboard.php?id=projects&select_arrange=headnum&desc=asc&page_num=5&selected=&exec=&sn=off&ss=on&sc=off&category=10&ss=on&ss=on&keyword</p>

Table B-1: State Intersection Design Guidance (continued)

State	Intersection Design Guidance
Massachusetts	<p>MUTCD used to warrant traffic control devices. Capacity and Level of Service must be determined for intersections, based on Highway Capacity Manual. Design vehicles, alignment, profile and vehicular safety are also considered.</p> <p>http://www.mhd.state.ma.us/downloads/manuals/design.pdf</p>
Michigan	<p>Angle of intersection, grade, and sight distances are considered in intersection design.</p> <p>http://mdotwas1.mdot.state.mi.us/public/design/englishroadmanual/</p>
Minnesota	<p>Design considerations include: desirable traffic controls, capacity analysis, degree of access control for facility, pedestrian traffic, bicycle traffic, and lighting warrants. The road design guide references MN/DOT Traffic Engineering Manual, MN MUTCD, Highway Capacity Manual, MN Bike Transportation Plan and Design Guidelines, and AASHTO's A Policy on Geometric Design of Highways and Streets.</p> <p>http://www.dot.state.mn.us/design/rdm/english/5e.pdf</p>
Mississippi	<p>Intersection design considerations include: design vehicle, horizontal alignment, profile, capacity, and level of service.</p> <p>MUTCD used to warrant traffic control devices.</p> <p>http://www.gomdot.com/Divisions/Highways/Resources/RoadwayDesign/pdf/Manual/2001/chapter06.pdf</p>
Missouri	<p>Capacity and sight distance are the factors used in intersection design.</p> <p>MUTCD used to warrant traffic control devices.</p> <p>http://epg.modot.mo.gov/index.php?title=Category:233_At_Grade_Intersections</p>
Montana	<p>Intersection design controls include: capacity, level of service, design vehicle, intersection spacing, intersection alignment, intersection profile, and turning radii.</p> <p>MUTCD used to warrant traffic control devices.</p> <p>http://www.mdt.mt.gov/other/roaddesign/external/montana_road_design_manual/13_intersection_at-grade.pdf</p> <p>http://www.mdt.mt.gov/other/traffic/external/pdf/chapter_12.pdf</p>

Table B-1: State Intersection Design Guidance (continued)

State	Intersection Design Guidance
Nebraska	<p>MUTCD used to warrant traffic control devices.</p> <p>Design considerations include capacity and level of service, sight distance, horizontal alignment, intersection skew, profile, design vehicle, and radius returns.</p> <p>http://www.nebraskatransportation.org/roadway-design/pdfs/rwydesignman.pdf</p>
Nevada	<p>Intersection design controls include: angles, grades, grading, and design vehicle path.</p> <p>Follows the MUTCD for traffic control.</p> <p>http://www.nevadadot.com/divisions/pdfs/010/2009designguide.pdf</p>
New Hampshire	<p>MUTCD used to warrant traffic control devices.</p> <p>http://www.nh.gov/dot/org/projectdevelopment/highwaydesign/designmanual/documents/HDMchapter05.pdf</p>
New Jersey	<p>General design considerations are capacity, spacing, alignment, profile, cross section, sight distance, turning movements, and channelization.</p> <p>MUTCD used to warrant traffic control devices.</p> <p>http://www.state.nj.us/transportation/eng/documents/RDM/sec6.shtm#generaldesignconsid http://www.state.nj.us/transportation/eng/documents/RDME/sect12E2001.shtm</p>
New York	<p>Green Book should be followed to determine the type of intersection to be used. Design considerations include: capacity and level of service, intersection geometrics, channelization, and sight distance.</p> <p>https://www.nysdot.gov/divisions/engineering/design/dqab/hdm/hdm-repository/chapt_05.pdf</p>
North Carolina	<p>AASHTO Green Book used for design guidance.</p> <p>http://www.ncdot.org/doh/preconstruct/altern/value/manuals/designmanual.html</p>
North Dakota	<p>MUTCD used to warrant traffic control devices.</p> <p>http://www.dot.nd.gov/manuals/design/designmanual/chapter3/DM-3-12_tag.pdf</p>
Ohio	<p>Ohio MUTCD used to warrant traffic control devices.</p> <p>http://www.dot.state.oh.us/Divisions/HighwayOps/Traffic/publications2/TEM/Documents/Part_04%20complete_011609%20Revision_020209%20file_bookmarked%20020309.pdf</p>

Table B-1: State Intersection Design Guidance (continued)

State	Intersection Design Guidance
Oregon	<p>AASHTO Green Book is used for design guidance. Includes consideration for pedestrian and bicyclists to be addressed in intersection design. A section devoted to roundabout design is also included as part of the design manual.</p> <p>ftp://ftp.odot.state.or.us/techserv/roadway/web_drawings/HDM/Rev_E_2003Chp09.pdf</p>
Pennsylvania	<p>MUTCD used to warrant traffic control devices.</p> <p>ftp://ftp.dot.state.pa.us/public/bureaus/design/Pub70M/Chapters/Chap02.pdf</p>
Rhode Island	<p>Design parameters include: design speed, level of service, terrain, and functional classification, type of improvement, control of access, design vehicle, traffic volumes, truck percentages, traffic projections, and capacity. Economics, safety, and environment are also considered.</p> <p>https://www.pmp.dot.ri.gov/PMP/DesktopDefault.aspx?aM=udoc&oM=list&c1P=cat&c2p=docs&appindex=0&appid=0&podid=-1&mth=1&label=Manual%20-%20Highway%20Des...#pageAnchor5</p>
South Carolina	<p>Design controls include: human factors, capacity, actual traffic volumes, ADT and/or DHV, vehicular composition, turning movements, vehicular speeds, transit involvement, crash history, bicycle and pedestrian movements. It also includes physical elements such as character and use of abutting property, right of way, vertical profiles, horizontal and vertical alignments, sight distance, intersection area, conflict area.</p> <p>MUTCD used to warrant traffic control devices.</p> <p><i>(based on email from Rob Bedenbaugh SCDOT)</i></p>
South Dakota	<p>Design criteria include: level of service, alignment, profile, width, radii, turning movements, design vehicles, encroachment, volumes, and channelization.</p> <p>http://www.sddot.com/pe/roaddesign/docs/rdmanual/rdmch12.pdf</p>
Tennessee	<p>MUTCD used to warrant traffic control devices.</p> <p>http://www.tdot.state.tn.us/Chief_Engineer/assistant_engineer_design/design/Traffic_Design_Manual.pdf</p>
Texas	<p>Capacity analysis is very important in intersection design. Traffic volumes, operational characteristics, and type of traffic control are key factors in geometric design. Intersection sight distance is also important.</p> <p>http://onlinemanuals.txdot.gov/txdotmanuals/rdw/rdw.pdf</p>
Utah	<p>Controls include: design vehicle, cross sections, projected traffic volumes, pedestrian traffic, speed, and traffic control devices.</p> <p>http://www.dot.state.ut.us/main/f?p=100:pg:0:::1:T,V:1498,</p>

Table B-1: State Intersection Design Guidance (continued)

State	Intersection Design Guidance
Vermont	<p>Adheres to MUTCD for traffic control devices.</p> <p>http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/910.pdf</p>
Washington	<p>Design manual references MUTCD, AASHTO Green Book and the Highway Capacity Manual. Non-geometric factors include: perception, contrast, and driver age. Geometric considerations include: intersection angle, lane alignment, intersection spacing, design vehicle, and sight distance.</p> <p>http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/910.pdf</p>
Wisconsin	<p>Design factors include: current and expected volumes on the crossroad, length of the crossroad, function of the through road, safety. MUTCD used to warrant traffic control devices.</p> <p>http://roadwaystandards.dot.wi.gov/standards/fdm/11-25-001.pdf</p>
Wyoming	<p>Uses MUTCD to warrant traffic control devices.</p> <p>http://dot.state.wy.us/Default.jsp?sCode=infrd</p>

Table B-2: State Roundabout Guidance and Policies

State	Roundabout Guidance/Policy
Arizona	Modern Roundabout Information Site http://www.dot.state.az.us/CCPartnerships/Roundabouts/
California	Design Information Bulletin for Roundabouts http://www.dot.ca.gov/hq/oppd/dib/dib80-01.htm#attachmenta
Delaware	FHWA Roundabout Guide
Florida	Roundabout Guide http://www.dot.state.fl.us/TrafficOperations/Doc_Library/PDF/roundabout_guide8_07.pdf
Georgia	Roundabout Policy FHWA Roundabout Guide for design guidelines http://www.dot.state.ga.us/travelingingeorgia/roundabouts/Pages/Policy.aspx
Kansas	Roundabout Guide (supplement to FHWA Roundabout Guide) http://www.ksdot.org:9080/burtrafficeeng/Roundabouts/Roundabout_Guide/RoundaboutGuide.asp
Maryland	Roundabout Safety Information http://www.sha.state.md.us/safety/oos/roundabouts/safety.asp
Minnesota	Roundabout Guide http://www.dot.state.mn.us/design/rdm/english/12e.pdf
Missouri	Roundabout Guide (supplement to FHWA Roundabout Guide) http://epg.modot.mo.gov/index.php?title=233.3_Roundabouts
Nebraska	FHWA Roundabout Guide http://www.nebraskatransportation.org/roadway-design/pdfs/rwydesignman.pdf
New Hampshire	Roundabout Guide (supplement to FHWA Roundabout Guide) http://www.nh.gov/dot/org/projectdevelopment/highwaydesign/roundabouts/documents/RoundaboutFundamentals.pdf
New York	Roundabout Design Guidance https://www.nysdot.gov/main/roundabouts/guide-engineers
State	Roundabout Guidance/Policy

Oregon	Roundabout Guide http://www.oregon.gov/ODOT/TD/TP_RES/docs/Reports/ModernRoundAbout.pdf
Pennsylvania	Roundabout Guide ftp://ftp.dot.state.pa.us/public/bureaus/design/GuideToRoundabouts.pdf
Utah	FHWA Roundabouts Guide http://www.udot.utah.gov/main/f?p=100:pg:4318999853036894:::1:T,V:1498
Washington	Roundabouts integrated in highway design manual http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/915.pdf
Wisconsin	Roundabout Design Information http://www.dot.wisconsin.gov/safety/motorist/roaddesign/roundabout-design.htm

APPENDIX C

USER'S GUIDE

Introduction

The purpose of this document is to summarize the input requirements, output analysis procedures and intended use of the Intersection Design Analysis Tool (IDAT) developed for the Kentucky Transportation Cabinet. IDAT provides an objective method for sizing and selecting conceptual intersection design alternatives. In total it evaluates 13 different intersection design alternatives with major street lane configuration including one, two and three through streets and eight different auxiliary lane configurations. IDAT provides the minimum lane configuration (i.e., minimum number of through lanes and minimum number of auxiliary lanes) for each alternative that is capable of operating at 90 percent of available capacity. These conceptual designs are then evaluated against three primary criteria: Safety, Right of Way requirements and Access Management. The following sections of this document identify the input methods and output analysis for the developed tool. Further discussion of the background of the development approach and related research can be found in KTC Research Report No. KTC-12-04/SPR 09-380-1F. "Improving Intersection Design Practices" available at www.ktc.engr.uky.edu.

User's Guide

The first version of the evaluation tool developed is relatively simple and is based on Microsoft Excel. Figure B-1 shows a screen capture of the main screen.

Figure 1: Intersection Design Tool Primary Screen.

INTERSECTION ALTERNATIVE	OPERATION EVALUATION	MINIMUM LANE CONFIGURATION						SAFETY					SCORE
		NB	SB	EB	WB	EB+WB	WB+WB	ROR	A.M.	A.M.			
2-Way Stop Control	Not Feasible							0.33	0.11	0.11	0.33	0.00	
4-Way Stop Control	Not Feasible							0.00	4.9	4.72	2.50	1.00	0.00
Signalized Intersection (1 Lane)	Not Feasible							0.00	5.0	4.62	3.50	2.50	0.00
Signalized Intersection (2 Lanes)	Feasible							2.50	5.0	2.89	2.00	3.00	3.34
Signalized Intersection (3 Lanes)	Not Recommended							3.50	4.9	2.49	2.00	3.00	3.18
Jughandle A EB (1 Lane)	Not Feasible							0.00	5.0	4.69	3.00	3.50	0.00
Jughandle A EB (2 Lanes)	Feasible							1.63	5.0	3.84	2.50	4.00	3.10
Jughandle A EB (3 Lanes)	Feasible							1.38	5.0	3.45	1.50	4.00	2.87
Jughandle A WB (1 Lane)	Not Feasible							0.00	5.0	4.69	3.00	3.50	0.00
Jughandle A WB (2 Lanes)	Feasible							1.50	5.0	4.22	2.50	4.00	3.10
Jughandle A WB (3 Lanes)	Feasible							1.38	4.9	4.22	1.50	4.00	2.94
Jughandle A EB+WB (1 Lane)	Not Feasible							0.00	5.0	4.69	3.00	3.50	0.00
Jughandle A EB+WB (2 Lanes)	Feasible							2.00	5.0	4.06	2.50	4.00	3.25
Jughandle A EB+WB (3 Lanes)	Not Recommended							1.50	5.0	3.82	1.50	4.00	2.95
Roundabout	Not Feasible							0.00	5.0	4.84	4.00	5.00	0.00
Median U-Turn (Signalized) (1 Lane)	Not Feasible							0.00	5.0	4.44	2.50	5.00	0.00
Median U-Turn (Signalized) (2 Lanes)	Feasible							1.88	5.0	2.17	2.00	5.00	3.28
Median U-Turn (Signalized) (3 Lanes)	Not Recommended							1.63	4.7	2.17	1.50	5.00	3.11
Median U-Turn (Unsignalized)	Not Feasible							0.00	5.0	2.17	2.50	5.00	0.00
Superstreet (Signalized)	Feasible							2.00	5.0	2.50	1.50	4.00	2.97
Superstreet (Unsignalized)	Not Feasible							0.00	5.0	1.50	1.50	4.00	0.00
Inside Left Turn (Signalized) (NB 'T') (1 Lane)	Not Feasible							0.00	5.0	1.00	1.00	3.50	0.00
Inside Left Turn (Signalized) (NB 'T') (2 Lane)	Not Feasible							0.00	5.0	1.00	1.00	4.00	0.00
Inside Left Turn (Signalized) (NB 'T') (3 Lane)	Not Feasible							0.00	5.0	0.50	0.50	4.00	0.00
Inside Left Turn (Signalized) (SB 'T') (1 Lane)	Not Feasible							0.00	5.0	1.00	1.00	3.50	0.00
Inside Left Turn (Signalized) (SB 'T') (2 Lane)	Not Feasible							0.00	5.0	1.00	1.00	4.00	0.00
Inside Left Turn (Signalized) (SB 'T') (3 Lane)	Not Feasible							0.00	5.0	0.50	0.50	4.00	0.00
Inside Left Turn (Unsignalized) (NB 'T')	Not Feasible							0.00	5.0	1.00	1.00	3.00	0.00
Inside Left Turn (Unsignalized) (SB 'T')	Not Feasible							0.00	5.0	0.00	1.00	3.00	0.00
Bowtie (1 Lane)	Not Feasible							0.00	5.0	4.50	2.50	5.00	0.00
Bowtie (2 Lane)	Not Feasible							0.00	5.0	4.50	2.00	5.00	0.00
Bowtie (3 Lane)	Not Feasible							0.00	5.0	4.50	1.50	5.00	0.00

The primary screen provides for traffic volume input (at the top left) and pedestrian counts and provides a summary of all model output in the large table.

Security Note: Prior to using IDAT it will be necessary to enable the associated macros in the spreadsheet. In Excel 2007 selecting “Options” under the “Security Warning” header under the toolbar and the “Enable this content” in the pop-up box can do this.

IDAT Data Input

Traffic volume is input in cell C4:G8 as shown in Figure B-2.

The model assumes major street traffic is those volumes in cells C5:C7 and G5:G7, or the east-west orientation on the screen. Minor or Side Street traffic is then entered in cells D4:F4 and D8:F8, or the north-west orientation. Entering data into the proper orientation is critical to assure proper evaluation of certain designs such as the median U-turn and superstreet.

Pedestrian traffic is entered in a similar manner and with the same orientation as the vehicular traffic. As the data is entered, the spreadsheet refreshes the output table. The final recommended alternatives are shown in the output table once all data is entered. Due to the high number of calculations embedded in the spreadsheet, data entry may take several minutes

Figure B-2: Traffic Volume Input.

IDAT Output Review

As identified above, IDAT will calculate the minimum lane configuration for each alternative assuming one, two and three through lanes on the major street. Output is shown in cells M2:T35 as shown in Figure B-3.

L	H	H	O	P	Q	R	S	T
INTERSECTION ALTERNATIVE	OPERATION EVALUATION	MINIMUM LANE CONFIGURATION						
		NB	SB	EB	WB	EB-U	WB-U	
2-Way Stop Control*	Not Feasible							
4-Way Stop Control	Not Feasible							
Signalized Intersection (1 lanes)	Not Feasible							
Signalized Intersection (2 lanes)	Feasible
Signalized Intersection (3 lanes)	Not Recommended
Jughandle A EB (1 Lanes)	Not Feasible							
Jughandle A EB (2 Lanes)	Feasible
Jughandle A EB (3 Lanes)	Feasible
Jughandle A WB (1 Lanes)	Not Feasible							
Jughandle A WB (2 Lanes)	Feasible
Jughandle A WB (3 Lanes)	Feasible
Jughandle A EB-WB (1 Lanes)	Not Feasible							
Jughandle A EB-WB (2 Lanes)	Feasible
Jughandle A EB-WB (3 Lanes)	Not Recommended
Roundabout	Not Feasible							
Median U-Turn (Signalized) (1 Lanes)	Not Feasible							
Median U-Turn (Signalized) (2 Lanes)	Feasible
Median U-Turn (Signalized) (3 Lanes)	Not Recommended
Median U-Turn (Unsignalized)*	Not Feasible							
Superstreet (Signalized)	Feasible
Superstreet (Unsignalized)	Not Feasible							
Inside Left Turn (Signalized) (NB 'T') (1 Lane)	Not Feasible							
Inside Left Turn (Signalized) (NB 'T') (2 Lane)	Not Feasible							
Inside Left Turn (Signalized) (NB 'T') (3 Lane)	Not Feasible							
Inside Left Turn (Signalized) (SB 'T') (1 Lane)	Not Feasible							
Inside Left Turn (Signalized) (SB 'T') (2 Lane)	Not Feasible							
Inside Left Turn (Signalized) (SB 'T') (3 Lane)	Not Feasible							
Inside Left Turn (Unsignalized) (NB 'T')*	Not Feasible							
Inside Left Turn (Unsignalized) (SB 'T')*	Not Feasible							
Bowtie (1 Lane)	Not Feasible							
Bowtie (2 Lane)	Not Feasible							
Bowtie (3 Lane)	Not Feasible							

Figure B-3: IDAT Output

Column 'N' indicates whether the design is feasible. An alternative is deemed feasible if any lane configuration is capable of operating at or below 90 percent of capacity. Alternatives with two or three through may also be identified as "Not Recommended" indicating that the alternative operates below the capacity threshold, but the same alternative option can also operate with fewer through lanes.

The proposed lane configuration is shown in graphic form by approach leg in columns O through T. Figure B-4 shows an example lane configuration. The number of required U-turn lanes is also provided for the major street legs to accommodate superstreet and median U-turn designs. (Note: two-lane U-turns are only proposed for signalized alternatives).

Figure B-4: Lane Configuration Output

INTERSECTION ALTERNATIVE	OPERATION EVALUATION	MINIMUM LANE CONFIGURATION					
		NB	SB	EB	WB	EB-U	WB-U
2-Way Stop Control*	Not Feasible						
4-Way Stop Control	Not Feasible						
Signalized Intersection (1 lanes)	Not Feasible						
Signalized Intersection (2 lanes)	Feasible
Signalized Intersection (3 lanes)	Not Recommended
Jughandle A EB (1 Lanes)	Not Feasible						
Jughandle A EB (2 Lanes)	Feasible
Jughandle A EB (3 Lanes)	Feasible

IDAT Evaluation

Evaluation criteria and final scores are presented in columns Y through Z (Figure B-5). These scores are determined by the individual intersection design and the lane configuration design for each. A composite total score is determined based on criterion weights assigned in cells Y3:ZZ3. An equal weighting has been entered but the user can modify these values to meet the unique needs of individual projects. Total scores are summed and presented in column AA. The highest composite score is then highlighted.

Figure B-5: Evaluation Criteria.

Intersection Alternative	Operation Evaluation	Minimum Lane Configuration						Row	Safety				A.M.	Score
		NB	SB	EB	WB	EB-U	WB-U		Veh.	Ped.	Bike			
								0.33	0.11	0.11	0.11	0.33		
2-Way Stop Control*	Not Feasible							0.00	4.9	4.72	2.50	1.00	0.00	
4-Way Stop Control	Not Feasible							0.00	5.0	4.72	5.00	1.50	0.00	
Signalized Intersection (1 lanes)	Not Feasible							0.00	5.0	4.62	3.50	2.50	0.00	
Signalized Intersection (2 lanes)	Feasible							3.50	5.0	2.89	3.00	3.00	3.34	
Signalized Intersection (3 lanes)	Not Recommended							3.50	4.9	2.49	2.00	3.00	3.18	
Jughandle A EB (1 Lanes)	Not Feasible							0.00	5.0	4.69	3.00	3.50	0.00	
Jughandle A EB (2 Lanes)	Feasible							1.63	5.0	3.84	2.50	4.00	3.10	
Jughandle A EB (3 Lanes)	Feasible							1.38	5.0	3.45	1.50	4.00	2.87	

Summary

The IDAT tool presented above is intended to identify potential intersection design alternatives and preliminary lane configuration to assist in the conceptual design process. This is achieved by quickly evaluating numerous alternatives and lane configurations that may not otherwise be examined within a typical project. However, prior to final design, it is recommended that a detailed operational analysis be conducted for the proposed feasible alternative(s) to ensure that the intersection operates within the specific site constraints and conditions of the project.