Improving Intersection Design Practices

FINAL REPORT — PHASE I
Our Mission

We provide services to the transportation community through research, technology transfer and education. We create and participate in partnerships to promote safe and effective transportation systems.
IMPROVING INTERSECTION DESIGN PRACTICES

Final Report – Phase I

by

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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 of this Phase I of 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. Recommendations for Phase II are also provided which seek to develop a more robust safety evaluation method for at-grade intersections.

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 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.
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 the 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.

2. A set of training material will be developed that could be used to train the Cabinet personnel.
**Report Organization**

This report documents the findings of the work completed in Phase I 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 next section of the report presents the current version of the evaluation tool and provides a guidance manual for its use. The final section of the report discusses the next steps to be carried out to complete the research.
LITERATURE REVIEW

Introduction
The literature review presented below 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 roundabouts 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 stop, all-way stop 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 which 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. The guide is used by professionals who design intersections 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

<table>
<thead>
<tr>
<th>Level of Service</th>
<th>Traffic Flow Condition</th>
<th>Volume to Capacity Ratio</th>
<th>Critical Lane Volumes</th>
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<td></td>
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<td>Two-Phase</td>
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<tr>
<td>A</td>
<td>Stable</td>
<td>&lt;0.6</td>
<td>900</td>
</tr>
<tr>
<td>B</td>
<td>Stable</td>
<td>&lt;0.7</td>
<td>1050</td>
</tr>
<tr>
<td>C</td>
<td>Stable</td>
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<td>1200</td>
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<tr>
<td>D</td>
<td>Unstable</td>
<td>&lt;0.85</td>
<td>1275</td>
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<tr>
<td>E</td>
<td>Capacity</td>
<td>&lt;1.0</td>
<td>1500</td>
</tr>
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</table>

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

<table>
<thead>
<tr>
<th>Reserve Capacity</th>
<th>Level of Service</th>
<th>Expected Delay to Minor Street Traffic</th>
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<tr>
<td>&gt;400</td>
<td>A</td>
<td>Little or no delay</td>
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<td>300-399</td>
<td>B</td>
<td>short traffic delays</td>
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<tr>
<td>200-299</td>
<td>C</td>
<td>Average traffic delays</td>
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<td>D</td>
<td>Long traffic delays</td>
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<tr>
<td>0-99</td>
<td>E</td>
<td>Very long traffic delays</td>
</tr>
<tr>
<td>&lt;0</td>
<td>F</td>
<td>*</td>
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</tbody>
</table>


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.

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

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

Where: \( c_{\text{crit}} \) = 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. Currently, safety of intersections is either examined (evaluated) or predicted. Past research efforts have utilized crash databases to conducted evaluation or examination of intersection related safety that involves statistical analysis of historical crash data at a site. Another approach towards intersection safety focuses on the ability to predict the safety performance at an intersection aiming to evaluate and compare alternative design options. For this purpose, models are developed based on different types of intersection control and features.

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% of all crashes. Pickering and Grimmer (1986) considered crashes at 3-legged intersections of 2-lane roads and developed a Poisson model with mean number of crashes per unit time related to ADT. Hauer et al. (1988) developed an approach developing a negative binomial model to correct the regression-to-mean bias in a study that reviewed signalized intersections in Toronto.

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% 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 6 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, where as 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 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.

Other types of intersections such as single point and tight diamond intersections were examined by Bared et al. (2005). The study did not find significant difference between the total numbers of crashes at the two intersections although the differences in the frequency of injury and fatality were significant, with the single point intersection being apparently safer than the tight diamond intersection.

In addition to the traditional approach of statistical evaluations of past crash history, various models have been developed to predict the safety of an intersection. Wang et al. (2009) developed the conflict-point detection (CD) model based on micro-simulation of motorized and non-motorized vehicles. The model was specifically developed for heterogeneous traffic in developing countries, where non-motorized vehicles did not have a separate lane. The model was based on Hyper-Petri Network to represent network, Collision Units to represent nodes in the network and the Poisson distribution model to generate Moving Units that formed the trajectories in the network. The algorithm contained a Collision Negotiating function (C) which is a pre-defined function to detect several moving units approaching a collision unit and negotiate a collision by screening only one through a given point at a given instance of time. Using this algorithm and functions, the simulation was conducted to increase capacity and safety of an intersection.

Another model was developed by Lu et al. (2008) that utilized conflict points to determine the level of safety service for heterogeneous traffic flow in an unsignalized
intersection. The study emphasized the importance of field survey activities and acquiring existing conditions and traffic demand at the facility site to determine the level-of-safety service of a facility. The model was based on the site characteristics, such as geometrics, traffic conditions, roadway and environmental conditions, traffic conflict point, and other site related conditions. Similar to the Level Of Service (LOS) range of A to F, the model quantified the safety performance of an intersection into several levels (Levels A to F) with each level having a defined safety range, “A” being the best scenario. The model was based on major, minor and traffic factors. Major factors included conflict points, minor factors included geometrics, traffic signs, traffic markings, pavement and lighting and the traffic factor included the approaching traffic volume. The severity and weights for the models were developed based on expert surveys and focus group discussion methods since the crash database was unable for the study area. The general form of the model was adjusted for ideal conditions that include intersection geometric characteristics, traffic signs, traffic markings, pavement conditions, and lighting conditions. The final model incorporated the general form along with adjustment factor to reflect the final potential dangerous degree under prevailing conditions that can be used to quantify the level-of-safety service. The study concluded by validating the model on fifteen un-signalized intersections from different areas that cover all six levels-of-safety service.

Dadic et al. (1999) conducted a study that aimed at increasing the overall capacity and safety of an intersection by identifying and eliminating the “unnecessary conflicts”. This study does not limit the review of conflict points to an intersection but extends it to a flow network that includes criss-crossing in a road segment. According to the study, the unnecessary conflicts are a result of (one or combination) of regulations, planning, education, and driver-environment influence. Formulae were developed to determine the number of criss-crossing points between traffic flow in an intersection which depends on number of access, direction of flow, and organization flow through intersection. The study concluded that the avoidance of unnecessary criss-crossing in a network reduces the amount of conflicts and increases the safety and passage capacity of intersection.

In addition to the use of conflict points, other parameters have been considered when developing predictive models. 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 focused on four different statistical approaches: lognormal regression, loglinear regression, discriminant analysis and cluster analysis. Lognormal regression was utilized as a screening tool to identify specific dependent variables (geometric design, traffic control) that could be considered for further analysis. The model was based on the assumption
that the logarithm of the number of accidents follows a normal distribution with mean and variance. Preliminary results indicated that the variables of geometric design, traffic control, and traffic volume variables explained 19 to 37% of the variation in intersection accidents. The traffic volume factor (ADT) 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. Therefore, to investigate the influence of geometric design elements only, ADT was treated as an independent variable and the analysis was carried out. In any case, the geometry of an intersection did not prove statistically significant in predicting a crash. Further analysis was conducted to develop better predictive models using loglinear regression that included Poisson and negative binomial models. The lognormal model assumption of normal distribution does not hold well when the number of accidents is small. In that case the number of accidents is assumed to follow a Poisson distribution. While modeling accidents, if the variance or dispersion of the data exceeds the estimated mean of the accident data distribution then the data is said to be over dispersed and then the Poisson distribution assumption is violated (note: in a Poisson distribution the variance is equal to the mean). This limitation was overcome by the negative binomial model that contained two parameters: alpha - a dispersion parameter that allows variance to exceed the mean of distribution; and k - the variance stabilizing factor. Regression models based on the negative binomial distribution models explained between 16 and 38 percent of the variability in the accident data. According to the analysis, geometric design features of intersections accounted for a small portion of variability but the individual effects on safety were statistically significant, which included presence of lane-turn lane, provision of channelization for free right turns, number of lanes on a major road, average lane width on a major road, presence of median on a major road, outside shoulder width on a major road and access control on a major road. Further analysis was conducted using discriminant analysis and cluster analysis to investigate whether better models could be developed in which geometric design variables explain more of the variation in accident data, but none of these statistical approaches proved better than the negative binomial, lognormal and logistic regression models. 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. A final investigation of hard copy
police crash reports was undertaken and found that only 14 to 15 percent of the accidents had causes related to geometric design of an intersection.

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 Factor (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, accident severity distribution, and accident type distribution, validate actual site-specific accident history (if available) using Empirical Bayes (EB) procedure. 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%, against 30% without calibration.

Persaud et al. (2002) developed a crash prediction model for injury and damage-only crashes at 3- and 4-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.

Wong et al. (2007) conducted a study to evaluate the associations between the crashes, geometric design, traffic characteristics, road environment, and traffic control at signalized intersections in Hong Kong, controlling for the influence of exposure. Crash records, traffic
surveys, signal timing details of 262 intersections were incorporated in the model that was based on Poisson regression and negative binomial regression to determine the safety performance of signalized intersections. It was observed that “killed and severe injury” crashes were rare incidents that were unlikely to be affected by the ADT.

An investigation by Vogt (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; variants of Poisson models that allow for over dispersion, that predicted crash counts indicated that almost all variables were statistically significant and specifically for injury crashes that intersection angle and minor road posted speed were significant.

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 2 of the 35 intersections they investigated had an influence area of 500 ft while others were in the range of only 100 ft. Joksch and Kostyniuk (1998) selected a maximum influence zone of 350 ft and a minimum of 7ft and stated that the influence zone was based on individual judgment and not based on specific functions.

Santos 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 volume, and skewness on the upstream influence area. A survey was conducted of twenty six states and two territories across the United States, of which fifteen 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 delay 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 provide a common basis for comparisons.

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 parameter that could have a positive or negative effect on the safety of conflicting vehicles and hence could be promoted or eliminated accordingly.
RESEARCH FINDINGS

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 intersections types are listed below and further discussion of their operating characteristics and layout are 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 Method 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 based on CMA. To proceed with the evaluation and validation of the relationship between intersection volumes as defined by CMA and delay, a simulation effort of various intersection designs and traffic control strategies was undertaken. Different scenarios of volumes 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

<table>
<thead>
<tr>
<th>Total Street Volume (vph)</th>
<th>Eastbound</th>
<th>Westbound</th>
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</thead>
<tbody>
<tr>
<td>1,800</td>
<td>1,080</td>
<td>720</td>
</tr>
<tr>
<td>1,400</td>
<td>840</td>
<td>560</td>
</tr>
<tr>
<td>1,000</td>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td>600</td>
<td>360</td>
<td>240</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total Street Volume (vph)</th>
<th>Northbound</th>
<th>Southbound</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,200</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>800</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>400</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>860</td>
<td>600</td>
<td>260</td>
</tr>
<tr>
<td>570</td>
<td>400</td>
<td>170</td>
</tr>
<tr>
<td>285</td>
<td>200</td>
<td>85</td>
</tr>
</tbody>
</table>

The east/west street used two different turning percentages. The first was 10% left turns and 10% right turns, and the second was 15% left turns and 15% 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

<table>
<thead>
<tr>
<th>Northbound Approach Volume (vph)</th>
<th>Left Turn (%)</th>
<th>Right Turn (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td>400</td>
<td>10</td>
<td>10</td>
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<td>30</td>
<td>60</td>
</tr>
<tr>
<td>200</td>
<td>30</td>
<td>60</td>
</tr>
</tbody>
</table>
A total of 96 different scenarios were created based on these approach volumes and turn percentages. 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

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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 vehicles per hour (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 run 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 find a line of best fit for the data that could 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 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](image)

**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 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).
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.
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 below 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

<table>
<thead>
<tr>
<th>Intersection Control</th>
<th>Volume (vph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal</td>
<td>1,350</td>
</tr>
<tr>
<td>All-Way Stop</td>
<td>1,200</td>
</tr>
<tr>
<td>Two-Way Stop</td>
<td>1,000</td>
</tr>
<tr>
<td>Roundabout</td>
<td>1,000</td>
</tr>
</tbody>
</table>

Intersection Design Evaluation 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 following subsections identify the metrics for each of the factors identified above.

Operations

The findings of the simulation efforts noted in the previous section 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 designs 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.

Right of Way

As all alternatives are developed to operate at the same level of efficiency, the size of the intersection becomes a critical determinant of suitability. 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 points for an approach with a single lane. Approaches with 5 or more lanes receive 0 points. Turn lanes, such as a left or right auxiliary lane are counted as ½ of a lane, since they will likely be required for only a short length. The average score of all approaches for the design is used in the final scoring. Jughandle and Bowtie designs were deducted 2 points 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 level of anticipated use of the evaluation tool.

Safety

Intersection safety is to be measured through the development of exposure estimates for different crash types. Exposure estimates would be based on the geometry of the intersection, traffic control and the volume of specific turn movements susceptible to certain crash types. As an example, left-turn angle crashes would be a function of the presence of a left-turn lane, signal phasing (i.e., protected or permitted left turns), and the volume of left-turns and opposing through traffic. This methodology will allow for a safety metric sensitive to the slight variations
among the various design options. Continuing the example above, jug-handle designs would eliminate left-turn angle crash potential, but potentially increase rear-ends and/or right angle crashes. This level of sensitivity in the safety analysis, will allow for the development of comparisons among the various intersection designs, based on the specific turning movements and constraints at the intersection. While this method shows promise in the conceptual stages, the work needed to complete it will be performed in Phase II.

For the current version of the evaluation tool a subjective method of scoring was developed based on the potential safety implications for each design. Each intersection design was evaluated based on a priori understanding of the level of safety that it provides and using the expertise of the Study Advisory Committee (SAC). The scoring method used a five-point scale where 1.0 represents the least safe and 5.0 the safest design. For intersection designs with similar control but greater number of approach lanes, relative scores were developed based again on the expertise of the SAC. The safety level was scored individually for vehicular, pedestrian and bicycle traffic creating a unique score for each category, since there are different safety concerns for each travel mode.

**Pedestrian and Bike**

The pedestrian and bike suitability 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 pedestrians and 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 can be 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 6. Figure 5 shows the final design tool and alternative scores.
<table>
<thead>
<tr>
<th>INTERSECTION ALTERNATIVE</th>
<th>ROW</th>
<th>Veh. Safety</th>
<th>Ped.</th>
<th>Bike</th>
<th>Access Mgmt</th>
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<tbody>
<tr>
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<td></td>
<td>4</td>
<td>4</td>
<td>3.5</td>
<td>2.5</td>
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<tr>
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<td>3</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Signalized Intersection (3 lanes)</td>
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<td>2.5</td>
<td>2</td>
<td>3</td>
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<tr>
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<td>2.5</td>
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<td>3.5</td>
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<tr>
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<td>1.5</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
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<td>1.5</td>
<td>1.5</td>
<td>4</td>
</tr>
<tr>
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<td>2.5</td>
<td>3</td>
<td>3.5</td>
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<td>1.5</td>
<td>2.5</td>
<td>4</td>
</tr>
<tr>
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<td>1.5</td>
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<tr>
<td>Roundabout</td>
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<td>5</td>
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<td>4</td>
<td>5</td>
</tr>
<tr>
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<td>3.5</td>
<td>2.5</td>
<td>5</td>
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<tr>
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<td>5</td>
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<tr>
<td>Median U-Turn (Unsignalized)*</td>
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<td>5</td>
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<tr>
<td>Superstreet (Signalized)</td>
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<td>1.5</td>
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<td>1.5</td>
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<td>1</td>
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<td>3</td>
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<td>1</td>
<td>4</td>
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<td>0.5</td>
<td>0.5</td>
<td>4</td>
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<tr>
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<td></td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>Inside Left Turn (Signalized) (SB 'T') (2 Lane)</td>
<td></td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Inside Left Turn (Signalized) (SB 'T') (3 Lane)</td>
<td></td>
<td>2.5</td>
<td>0.5</td>
<td>0.5</td>
<td>4</td>
</tr>
<tr>
<td>Inside Left Turn (Unsignalized) (NB 'T')</td>
<td></td>
<td>3.5</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Inside Left Turn (Unsignalized) (SB 'T')</td>
<td></td>
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<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Bowtie (1 Lane)</td>
<td></td>
<td>3.5</td>
<td>3.5</td>
<td>2.5</td>
<td>5</td>
</tr>
<tr>
<td>Bowtie (2 Lane)</td>
<td></td>
<td>2.5</td>
<td>2.5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Bowtie (3 Lane)</td>
<td></td>
<td>2</td>
<td>2</td>
<td>1.5</td>
<td>5</td>
</tr>
</tbody>
</table>
Appendix C contains a full discussion of and user guide for the Intersection Design Analysis Tool (IDAT) developed by this effort. The tool is available on the KTC website at www.ktc.engr.uky.edu.
CONCLUSIONS AND RECOMMENDATIONS

The remainder of this report presents the recommendations based on the Phase I work completed and the required steps for completing Phase II.

Recommendations

The software developed as part of Phase I 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 operations. The instructions provided in Appendix C allow for ease of implementation. The software will be updated to include the safety evaluation (once completed in Phase II) and any other improvements as deemed necessary.

Phase II Work Plan

The procedures for each step to be undertaken are discussed along with commentary on requirements based on the findings presented in the previous sections.

Task 1

This task will focus on developing a method for quantifying the safety performance of the intersection that is sensitive to varying traffic demands. As a result this will estimate the potential conflicts for each intersection design alternative evaluated for a given scenario. The model will be developed by applying the FHWA Safety Surrogate Assessment Model (SSAM) on a series of simulated scenarios for each design option. The 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 will be used for each scenario simulated and models will be developed that will allow the user to predict the number of potential conflicts for each design alternative for a given set of design volumes. These models will be incorporated in the existing tool for screening design alternatives and allow for a complete and systematic approach for identifying appropriate intersection designs.

Task 2

A PowerPoint presentation will be developed to be used for training the Cabinet personnel. The presentation will include the factors defined and their influence on design to allow for an understanding of the rationale for the guidelines, and it will present the guidelines in
a clear and concise manner. Examples of application will also be included to clearly demonstrate the application of the guidelines.

**Task 3**

The final task will be the development of the final report that will document the research completed. The research team working closely with the SAC fully expects to produce results that can and should be applied in practice by the state and local transportation agencies, and consulting firms in determining appropriate designs for intersections. These results will provide a focused resource tool and document that will allow these professionals to improve the selection process of candidate intersection designs.
REFERENCES


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 3 or more legs, though intersections with greater than 4 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

**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 3 or more legs, though intersections with greater than 4 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**

- KYTC Highway Design Manual. KYTC Division of Design. Frankfort, KY.
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 3 or more legs, though intersections with greater than 4 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 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
- 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

KYTC Highway Design Manual. KYTC Division of Design. Frankfort, KY.
MODERN ROUNDBOUD
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 3 or more legs, though intersections with greater than 4 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 pedestrian in front of approaching vehicle, 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

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

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

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 recommends 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**

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 need 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 recommends 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

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 design 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

INSIDE LEFT-TURN (UN SIGNALIZED)

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

Geometric Design
The primary design 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

**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**


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

APPENDIX B
STATE DOT INTERSECTION DESIGN GUIDANCE
<table>
<thead>
<tr>
<th>State</th>
<th>Intersection Design Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alaska</td>
<td>Design policy follows the AASHTO Green Book.</td>
</tr>
<tr>
<td>California</td>
<td>Design considerations identified as driver, vehicle, environment, pedestrian, bicyclist, capacity, accident data, preference to major movements, areas of conflict, and angle of intersection.</td>
</tr>
<tr>
<td>Colorado</td>
<td>Intersection design based on capacity analysis and Highway Capacity Manual, alignment and grade.</td>
</tr>
<tr>
<td>Connecticut</td>
<td>Traffic Control and Intersection Design Manual provides preliminary considerations for signal installations and the use of dual left turn lanes.</td>
</tr>
<tr>
<td>Delaware</td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>MUTCD is used to warrant traffic control devices.</td>
</tr>
<tr>
<td></td>
<td><a href="http://www.deldot.gov/information/pubs_forms/manuals/road_design/pdf/07_intersections.pdf">http://www.deldot.gov/information/pubs_forms/manuals/road_design/pdf/07_intersections.pdf</a></td>
</tr>
<tr>
<td>Florida</td>
<td>A separate intersection design guide was developed including guidance for identifying requirements and providing guidelines for selecting a design when there are alternatives.</td>
</tr>
<tr>
<td></td>
<td>MUTCD is used for signalization.</td>
</tr>
</tbody>
</table>
Table B-1: State Intersection Design Guidance (continued)

<table>
<thead>
<tr>
<th>State</th>
<th>Intersection Design Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Georgia</td>
<td>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. Signalization depends on existing and projected traffic volumes, including turning percentages. Must also conform to the GDOT’s TOPPS 6785-1, Traffic Signals. <a href="http://wwwb.dot.ga.gov/dpm/desmanual/ch07/ch07.5.html">http://wwwb.dot.ga.gov/dpm/desmanual/ch07/ch07.5.html</a> <a href="http://wwwb.dot.ga.gov/dpm/desmanual/ch07/Ch07.1.html">http://wwwb.dot.ga.gov/dpm/desmanual/ch07/Ch07.1.html</a></td>
</tr>
<tr>
<td>Idaho</td>
<td>Uses the MUTCD to warrant traffic control and the Green Book for intersection design. <a href="http://itd.idaho.gov/manuals/Downloads/design.htm">http://itd.idaho.gov/manuals/Downloads/design.htm</a></td>
</tr>
<tr>
<td>Illinois</td>
<td>General design controls include intersection alignment, profiles, capacity analysis, design vehicles, pedestrian and bicycles, turning radii. <a href="http://www.dot.il.gov/blr/manuals/Chapter%2034.pdf">http://www.dot.il.gov/blr/manuals/Chapter%2034.pdf</a></td>
</tr>
<tr>
<td>Indiana</td>
<td>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. Conforms to the MUTCD for traffic control. <a href="http://www.in.gov/dot/div/contracts/design/mutcd/mutcd.html">http://www.in.gov/dot/div/contracts/design/mutcd/mutcd.html</a> <a href="http://www.in.gov/dot/div/contracts/standards/dm/english/Part5Vol1/ECh46/ch46.htm">http://www.in.gov/dot/div/contracts/standards/dm/english/Part5Vol1/ECh46/ch46.htm</a></td>
</tr>
<tr>
<td>Iowa</td>
<td>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. <a href="http://www.iowadot.gov/design/dmanual/06a-01.pdf">http://www.iowadot.gov/design/dmanual/06a-01.pdf</a></td>
</tr>
<tr>
<td>State</td>
<td>Intersection Design Guidance</td>
</tr>
<tr>
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<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Kansas  | **Intersection Control**  
Two-way stop control at intersections unless a traffic investigation and guidelines from the MUTCD indicate otherwise.  
New intersection primarily based on traffic volumes. Crash history is used for existing locations.  
**Lane Configuration and Intersection Size**  
Peak hour turning movements are used to determine lane configuration, particularly when determining if auxiliary lanes are used.  
Right of way, utilities, funding are variables which may limit what can be done regarding lane configuration and intersection size.  
*(Based on conversation with Brian Gower of the KDOT office of Design).* |
| Kentucky | 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.  
Three intersection types identified: three-leg, four-leg, and multi-leg. Central Office has final decision on when a traffic control device is warranted. |
| Louisiana | 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. |
| Maryland | 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. |

For more information, please visit the following links:

- [Kentucky](http://transportation.ky.gov/design/designmanual/chapters/12Chapter%2090%20AS%20PRINTED%202006.pdf)
- [Louisiana](http://www.dotd.louisiana.gov/highways/project_devel/design/road_design/road_design_manual/Road_Design_Manual_(Full_Text).pdf)
- [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)
<table>
<thead>
<tr>
<th>State</th>
<th>Intersection Design Guidance</th>
</tr>
</thead>
</table>
| Massachusetts| 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.  
http://www.mhd.state.ma.us/downloads/manuals/design.pdf |
| Michigan     | Angle of intersection, grade, and sight distances are considered in intersection design.                                                                                                                                       |
|              | http://mdotwas1.mdot.state.mi.us/public/design/englishroadmanual/                                                                                                                                                    |
http://www.dot.state.mn.us/design/rdm/english/5e.pdf |
| Mississippi  | Intersection design considerations include: design vehicle, horizontal alignment, profile, capacity, and level of service.                                                                                                     |
|              | MUTCD used to warrant traffic control devices.                                                                                                                                                                                |
| Missouri     | Capacity and sight distance are the factors used in intersection design.                                                                                                                                                        |
|              | MUTCD used to warrant traffic control devices.                                                                                                                                                                                |
|              | http://epg.modot.mo.gov/index.php?title=Category:233_At_Grade_Intersections                                                                                                                                                    |
| Montana      | Intersection design controls include: capacity, level of service, design vehicle, intersection spacing, intersection alignment, intersection profile, and turning radii.                                                            |
|              | MUTCD used to warrant traffic control devices.                                                                                                                                                                                |
Table B-1: State Intersection Design Guidance (continued)

<table>
<thead>
<tr>
<th>State</th>
<th>Intersection Design Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nebraska</td>
<td>MUTCD used to warrant traffic control devices. Design considerations include capacity and level of service, sight distance, horizontal alignment, intersection skew, profile, design vehicle, and radius returns. <a href="http://www.nebraskatransportation.org/roadway-design/pdfs/rwydesignman.pdf">http://www.nebraskatransportation.org/roadway-design/pdfs/rwydesignman.pdf</a></td>
</tr>
<tr>
<td>New York</td>
<td>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. <a href="https://www.nysdot.gov/divisions/engineering/design/dqab/hdm/hdm-repository/chapt_05.pdf">https://www.nysdot.gov/divisions/engineering/design/dqab/hdm/hdm-repository/chapt_05.pdf</a></td>
</tr>
<tr>
<td>State</td>
<td>Intersection Design Guidance</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Oregon</td>
<td>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. ftp://ftp.odot.state.or.us/techserv/roadway/web_drawings/HDM/Rev_E_2003C hp09.pdf</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>MUTCD used to warrant traffic control devices.</td>
</tr>
<tr>
<td></td>
<td>ftp://ftp.dot.state.pa.us/public/bureaus/design/Pub70M/Chapters/Chap02.pdf</td>
</tr>
<tr>
<td>Rhode Island</td>
<td>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. <a href="https://www.pmp.dot.ri.gov/PMP/DesktopDefault.aspx?aM=udoc&amp;oM=list&amp;c1">https://www.pmp.dot.ri.gov/PMP/DesktopDefault.aspx?aM=udoc&amp;oM=list&amp;c1</a> P=cat&amp;c2p=docs&amp;appindex=0&amp;appid=0&amp;podid=-1&amp;mth=1&amp;label=Manual%20-%20Highway%20Design...#pageAnchor5</td>
</tr>
<tr>
<td>South Carolina</td>
<td>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. MUTCD used to warrant traffic control devices. (based on email from Rob Bedenbaugh SCDOT)</td>
</tr>
<tr>
<td>South Dakota</td>
<td>Design criteria include: level of service, alignment, profile, width, radii, turning movements, design vehicles, encroachment, volumes, and channelization.</td>
</tr>
<tr>
<td>Tennessee</td>
<td>MUTCD used to warrant traffic control devices.</td>
</tr>
<tr>
<td>Texas</td>
<td>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.</td>
</tr>
<tr>
<td>Utah</td>
<td>Controls include: design vehicle, cross sections, projected traffic volumes, pedestrian traffic, speed, and traffic control devices.</td>
</tr>
<tr>
<td></td>
<td><a href="http://www.dot.state.ut.us/main/f?p=100:pg:0:::1:T,V:1498">http://www.dot.state.ut.us/main/f?p=100:pg:0:::1:T,V:1498</a>,</td>
</tr>
</tbody>
</table>
Table B-1: State Intersection Design Guidance (continued)

<table>
<thead>
<tr>
<th>State</th>
<th>Intersection Design Guidance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vermont</td>
<td>Adheres to MUTCD for traffic control devices.</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>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.</td>
</tr>
<tr>
<td>Wyoming</td>
<td>Uses MUTCD to warrant traffic control devices.</td>
</tr>
<tr>
<td>State</td>
<td>Roundabout Guidance/Policy</td>
</tr>
<tr>
<td>---------------</td>
<td>-------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| 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  
| 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)  
| Maryland      | Roundabout Safety Information  
http://www.sha.state.md.us/safety/oots/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)  
| Nebraska      | FHWA Roundabout Guide  
http://www.nebraskatransportation.org/roadway-design/pdfs/rwydesignman.pdf |
| New Hampshire | Roundabout Guide (supplement to FHWA Roundabout Guide)  
| New York      | Roundabout Design Guidance  
https://www.nysdot.gov/main/roundabouts/guide-engineers |
<table>
<thead>
<tr>
<th>State</th>
<th>Roundabout Guidance/Policy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oregon</td>
<td>Roundabout Guide</td>
</tr>
<tr>
<td>Pennsylvania</td>
<td>Roundabout Guide</td>
</tr>
<tr>
<td>Utah</td>
<td>FHWA Roundabouts Guide</td>
</tr>
<tr>
<td>Washington</td>
<td>Roundabouts integrated in highway design manual</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>Roundabout Design Information</td>
</tr>
</tbody>
</table>
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 objective methods for sizing and selecting conceptual intersection design alternatives. In total it evaluates 15 different intersection design alternatives with major street lane configuration including 1, 2 and 3 through streets and 8 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 which 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 and manipulation. Further discussion of the background of the development approach and related research can be found in KTC Research Report No. 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.

The primary screen provides for traffic volume input (at the top left) 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 this can be done by selecting “Options” under the “Security Warning” header under the toolbar and the “Enable this content” in the pop-up box.
**IDAT Data Input**
Traffic volume is input in cell D4:F8 as shown in Figure B-2. The model assumes major street traffic are those volumes in cells D5:D7 and F5:F7, or the east-west orientation on the screen. Minor or Side Street traffic is then entered in cells C4:E4 and C8:E8, 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. Once data is entered, click on the “GO” button and all calculations for each intersection is computed. Depending on the speed of your computer this may take several minutes.

Figure B-2: Traffic Volume Input.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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</tr>
</tbody>
</table>

**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 J2:X35 as shown in Figure B-3.
Column ‘K’ indicates if the design is feasible or infeasible. An alternative is deemed feasible if any lane configuration is capable of operating below 90 percent of capacity. Alternatives with 2 or 3 through may also be identified as “Not Recommended;” this indicates that the alternative operates below the capacity threshold, but the same alternative can also operate with fewer through lanes.

The proposed lane configuration is shown in graphic form by approach leg in columns M through R. 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: 2-lane u-turns are only proposed for signalized alternatives).
### Figure B-4: Lane Configuration Output

<table>
<thead>
<tr>
<th>Intersection Alternative</th>
<th>Operation Evaluation</th>
<th>Minimum Lane Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-Way Stop Control*</td>
<td>Not Feasible</td>
<td></td>
</tr>
<tr>
<td>4-Way Stop Control</td>
<td>Not Feasible</td>
<td></td>
</tr>
<tr>
<td>Signalized Intersection (1 lanes)</td>
<td>Feasible</td>
<td></td>
</tr>
<tr>
<td>Signalized Intersection (2 lanes)</td>
<td>Not Recommended</td>
<td></td>
</tr>
<tr>
<td>Signalized Intersection (3 lanes)</td>
<td>Not Recommended</td>
<td></td>
</tr>
</tbody>
</table>
IDAT Evaluation
Evaluation criteria and final scores are presented in columns T through Y (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 T3:X3. An equal weighting has been entered but these values can be modified by the user to meet the unique needs of individual projects. The highest composite score is then highlighted.

Figure B-5: Evaluation Criteria.

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 detailed operational analysis be conducted for the preferred alternative(s) to ensure that it operates within the specific sight constraints and conditions of the project.