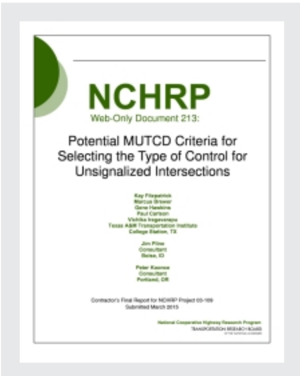

Potential MUTCD Criteria for Selecting the Type of Control for Unsignalized Intersections

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Potential MUTCD Criteria for Selecting the Type of Control for Unsignalized Intersections

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National Cooperative Highway Research Program
TRANSPORTATION RESEARCH BOARD
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ABSTRACT

The 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) includes guidance for the use of various types of traffic control at unsignalized intersections. Despite changes and advances in traffic engineering in recent decades, the MUTCD content related to selection of traffic control in Part 2B has seen only minor changes since 1971. In an effort to update the MUTCD, this research addressed the following types of unsignalized traffic control: no control, yield control, two-way stop control, and all-way stop control. The research team developed recommendations using information available from reviews of existing literature, policies, guidelines, and findings from an economic analysis, along with the engineering judgment of the research team and panel. The language proposed for the next edition of the MUTCD for unsignalized intersections developed at the conclusion of this research is provided in the appendix. It includes consideration of high-speed (rural) and low-speed (urban) conditions along with the number of legs at the intersection. Because the number of expected crashes at an intersection is a function of the number of legs, the decision on appropriate traffic control should also be sensitive to the number of legs present. The proposed language includes introductory general considerations, discusses alternatives to changing right-of-way control, and steps through the various forms of unsignalized control from least restrictive to most restrictive, beginning with no control and concluding with all-way stop control. Supplemental notes are provided to suggested additions to the current text, which show the reader the source(s) of the material and/or the research team's reasoning for proposing the text.

SUMMARY

INTRODUCTION

The 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) includes guidance for the use of various types of traffic control at unsignalized intersections. Despite changes and advances in traffic engineering in recent decades, the MUTCD content related to selection of traffic control in Part 2B has seen only minor changes since 1971. The values for volumes and crashes contained within Sections 2B.04, 2B.06, 2B.07, and 2B.09 of the 2009 edition of the MUTCD have not been evaluated based on research since that time. Research was desired to examine the warrants (criteria) in Part 2B for determining whether an intersection should have no control, yield control, or stop control.

This National Cooperative Highway Research Program project was tasked with developing criteria and supporting material for determining appropriate traffic control at unsignalized intersections. The types of unsignalized traffic control to be addressed included no control, yield control, two-way stop control, and all-way stop control. The material produced was to be suitable for integration into an update to the 2009 MUTCD Sections 2B.04 through 2B.09.

Within the context of this research, an unsignalized intersection is one where one of the following methods of right-of-way control is used on one or more of the approaches:

- No control: Right of way is based on the rules of the road where the first to arrive at the intersection has the right of way, and if two vehicles arrive at the same time, a driver yields to the vehicle to the right.
- Yield control: YIELD sign(s) are installed on the minor approach or approaches. At a roundabout intersection, YIELD signs are installed on all approaches.
- Minor-road stop control: STOP sign(s) are installed on one approach for a three-leg intersection or on two approaches for a four-leg intersection. The STOP sign is normally installed on the minor road but in some cases may be installed on the major road with no control on the minor road.
- All-way stop control: STOP signs are installed on all approaches to the intersection.

The next level of right-of-way control for an intersection is a traffic control signal, criteria for which were not included in the scope of this research.

RESEARCH ACTIVITIES

Review of Policies and Guidelines

Researchers reviewed the current MUTCD and the supporting material for the guidance found therein. The research team also conducted searches of guidelines and manuals from all 50 states (available online) to review their current policies. In addition, researchers asked practitioners for information on novel approaches they were considering for selecting traffic control at unsignalized intersections. Several states provide guidance in addition to that found in the MUTCD, but in many jurisdictions, the MUTCD (or a particular state's equivalent) is the prevailing source for guidance. Much of the existing text in the MUTCD has remained largely intact for several decades.

Literature Review

The research team had a three-pronged approach to reviewing the relevant literature: key reference documents, previous literature that discussed methods for selecting traffic control at unsignalized intersections, and previous literature that discussed methods for selecting traffic control at unsignalized pedestrian crossings. Key reference documents included the *Highway Capacity Manual*, *Highway Safety Manual*, and the Institute of Transportation Engineers' *Manual of Traffic Engineering Studies*. Literature that described the selection of traffic control included processes that considered delay, traffic volumes, number of lanes, crashes, and other variables. Some processes resulted in regression equations or charts to calculate the variables of interest, while others were based on a point system that described a recommended traffic control for a certain point score.

Critical Review of MUTCD

Researchers reviewed key sections of MUTCD Chapter 2B to determine which sections could have the most potential benefit from new research to support revised guidance. Based on the activities in the initial phase of the project, the research team, with the guidance of the project panel, conducted a study in the second phase of the project that focused on the following items:

- Set a higher priority on investigating when to go from two-way to all-way stop control rather than when to go from no control to yield or two-way stop control.
- Develop criteria that reflect urban and rural environments or speed conditions.
- Develop criteria that are sensitive to the number of legs at the intersection.
- Consider roundabouts as a geometric design alternative within the evaluation.
- Consider a variety of major- and minor-road volume splits and not just when the split is "approximately equal."
- Consider the existing and ongoing revisions to relevant sections of the MUTCD, such as the changes suggested for the reorganization.

Economic Analysis Procedure

The research team used a procedure for comparing traffic control alternatives based on the relative economic costs and benefits of those alternatives for particular intersection types (three-leg or four-leg), environments (urban or rural), and volumes (varying levels of major- and minor-road volumes). Based on information from a variety of relevant sources, the research team selected user delay, crashes, vehicle operating, and construction as the four costs for consideration in the project. Researchers used microsimulation to measure the effects of delay. A multi-step process for calculating crash costs was adapted from the *Highway Safety Manual*. Vehicle operating costs were estimated using information from federal sources such as the Environmental Protection Agency and the Energy Information Administration. Roundabout construction costs were estimated from information from the Federal Highway Administration.

Potential Criteria

Potential criteria for no control, yield control, minor-road stop control, and all-way stop control were identified from the literature, reviews of policies and guidelines, and the economic analysis.

RECOMMENDATIONS

Use of Findings from Economic Analysis

A portion of the research efforts focused on an economic analysis to determine when all-way stop control or roundabout geometric design should be considered based on cost considerations. The research team members do not support implementation of these findings at this time for several reasons as discussed in this report. While the findings from the economic analysis are based on thorough research, the research team identified some important inconsistencies between the methodologies used for the current MUTCD signal criteria and those used for the potential all-way stop-control criteria developed in this research. The differences in basis between these criteria and those that are currently in the MUTCD mean that the criteria developed from the economic analysis may not be ready for inclusion in the MUTCD until such time as the existing MUTCD criteria and warrants for traffic signals can also be reevaluated in a manner that considers the impacts of user safety costs in the same manner that this research project did. Only through the use of consistent decision-making criteria can practitioners correctly determine the most appropriate means of providing right-of-way control at an intersection.

Recommended Language for Next Edition of the MUTCD

Using information available from reviews of existing literature, policies, guidelines, and findings from the economic analysis, along with the engineering judgment of the research team and panel, recommendations were developed. The language proposed for the next edition of the MUTCD for unsignalized intersections developed at the conclusion of this research is provided in the appendix.

The proposed language includes introductory general considerations, discusses alternatives to changing right-of-way control, and steps through the various forms of unsignalized control from least restrictive to most restrictive, beginning with no control and concluding with all-way stop control. Supplemental notes are provided to suggested additions to the current text, which show the reader the source(s) of the material and/or the research team’s reasoning for proposing the text.

CHAPTER 1: INTRODUCTION

RESEARCH PROBLEM STATEMENT

The 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) (*1*) includes guidance for the use of various types of traffic control at unsignalized intersections. Despite changes and advances in traffic engineering in recent decades, the MUTCD content related to selection of traffic control in Part 2B has seen only minor changes since 1971. The values for volumes and crashes contained within Sections 2B.04, 2B.06, 2B.07, and 2B.09 of the 2009 edition of the MUTCD have not been evaluated based on research since that time. Research was desired to examine the warrants (criteria) in Part 2B for determining whether an intersection should have no control, yield control, or stop control.

This National Cooperative Highway Research Program (NCHRP) project was tasked with developing criteria and supporting material for determining appropriate traffic control at unsignalized intersections. The types of unsignalized traffic control to be addressed included no control, yield control, two-way stop control, and all-way stop control. The material produced was to be suitable for integration into an update to the 2009 MUTCD Sections 2B.04 through 2B.09.

RESEARCH OBJECTIVES

The objective of this NCHRP project was to develop criteria and supporting material for determining appropriate traffic control at unsignalized intersections.

RESEARCH APPROACH

The research was conducted within seven tasks. Each task listed is followed by the objectives of that task:

- **Task 1. Compile Policies and Guidelines, and Conduct Literature Review.** The objective of this task was to compile policies and guidelines used by state and local transportation agencies related to unsignalized traffic control. In addition, the research team reviewed literature on the effectiveness and selection of different types of unsignalized traffic control.
- **Task 2. Identify Intersection and Traffic Characteristics.** The objective of this task was to identify intersection and traffic characteristics that may influence the selection of an appropriate type of unsignalized traffic control for an intersection.
- **Task 3. Critically Evaluate MUTCD Sections 2B.04 through 2B.09.** The objective of Task 3 was to evaluate quantitative and qualitative criteria currently included in MUTCD Section 2B.04 through 2B.09, along with the findings from Task 1 and Task 2 related to the choice of unsignalized traffic control, including the underlying research and rationale.
- **Task 4. Develop Task 5 Work Plan and Submit Interim Report.** The objective of this task was to develop and submit the interim report summarizing the results of Tasks 1 through 3, identifying provisions that deserve further study, and presenting a Task 5 work plan for addressing critical weaknesses.
- **Task 5. Conduct Work Plan.** The objective of this task was to conduct the approved work plan from Task 4.

- **Task 6. Develop Potential MUTCD Materials.** The objective of this task was to develop materials for the MUTCD that would be ready for consideration by the National Committee on Uniform Traffic Control Devices (NCUTCD) and recommended to the Federal Highway Administration (FHWA).
- **Task 7. Prepare Final Report.** The objective of this task was to prepare this final report. The final report describes the work done; presents the potential MUTCD text, tables, and figures; and documents the rationale for the proposed MUTCD material.

REPORT STRUCTURE

This final report summarizes the results of the various project tasks, documenting the research team's activities, methodology, and findings. This report has seven chapters and one appendix:

- **Chapter 1: Introduction** describes the problem statement, objective of the project, research approach, and report structure.
- **Chapter 2: Review of Policies and Guidelines** includes a summary of guidelines in the 2009 MUTCD and policies listed in various state and local manuals. It also includes a summary of findings from outreach to traffic engineering practitioners.
- **Chapter 3: Literature Review** includes a summary of key reference documents along with previous research on selecting traffic control devices for unsignalized intersections and pedestrian traffic control device treatments at unsignalized intersections.
- **Chapter 4: Intersection and Traffic Characteristics** identifies the intersection, traffic, and safety characteristics that affect decisions made regarding traffic control at an unsignalized intersection.
- **Chapter 5: Critical Review** includes a summary of the research team's observations and review of the numeric and general criteria in the 2009 MUTCD. It also summarizes the key considerations for the Phase II work plan.
- **Chapter 6: Economic Analysis** documents the steps taken by the research team to conduct the economic analysis used as a basis for recommending guidance on appropriate traffic control.
- **Chapter 7: Overview, Conclusions, and Recommendations** summarizes the research team's efforts in conducting the research and describes researchers' recommendations for revised traffic control at unsignalized intersections based on the findings and conclusions from the research.
- **Appendix** provides the research team's recommended text of proposed changes to the 2009 MUTCD developed at the conclusion of the project.

CHAPTER 2: REVIEW OF POLICIES AND GUIDELINES

BACKGROUND

This chapter summarizes the findings from the review of policies and guidelines used by state and local transportation agencies. It opens with a broad overview of the criteria in the current edition of the MUTCD and summarizes previous and anticipated changes to the sections of interest.

MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES

2009 MUTCD Sections 2B.04 to 2B.09

The 2009 MUTCD (*1*) provides guidance on application of YIELD signs (Sections 2B.08 and 2B.09) and STOP signs (Sections 2B.05 through 2B.07) on one or more approaches to an intersection. STOP and YIELD signs are also discussed in Section 2B.04, which covers right of way at intersections.

History of Existing MUTCD Sections 2B.04 through 2B.09

The current MUTCD (*1*) has been revised several times including in the 1948 (*2*), 1961 (*3*), 1988 (*4*), 2000 (*5*), and 2003 (*6*) editions. The following subsections address the major revisions that have been made to the MUTCD up to and including the 2009 edition (*1*).

Right of Way at Intersections

The 2009 MUTCD includes a new section addressing right of way at intersections pertaining to both STOP and YIELD signing. The new section provides a general overview of the criteria to be considered for any intersection control, using a combination of new text and text moved from other sections of the previous manual.

The 2009 MUTCD provisions include the following:

> Engineering judgment should be used to establish intersection control. The following factors should be considered:
>
> A. Vehicular, bicycle, and pedestrian traffic volumes on all approaches;
>
> B. Number and angle of approaches;
>
> C. Approach speeds;
>
> D. Sight distance available on each approach; and
>
> E. Reported crash experience.
>
> YIELD or STOP signs should be used at an intersection if one or more of the following conditions exist:

> > A. An intersection of a less important road with a main road where application of the normal right-of-way rule would not be expected to provide reasonable compliance with the law;
> >
> > B. A street entering a designated through highway or street; and/or
> >
> > C. An un-signalized intersection in a signalized area.
>
> In addition, the use of YIELD or STOP signs should be considered at the intersection of two minor streets or local roads where the intersection has more than three approaches and where one or more of the following conditions exist:
>
> > A. The combined vehicular, bicycle, and pedestrian volume entering the intersection from all approaches averages more than 2,000 units per day;
> >
> > B. The ability to see conflicting traffic on an approach is not sufficient to allow a road user to stop or yield in compliance with the normal right-of-way rule if such stopping or yielding is necessary; and/or
> >
> > C. Crash records indicate that five or more crashes that involve the failure to yield the right-of-way at the intersection under the normal right-of-way rule have been reported within a 3-year period, or that three or more such crashes have been reported within a 2-year period.

STOP Sign Applications

The initial criteria for STOP sign applications were included in the 1948 edition (*2*) and remained the same through the 2003 edition (*6*). Those criteria considered the following conditions:

- Intersection of a less important road with a main road where application of the normal right-of-way rule would not be expected to provide reasonable compliance with the law.
- Street entering a through highway or street.
- Unsignalized intersection in a signalized area.
- High speeds, restricted view, or crash records indicating a need for control by a STOP sign.

The 2009 MUTCD (*1*) relocated the above criteria into the new Section 2B.04 and added the following for STOP sign applications:

> The use of STOP signs on the minor-street approaches should be considered if engineering judgment indicates that a stop is always required because of one or more of the following conditions:
>
> > A. The vehicular traffic volumes on the through street or highway exceed 6,000 vehicles per day;
> >
> > B. A restricted view exists that requires road users to stop in order to adequately observe conflicting traffic on the through street or highway; and/or
> >
> > C. Crash records indicate that three or more crashes that are susceptible to correction by the installation of a STOP sign have been reported within a

12-month period, or that five or more such crashes have been reported within a 2-year period. Such crashes include right-angle collisions involving road users on the minor-street approach failing to yield the right-of-way to traffic on the through street or highway.

Four-way or Multi-way STOP Signs

The application of four-way or multi-way STOP signs was added to the 1961 MUTCD (*3*) and remained basically the same through the 1988 edition (*4*). The following conditions may warrant a multi-way STOP sign installation in the 1988 edition:

1. Where traffic signals are warranted and urgently needed, the multi-way stop is an interim measure that can be installed quickly to control traffic while arrangements are being made for the signal installation.

2. An accident problem, as indicated by five or more reported accidents of a type susceptible of correction by a multi-way stop installation in a 12-month period.

3. Minimum traffic volumes:

    a. The total vehicular volume entering the intersection from all approaches must average at least 500 vehicles per hour for any 8 hours of an average day, and

    b. The combined vehicular and pedestrian volume from the minor street or highway must average at least 200 units per hour for the same 8 hours, with an average delay to minor street vehicular traffic of at least 30 seconds per vehicle during the maximum hour, but

    c. When the 85th-percentile approach speed of the major street traffic exceeds 40 miles per hour, the minimum vehicular volume warrant is 70 percent of the above requirements.

The 2000 (*5*), 2003 (*6*), and 2009 (*1*) MUTCD editions revised Item 3a above on minimum volumes and added other conditions that could be considered. The criteria presently read as follows:

> The following criteria should be considered in the engineering study for a multi-way STOP sign installation:
>
> A. Where traffic control signals are justified, the multi-way stop is an interim measure that can be installed quickly to control traffic while arrangements are being made for the installation of the traffic control signal.
>
> B. Five or more reported crashes in a 12-month period that are susceptible to correction by a multi-way stop installation. Such crashes include right-turn and left-turn collisions as well as right-angle collisions.

C. Minimum volumes:

1. The vehicular volume entering the intersection from the major street approaches (total of both approaches) averages at least 300 vehicles per hour for any 8 hours of an average day; and

2. The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor street approaches (total of both approaches) averages at least 200 units per hour for the same 8 hours, with an average delay to minor-street vehicular traffic of at least 30 seconds per vehicle during the highest hour; but

3. If the 85th-percentile approach speed of the major-street traffic exceeds 40 mph, the minimum vehicular volume warrants are 70 percent of the values provided in Items 1 and 2.

D. Where no single criterion is satisfied, but where Criteria B, C.1, and C.2 are all satisfied to 80 percent of the minimum values. Criterion C.3 is excluded from this condition.

Other criteria that may be considered in an engineering study include:

A. The need to control left-turn conflicts;

B. The need to control vehicle/pedestrian conflicts near locations that generate high pedestrian volumes;

C. Locations where a road user, after stopping, cannot see conflicting traffic and is not able to negotiate the intersection unless conflicting cross traffic is also required to stop; and

D. An intersection of two residential neighborhood collector (through) streets of similar design and operating characteristics where multi-way stop control would improve traffic operational characteristics of the intersection.

YIELD Sign Applications

The YIELD sign was added to the MUTCD in the 1961 edition (*3*), and the criteria for application remained the same through the 1988 edition (*4*), with the following conditions:

1. On a minor road at the entrance to an intersection where it is necessary to assign right-of-way to the major road, but where a stop is not necessary at all times, and where the safe approach speed on the minor road exceeds 10 miles per hour.
2. On the entrance ramp to an expressway where an acceleration lane is not provided.
3. Within an intersection with a divided highway, where a STOP sign is present at the entrance to the first roadway and further control is necessary at the entrance to the second roadway, and where the median width between the two roadways exceeds 30 feet.
4. Where there is a separate or channelized right-turn lane, without an adequate acceleration lane.

5. At any intersection where a special problem exists, and where an engineering study indicates the problem to be susceptible to correction by the use of the YIELD sign.

The 2000 (*5*), 2003 (*6*), and 2009 (*1*) MUTCD editions consolidated the criteria into four items for consideration as follows:

> YIELD signs may be installed:
>
> > A. On the approaches to a through street or highway where conditions are such that a full stop is not always required.
> >
> > B. At the second crossroad of a divided highway, where the median width at the intersection is 30 feet or greater. In this case, a STOP or YIELD sign may be installed at the entrance to the first roadway of a divided highway, and a YIELD sign may be installed at the entrance to the second roadway.
> >
> > C. For a channelized turn lane that is separated from the adjacent travel lanes by an island, even if the adjacent lanes at the intersection are controlled by a highway traffic control signal or by a STOP sign.
> >
> > D. At an intersection where a special problem exists and where engineering judgment indicates the problem to be susceptible to correction by the use of the YIELD sign.

The 2009 edition (*1*) of the MUTCD also added a fifth item to the YIELD options as follows:

> > E. Facing the entering roadway for a merge-type movement if engineering judgment indicates that control is needed because acceleration geometry and/or sight distance is not adequate for merging traffic operation.

Potential Change to MUTCD

NCUTCD recently reviewed the term "approximately equal" as used within the multi-way stop control section. The committee presented the following discussion (*7*):

> The support statement in Section 2B.07 states: Multi-way stop control is used where the volume of traffic on the intersecting roads is approximately equal.
>
> How do we define the term "approximately equal"?
>
> Section 2B.07 guidance provides criteria in paragraph C as follows:
>
> - Vehicular volume entering the intersection from the major street approaches (total of both approaches) averages at least 300 vehicles per hour for any 8 hours of an average day; and
> - The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor street approaches (total of both approaches) averages at least 200 units per hour for the same 8 hours.

This language provides a reasonable indication that approximately equal at the minimum value is 200 units on the minor street and 500 units in total volume. This is a ratio of 40% minor street volumes to the total volume. However, this does not provide a definition or indication of the maximum volumes on either the major or minor street. It only deals with the minimum volume end of the spectrum.

The *Highway Capacity Manual* (HCM) does provide some insights in Chapter 17, Unsignalized intersections. The critical criteria may be found in the critical gap and delay studies. The delay study along with the level of service at the intersection must be factored in along with the turning volumes. The MUTCD already has language in this section indicating a delay of at least 30 seconds for the minor street approach during the highest hour.

The principal elements affecting selection of intersection traffic control are:

- Functional classification of each intersecting street
- Peak hour traffic volumes (vehicular and pedestrian)
- Crash History
- Intersection geometrics
- Sight Distance

Functional classification and traffic volumes are the two parameters that largely influence the question of “approximately equal volumes”.

The classification of intersecting legs should also be factored in before electing to use a multi-way stop control.

- At a local-local intersection, no control or yield control is more appropriate.
- At a local-collector intersection, a yield or one- or two-way stop control is more appropriate.
- At a local-major intersection a one- or two-way stop control is more appropriate.
- Where a collector intersects with a collector with medium vehicular activity level, an all-way stop control may be appropriate.
- Where two major roadways intersect, an all-way stop control may be appropriate or signal.

ITE studies have demonstrated that when the 8 hour minimum volumes from all approaches of 180–400 vehicles per hour with at least 40% from the minor or secondary street would then provide the point at which a multi-way stop could be considered. More recent studies have shown that when the 8 hour minimum volumes from all approaches of 500 vehicles per hour with at least 40% from the minor or secondary street would provide the point at which a multi-way stop could be considered, in addition to the sight distance criteria.

Based upon these considerations, the following suggested change was made and endorsed by the full NCUTCD within item number 2 of the minimum volume criteria:

> 2. The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor street approaches (total of both approaches) is at least 40% of the total vehicular volume entering from all approaches ~~and averages at least 200 units per hour~~ for the same 8 hours, with an average delay to minor-street vehicular traffic of at least 30 seconds per vehicle during the highest hour;…

Another recent effort is to develop revisions to the MUTCD to define the application of traffic control devices to sites open to public travel. Several changes are being considered by the NCUTCD for sites open to public travel, such as sign size or the use of a STOP or YIELD sign at the end of a parking lot aisle.

There is also an ongoing effort to consider reorganization of the MUTCD to group existing sections into chapters by topic area. The purpose of this effort is to enhance the usability of the MUTCD in both the print edition and the electronic edition.

REVIEW OF STATE AND LOCAL DOCUMENTS

The research team conducted online searches for guidelines and manuals from all 50 states to review their current policies. The two main online sources for locating state manuals used in this task were:

- FHWA website for MUTCDs and Traffic Control Devices Information by State (http://mutcd.fhwa.dot.gov/resources/state_info/) (accessed in October 2013).
- FHWA website for State Roadway Design Manuals (http://www.fhwa.dot.gov/programadmin/statemanuals.cfm) (accessed in October 2013).

Many manuals recommend selection of traffic control devices based on an engineering study/investigation or after consultation with the agency's traffic department on an intersection-by-intersection basis, and they point to the federal or state MUTCD for guidance. In some cases the language focuses on two-way stop control (TWSC) or all-way stop control (AWSC). A few states (Minnesota, Washington, and Wisconsin) provide specific procedures or processes for intersection control selection. A few other states (Indiana and Maryland) have language in their manual that provides additional guidance on application of STOP and YIELD signs. Table 1 and Table 2 categorize states by the level of guidance on selecting traffic control devices for unsignalized intersection.

Table 1. Level of Guidance on Selecting Traffic Control Device for Unsignalized Intersections Available in (Online) State Manuals.

States with Guidance (in Addition to or Different from MUTCD) on Selecting Traffic Control Device for Unsignalized Intersection	States with Guidance on Converting Stop or Yield Control	States with Intersection Control Evaluation/Analysis Procedure
Florida (TWSC)	Indiana	Minnesota
Idaho	Maryland	Washington
Indiana		Wisconsin
Kentucky (YIELD)		
Maryland		
Montana		
Pennsylvania		
Wisconsin		

Table 2. States Not Included in Table 1.

States without Online State MUTCD or Other Manual on Selecting Traffic Control Device for Unsignalized Intersection	States with MUTCD Criteria Same as 2009 MUTCD	States with Guidance to Use MUTCD for Traffic Control Device Selection at Unsignalized Intersection
Alabama	Alaska	Arizona
Arkansas	Arizona	Colorado
Connecticut	California	Delaware
District of Columbia	Colorado	Florida (AWSC)
Georgia	Iowa	Illinois
Hawaii	Maine	Indiana
Kansas	Michigan	Kentucky (STOP)
Louisiana	Missouri	Massachusetts
Mississippi	Nebraska	Nebraska
Nevada	New Mexico	Nevada
New Jersey	New York	New Hampshire
North Dakota	North Carolina	Ohio
Oklahoma	Ohio	Oregon
Rhode Island	South Carolina	Tennessee
South Dakota	Tennessee	Utah
Vermont	Texas	Virginia
West Virginia	Virginia	Washington (AWSC, local roads)
Wyoming		

State Guidance in Addition to MUTCD

STOP Sign

Idaho's *Traffic Manual* (*8*) recommends use of STOP signs on minor-road approaches at intersections with arterials and other major roadways, except when a traffic signal is warranted or an engineering investigation determines other control to be safer, operationally better, and more desirable. Idaho's *Traffic Manual* also recommends STOP signs at other intersections with state highways. Examples are alleys or shopping centers or high-volume (greater than

500 average daily traffic [ADT]) private approaches where it has been determined that the installation of such signs is in the best interest of safety and mobility on the State Highway System.

The 2011 *Indiana Design Manual* (*9*) provides guidance for use of multi-way stop control in residential areas (in addition to the warrants provided in the MUTCD). Multi-way stop control is recommended at intersections of two collector streets that are primary to the area, or at intersections where there are three or more crashes in 1 year. The volume split guideline is 60–40 percent (or closer) for four-way intersections and 75–25 percent (or closer) for three-way intersections.

Maryland MUTCD Section 2B.04 (Right-of-Way at Intersections) (*10*) has the following text in addition to the support statement in the federal MUTCD:

- STOP signs should not be used to control cross traffic within medians less than 50 ft in width. Even within medians wider than 50 ft, YIELD signs should be considered rather than STOP signs.
- STOP signs are not to be placed along any two adjacent intersection approaches where all traffic along that approach is not expected or required to stop unless channelizing is provided to direct certain movements away from the STOP sign.
- STOP signs are not to be placed along certain intersection approaches, and omitted from other intersection approaches, when driver expectations are violated as to which approaches stop and which do not.

Section 18.2.1 (STOP/YIELD Signs) of Montana's *Traffic Engineering Manual* (*11*) provides the following guidelines, in addition to the criteria in the MUTCD, for appropriate application of STOP signs along state facilities:

- Use a STOP sign on the approach of a county/city facility where it intersects the state facility.
- Provide a STOP sign at the minor approach of an intersection with a private facility or service road that provides access to major traffic generators such as an office complex.
- AWSC should not be used unless the traffic volume for each approach leg is approximately equal.
- STOP or YIELD signs may be used at railroad/highway grade crossings that have two or more trains per day and are without an automatic traffic control device.
- STOP or YIELD signs may also be used where a state facility crosses over an at-grade railroad crossing just prior to a stop/yield-controlled intersection, ensuring the availability of sufficient sight distance. Depending on the available and needed storage length, a DO NOT STOP ON TRACKS sign needs to be added.

Pennsylvania's *Official Traffic Control Devices* publication (*12*) allows inclusion of both reportable crashes and non-reportable crashes documented in the police files when checking for the MUTCD multi-way STOP sign warrant B (crashes). Additionally, the crashes considered are to be within a 12-month period during the most recent 3 years of available crash data. Pennsylvania's guidelines also prohibit the use of multi-way stop control at intersections with limited available corner sight distance unless there is no practical method of improving the sight distance or reducing the speed limit to satisfy the minimum corner sight distance values.

Washington's *Design Manual* (*13*) states that multi-way stop control is most effectively used on low-speed facilities with approximately equal volumes on all legs and total entering volumes not exceeding 1,400 vehicles during the peak hour. The text refers to the MUTCD for guidance on the application of multi-way stop control.

The *Florida Intersection Design Guide* (*14*) notes that the TWSC mode requires minimal justification, and there are no numerical warrants to be applied.

YIELD Sign

The research team found that few state manuals had any information on the application of YIELD signs. The *Indiana Design Manual* (*9*) recommends the use of a YIELD sign at an intersection only if it is operating in a merge condition (e.g., channelized intersection with a turning roadway). Kentucky's *Traffic Operations Guidance Manual* (*15*) recommends that YIELD signs be used to assign right of way for turning movements and not be used to assign right of way for an entire approach at any intersection.

Convert STOP to YIELD Sign

The *Indiana Design Manual* (*9*) references the following publications that engineers can use to select between STOP and YIELD signs:

- ***Stop, Yield, and No Control at Intersections,* Report No. FHWA/RD-81/084, FHWA, June 1981.** This document provides analysis of control type, region, location (urban/rural), geometry (three-leg/four-leg), major-roadway volume, and sight distance at 140 low-volume intersections in the United States. The authors found that stop control produces the longest travel times/road-user costs, and yield control resulted in the lowest road-user costs.
- ***NCHRP Report 320: Guidelines for Converting Stop to Yield Control at Intersections*, Transportation Research Board (TRB), October 1989.** This document provides a review of crash experience at 756 yield- and stop-controlled intersections in six cities. Some of these intersections were converted from stop to yield control, providing a before-after perspective. The researchers found that intersections converted from stop to yield control are likely to experience an increase in crashes, especially at higher traffic volumes. Also, four-leg intersections with yield control had a higher crash rate than T-intersections with yield control. On the other hand, because of reduced delay, lower fuel costs, and lower vehicle operating costs, it was found that yield control is more cost effective than stop control at all volume levels studied.

Section 2B.06 of the Maryland MUTCD (*10*) provides guidance on STOP sign applications and conversion from Stop to Yield control. Table 3 lists these guidelines.

Table 3. Maryland MUTCD Table 2B-1a: Guidelines for Conversion from Stop to Yield Control (*10*).

1		Identify a stop controlled intersection candidate for change to yield control.
2		Review with the local traffic engineer and police for any known problems that might be impacted by less restrictive control.
3		Determine whether current MUTCD warrants for stop control are met by current traffic conditions.
4		Review accident data for the past three years. Intersections should not be considered for STOP to YIELD sign conversion unless there have been two or less reported accidents in a year, or four or less in three years.
5		Based on the ADT's (or estimated volume ranges) for both the major and minor approaches, determine the relative priority of conversion, as follows:
	a.	Major roadway volume (ADT) of less than 2,000 and minor roadway volume of less than 200 indicates a high priority for probable conversion. Field confirmation of good sight distance shall be obtained.
	b.	If either the major ADT is between 2,000 and 3,000 or the minor ADT is between 200 and 500, the priority drops to medium. A field study to confirm good sight distance shall be obtained; a short peak period turning movement count shall be obtained to determine that volumes have not increased substantially, and confirm that no problems such as abnormal amounts of forced stops or conflicts with major street traffic exists.
	c.	Greater volumes up to 10,000 major and 1,000 minor indicate a low priority and consideration shall proceed only after a more detailed study of volumes, conflicts and driver behaviors to determine if the safety risk from proposed conversion is acceptable.
6		Field check to measure the sight distance at the intersection approach where the stop control is being considered for change to yield control. Ascertain that the measured sight distance complies with sight distance standards that are consistent with the latest edition of AASHTO's "A Policy on the Geometric Design of Highways and Streets."
7		After following the procedure outlined above and concluding that traffic demand can be accommodated safely and more effectively, stop control may be changed to yield control.

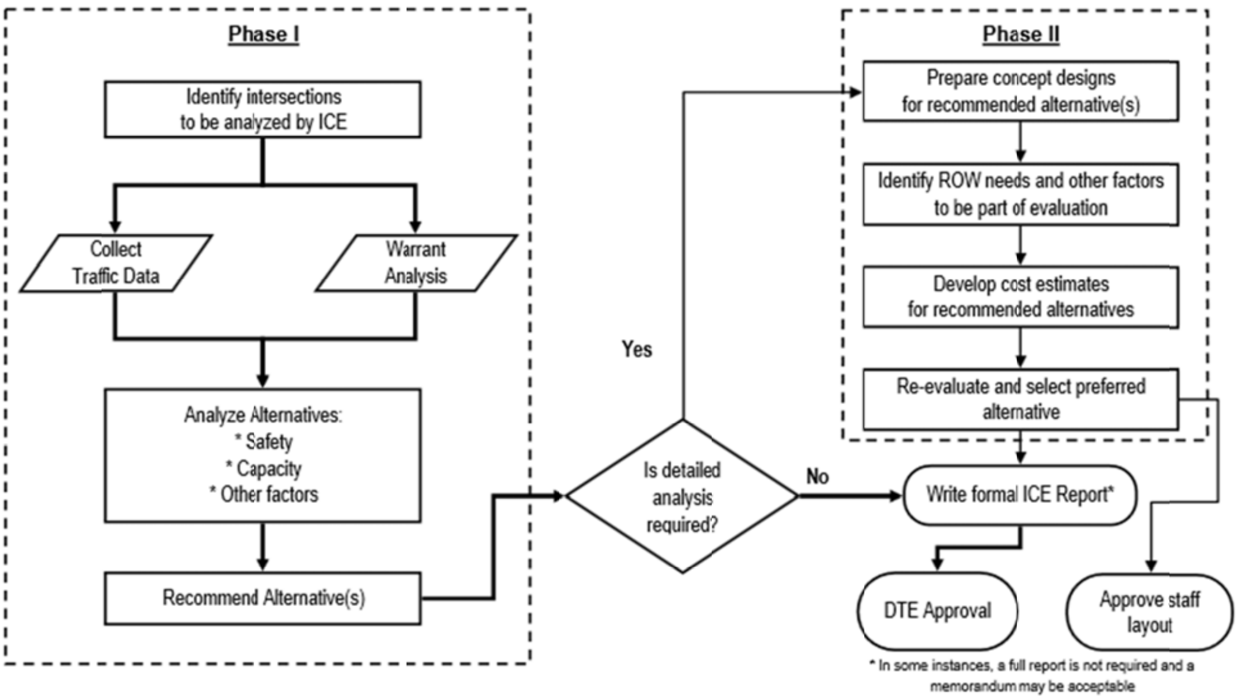
Intersection Control Evaluation Processes

Minnesota

The Minnesota Department of Transportation's (MnDOT's) Office of Traffic, Safety, and Operations provides guidelines on intersection control evaluation (ICE) for intersections on trunk highways. MnDOT does not require an ICE report for intersections that are determined to need minimal traffic control (two-way stop or no control), but requires it for any other type of control (all-way stop, roundabout, traffic signal, median treatment to reduce traffic movements, or other advanced traffic control systems such as continuous flow intersections). Also, if the ADT for the minor leg or the intersection is less than 1,000 ADT, an ICE is not required. The guidelines recommend evaluation of the four-way stop if the combined ADT is between 7,500 and 50,000. Table 4 is the guide provided in the *Intersection Control Evaluation* report (*16*) for determining which intersection options should be evaluated based upon combined ADT volumes. For intersections with volumes close to the range boundaries in the table, it is recommended that options given for both ranges be evaluated. Figure 1 shows a flowchart summarizing the ICE process. For analysis of multi-way stop control, the Minnesota MUTCD warrants (same as those in the federal MUTCD) are to be considered.

Table 4. Potential Intersection Control by ADT Volume (Table 1 in *16*)

Approximate Combined ADT	Four-Way Stop	Signal	Roundabout	Non-Traditional Intersection	Access Management Treatments	Grade Separation
7,500–10,000	X		X		X	
10,000–50,000	X	X	X	X	X	X
50,000–80,000		X	X	X	X	X
>80,000						X



Source: MnDOT *Intersection Control Evaluation*, Figure 15

Figure 1. The Minnesota Intersection Control Evaluation Process (*16*).

Washington

Washington's *Design Manual* (*13*) identifies that an intersection control decision requires the consideration of all potential users of the facility such as motorcycles, passenger cars, heavy vehicles, public transit, bicyclists, and pedestrians. The manual recommends using the guidance for consideration of the application of multi-way stop control provided in the MUTCD. The manual notes that multi-way stop control is most effective on low-speed facilities with approximately equal volumes on all legs and total entering volumes that do not exceed 1,400 vehicles during the peak hour.

Washington's *Design Manual* (*13*) provides procedures for determining traffic control at a new intersection or for modifying existing traffic control. The following considerations are included in the intersection control analysis procedure described in the *Design Manual* for selecting traffic control that facilitates efficient multimodal traffic flow through intersections:

- Existing condition: Current physical characteristics (e.g., speed and sight distance) and collision history are to be reviewed to identify any problematic movements.
- Delay analysis: The delay analysis focuses on determining the peak-hour level of service (LOS) of an individual intersection. When the through roadway daily traffic is 3,500 or less, delay analysis is not required except in cases where the higher-volume roadway is controlled or where channelization is proposed. For AWSC, guidance provided in the MUTCD is to be followed.
- Operational considerations: An operational analysis is a more encompassing review of the ability of the intersection to provide sufficient capacity in the network, and includes consideration of the environment that users will encounter at all hours of the day. In an operational analysis, the effect of the type of intersection control on the surrounding network is to be reviewed.
- Benefit/cost analysis: The only societal costs/benefits the Washington State Department of Transportation evaluates are those due to collisions and delay. Project costs include cost of design, right of way, construction, and annual maintenance.
- Bicycle/pedestrian facilities: The need for pedestrian/bicycle facilities is to be reviewed, along with required Americans with Disabilities Act accommodations.
- Context-sensitive/sustainable design: The intersection should be reviewed not only for its physical aspects as a facility serving specific transportation objectives, but also for its effects on the aesthetic, social, economic, and environmental values, needs, constraints, and opportunities in a larger community setting.

Wisconsin

Wisconsin's *Facilities Development Manual* (*17*) provides guidance on the selection of intersection control through the ICE process for intersections on state trunk highways. The ICE process is conducted in two distinct phases: scoping and alternative selection. In the scoping phase, a memorandum that recommends traffic control alternatives for further evaluation in the next phase is prepared. As part of this phase, a review of crash diagrams, signal warrants, all-way stop warrants, operations (using the 2010 *Highway Capacity Manual*), and alternative feasibility (e.g., potential environmental impacts and right-of-way impacts) is conducted. In the alternative selection phase, a more detailed evaluation of the alternatives is documented in the ICE worksheet to assist the region in selecting the type of traffic control, lane configuration, and intersection type for the studied intersection. In the alternative selection phase, factors considered include safety, operational analysis, right-of-way impacts, costs, practical feasibility, pedestrians and bicycle users, oversize-overweight freight network, and environmental impacts.

AWSC warrants are discussed in Wisconsin's *Traffic Guidelines Manual* (*18*) within Section 13-26-5. This review includes all of the criteria in MUTCD Section 2B.07, both guidance and optional, and the following supplemental criteria:

- Functional highway classification: For desirable AWSC, the intersecting roadways should have the same or similar functional class (i.e., different by only one level) on at least three approaches.
- ADT: For AWSC, it is highly desirable for the intersecting roadways to have closely balanced ADTs on at least three approaches, i.e., the volume of at least one of the minor

roadway approaches (stop control on a two-way stop) is not less than 70 percent of the higher volume of the two approaches on the major roadway (through the state trunk highways).

- Crash history: AWSC should be considered if it is expected to correct a significant number of intersection crashes that have occurred in the last 5 years (that are susceptible to correction by a multi-way stop installation), and/or are expected to significantly reduce the overall severity of future crashes from what previously occurred.
- Alternatives: Improvement alternatives that are less restrictive than AWSC shall be considered and evaluated.
- Mobility impact: Impacts of stopping the existing "through" state trunk highway should be considered in terms of average vehicle delay and queue length. An AWSC capacity analysis is to be performed and compared to the existing TWSC capacity analysis.
- Right-turn inclusion: Similar to signal warrant evaluation, the inclusion of right turns from the minor approach(es) in the AWSC warrant analysis should be evaluated.

Wisconsin's *Facilities Development Manual* (*17*) also discusses intersections on rural high-speed multilane divided highways (rural expressways). Typically, rural expressway intersections are at-grade TWSC with the stop control on the minor (usually two-lane) roadway. TWSC rural expressway intersections often experience safety problems long before the end of the design life of the facility and even before meeting traffic signal volume warrants. There is typically an increase in the percentage of total expressway crashes as the mainline traffic volumes increase, and there is an increase in frequency and severity of all intersection crashes with increase in minor-roadway volumes. Right-angle collisions are the most frequent crash type, and collisions at the far-side intersection are the most severe. The underlying cause of these collisions in most cases is not failure to yield but the inability of the driver stopped on the minor-road approach to judge the arrival time of approaching expressway traffic (i.e., gap selection). The Wisconsin Department of Transportation manual provides a matrix (reproduced here as Figure 2) from NCHRP Report 650 (*19*) to be used as a guide to select safety countermeasures at TWSC rural expressway intersections.

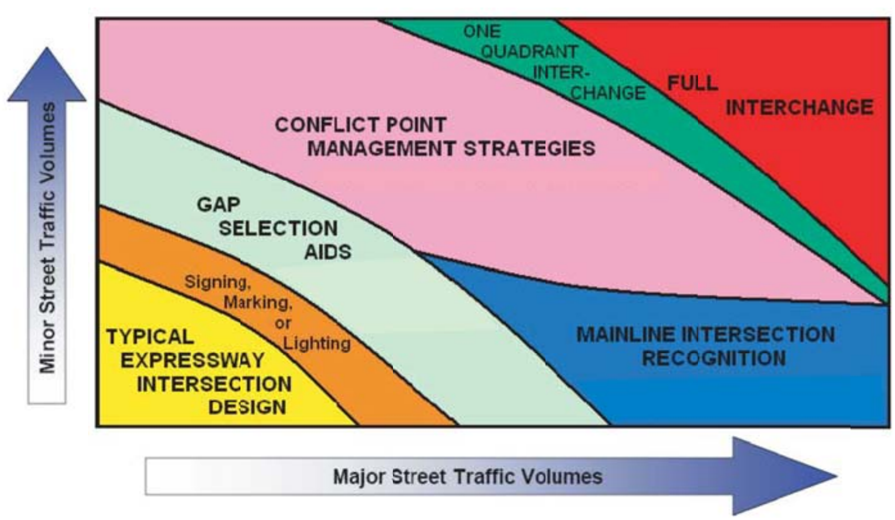


Figure 2. Countermeasure Matrix for TWSC Expressway Intersection (Figure 1.1b from *17*)

OUTREACH TO PRACTITIONERS

While some potential methodologies have been documented through large-scale research studies and distributed through national publications, other methodologies may be under consideration and/or experimentation in more localized applications. To try to identify these guidelines, the research team used the following posting on the ITE Online Community on October 23, 2013:

> Dear Colleagues,
>
> NCHRP Project 3-109 is evaluating criteria for selecting the type of control at unsignalized intersections. These criteria will be considered for inclusion in the MUTCD. The reason for this investigation is that the current MUTCD guidelines date back to 1971. As part of this process, we are looking for novel approaches for selecting traffic control at unsignalized intersections used by state and local agencies. Please email your agencies' approach to selecting traffic control at unsignalized intersections to me or respond to this forum post.

Responses regarding STOP and YIELD signs were received from six individuals. Three respondents provided documents from MnDOT, including the fall 2007 *Intersection Control Evaluation* report (*16*) and the *2007 Intersection Control Evaluation* (*20*) draft document. These documents provide a process that identifies the best intersection control through a comprehensive analysis. One of these respondents also included a sample report.

Two of the respondents were from Wisconsin. One of the respondents shared Wisconsin's *Traffic Guidelines Manual* (*18*) section on STOP signs. This document is discussed in the "Intersection Control Evaluation Processes" section. The other Wisconsin respondent shared the City of Janesville, Wisconsin, criteria (*21*); see Table 5. The criteria provide the following support for their STOP and YIELD sign procedures:

> STOP Sign Procedure
>
> As is documented in the report, our recommendations are influenced by the fact that a consistent, predictable pattern of arterial streets (STOP signs) results in an overall safer system than having control at all intersections. We, therefore, first look at whether a requested STOP sign location fits into that system. Minimum traffic volumes, as outlined in the criteria of 2,000 vehicles per day entering the intersection, are generally required before consideration of installation of an isolated STOP sign that is not part of the overall arterial street system.
>
> General YIELD Sign Procedure
>
> YIELD signs are most useful at intersections which are isolated and are not part of the arterial street system where entering volumes are greater than 1,000 vehicles per day. In many YIELD sign requests, the concern is blocked vision. In such cases, our first response is to look at the intersection, determine if a vision blockage is in violation of the City's vision triangle ordinance. If so, we administratively enforce the ordinance which usually requires trimming of bushes or trees which may in turn eliminate the need for the traffic control sign. In other cases where the isolated volumes are higher than 1,000 vehicles per day and/or

where vision problems are not able to be so easily corrected, a YIELD sign is appropriate.

A representative of Portland noted that he uses NCHRP Report 562 (*22*) to guide decisions on how to enhance pedestrian/bike crossings.

Table 5. City of Janesville, Wisconsin, Criteria (*21*) for Installation of Traffic Control Devices, Dated August 1977.

Criteria	Yield Control	Stop Control	Multiway Stop Control	Signals[a]
1. Arterial Street	N/A	Yes	Both	Both
2. Entering Volume (Minimum)	1,000 vpd[b]	2,000 vpd	4,000 vpd Major 65% of Total	Major street 400 vph[c] for any 8 hr, both legs; minor street 120 vph for same 8 hr, either leg.
3. Preventable Crashes (Last 12 Months)	3	3	5	5
	NOTE: If crashes exceed these figures, volume requirements can be reduced by 25%			
4. Safe Approach Speed	>10 mph (by Vision)	<10 mph (by Vision)	N/A	N/A
5. Interruption of Continuous Flow	N/A	N/A	N/A	Major street 750 vph for any 8 hr, both legs; minor street 75 vph for same 8 hr, either leg.
6. Progressive Movement	N/A	N/A	N/A	Major street 300 vph for any 8 hr, both legs; minor street 120 vph for same 8 hr, one leg.
7. School Crossing Volume	N/A	N/A	N/A	100 grade school children for each of 2 hr; 400 vph for same 2 hr.
8. Pedestrian Volume (Minimum)	N/A	N/A	N/A	150 pedestrians for each of 4 hr/day, 400 vph for same 4 hr.
9. Turning Movements	N/A	N/A	N/A	N/A
10. Actual Approach Speed	N/A	N/A	N/A	N/A
Minimum Number of Criteria to Be Met	One of the Above	One of the Above	All of the Above	#1 and One Other

[a] Signal criteria now follow state/federal guidelines (as of 1996).
[b] vpd = vehicles per day
[c] vph = vehicles per hour

CHAPTER 3: LITERATURE REVIEW

BACKGROUND

The literature review task was subdivided into the following focus areas:

- Key reference documents, including the TRB HCM (*23*), American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual* (HSM) (*24*), and ITE *Manual of Traffic Engineering Studies* (*25*).
- Previous literature that discusses methods for selecting traffic control devices, such as YIELD or STOP signs, for unsignalized intersections.
- Previous literature that discusses methods for selecting traffic control devices for unsignalized pedestrian crossings. These methods present additional approaches, such as calculating delay using a series of equations or using a point system, for selecting a traffic control device at an unsignalized intersection.

SUMMARY OF KEY REFERENCE DOCUMENTS

2010 *Highway Capacity Manual*

The 2010 HCM (*23*) Chapter 17 (Urban Street Segments) refers users to the following three documents for guidelines on selecting the appropriate type of traffic control:

- Pline, J. (ed.). *Traffic Control Device Handbook*. Institute of Transportation Engineers, Washington, D.C., 2001 (*26*).
- Koonce, P., L. Rodegerdts, K. Lee, S. Quayle, S. Beaird, C. Braud, J. Bonneson, P. Tarnoff, and T. Urbanik. *Traffic Signal Timing Manual*. Report No. FHWA-HOP-08-024, Federal Highway Administration, Washington, D.C., June 2008 (*27*).
- Federal Highway Administration. *Manual on Uniform Traffic Control Devices for Streets and Highways*. Washington, D.C., 2009 (*1*).

Chapters 19, 20, and 32 of the 2010 HCM provide methodologies for TWSC capacity calculations (accounting for pedestrians) and capacity analysis methodology for three-lane AWSC approaches.

2000 *Highway Capacity Manual*

The average vehicle control delay can be determined from equations in the HCM (*28*). These equations have been developed to analyze the capacity, lane requirements, and effects of traffic and design features of unsignalized intersections. Each type of unsignalized intersection has a set of procedures that address the unique elements of its operation. The procedures have been written to focus on the user-defined analysis period under a steady-state condition, meaning that the traffic volumes and units should be relatively stable over the time period being studied. The HCM cautions against using the method for analysis of any transitional period where units within the intersection are changing, leaving that analysis type to the use of simulation models.

The HCM defines LOS by computing or measuring control delay for each movement. These delays are based on the priorities of the traffic streams at the intersection, considering the traffic control devices as applied (or proposed) and the availability of acceptable gaps based on the critical gap and follow-up time.

The typical analysis period is the peak-hour turning movement volume factored to reflect conditions during the peak 15 minutes using the peak-hour factor. In practice, the traffic volumes are factored from a peak-hour count to assess the warrants identified in the MUTCD. These factors may be based on a 24-hr tube count or a multi-hour manual turning movement count.

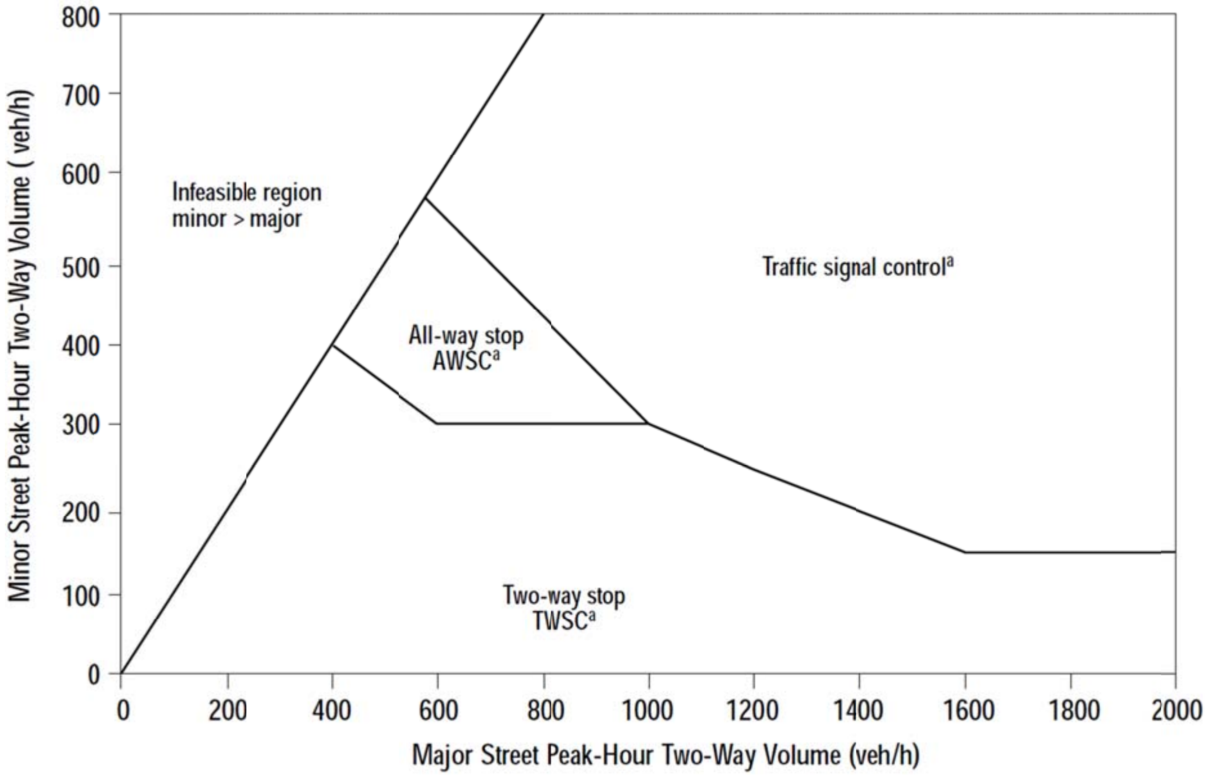
The HCM procedure and its delay estimations are often used to assess the potential risk for a motorist making a risky move at an unsignalized intersection. Of interest from a multimodal perspective is that the HCM highlights that pedestrians "must use acceptable gaps in major-street traffic streams, but they have priority over all minor-street traffic at a TWSC." Chapter 18 describes the LOS criteria for pedestrians at unsignalized intersection and highlights that there is a "high" likelihood of risk-taking behavior (acceptance of short gaps) when delays exceed 30 sec and a "very high" likelihood as delays exceed 45 sec. This is reiterated in Chapter 17: "LOS F may also appear in the form of drivers on the minor street selecting smaller than usual gaps. In such cases, safety may be a problem, and some disruption to the major traffic stream may result. Note that LOS F may not always result in long queues but in adjustments to the normal gap acceptance behavior."

The 2000 HCM (*28*) also includes a graphic (shown in Figure 3) that was adapted from the 1983 edition of the ITE *Traffic Control Device Handbook*. The figure can be used to forecast the likely intersection control type based on two-way entering traffic volumes. The figure was generated by converting the 8-hr warrants to two-way peak-hour volumes, assuming ADT equals twice the 8-hr volume, peak hour is 10 percent of daily, and the two-way volumes are 150 percent of peak-direction volume.

2010 *Highway Safety Manual*

Crash Prediction

The predicted average crash frequency for an intersection can be determined from equations in the HSM (*24*). These equations, called safety performance functions (SPFs), are regression models for estimating the predicted average crash frequency of individual roadway segments or intersections for a set of specific base conditions. As discussed in the HSM, each SPF in the predictive method was developed with observed crash data for a set of similar sites. The SPFs, like all regression models, estimate the value of a dependent variable as a function of a set of independent variables. In the SPFs developed for the HSM, the dependent variable estimated is the predicted average crash frequency for an intersection under base conditions, and the independent variables are the annual average daily traffic (AADT) of the major and minor intersection legs.



[a] Roundabouts may be appropriate within a portion of these ranges.
Source: Adapted from *Traffic Control Devices Handbook* (1983 edition, pp. 4–18). Peak-direction, 8-hr warrants converted to two-way peak-hour volumes assuming ADT equals twice the 8-hr volume and peak hour is 10 percent of daily. Two-way volumes assumed to be 150 percent of peak-direction volume.

Figure 3. Intersection Control Type and Peak-Hour Volumes (Exhibit 10-15 in *28*).

SPFs and adjustment factors have been developed for four types of intersections and suburban arterials:

- Three-leg intersections with stop control on the minor-road approach (3ST).
- Three-leg signalized intersections (3SG).
- Four-leg intersections with stop control on the minor-road approach (4ST).
- Four-leg signalized intersections (4SG).

Other types of intersections may be found on urban and suburban arterials but are not addressed by the HSM Chapter 12 SPFs. The equations for stop control are of interest to this research.

Determining the average crash frequency prediction for intersections requires the determination of several items including multiple-vehicle collisions by severity and single-vehicle collisions by severity. There is also a step for estimating the number of vehicle-pedestrian collisions per year at a stop-controlled intersection. Spreadsheets are available to assist in the calculations.

The predicted average crash frequency for base conditions is adjusted using crash modification factors (CMFs) and a calibration factor to adjust for a particular geographical area.

Crash Modification Factor

A CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site. The CMFs currently in the HSM for stop-controlled urban and suburban arterials are intersection left-turn lanes, intersection right-turn lanes, and lighting. The HSM (*24*) includes the potential crash effects of converting a minor-road stop control into AWSC (see Table 6). The safety findings shown in Table 6 are different for urban and rural settings. This observation indicates that perhaps the MUTCD should have different criteria depending on whether the intersection is in an urban setting or a rural setting.

Table 6. *Highway Safety Manual* (*24*) Table 14-5. Potential Crash Effects of Converting Minor-Road Stop Control into AWSC.

Treatment	Setting	Traffic Volume	Crash Type (Severity)	CMF[a]	Standard Error
Convert minor-road stop control to all-way stop control (MUTCD Warrants Are Met)	Urban	Unspecified (assumes that MUTCD warrants for all-way stop control are met)	Right-angle (All severities)	**0.25**	**0.03**
			Rear-end (All severities)	**0.82**	**0.1**
			Pedestrian (All severities)	*0.57*	*0.2*
			All types (injury)	**0.30**	**0.06**
	Rural		All types (All severities)	**0.52**	**0.04**

[a] CMF=Crash modification factor, **bold** text is used for the most reliable, and *italic* text is for less reliable CMFs.

From *Highway Safety Manual*, 2010, by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by Permission.

FHWA Crash Modification Factor Clearinghouse

Additional potential CMFs are available on the Crash Modification Factors Clearinghouse website (see Table 7 for examples). FHWA has established the Crash Modification Factors Clearinghouse (*29*) to provide an online repository of CMFs and crash reduction factors (CRFs) with a searchable database. Searching for CMFs related to STOP signs revealed several studies. The studies that may be relevant to this project include the following:

- 2006 study on the safety evaluation of STOP Sign In-Fill (SSIF) program (*30*).
- 2010 study that used a full Bayes (FB) approach to determine the effectiveness of the SSIF program (*31*).
- 2010 study that evaluated the conversion from TWSC to AWSC (*32*).

Table 7. Crash Modification Factors from Clearinghouse (*29*).

Countermeasure	CRF	CMF	Sev[a]	Major Min	Major Max	Minor Min	Minor Max	Num Lane
Convert minor-road stop control to all-way stop control (*32*)[b]	77	0.23	F, S, M	680	15,400	680	15,400	1
Convert two-way (without flashing beacons) to all-way stop control (without flashing beacons) (*32*)[b]	72.4	0.276	F, S, M	680	15,100	680	15,100	1
Convert two-way (with flashing beacons) to all-way stop control (with flashing beacons) (*32*)[b]	86.5	0.135	F, S, M	3,550	13,650	3,550	13,650	1
Convert two-way (without flashing beacons) to all-way stop control (with flashing beacons) (*32*)[2]	86.6	0.134	F, S, M	1,340	9,900	1,340	9,900	1
Install STOP signs at alternate intersections in residential areas (*30*)[c]	54.8	0.45	All	NS[d]	NS	NS	NS	2
Install STOP signs at alternate intersections in residential areas (*30*)[c]	72.3	0.28	F, S, M	NS	NS	NS	NS	NS
Install two-way stop-controlled intersections at uncontrolled intersections (*31*)[e]	51.1	0.489	All	NS	NS	NS	NS	NS

[a] Sev = severity, F = fatal, S = serious injury, M = minor injury.
[b] All crash types; before/after using empirical Bayes; four-leg.
[c] All crash types; simple before/after; 380 sites in Vancouver.
[e] NS = not specified.
[e] All crash types; before/after using empirical Bayes or full Bayes; 513 sites.

The 2006 study (*30*) evaluated the safety impacts associated with the SSIF program. The SSIF program was launched by the Insurance Corporation of British Columbia (Canada) in 1998 and consisted of installing STOP signs alternately at every second intersection in residential neighborhoods in the Greater Vancouver Regional District. This alternating pattern provides consistency in the application of STOP signs within a residential neighborhood. The main objective of the program was to reduce the frequency and severity of collisions and thereby reduce insurance claim costs in addition to providing a traffic-calming effect on residential neighborhoods. The evaluation included a time series analysis to investigate the effectiveness of the SSIF program on road safety performance at 380 intersections. The evaluation used comparison groups and three techniques to determine the safety impacts of the SSIF program. The first two techniques were based on the odds ratio methodology, while the third was based on the likelihood method. The results of the three techniques were consistent and showed that injury collisions were reduced 61 percent to 72 percent, while total collisions were reduced 45 percent to 55 percent. It was concluded that the installation of STOP signs at uncontrolled intersections in residential neighborhoods was an effective measure for reducing both the frequency and severity of collisions in urban areas.

A later paper (*31*) evaluated the effectiveness of the SSIF program by using different modeling techniques. The analysis revealed an overall significant reduction in predicted collision frequency of 51 percent.

A study in North Carolina (*32*) evaluated the conversion from TWSC to AWSC with or without flashing beacons using the empirical Bayes method. The purpose of the project was to develop CRFs for the conversion from two-way to AWSC. A total of 53 treatment sites located in urban, suburban, and rural areas were used in the analysis. The authors divided the treatment locations into three groups based upon the presence of an overhead and/or sign-mounted flashing beacon:

- Group 1 consisted of 33 intersections without flashing beacons.
- Group 2 consisted of 8 intersections with flashing beacons in the before and after period.
- Group 3 consisted of 8 intersections where the flashing beacon was installed with the AWSC.

The results from the North Carolina study showed a substantial decrease in total, injury, and frontal-impact crashes in the after period. The recommended CRFs from the overall group are a 68 percent reduction in total crashes, a 77 percent reduction in injury crashes, a 75 percent reduction in frontal-impact crashes, and a 15 percent reduction in ran-STOP-sign crashes.

ITE *Manual of Traffic Engineering Studies*

The ITE *Manual of Transportation Engineering Studies* (*25*) contains several relevant studies of interest to the topic of unsignalized intersection traffic control, including:

- Volume studies (Chapter 4).
- Spot speed studies (Chapter 5).
- Intersection and driveway studies (Chapter 6), including delay, queue length, gap and gap acceptance, and intersection sight distance.
- Traffic control device studies (Chapter 7).
- Compliance with traffic control devices (Chapter 8).
- Pedestrian and bicycle studies (Chapter 12).
- Traffic collision studies (Chapter 17).

SELECTING TRAFFIC CONTROL DEVICE FOR UNSIGNALIZED INTERSECTION

Safety Studies

The North Carolina study by Simpson and Hummer (*32*) included a comprehensive summary of recent literature on stop-controlled intersections. The following is part of their literature summary:

> Lovell and Hauer's study [*33*], which focused primarily on treatment sites located in an urban environment, is regarded as the most comprehensive review of the safety effects of converting intersections to all-way stop control. They reanalyzed

data from three previous safety studies in San Francisco, Philadelphia, and Michigan and added a new data set from Toronto, Canada. Intersections were converted from either two-way stop control or one-way streets to all-way stop control. Reference sites were used to account for regression to the mean.

The San Francisco data consisted of one-year before and after comparisons of crashes occurring at 49 urban intersections converted from two-way to all-way stop control between 1969 and 1973. The San Francisco reference data was obtained for a different time frame than the treatment data, from 1974 to 1977. The unbiased results for the San Francisco data showed a 62 percent reduction in total crashes, an 83 percent reduction in right-angle crashes, and a 74 percent reduction in injury crashes. The Philadelphia data contained the largest treatment sample, with 222 urban intersections. The data contained only intersections converted from one-way streets to all-way stop control between 1968 and 1975 and used 2-year before-and-after comparisons. The unbiased results for the Philadelphia data showed a 43 percent reduction in total crashes, a 77 percent reduction in right-angle crashes, and a 73 percent reduction in injury crashes. Along with the data from San Francisco and Philadelphia, the Toronto data contained only urban intersections. The Toronto data analyzed 79 intersections converted from two-way to four-way stop control between 1975 and 1982. The unbiased results for the Toronto data showed a 40 percent reduction in total crashes, a 50 percent reduction in right-angle crashes, and a 63 percent reduction in injury crashes.

The Michigan data was the only group pertaining to low-volume, high-speed rural roads and contained a set of 10 intersections. The Michigan data used 2- and 3-year before- and-after periods for intersections converted from two-way to all-way stop control between 1971 and 1977. The reference data was obtained from 1974 through 1976. The unbiased results for the Michigan data showed a 53 percent reduction in total crashes, a 65 percent reduction in right-angle crashes, and a 61 percent reduction in injury crashes.

Lovell and Hauer’s study [*33*] revealed consistent safety effectiveness for all-way stop conversion. In the four data sets, total crashes were reduced by 40 percent to 62 percent, right-angle crashes were reduced by 50 percent to 83 percent, and injury crashes were reduced by 61 percent to 74 percent. Likelihood functions were then used to merge the four sets of results into joint estimates of crash reduction factors. After combining results, they found that the conversion to all-way stop control reduced total crashes by 47 percent and right-angle and injury crashes by 72 percent and 71 percent, respectively.

Persaud [*34*] used the Philadelphia sample converted from one-way streets to all-way stop control in a study that examined how traffic volumes and other issues play a role in crash reductions at urban all-way stops. The results show that the effectiveness of all-way stop conversion in urban areas is not limited to a certain range of entering volumes that follow MUTCD warrants. When analyzing total and right angle crashes, it “can be just as effective for total entering volumes less than 6,000 per day as it is for higher volumes” [*34*]. The study also showed that for total and right-angle crashes, all-way stop conversion in urban areas is no less effective when approach volumes are unbalanced as when they are equal on all approaches. For rear-end crashes, which make up a small percentage of total crashes, the effectiveness decreases as total entering volumes increase and as the minor road volume drops below 25 percent. The study examined whether there is an increase in crashes in the acquaintance period immediately after conversion and found there is no significant difference in crashes during the first six months after conversion to all-way stop. The study also suggests that the effectiveness of all-way stop control does not decrease as its use becomes commonplace (*32*).

A 2006 paper (*35*) examined the proper level of traffic control on low-volume rural roads. The authors used 10 years of crash data for more than 6,000 rural, unpaved intersections in Iowa. Stop-controlled intersections were compared to uncontrolled intersections. Crash models were developed with logistic regression and hierarchical Poisson estimations. For ultralow-volume intersections, those used by fewer than 150 vehicles per day, results indicated no statistical difference in the safety performance of each level of control. The authors' review of the literature found that the most frequent crash factor was not STOP sign violations but failure to yield right of way from the stop position (*36, 37, 38*), and that other research found that available sight distance at low-volume intersections might have negligible effect on safety and operations *(39, 40*).

NCHRP Report 320 (*36*) discusses the conversion of stop to yield control. The report found that converted intersections experienced an increase in crashes, the severity and distribution of crashes did not change significantly, and converted intersections had higher crash rates overall than unchanged intersections. According to the study, candidates for conversion to yield control should have adequate sight distance, volume less than 1,800 ADT (1,500 ADT for major roads and 600 ADT for minor roads), and fewer than three crashes in 2 years.

A 1983 study (*41*) compared crash experience at stop-controlled and no-control intersections in rural Michigan and found that there was no statistical difference for intersections with major street volumes less than 1,000 vpd.

Polus's before-after study (*42*) of hazardous urban intersections where level of control was increased because of crash history (no control to yield control, no control to stop control, and yield control to stop control) showed that increase in control often resulted in more vehicular crashes (although the changes were mostly statistically insignificant), and introducing traffic control at an uncontrolled intersection resulted in reduction in pedestrian crashes. To understand the increase in vehicular crashes with increase in traffic control, Polus studied the gap and lag acceptance characteristics at stop and yield control movements. He concluded that the increase in mean accepted gap value at movements controlled by STOP signs (compared to yield controlled movements) was significant and probably reduced the safety at such movements.

A 2000 study (*43*) that reviewed the effectiveness of various strategies in reducing crashes and concluded an accident modification factor (AMF) of 0.53 for conversion from two-way to all-way stop for total intersection crashes. This value was based on the Lovell and Hauer study discussed earlier (*33*). In the rural expressway intersection safety toolbox developed for the Iowa Department of Transportation, Hochstein et al. (2011) (*44*) note the effectiveness of converting

TWSC to AWSC to be about 47 to 64 percent, and they include references to the 2000 Harwood et al. study (*43*), 1984 Briglia study (*45*), and the CMF Clearinghouse (*29*).

A 2009 study (*46*) identified about 2,500 unsignalized intersections under 60 categories (based on traffic control, number of lanes, median type, entering volume, etc.), representing nearly all possible types of unsignalized intersections existing. Annual crash profile tables for these categories were developed that can be used as reference values that can assist in identifying unsignalized intersections with specific problems, such as a high number of fatal crashes or high number of rear-end crashes. This information is presented in the form of a database application for easy access.

Charbonneau (*47*) developed modified TWSC warrants in 1995. The modified warrants include:

1. Where a street enters a through street.
2. Where an unsignalized intersection is in a signalized area.
3. Where the safe approach speed is less than 10 mph due to unremovable visibility obstructions, such as a building or topography.
4. Where the crash history indicates three or more reported crashes for the last 3 years that might be corrected by the use of STOP signs.
5. Where an engineering study indicates the application of the normal right of way is unduly hazardous.

The study found that two-way STOP sign warrants may not adequately address crash problems, and all-way warrants do not distinguish the wide variation in risk associated with the range of volumes between different levels of streets (i.e., local, collectors, and arterials). It was also observed that crashes decrease at warranted all-way stops and increase at unwarranted stops.

A 1998 paper (*48*) discussed research that developed a method where the safety of a two-way, stop-controlled intersection could be estimated based on parameters such as intersection geometry, traffic volume, pavement conditions, traffic composition, and available sight distance. They used a simulation model to estimate the frequency of potential conflicts or collisions resulting from sight distance restrictions. Table 8 summarizes the LOS categories and the equations that can be used to determine the numeric value.

The crash warrants for signals were investigated as part of an NCHRP project (*49*). A procedure was developed for quantifying the safety effect of signal installation based on the predictive methods in the HSM. The procedure was used to develop revised content for the crash signal warrant. Application of the procedure to a range of typical intersection conditions indicated that there is a threshold volume of observed crashes beyond which signal installation is likely to improve safety. The threshold values were found to vary by area type, intersection legs, and number of lanes on each intersection approach. Table 9 shows the threshold values recommended in the research and recommended for the next edition of the MUTCD.

Table 8. LOS for Two-Way Stop-Controlled Intersections Developed Using Simulation (*48*).

Total Number of Conflicts per Crossing Vehicle, Con[1]	Total Hazard per Crossing Vehicle, HZ[2] ($[kg\text{-}m^2/sec^2]/10^4$)	LOS
<0.05	<1.46	A
0.05–0.10	1.49–2.93	B
0.10–0.15	2.93–4.39	C
0.15–0.20	4.39–5.85	D
0.20–0.25	5.85–7.32	E
>0.25	>7.32	F

[1] Con = 43.1 – 0.092 (AVSDR) + 0.89 (ADT) + 2.30 (Speed) – 0.063 (AVSDL) + 9.45 (T)
[2] HZ = –15924 + 1551 (Speed) – 16 (AVSDR) – 10 (AVSDL) + 1.467 (ADT) + 979 (T)

Where:
ADT = average daily traffic on the major road (thousands of vehicles/day).
AVSDL = average sight distance from the left (m).
AVSDR = average sight distance from the right (m).
Con = total number of conflicts per year per 1,000 crossing vehicles.
HZ = total hazard per year per crossing vehicle, used to account for severity and measured as the potential kinetic energy per year per vehicle conflict.
Speed = prevailing speed on the major road (km/h).
T = trucks on the major road (percent).

Table 9. Recommended Crash Numbers from Bonneson et al. (*49*).

Area Type	Number of Through Lanes on Each Approach		Minimum Number of Reported Crashes in One-Year Period and Three-Year Period			
			Total of Angle Crashes and Pedestrian Crashes (All Severities)[b]		Total of Fatal-and-Injury Angle Crashes and Pedestrian Crashes[b]	
	Major	Minor	Four Legs	Three Legs	Four Legs	Three Legs
Urban	1	1	5 (6)[c]	4 (5)	3 (4)	3 (4)
	2+	1	5 (6)	4 (5)	3 (4)	3 (4)
	2+	2+	5 (6)	4 (5)	3 (4)	3 (4)
	1	2+	5 (6)	4 (5)	3 (4)	3 (4)
Rural[a]	1	1	4 (6)	3 (5)	3 (4)	3 (4)
	2+	1	10 (16)	9 (13)	6 (9)	6 (9)
	2+	2+	10 (16)	9 (13)	6 (9)	6 (9)
	1	2+	4 (6)	3 (5)	3 (4)	3 (4)

[a] Rural values apply to intersections where the major-road speed exceeds 40 mph or intersections located in an isolated community with a population of less than 10,000.
[b] Angle crashes include all crashes that occur at an angle and involve one or more vehicles on the major road and one or more vehicles on the minor road.
[c] Reported crashes for the three-year period appear in parentheses.

Capacity and Volume Studies

A 1983 ITE paper by Upchurch (*50*) developed a procedure for selecting the most economical type of sign control at an intersection. The guidelines were developed based on an economic analysis that quantified the effect of each sign type (yield, two-way stop control, and four-way stop control) in terms of intersection operation costs. These costs include fuel costs; vehicle operating costs; the cost of delay to motorist and passengers; air pollution costs; crash costs; and sign material, installation, and maintenance costs. The costs were evaluated for various intersection conditions using a traffic simulation model and published crash prediction equations. Based on the crash rates used in the study, yield control was found to be more economical than the two types of stop control. Both stop controls were found to have capacity limits beyond which they did not provide a satisfactory LOS. The paper estimates that by using the proposed more efficient sign control selection procedure, the nationwide intersection operating costs could be reduced by as much as $15.1 billion per year.

A 1988 ITE paper (*51*) reviewed issues related to traffic management in residential areas and developed a decision-making framework for uniform and effective traffic control implementation. Specific criteria for traffic control installation at urban residential (low-volume) intersections were not included in the 1980 MUTCD. The authors proposed a set of criteria (shown in Table 10) based on network consideration, traffic volume, crash history, sight distance, and speed patterns.

Table 10. Criteria for Various Traffic Control (Table 1 in *51*).

Traffic Control	Network Function	Traffic Volume	Crash History	Sight Distance Minimum SAS[a]
No Control	Local/Local	<1,500 vpd intersection volume	0–2 crashes per year	Posted speed limit, all approaches
Yield	Local/Collector Local/Local	1,500–3,000	Pattern ≥ 2 per year in 3 years	≥10 mph
Two-Way	Local/Local Local/Collector Collector/Collector	≥3,000	≥3 per year with pattern	<10 mph
Multi-way	Collector/Collector	See MUTCD	≥5 per year with pattern	<10 mph, highly restricted visibility on opposing approaches

[a] SAS = safe approach speed

In 1995, Box (*52*) developed guidelines for use of traffic control signs at low-volume urban intersections. He recommended consideration of roadway classification, crash history, and safe approach speed in determining the most appropriate control mode. Box's recommendations were incorporated into a table by Bonneson et al. (*53*), which is reproduced in Table 11. Box (*52*) indicates that this table should only be used for intersections with a total entering traffic volume of 300 veh/hr or less during the peak hour. He also cautions that the no-control or yield-control options may not work well when the total entering volume exceeds 100 veh/hr.

Table 11. Candidate Control for Minor-Road Approach by Box (*52*).

Roadway Classification[a]		Crash History[b]		Minor-Road Control for Minor-Road Sight Distance Approach Speed[c] (mph) of…			
Major	**Minor**	**1 yr**	**3 yr**	**<10**	**10 to 20**	**21 to 30**	**≥30**
Local	Local	<2	<4	Stop	Stop	Yield	None[d]
Local	Local	≥2	≥4	Stop	Stop	Yield or Stop	Yield
Collector	Local	<2	<4	Stop	Stop	Yield	Yield
Collector	Local	≥2	≥4	Stop	Stop	Stop	Yield
Collector	Collector	<2	<4	Stop	Stop	Stop	Yield or Stop
Collector	Collector	≥2	≥4	Stop	Stop	Stop	Yield or Stop

[a] The table is only applicable to intersections in urban areas with a total entering volume of 300 veh/hr or less during the peak hour. Two-way stop, multi-way stop, or signal control should be considered for higher volumes.
[b] Collisions susceptible to correction by stop or yield control (e.g., right-turn, left-turn, and right-angle collisions) on the lower-volume approach. Two collisions in a 12-month period or four in a 3-year period.
[c] Approach speed for minor-road drivers; based on an evaluation of their sight distance to major-road vehicle.
[d] None means no control at intersection. May be limited to a total entering volume of 100 veh/hr during the peak hour.

A 1997 ITE paper (*54*) provides a guide for selecting intersection traffic control based on peak-hour intersection volumes. Three graphs were developed based on intersection LOS, intersection delay, and intersection queue length. The graphs incorporate 1988 MUTCD warrants and 1994 HCM methodologies. Intersection LOS and delay were calculated using the weighted average of all approaches, and intersection queue length was computed from average intersection delay and overall intersection volume. In the graphs (shown in Figure 4, Figure 5, and Figure 6), T stands for TWSC, A stands for AWSC, and S stands for a traffic signal. Figure 5 and Figure 6 show that the split between TWSC and AWSC occurs when the major-street volume is about 1,000 veh/hr and the minor-street volume is approximately 210 veh/hr. The study did not explicitly consider pedestrians and bicyclists.

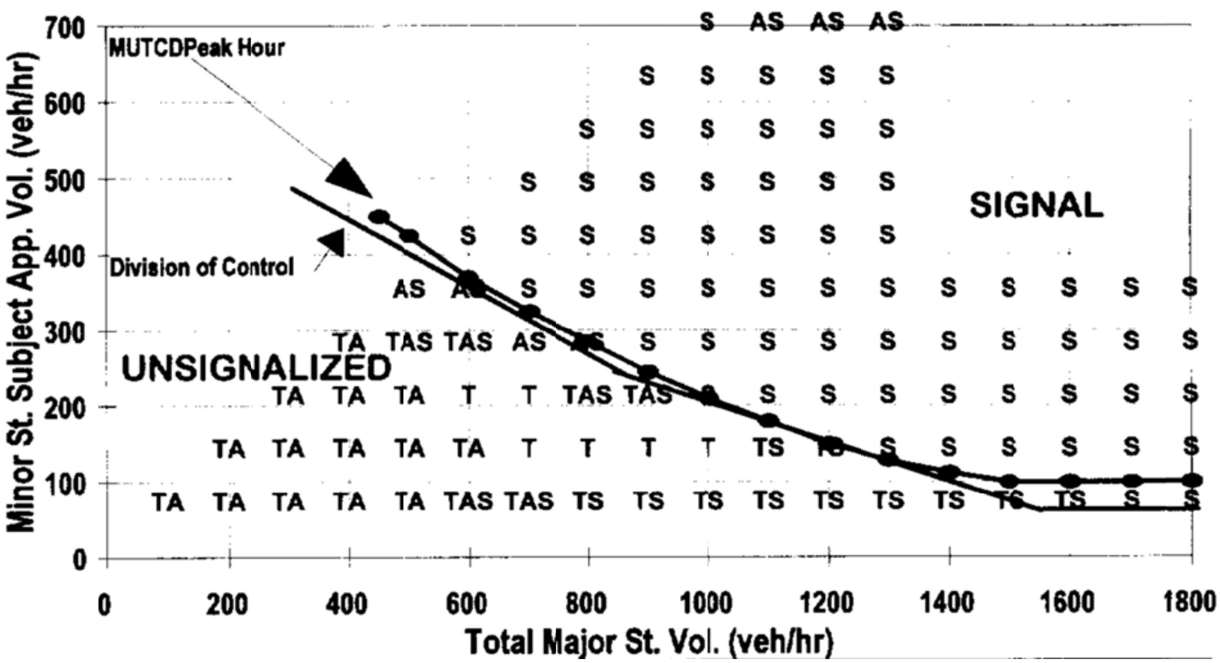


Figure 4. Optimal Intersection Control Based on LOS (Figure 1 in *54*).

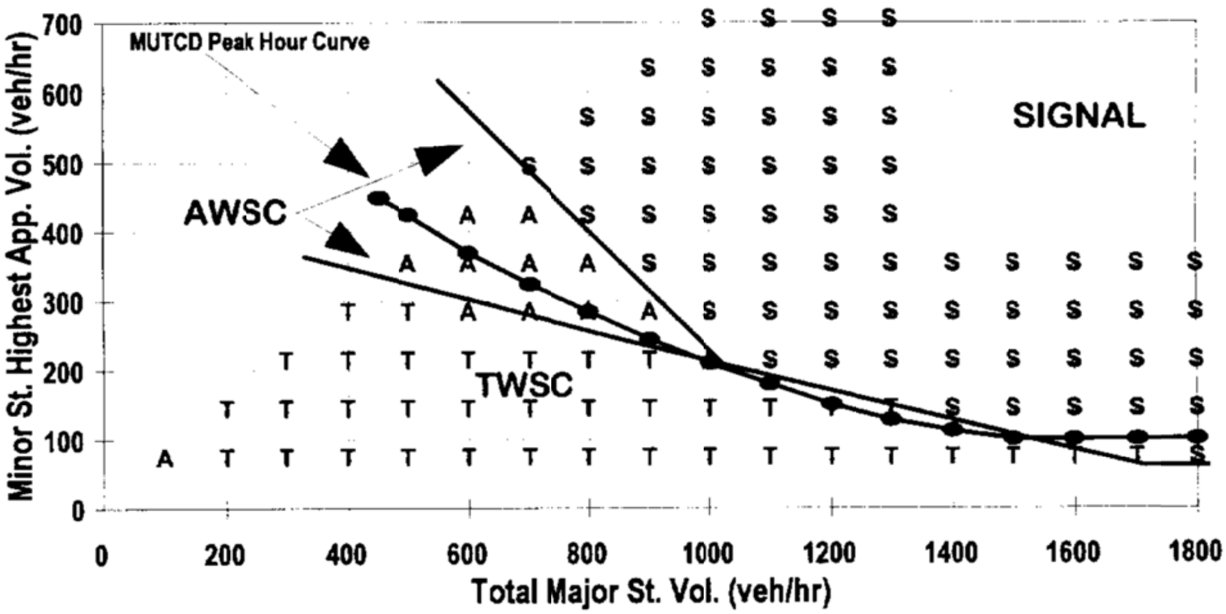


Figure 5. Optimal Intersection Control Based on Average Delay (5-sec Significance Level) (Figure 2 in *54*).

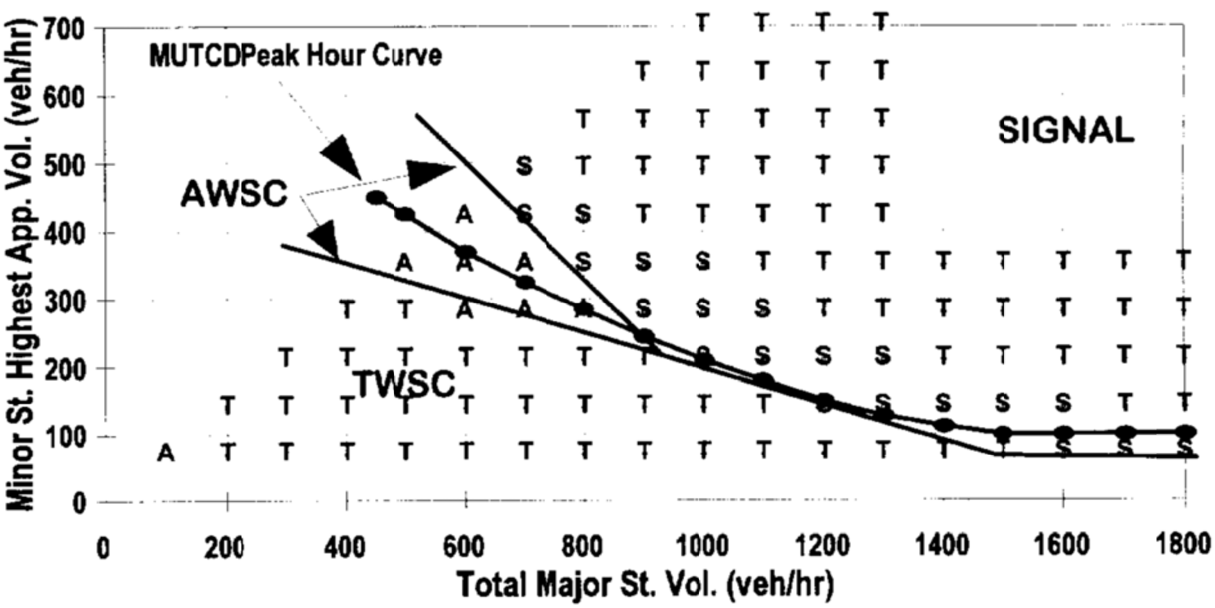


Figure 6. Optimal Intersection Control Based on Average Queue Length (Figure 3 in *54*).

Another ITE paper from 2004 (*55*) found that turning percentages have a major impact on the performance of stop-controlled intersections; the paper contained discussion of guidelines for selection of appropriate stop control based on turning movements. Corridor Simulation (CORSIM) was used to analyze different combinations of vehicular volumes and road characteristics and obtain the associated delay in each case. Average control delay in seconds per vehicle was chosen as the best measure of effectiveness for the study. Three turning distribution combinations (10 left-80 through-10 right, 20 left-60 through-20 right, and 30 left-40 through-30 right) and 50 volume combinations for each turning distribution for each type of stop control were run, resulting in a total of 300 simulations. The analysis showed that the use of a two-way stop is preferred at lower traffic volumes due to lower delays, and as the intersection volume increases, delay values for two-way and four-way stop control become closer until they reach a point where either control can be used, beyond which four-way stop control is preferred. This point is termed the transition point in the study. The graph shown in Figure 7 was developed to show the transition point volumes for major and minor streets for various turning distributions.

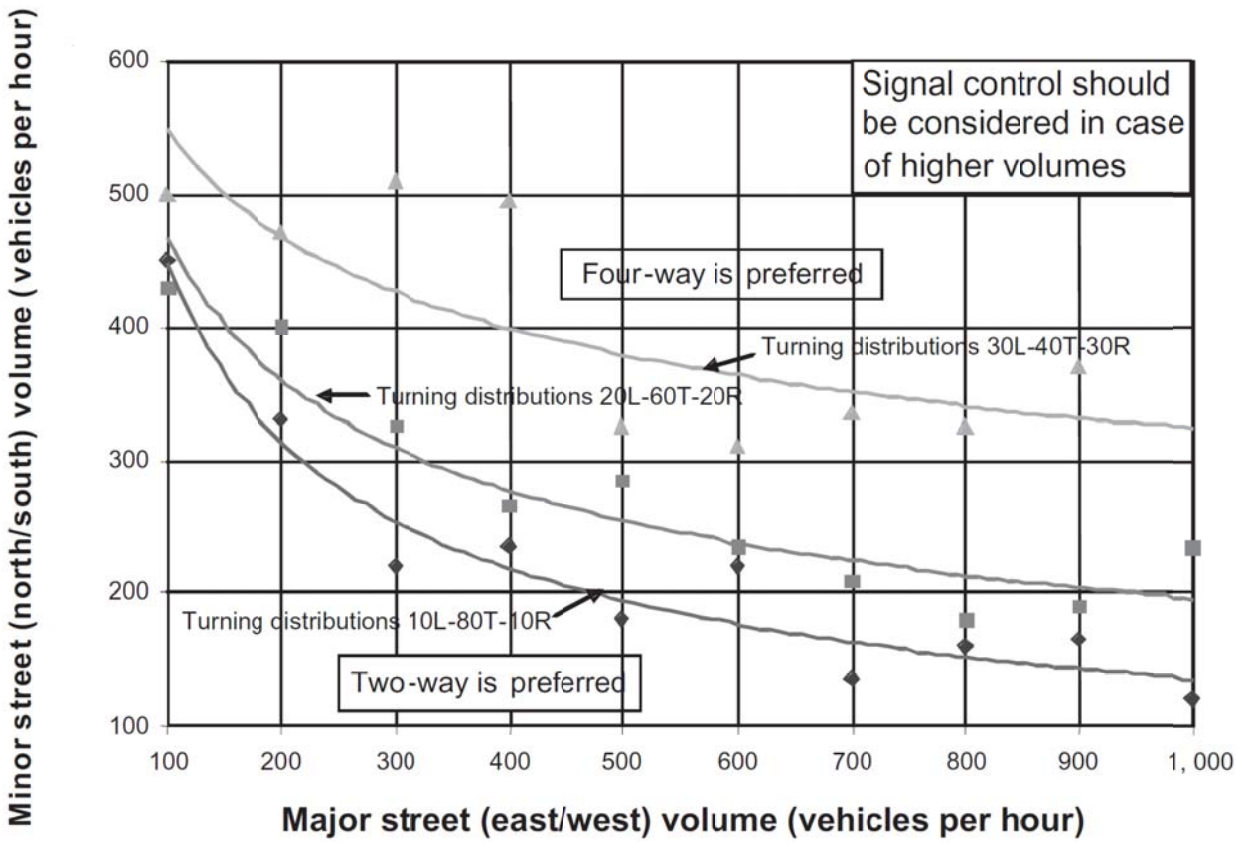


Figure 7. Major Street–Minor Street Volume Relationship for a Two-Lane Major Street and a One-Lane Minor Street (Figure 6 in *55*).

A 2008 study (*56*) verified HCM 2000 Exhibit 10-15 using HCM 2000 methodologies (and the Highway Capacity Software) for the estimation and comparison of control delay for more than 5,000 cases. The results showed that Exhibit 10-15 was inconsistent with the results from HCM methodologies, and it was recommended that the graphs developed in the study be used instead. The study also found that the percentage of left-turning vehicles has a significant impact on the choice of intersection control type. Graphs were developed for no left turns as well as 5 percent, 10 percent, 15 percent, and 20 percent left turns. Figure 8 shows a comparison of control type recommendations from the study and Exhibit 10-15 of HCM 2000, with 10 percent left turns. The authors concluded the following: "On the basis of the criterion of minimizing delay alone, it is found that if demand is unbalanced between major and minor streets and if the traffic is low on minor streets, two way-stop control should be used; if demand is somewhat balanced and minor streets see low to medium traffic, all-way-stop control is preferred; otherwise, signal control should be favored."

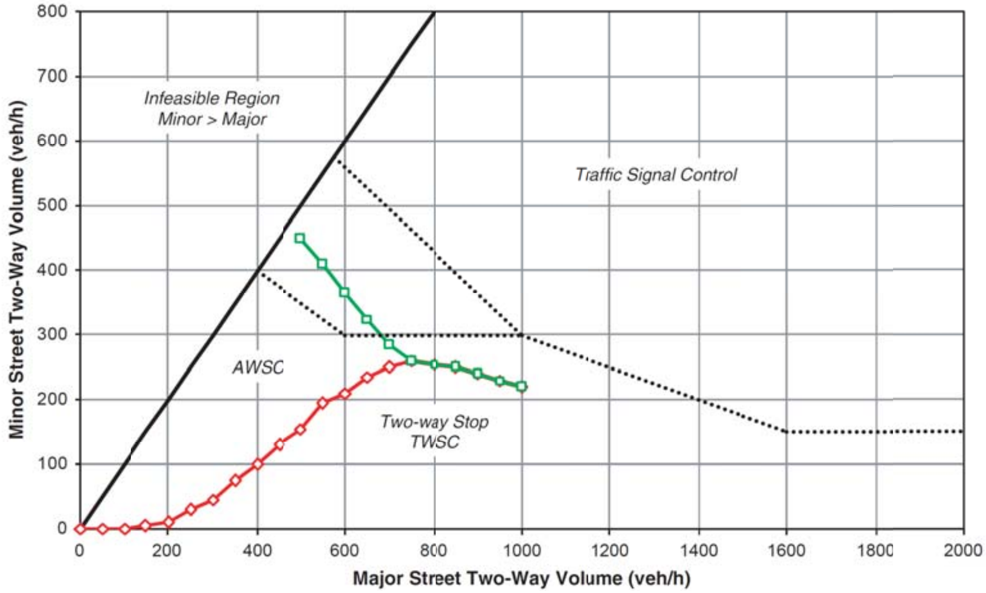


Figure 8. Comparison of Control Type with HCM 2000 Exhibit 10-15, with 10 Percent Left Turns (Figure 7 in *56*).

In 2012, Jiang et al. (*57*) also developed a set of charts for selecting intersection control types, with the options of two-way stop, signal, and roundabout. The charts were based on LOS as the performance index for type selection. The researchers considered 8,160 combinations of demand and left-turn volumes; they completed over 24,000 simulation runs, using left-turn percentages of 5, 10, 15, and 20 percent of the volume. Each scenario was run for signal control, TWSC, and roundabout (yield) control. The resulting set of charts, an example of which is shown in Figure 9, was produced as the basis for choosing intersection control in light of anticipated benefits for intersection operations.

A number of studies have focused on developing methodologies that improve or supplement the TWSC and AWSC intersection capacity analysis methodologies provided in the 2000 HCM. Some of these improvements are incorporated in the 2010 HCM (e.g., 95th percentile queue length calculation).

NCHRP Report 457 (*53*) documents the steps involved in the formal engineering study of improvement alternatives and focuses on the use of capacity analysis procedures and simulation models to evaluate the operational impacts of traffic control alternatives. The guide provides a step-wise process for evaluating the operational effects of alternative geometrics and control modes at a problem intersection. The effectiveness of an alternative is identified based on either the LOS (threshold of LOS D) or total delay (threshold of 4 vehicle-hours for single-lane movement or 5 vehicle-hours for multi-lane movement). A graph combining the effect of both delay and LOS in terms of average control delay, based on HCM 2000 is provided (shown in Figure 10). Finally, the guide emphasizes that the best alternative is selected on the basis of its effectiveness and its other, non-motorist-related effects.

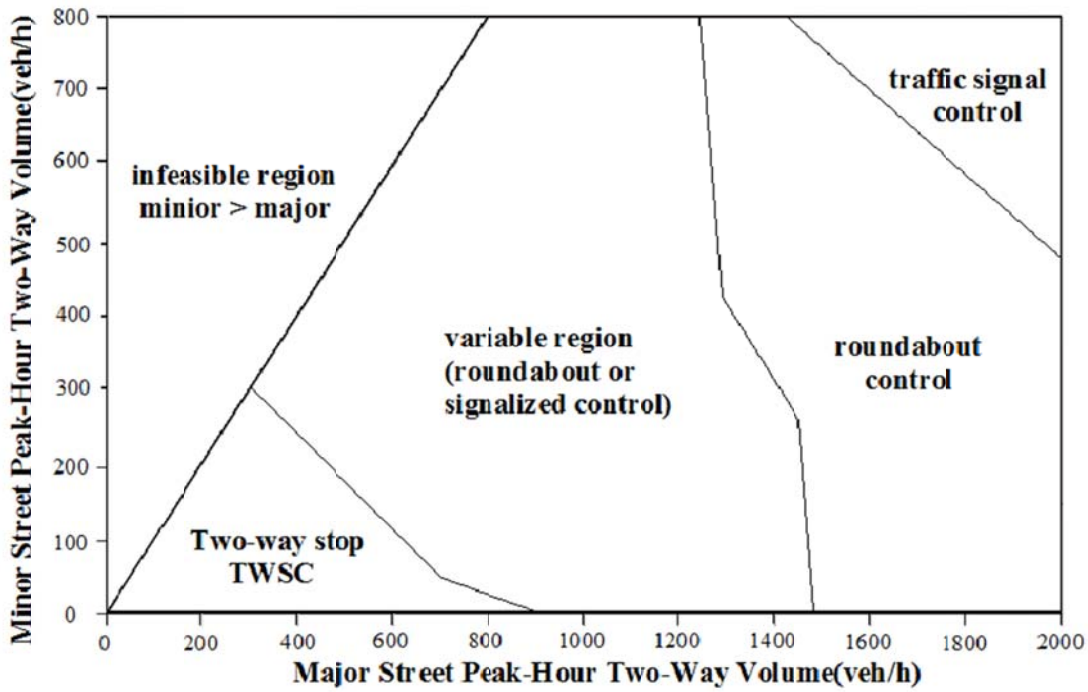


Figure 9. Intersection Control Type and Peak-Hour Volumes with 10 Percent Left-Turning Traffic (*57*).

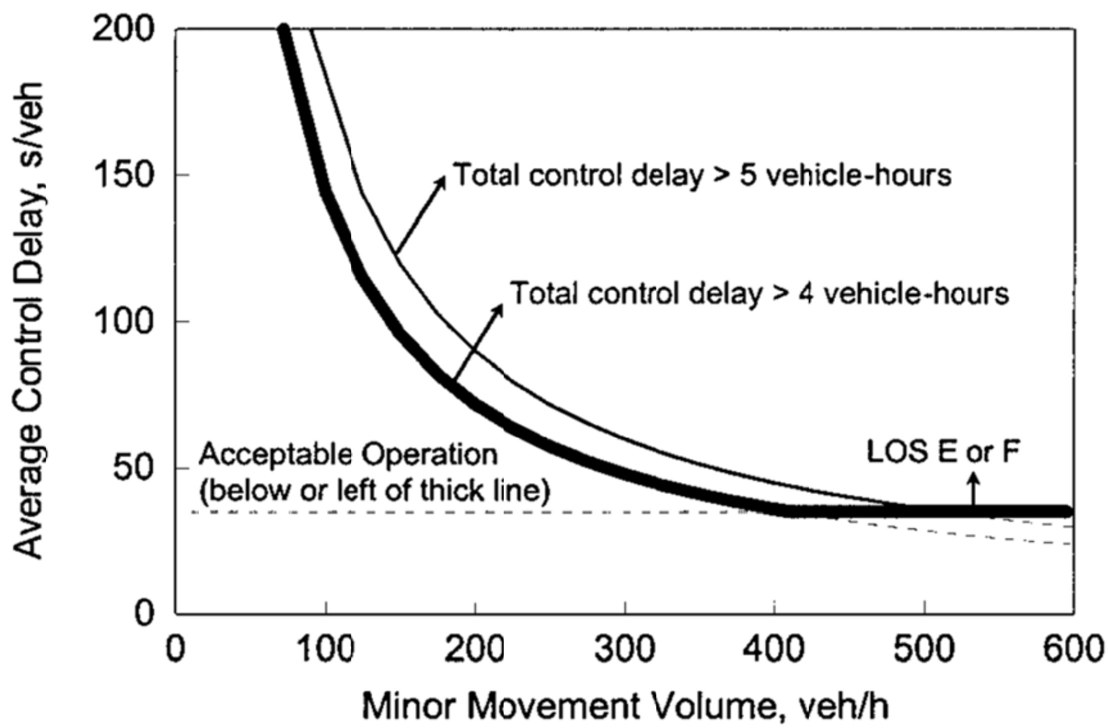


Figure 10. Acceptable Operating Conditions at Unsignalized Intersections (*53*).

In a 2000 paper, Wu (58) discusses a new capacity analysis methodology based on the additional-conflict-flow method (developed from graph theory) as an alternative to the traditional gap acceptance method. This methodology takes into account the number of pedestrians per approach, which is not included in the HCM AWSC methodology.

Brilon and Miltner (*59*) developed a method for evaluating capacity at unsignalized intersections based on the influence of pedestrians and bicyclists. Called the conflict technique, their method allows practitioners to consider the influence of nonmotorized road users on motor vehicle operations. Moreover, the method simplifies the theoretical approach. Different modalities of operation, such as a pedestrian crossing at the entries to an intersection, can be considered, as can the fact that some road users do not comply with priority rules. To calibrate the calculation method, traffic at several intersections was observed by video and analyzed for traffic volume, delay, compliance with priority rules, and other parameters. With these field measurements, the calculation method was calibrated to actual road-user behavior. Comparison of the conventional calculation concept based on gap acceptance and the new conflict technique showed that they provide similar results. In particular, the authors concluded that consideration of pedestrians and limited priority effects is a considerable benefit of the new method.

Gard (*60*) developed empirical equations to predict the maximum queue length for major-street left turns and minor-street movements at TWSC intersections. The regression equations were found to closely fit the data (40 percent of the 184 observed maximum vehicle queues were correctly predicted, and 85 percent were predicted within one vehicle).

Tian and Kyte (*61*) also developed an empirical model for estimating the 95th percentile queue length for AWSC approaches and showed that the methodology for predicting queues at TWSC intersections can be applied to AWSC intersections. This finding is incorporated in the 2010 HCM.

Kirk et al. (*62*) conducted a study to use operational characteristics to determine the size and the design of intersections based upon a targeted level of operation. This approach was designed to allow for a preliminary evaluation of a broader range of possible designs, by screening out those designs considered less desirable or inappropriate on the basis of operational performance. An intended benefit of this approach was to also allow for a more objective comparison of all alternatives because all options targeted the same operational service level. The use of the critical lane analysis method was considered an appropriate approach for developing size estimates for intersections. Similar methods for stop-controlled and yield-controlled intersections were also identified because it was necessary to expand these methods to include unsignalized designs as well.

The result of the project was the development of the Intersection Design Alternative Tool, capable of evaluating 13 intersection alternatives and identifying preferred lane configurations from more than 12,000 available configurations. The tool identifies the most efficient design (minimum number of lanes) that is capable of meeting a targeted level of operation. A designer is presented with several options that meet the minimum operational requirements, allowing examination of other trade-offs such as right-of-way impacts, safety considerations, and the like. This approach eliminates the need to compare alternatives with varying operating levels across different types of traffic control. The proposed approach aims to provide greater efficiency in the evaluation and conceptual design of intersection alternatives, with the intent to achieve greater operational efficiency and improved safety performance. The approach allows for a more appropriate and properly customized design for each intersection, avoiding the use of standard or typical designs.

SELECTING TRAFFIC CONTROL DEVICES FOR UNSIGNALIZED PEDESTRIAN CROSSINGS

2009 *Manual on Uniform Traffic Control Devices*

Figure 11 shows part of the 2009 MUTCD pedestrian hybrid beacon guidance. The decision is based on major-street volume, pedestrian volume, crossing length, and speed. The guidance was developed based upon the findings from NCHRP Report 562/TCRP Report 112 (*22*).

Figure 4F-2. Guidelines for the Installation of Pedestrian Hybrid Beacons on High-Speed Roadways

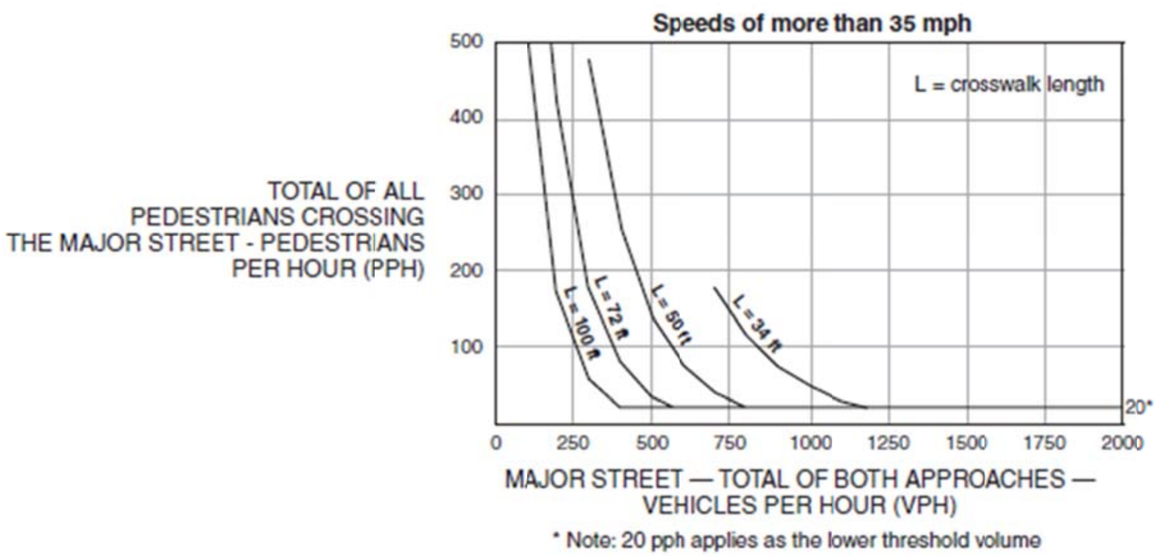


Figure 11. 2009 MUTCD Pedestrian Hybrid Beacon Guidance Figure.

NCHRP Report 562/TCRP Report 112

NCHRP Report 562/TCRP Report 112 (*22*) presents guidelines for the application of pedestrian crossing treatments. After selecting the proper speed category, the guidelines call for the engineer to check the pedestrian volume. The minimum pedestrian volume for a peak-hour evaluation is 20 pedestrians per hour for both directions (14 pedestrians per hour if the major-road speed exceeds 35 mph). If fewer pedestrians are crossing the street, then geometric improvements (rather than signs, signals, or markings) such as traffic calming, median refuge islands, and curb extensions are alternatives that can be considered.

Traffic signal warrants in the MUTCD can also be evaluated for the intersection to support the NCHRP Report 562 analysis. If one or more signal warrants are met, then a signal can be considered; otherwise, the engineer can consider other devices in the context of estimated pedestrian delay. The report discusses five categories of devices:

- Crosswalk: This category encompasses standard crosswalk markings and pedestrian crossing signs, as opposed to unmarked crossings.
- Enhanced: This category includes those devices that enhance the visibility of the crossing location and pedestrians waiting to cross. Warning signs, markings, or beacons in this category are present or active at the crossing location at all times.
- Active: Also called active when present, this category includes those devices designed to display a warning only when pedestrians are present or crossing the street.
- Red: This category includes those devices that display a circular red indication (signal or beacon) to motorists at the pedestrian location.
- Signal: This category pertains to traffic control signals.

The guidelines also provide a series of plots to assist the engineer in determining which device is appropriate for a given location. The plots correspond to specific combinations of speeds, crossing distances, and walking speeds (see Figure 12 for an example). Paper worksheets and a spreadsheet tool are also available for a user to enter the specific characteristics of a particular location.

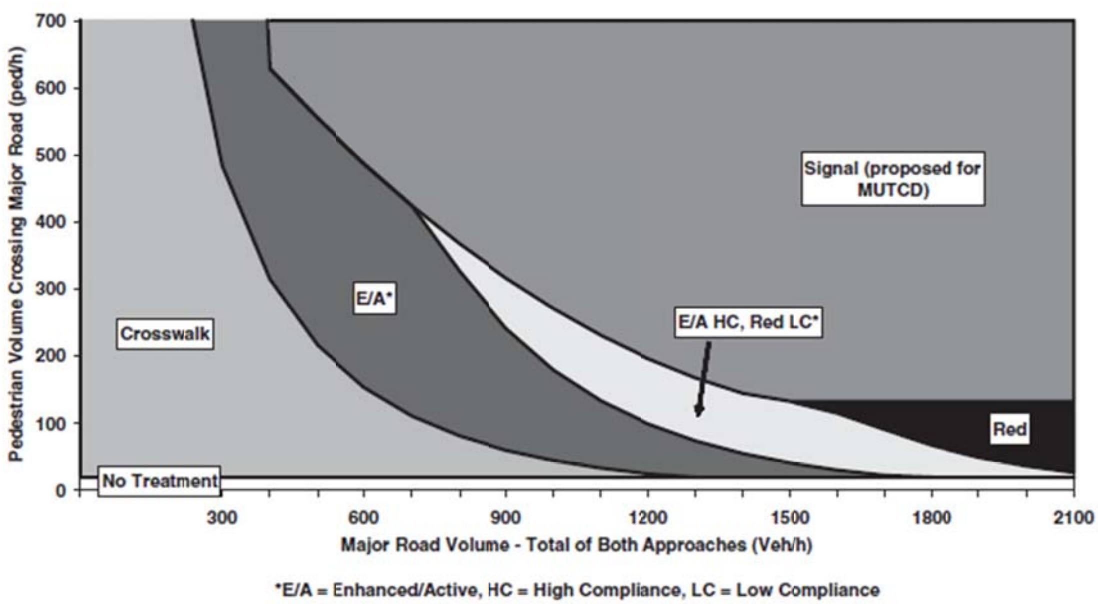


Figure 12. Guidelines Plot, 34-ft Pavement, ≤ 35 mph, 3.5 ft/sec Walking Speed (*22*).

City of Tucson

The City of Tucson, Arizona, (*63*) has a number of guidelines in place for the installation of pedestrian crossing treatments. Because they developed the pedestrian hybrid beacon (PHB), their PHB installation policy is often referred to by other jurisdictions. Their policy used a priority evaluation form consisting of several questions, with points assigned to each answer based on the characteristics of the site under consideration.

City of Phoenix

The City of Phoenix, Arizona, (*64*) adopted guidelines similar to Tucson's for installation of PHBs. Key differences between guidelines in Tucson and Phoenix are:

- Crashes receive twice as many points in Phoenix as in Tucson.
- Phoenix gives additional points for very high (>40) crossing counts.
- Phoenix has more subdivisions of distances to the nearest controlled crossing.
- Phoenix accounts for the number of through lanes.
- Phoenix provides for "unique circumstances."

The Phoenix guidelines state that locations with fewer than 30 total points should not be considered for PHB installation. Unmarked locations should be considered for signing/striping enhancements before PHB installation is considered. Locations where a signal warrant exists will not be considered for PHB installation.

Arizona Department of Transportation

The Arizona Department of Transportation (ADOT) has developed a set of draft PHB installation guidelines based on existing guidance in Tucson and Phoenix, as well as ADOT's own Pedestrian Safety Deficiency Index (*65*). ADOT's draft guidelines state that there are many possible treatments to improve pedestrian crossings, including, but not limited to, marked crosswalk, high-visibility crosswalk, two-stage crosswalk, median refuge, street lighting, in-pavement lights, rectangular rapid flash beacon (RRFB), PHB, and pedestrian signal. A comprehensive evaluation of pedestrian crossing safety should be conducted in order to identify the most effective treatment.

A minimum total score of 35 points merits consideration of a PHB, and ADOT advises that PHBs should not be installed on roadways with speed limits greater than 45 mph. The draft guidelines are shown in Table 12.

Table 12. Arizona DOT PHB Evaluation Draft Guidelines (*65*).

Question	Points
1. Motor vehicle crashes correctable by installation of PHB (most recent 5 years of data) involving pedestrians, bicyclists, wheel chairs, skateboards, motorized scooters, or golf carts crossing within 500 feet on either side of the proposed PHB location, or half the distance to the nearest signal (whichever is less): 5 points per crash	
2. Average peak hour pedestrian crossing volume within 500 feet on either side of the proposed PHB location, or half the distance to the nearest traffic signal (whichever is less): 0–10 0 points 11–20 2 points 21–39 4 points 40 + 6 points	
3. Location of nearest existing traffic signal or existing PHB: Less than 500 ft −5 points 500–1000 ft 0 points Over 1000 ft 10 points	
4. Posted speed limit: Under 30 0 points 30 and 35 2 points 40 and 45 4 points	
5. Roadway traffic volume (ADT): Less than 5000 0 points 5000–9999 2 points 10000–14999 4 points 15000 + 6 points	
6. If the roadway does not have a raised median with a minimum width of 6 feet: 5 points.	
7. If a designated, maintained, and permitted shared-use path or walkway crosses the road at the proposed PHB location: 5 points	
8. If the proposed PHB location is within 500 feet of a senior center, medical facility, community center, school or other pedestrian activity generator: 5 points	
9. If the proposed PHB location does not have roadway illumination: 5 points	
10. If the crossing distance is greater than 36 feet: 5 points. If a raised median with a minimum width of 6 feet is present, the crossing distance is measured to the median.	
TOTAL	
Additional factors to be considered when a crossing merits PHB consideration: • Is the location within a coordinated signal network? • Does the roadway environment support the installation of the PHB? Does the street have adjoining sidewalks and/or pathways that will result in a logical utilization of the PHB? • Is right-of-way needed? Are there utility conflicts? Is there significant potential for environmental or cultural issues? • Is funding of the PHB available? • Is 120/240 single phase power available at a reasonable cost? Does the local jurisdiction support the installation of a PHB? Is the local jurisdiction willing to pay for the power for the PHB? Is the local jurisdiction willing and capable of accepting the maintenance and operation of the PHB? Will the local jurisdiction pay the power for lighting the crosswalk?	

City of Boulder

The City of Boulder, Colorado, has pedestrian crossing treatment installation guidelines that use the minimum pedestrian volume thresholds for the installation of any pedestrian crossing treatment (e.g., marked crosswalks, RRFB crossings, and underpasses) (*66*). A unique element of the Boulder criteria is that young, elderly, and disabled pedestrians count twice towards volume thresholds (Table 13).

The city revised their guidelines in November 2011; those guidelines provide much greater detail on the procedures and considerations for installing pedestrian treatments (*67*). The guidelines state that the use of RRFBs may not be appropriate in locations where there is a combination of both high traffic volumes and high pedestrian volumes. In these extreme conditions, there may be an increase in traffic crashes and/or traffic delay that makes the use of RRFBs inappropriate. In these cases, the use of conventional pedestrian traffic signals or high-intensity activated crosswalk (HAWK) beacons may be more appropriate. While the decision not to use RRFBs at a pedestrian crossing should be based on engineering judgment, the limit line in Figure 13 has been prepared to aid in this determination. Figure 13 is for low-speed (35 mph or less) roadways; a similar figure exists for high-speed roadways.

Table 13. Boulder, Colorado, Minimum Pedestrian Volume Thresholds (*66*).

Minimum Pedestrian Volume: 20 peds per hour* in any one hour, or 18 peds per hour* in any two hours, or 15 peds per hour* in any three hours 10 school-aged pedestrians traveling to/from school** in any one hour * Young, elderly, and disabled pedestrians count twice towards volume thresholds ** School Crossing defined as a crossing location where ten or more student pedestrians per hour are crossing

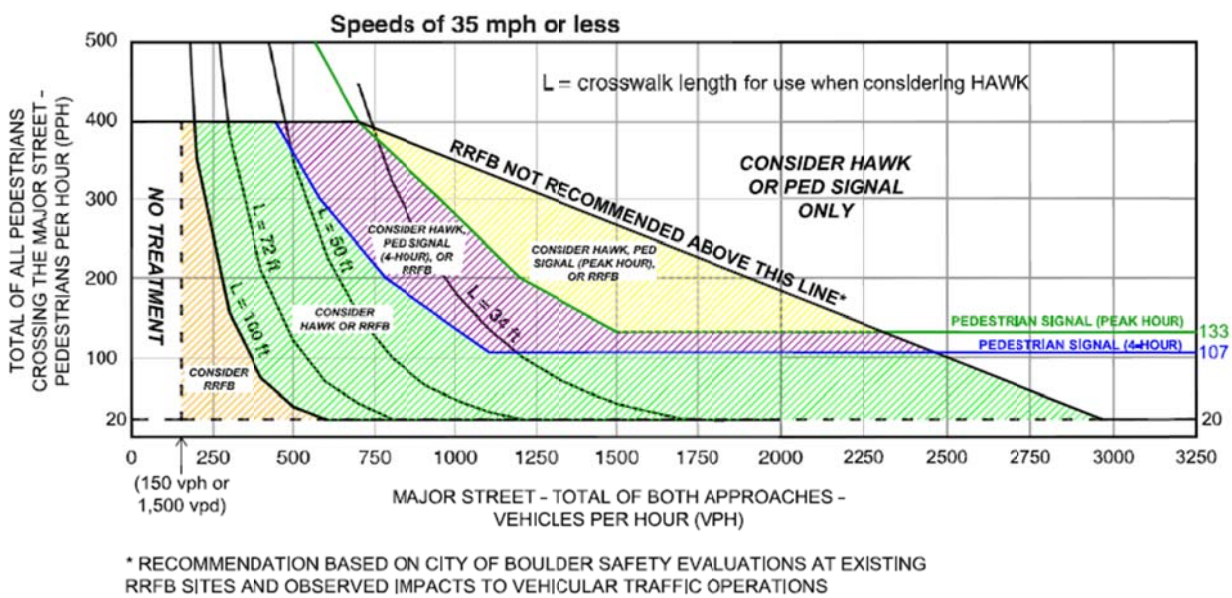


Figure 13. City of Boulder Pedestrian Crossing Treatment Installation Guidelines prepared by Fox, Tuttle, Hernandez (*67*).

Virginia Department of Transportation

The Virginia Department of Transportation (VDOT) (*66*) has proposed RRFB installation criteria as follows:

- At least 20 pedestrians crossing in the highest hour and,
- There is a marked crosswalk existing or justified at the location and,
- Other applicable pedestrian options have been reviewed and determined by engineering judgment to not be applicable.

Pedestrian counts, a crossing gap study, and other key pieces of data must be obtained before and after installation.

Washington County, Oregon

In 2010, commissioners in Washington County, Oregon, changed their policy on midblock crossings (*68*). Previously, Washington County had approved pedestrian crossings only at road intersections, with few exceptions. However, with the increasing demand for pedestrian and bicycle facilities (e.g., trails) that cross the street network at locations other than intersections, the county decided it was appropriate to review and change the county's policy and practice. The new policy authorizes the county engineer to approve a modification or design exception under the appropriate county code for a midblock crossing. The application for a midblock crossing requires the applicant to describe the need for the crossing, document the current and anticipated characteristics of the roadway and adjacent area (including transit service, land use, and nearby pedestrian generators), and conduct a pedestrian and vehicle volume count and a gap analysis. Midblock crossing treatments are organized into a progressive tier system shown in Table 14.

Table 14. Washington County, Oregon, Tiered Midblock Crossing Treatments (*68*).

Tier	Standard	Additional Treatments Considered
Tier One	Crosses a 2-lane street with or without an island/refuge – install high-visibility mounted signs and markings	Refuge islands, curb extensions, staggered pedestrian refuges
Tier Two	Crosses a 3-lane street with an island/refuge – install high-visibility signs and markings	Flashing beacons, pedestrian-actuated signal/beacon
Tier Three	Crosses a 2-lane street without an island/refuge or a 4-lane street with island/refuge – install high-visibility signs and markings or pedestrian-actuated signal	Pedestrian-actuated signal/beacon
Tier Four	Crosses a 4-lane or greater street without an island/refuge – install pedestrian-actuated signal or beacon	Pedestrian-actuated signal, pedestrian over- or undercrossing

County guidelines include the use of the table produced by Zegeer et al. (*69*) for FHWA that provides recommendations for installing pedestrian treatments at uncontrolled locations based on ADT.

Texas Department of Transportation

In December 2012, the Texas Department of Transportation (TxDOT) distributed guidelines regarding PHBs (*70*) and guidelines regarding RRFBs (*71*). All of the following conditions must be met before one of these devices can be considered:

- An engineering study must be performed and meet the guidelines detailed in Chapter 4F of the Texas MUTCD.
- The location has an established crosswalk with adequate visibility, markings, and signs.

- The posted speed limit is 40 mph or less (does not include school speed zones).
- The location has 20 or more pedestrians crossing in 1 hr.
- The location is deemed a high-risk area (e.g., schools and shopping centers).
- The crosswalk is more than 300 ft from an existing traffic-controlled pedestrian crossing.

CHAPTER 4: INTERSECTION AND TRAFFIC CHARACTERISTICS

BACKGROUND

The 2009 MUTCD provides specific guidance for two-way stop-control and all-way stop-control conditions. It identifies the following factors to consider when making intersection control decisions:

- Vehicular, bicycle, and pedestrian traffic volumes on all approaches.
- Reported crash experience.
- Approach speeds.
- Delay on the minor-road approach.
- Number and angle of approaches.
- Sight distance available on each approach.

While the 2009 MUTCD provides guidance on type of intersection or traffic characteristics, some states and local agencies use other requirements that are different or more specific. The consideration of a yield, stop, or all-way stop condition may also be influenced by the characteristics of the intersection.

FINDINGS

Table 15 lists the all-way stop-control criteria for the 2009 MUTCD along with the criteria for a number of states. In addition, it lists the criteria for the ICE process, which is used by several states. Table 16 lists the criteria for traffic control selection at unsignalized intersections, as described in various published studies. Table 17 lists the criteria for several techniques used for selecting pedestrian traffic control devices at an unsignalized crossing. Comparing the criteria listed in Table 15 and Table 16 for stop control and Table 17 for pedestrian traffic control devices demonstrates that a larger variety of criteria are being considered for pedestrian traffic control devices at unsignalized intersections. For example, several criteria are considered with pedestrian traffic control devices but not stop control, some of which could be considered unique for a pedestrian crossing (e.g., crossing distance, distance to the nearest signal or stop, and the presence of a pedestrian generator). Other criteria may also be appropriate for being part of stop-control warrants, such as median presence or the number of lanes on approach.

Another way of looking at the various techniques available for making traffic control device selection is to examine the methodology being used within the technique. Table 18 lists existing techniques for selecting a traffic control device. To illustrate the intersection and traffic characteristics used in each of the techniques described in this chapter, a sample unsignalized intersection was identified, and several of the techniques discussed here were applied to select a traffic control device. Table 19 illustrates the intersection and traffic characteristics used in each technique.

Table 15. Minimum Data Increments for Variables Used to Evaluate the Need of AWSC at Unsignalized Intersections.

Criteria	2009 MUTCD (*1*)	In Addition to MUTCD					ICE Process		
		ID (*8*)	IN (*9*)	MD (*10*)	MT (*11*)	PA (*12*)	MN (*20*)	WA (*13*)	WI (*18*)
Area type			PI				PI		PI
Benefit-cost ratio								PI	PI
Conflicts, vehicle-pedestrian	PA						PA		
Crash history	1 Year		1 Year			3 Years	3 Years		5 Years
Delay	PA						Peak delay for all movements, approaches, and entire intersection	PA	Each movement
Driver expectation				PI					
Left-turn conflicts	PA						PA		
LOS								PI	Each movement
Roadway functional class	PA	PA	PA		PA				PA
Sight distance restriction	PA				PA	PA		PA	
Speed	85th Percentile							PSL	
Volume, approach	8 hr	ADT	ADT		ADT		48 hr, peak-hour TMC	Peak hour, ADT	12 hr
Volume, bicycle									PA
Volume, pedestrian	8 hr						ADT		PA

PA = per approach, PI = per intersection, PSL = posted speed limit, TMC = turning movement count.

Table 16. Minimum Data Increments for Variables Used to Evaluate the Type of Traffic Control at Unsignalized Intersections.

Criteria	Box, 1995 (*52*)	Nitzel et al., 1988 (*51*)	2000 HCM (*28*)	Elbermawy, 2004 (*55*)	Han et al., 2008 (*56*)	Jiang et al., 2012 (*57*)
Approach Volume			Peak Hour	Peak Hour	Peak Hour	Peak Hour
Crash History	2 Years	1 Year				
Entering Volume	Peak Hour	ADT				
Functional Class	PA	PA				
Major Left-Turn Volume				Peak Hour	Peak Hour	Peak Hour
Posted Speed Limit	PA					

PA = per approach.

Table 17. Minimum Data Increments for Variables Used to Evaluate the Need for a Pedestrian Traffic Control Treatment at an Unsignalized Intersection.

Source, Treatment	**NCHRP 562 (*22*)**	**Tucson (*63*)**	**Phoenix (*64*)**	**ADOT (*65*)**	**Boulder, CO (*67*)**	**VDOT (*66*)**	**OR (*68*)**	**TxDOT (*70, 71*)**
	Ped. Treat.	**PHB**	**PHB**	**PHB**	**Ped. Treat.**	**RRFB**	**Ped. Treat.**	**PHB or RRFB**
Criteria								
Coordinated signal network				Pr				
Crash history by type		1 Year	1 Year	5 Years				
Crossing distance	PA			PA	PA			
Crosswalk marking warrant		PA	PA					
Distance to nearest signalized or stop		PA	PA	PA				PA
Illumination		Pr	Pr	Pr				
Median		Pr	Pr	Pr			Pr	
Number of lanes on approach			PA			PA	PA	
On route (school, bike, ped., etc.)		Pr	Pr	Pr				
Pedestrian generator				Pr				Pr
Pedestrian walking speed	Slowest Group							
Sight distance restrictions						PA		PA
Speed	85th or PSL	PSL	PSL	PSL		PSL	PSL	PSL
Typical compliance with ped. treatments	High or Low							
Unique circumstances			PA					
Volume (bicycle)		Peak Hour	Peak Hour					
Volume (pedestrian)	1 hr	Peak Hour	Peak Hour	Peak Hour	1–3 hr	1 hr	1 hr	1 hr
Volume (vehicular)	1 hr	ADT	ADT	ADT	1 hr		ADT	

PA = per approach, Pr = presence, PSL = posted speed limit, ADT = average daily traffic.

Table 18. Summary of Existing Techniques That May Be of Interest for Phase II.

Technique[a]	Overview	O	S	C	F	PB	Reason to Consider for Further Research
2009 MUTCD (*1*)	Existing Criteria			X	X	X	Baseline
Box, 1995 (*52*)	Stop/Yield Warrants			X	X		Focus on low-volume, low-speed urban/suburban intersections
NCHRP 562 (*22*)	Pedestrian Treatments Warrants	X				X	Criteria consider various pedestrian crossing aspects
Tucson, Phoenix, or ADOT (*65*)	Point System for Selecting Pedestrian Treatment					X	Point system allows for integrating multiple criteria
Nitzel et al. 1988 (*51*)	Traffic Control Warrants	X	X		X		Considers functional class along with traffic volume, crash history, sight distance, and approach speed
Box, 1995 (*52*)	Guidelines for Low-Volume Urban Intersections			X	X		Provides recommendations for lower-volume intersections (total entering volume of 300 veh/hr or less during peak hour)
Elbermawy, 2004 (*55*)	Traffic Control Warrants Developed through Simulation Runs of Various Volume Combinations	X					Based on average control delay and considers turning volume distribution; however, minimal, if any, consideration of pedestrians and bicycles
Han et al., 2008 (*56*)	Traffic Control Warrants Developed through Simulation Runs of Various Volume Combinations	X					
Jiang et al., 2012 (*57*)	Traffic Control Warrants (Includes Roundabouts instead of AWSC) Developed through Simulation Runs of Various Volume Combinations	X					

[a] Column headings:
Technique = brief name to describe the technique of interest.
Overview = brief overview of the main characteristics of the technique.
O = Operations: number of vehicles or users, delay, and LOS.
S = Safety: conflicts, number of crashes, and change in crash prediction because of a change in traffic control.
C = Combination of operations and safety: criteria that include unique criterion for both operation and safety or criteria based on a formal combination of operations and safety considerations such as benefit-cost ratio.
F = Functional class and/or design: such as local or collector versus arterial and roundabouts.
PB = Pedestrian and bicycle volume data.
Reason to Consider for Additional Review = research team's reason that the technique should be considered.

Table 19. Intersection and Traffic Characteristics Considered for Each Technique.

Criteria	Units	2009 MUTCD AWSC (*1*)	2009 MUTCD TWSC (*1*)	Nitzel et al., 1988 (*51*)	Box, 1995 (*52*)	2000 HCM (*28*)	Elbermawy, 2004 (*55*)	Han et al., 2008 (*56*)	Jiang et al., 2012 (*57*)
Major Street									
Peak-Hour Volume	vph					X	X	X	X
Left-Turn Volume	%						X	X	X
8 Highest Hourly Volumes (Vehicular)	vph	X							
Average Daily Traffic	vpd		X						
Functional Classification	-	X		X	X				
Speed (85th Percentile or Posted)	mph	X							
Minor Street									
Peak-Hour Volume, Both Approaches	vph					X	X	X	X
8 Highest Hourly Volumes (Combined Vehicular, Pedestrian, and Bicycle)	vph	X							
Delay during Highest Hourly Volume	sec/veh	X							
Functional Classification	-			X	X				
Speed (85th Percentile or Posted)	mph				X				
Intersection									
Entering Peak-Hour Volume	vph				X				
Entering Daily Volume	vpd			X					
Crashes in Past 12 Months	-	X	X	X	X				
Crashes in Past 2 Years	-	X	X						
Crashes in Past 3 Years	-	X			X				
Legs at the Intersection	-	X							
Geometry/Sight Distance	-	X	X						
Safe Approach Speed	mph			X					

X = variable is considered within the technique.

CHAPTER 5: CRITICAL REVIEW

REVIEW OF MUTCD

Sections 2B.04, 2B.06, and 2B.07 of the MUTCD contain numeric criteria for selecting unsignalized intersection traffic control. Key parts of the opening text, volume criteria, and sight distance criteria are reproduced in Table 20, while Table 21 shows the crash and combination criteria. Observations regarding the numeric and general criteria include the following:

- The criteria are a combination of past practices and quantifiable traffic characteristics. However, there appears to be no research that directly supports the numerical criteria of these sections.
- Some of the sections include bicycle and pedestrian volumes (Sections 2B.04 and 2B.07 for minor approaches only), while other sections only include vehicle volumes (Sections 2B.06 and 2B.07 for major approaches).
- Bicycles are cited as a separate item in some, but not all, volume criteria. It is assumed that the criteria for vehicles include bicycles, but it is not clear. The MUTCD definition of a vehicle includes bicycles; a vehicle is defined in the MUTCD as "every device in, upon, or by which any person or property can be transported or drawn upon a highway, except trains and light rail transit operating in exclusive or semi-exclusive alignments. Light rail transit equipment operating in a mixed-use alignment, to which other traffic is not required to yield the right-of-way by law, is a vehicle."
- Pedestrian traffic is included in only selected volume criteria. Intersection pedestrian traffic is a portion of the volume considered for intersection conflicts and potentially needs more consideration. Guidance related to the application of pedestrian volumes is not adequate.
- Crash criteria should only consider crashes that are susceptible to correction by the recommended treatment, as appropriately stated in the MUTCD sections. The magnitude of the number of crashes varied between the sections: five in 2 years in Section 2B.04 (YIELD or STOP sign), three in 1 year or five in 2 years in Section 2B.06 (STOP sign), and five in 1 year (multi-way STOP signs). While a difference should exist between Sections 2B.06 and 2B.07, how the criteria should differ between Section 2B.04 and the other two sections with numeric criteria is not as obvious.
- Potential non-numeric criteria to install STOP signs could include the considerations listed in Table 22.
- Section 2B.06 on STOP sign application is currently not sensitive to the difference between rural and urban conditions or the speed of the major street. It also does not discuss the differences in application between three- and four-leg intersections.
- Currently, Section 2B.07 includes a 70 percent adjustment to cover higher-speed situations. This adjustment may be replaced with criteria developed based on the speed at the intersection.

Table 20. Opening Text and Criteria for MUTCD Sections with Numeric Criteria.

Criteria	2B.04 Right-of-Way at Intersections	2B.06 STOP Sign Applications	2B.07 Multi-Way Stop Applications
Opening Text	…the use of YIELD or STOP signs should be considered at the intersection of two minor streets or local roads where the intersection has more than three approaches and where one or more of the following conditions exist:	The use of STOP signs on the minor-street approaches should be considered if engineering judgment indicates that a stop is always required because of one or more of the following conditions:	The following criteria should be considered in the engineering study for a multi-way STOP sign installation:
Volume	A. The combined vehicular, bicycle, and pedestrian volume entering the intersection from all approaches averages more than 2,000 units per day	The vehicular traffic volumes on the through street or highway exceed 6,000 vehicles per day	C. Minimum volumes: 1. The vehicular volume entering the intersection from the major street approaches (total of both approaches) averages at least 300 vehicles per hour for any 8 hours of an average day; and 2. The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor street approaches (total of both approaches) averages at least 200 units per hour for the same 8 hours, with an average delay to minor-street vehicular traffic of at least 30 seconds per vehicle during the highest hour; but 3. If the 85th-percentile approach speed of the major-street traffic exceeds 40 mph, the minimum vehicular volume warrants are 70 percent of the values provided in Items 1 and 2.
Sight Distance	B. The ability to see conflicting traffic on an approach is not sufficient to allow a road user to stop or yield in compliance with the normal right-of-way rule if such stopping or yielding is necessary	A restricted view exists that requires road users to stop in order to adequately observe conflicting traffic on the through street or highway	

Table 21. Sight Distance and Crash Criteria for MUTCD Sections with Numeric Criteria.

Criteria	2B.04 Right-of-Way at Intersections	2B.06 STOP Sign Application	2B.07 Multi-Way Stop Applications
Crashes	C. Crash records indicate that five or more crashes that involve the failure to yield the right-of-way at the intersection under the normal right-of-way rule have been reported within a 2-year period	C. Crash records indicate that three or more crashes that are susceptible to correction by the installation of a STOP sign have been reported within a 12-month period, or that five or more such crashes have been reported within a 2-year period. Such crashes include right-angle collisions involving road users on the minor-street approach failing to yield the right-of-way to traffic on the through street or highway.	B. Five or more reported crashes in a 12-month period that are susceptible to correction by a multi-way stop installation. Such crashes include right-turn and left-turn collisions as well as right-angle collisions.
Other			Where no single criterion is satisfied, but where Criteria B, C.1, and C.2 are all satisfied to 80 percent of the minimum values. Criterion C.3 is excluded from this condition.

Table 22. Suggested Considerations to Install a STOP Sign.

Source	Considerations
2009 MUTCD Section 2B.04 (Support, 09)	• Controlling the direction that conflicts the most with established pedestrian crossing activity or school walking routes. • Controlling the direction that has obscured vision, dips, or bumps that already require drivers to use lower operating speeds. • Controlling the direction that has the best sight distance from a controlled position to observe conflicting traffic.
2009 MUTCD Section 2B.04 (Standard, 10)	• If the signal indication for an approach is a flashing red at all times. • If a minor street or driveway is located within or adjacent to the area controlled by the traffic control signal, but does not require separate traffic signal control because an extremely low potential for conflict exists. • If a channelized turn lane is separated from the adjacent travel lanes by an island and the channelized turn lane is not controlled by a traffic control signal.
2009 MUTCD Section 2B.07 (Option, 05)	• The need to control left-turn conflicts. • The need to control vehicle/pedestrian conflicts near locations that generate high pedestrian volumes. • Locations where a road user, after stopping, cannot see conflicting traffic and is not able to negotiate the intersection unless conflicting cross traffic is also required to stop. • An intersection of two residential neighborhood collector (through) streets of similar design and operating characteristics where multi-way stop control would improve traffic operational characteristics of the intersection.
Other Suggestions from Research	• Lower functional classification street intersects a higher functional class street. • Modal priority, for example, to establish a bike route. • To redirect traffic within a grid network. • To improve operations within a network. • SSIF program.

IDENTIFY INTERSECTION AND TRAFFIC CHARACTERISTICS

The literature and state manual review tasks generated tables of the different methods being used to evaluate the need for STOP or YIELD signs at an intersection. The intersection, traffic, and safety characteristics required for these methods were identified to understand how these characteristics affect decisions made regarding traffic control.

Most techniques include the following criteria for making traffic control decisions:

- Functional class.
- Vehicular volume (either approach or entering, measured per hour or ADT).
- Reported crash experience.
- Speed.

The following criteria are also considered:

- Sight distance available on each approach.
- Angle of approach.
- Geometric (e.g., in median, roundabouts, channelized right-turn lanes, and railroad grade crossings).

Some also consider:

- Volume (either approach or entering, measured per hour or ADT) of bicycles and pedestrians.
- Delay.
- Left-turn volume on major approaches.
- Volume split (e.g., 60/40 for four-leg and 75/25 for three-leg intersections, or approximately equal).

Other criteria mentioned but not obviously used in existing warrants include:

- Queue length.
- LOS.

Additional criteria considered when making a pedestrian traffic control device decision at an unsignalized intersection include the following:

- Crossing distance.
- Number of lanes.
- Distance to nearest signalized or all-way stop-controlled intersection.

SUGGESTIONS

Suggestions regarding the numeric and general criteria include the following:

- All numeric criteria should include consideration of pedestrians and bicycles or have justification for why these counts are not considered (e.g., they are considered in other criteria).
- Potential, non-numeric reasons to install STOP signs could include the considerations suggested in Table 22.
- The MUTCD should have both numeric criteria and non-numeric criteria (examples listed in Table 22).

QUESTIONS

Based on these observations, the following questions are raised:

- Perhaps the numeric criteria within Section 2B.04 should be removed and the reader referred to Sections 2B.06 and 2B.07. Another approach could be to create a section that specifically addresses numeric criteria for YIELD sign or no control situations. Another suggestion is to have Section 2B.04 focus on non-numeric situations or focus on the local road (residential street) condition.
- Should some or all of the criteria listed in Section 2B.07 (reproduced in Table 22) be considered at two-way stop-controlled intersections?
- How should the need for STOP or YIELD signs at roundabouts or right-turn channelization lanes be discussed—within a non-numeric section, or should criteria be established?
- If the number of legs at the intersection becomes a factor, how should the section address the condition when the predominant flow on the three-leg intersection is from the stem?
- Another geometric concern is when the angle of intersection is less than 75 degrees as documented in several publications including the *Handbook for Designing Roadways for the Aging Population* (*72*). Is it sufficient to say that the sight distance check will cover the situation when a skew angle exists?
- With greater use of the RRFB, there is a pressing need to understand how the device affects TWSC intersection operations and safety. Should the RRFB be considered in an HCM methodology to change the relative priorities of traffic streams to actually have pedestrians be the first priority? What effect would that have in the operations analysis? How should the RRFB be considered with respect to making a decision regarding TWSC or AWSC?
- How should the procedure handle bicyclists that dismount and walk their bike across the intersection? Should this maneuver be considered a pedestrian or a vehicle (bicycle)?
- Should the MUTCD explicitly address the question of whether to consider induced pedestrians—in other words, to increase the pedestrian count in recognition that the addition of the traffic control will result in additional pedestrians at the unsignalized intersection?
- The criteria in the STOP sign section (Section 2B.06) do not appear to consider delay or queue length. Should this section include criteria that address either of these measures?
- An approach used in Portland is to evaluate a series of intersections throughout the city to determine where pedestrian traffic is highest on streets that are difficult to cross. This is applied specifically on streets where a person crossing the street has died due to a crash. In

application, the location of the fatality, if likely to reduce the risk of future crashes, is selected. If a nearby location or downstream intersection is likely to reduce crashes further, a conversation with the community often ensues to determine the appropriate location.

DIRECTION FOR PHASE II

Based upon the review of the literature, policies, the existing criteria in the MUTCD, and discussions with practitioners, key considerations for the Phase II work plan included the following:

- Set a higher priority on investigating when to go from TWSC to AWSC rather than when to go from no control to yield control or TWSC. Functional classification of the intersection approach legs is often used to determine no control, yield control, and TWSC.
- Develop criteria that reflect urban and rural conditions and develop criteria based on speed. A similar comment was that local/residential streets in dense urban areas should have unique criteria rather than having the same criteria for both lower-speed and higher-speed roads or having the same criteria for both local/residential streets as compared to collectors/arterial streets.
- Consider roundabouts as a geometric design alternative within the evaluation.
- Include sight distance as a factor in the warrants.
- Consider a variety of major- and minor-road volume splits and not just when the split is "approximately equal."
- Select an approach that will permit findings to be available by June 2014 so that the criteria may be considered for the next edition of the MUTCD.
- Consider the existing and ongoing revisions to relevant sections of the MUTCD, such as the changes being proposed for defining "approximately equal" and the changes suggested for the reorganization.

If resources permitted, the following were also to be considered:

- Present a list of alternative treatment ideas (e.g., a beacon with a STOP sign or advance signing); however, NCHRP Project 3-109 should focus on the warrants for STOP signs and not on warrants for these alternative treatments.
- Explore the concept of prioritization of traffic control installation based on risk (e.g., the likelihood of pedestrians in urban areas with higher speeds and assuming limited budgets to provide signs, beacons, and lighting).
- Consider the presence of transit and sidewalks as a part of the process.

CHAPTER 6: ECONOMIC ANALYSIS

INTRODUCTION

This chapter describes the activities related to the economic analysis procedure. It contains discussion of the sources used as a basis for the analysis, as well as steps taken to collect the necessary information and perform the analysis.

SELECTION OF TYPE OF COSTS TO CONSIDER IN ANALYSIS

Creating an economic analysis procedure requires consideration of what benefits and costs to include in the analysis. Several documents provide guidance on how to determine total costs for traffic control, including:

- AASHTO's *User and Non-User Benefit Analysis for Highways* (commonly known as the *Red Book*) (*73*).
- NCHRP Project 3-110, *Estimating the Life-Cycle Cost of Intersection Designs: Interim Report* (*74*).
- FHWA's *Highway Economic Requirements System—State Version: Technical Report* (HERS-ST) (*75*).
- NCHRP Web-Only Document 193, *Development of Left-Turn Lane Warrants for Unsignalized Intersections* (*76*).
- Upchurch's "Guidelines for Use of Sign Control at Intersections to Reduce Energy Consumption" *(50*) and *Development of an Improved Warrant for Use of Stop and Yield Control at Four-Legged Intersections* (*77*).

Table 23 lists the costs that these references suggest should be considered when evaluating a change in an intersection's design or operations. The key costs considered in most of these documents are user delay, crash, and vehicle operating costs. Depending upon the source, other costs are considered such as pollution or travel time reliability. How each cost is calculated also varies depending upon the source.

The AASHTO *Red Book* notes that, in general, control devices yield higher travel time costs and operating and ownership costs, which are offset by safety-related benefits. Operating costs include fuel, oil, maintenance, and tires. Ownership costs include insurance, license and registration fees and taxes, economic depreciation, and finance changes. To calculate the effect of the change in traffic control, the costs need to be calculated both before and after the change. Ownership costs are typically considered on a per-mile basis; however, because intersection traffic control will not change the total distance, these costs should not vary between the alternatives being considered in this study and, therefore, were not included in the analysis. The AASHTO *Red Book* also provides fuel costs as a function of time rather than a function of travel speed for those analyses where an improvement—such as a change in intersection traffic control—results in traffic delay. The *Red Book* notes that although these factors are a function of delay, the fuel consumption is due primarily to acceleration of vehicles after being delayed, rather than fuel consumed idling during delay periods.

Table 23. Costs Suggested for Evaluating Changes to Intersections from Several Sources.

Source	Costs
AASHTO *Red Book* (*73*)	• Travel time (delay) costs • Crash costs • Vehicle operating and ownership costs
NCHRP 3-110, *Estimating the Life-Cycle Cost of Intersection Designs* Interim Report (*74*)	User costs: • Construction • User delay at the intersection • Travel time reliability • Safety • Operating (e.g., fuel, oil, maintenance, and tires) Other costs: • Delay to travelers on other parts of the network • Emissions • Effects on businesses • Right-of-way acquisition • Public safety
Upchurch (*50, 77*)	• Vehicle operating costs • Delay • Crashes • Air pollution • Sign material, installation, and maintenance costs • Noise pollution
FHWA *Highway Economic Requirements System—State Version: Technical Report* (*75*)	Constant speed and excess speed cost components: • Fuel consumption • Oil consumption • Tire wear • Maintenance and repair • Depreciable value
NCHRP Web-Only Document 193 (*76*)	• User delay at the intersection • Safety

HERS-ST was developed to estimate highway system performance for various investment levels. It contains detailed equations for estimating constant and variable speed operating costs for seven vehicle types by determining the estimated costs associated with fuel, oil, tire wear, maintenance and repair rate, and depreciation for each vehicle type. In addition, the equations consider grade, pavement condition adjustments, and other adjustment factors such as fuel efficiency. The equations for estimating the effect of speed-change cycles calculate the excess operating costs due to STOP signs; however, these equations only consider maximum speed during the speed-change cycle. Because the research team has the estimated change in delay at the intersection associated with the change in the traffic control, the AASHTO *Red Book* methodology was used for estimating vehicle operating costs.

The NCHRP 3-110 Interim Report on *Estimating the Life-Cycle Cost of Intersection Designs* (*74*) recommends the consideration of construction and travel time reliability in addition to the costs already discussed. For the scenarios being considered, construction should be nominal with the exception of a conversion to a roundabout, and consideration of those construction costs was added to the analysis. For this analysis, the research team assumed that the change in intersection traffic control at the volumes being considered would have no impact on travel time reliability.

Upchurch (*50, 77*) recommended that pollution (both air and noise) and sign material, installation, and maintenance costs should be considered along with the costs discussed above. Researchers investigated the applicability of tools such as the Environmental Protection Agency's Motor Vehicle Emissions Simulator (MOVES) to quantify the effects of air pollution from emissions, but some of the underlying conditions and assumptions used in these tools were not directly applicable to the unsignalized intersection scenario in this project, and identifying ways to adapt to this project proved very difficult at best. In addition, preliminary results obtained from MOVES indicated that costs associated with pollution from emissions would be very low compared to other costs in the analysis. The NCHRP 3-110 methodology includes pollution (emissions) along with several other costs as non-user costs. These non-user costs are costs endured by users elsewhere on the network or societal costs associated with the use of the network. Because of the low annual costs for signs, pollution, and societal costs as compared to other costs, they were not included in the analysis.

Based upon the discussions from the sources referenced above, the research team selected the following costs for consideration in this project:

- User delay (travel time).
- Crash.
- Vehicle operating.
- Construction (for roundabouts).

To obtain the information needed to calculate delay, which is needed for both user (time) and vehicle operating costs, simulation models were run for several scenarios. The HSM (*24*) was used to determine the crash prediction estimates. The following section present information on these efforts.

SIMULATION

Base Models

To conduct the operational analysis, a microsimulation model (VISSIM) was used to measure the impact of intersection traffic control on intersection delay for cars, trucks, and pedestrians. The base models for three-leg intersections included the following:

- All-way stop control (AW3).
- Two-way stop control (TW3).

The four-leg base intersections were:

- All-way stop control (AW4).
- Two-way stop control (TW4).
- Roundabout (RO4).

Table 24 lists the values of the variables that were not modified between simulation runs. Table 25 lists the values of the variables that were modified, except for volume, which is provided in Table 26.

Table 24. Non-changing Simulation Variable Values.

Variable	Value	Major or Minor	No. of Legs
Approach segment length	2640 ft	Both	3 and 4
Bicycle free-flow speed	15 mph	Both	3 and 4
Critical gap for pedestrians	6 sec	Both	3 and 4
Critical gap for vehicles	3 sec	Both	3 and 4
Dedicated left-turn lane	None	Both	3 and 4
Dedicated right-turn lane	None	Both	3 and 4
Lane width	12 ft	Both	3 and 4
Median type	None	Both	3 and 4
Heavy-vehicle percent	5%	Major	3 and 4
Through percent	80%	Major	3
Turn (either left or right) percent	20%	Major	3
Left-turn percent	15%	Major	4
Right-turn percent	15%	Major	4
Through percent	70%	Major	4
Left-turn percent	50%	Minor	3
Right-turn percent	50%	Minor	3
Through percent	20%	Minor	4
Heavy-vehicle percent	1%	Minor	3 and 4
Number of lanes on approach	1 lane	Minor	3 and 4

Table 25. Changing Simulation Variable Values.

Variable	Value	Major or Minor
Geometry	Three legs, four legs, or roundabout	Intersection
Traffic control	Two-way stop, all-way stop, or roundabout	Intersection
Number of lanes	2- or 4-lane roads (1- or 2-lane approach)	Major
Posted speed limit	25 or 40 mph	Minor
Posted speed limit	25, 40, or 55 mph	Major
Directional bicycle flow rate	0, 10 bikes/hr	Both
Directional pedestrian flow rate	5, 10, or 20 ped/hr	Both

Table 26. Major and Minor Approach Volume Pairs.

Major (veh/hr/approach)	210	300	450	500	600	700	750	1000
Minor (veh/hr/approach)	140	200	300	300	400	400	350	500

Assumptions

Assumptions for the simulation runs included:

- Arrival is random.
- The standard deviation for speeds is 5 mph.
- Driveways or unsignalized intersections do not exist along any of the approaches except for the one intersection of interest.

- The pedestrian will wait until a sufficient gap is present, either created because a vehicle stopped or due to available headway within the traffic stream. If a marked crosswalk is present, drivers should yield or stop to a pedestrian in the crosswalk, even if a STOP sign is not present. Previous research (*22*), however, has demonstrated that few drivers will yield to pedestrians in an uncontrolled yet marked crosswalk. Therefore, the assumption for this simulation is that pedestrians on uncontrolled approaches will wait and only cross when there is a sufficient gap. Pedestrians will have no delay when crossing a stop-controlled approach.

Modeling Runs

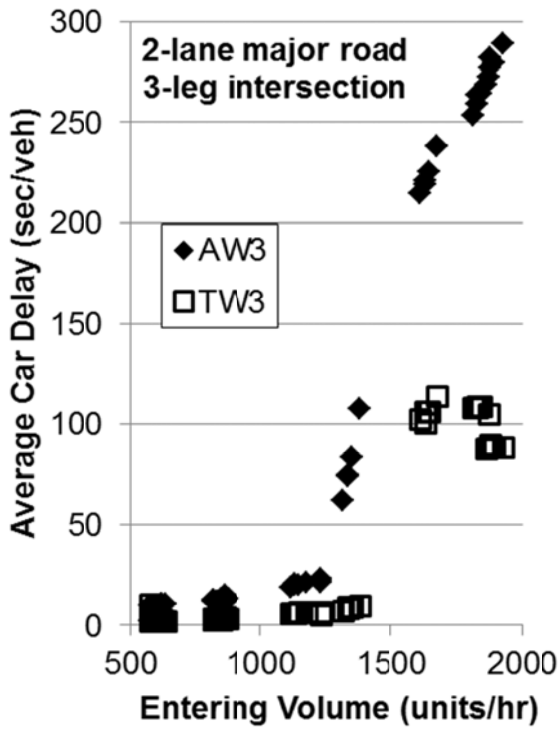
A series of simulation modeling runs were conducted. Initially, the range of speed was a variable of emphasis to be able to determine warrants for a range of posted speed limits or for rural (high-speed) and urban (low-speed) conditions. Examining the results from these earlier runs revealed, however, that delay did not vary greatly due to posted speed limit. Table 27 shows the result for a subset of the trials where the major, minor, pedestrian, and bicycle volumes were constant and the major and minor speeds were varied. For cars within the trials shown in Table 27, the maximum average intersection delay was 7.8 sec, and the minimum delay was 6.7 sec, representing a range of only 1.1 sec. When compared to the variation in delay due to a change in volume, the variation in delay due to changing speed is nominal. Because delay was not as affected by speed, later simulation efforts focused on varying vehicle volume and the number of pedestrians.

Table 27. Simulation Results Illustrating Variation Due to Speed Limit.

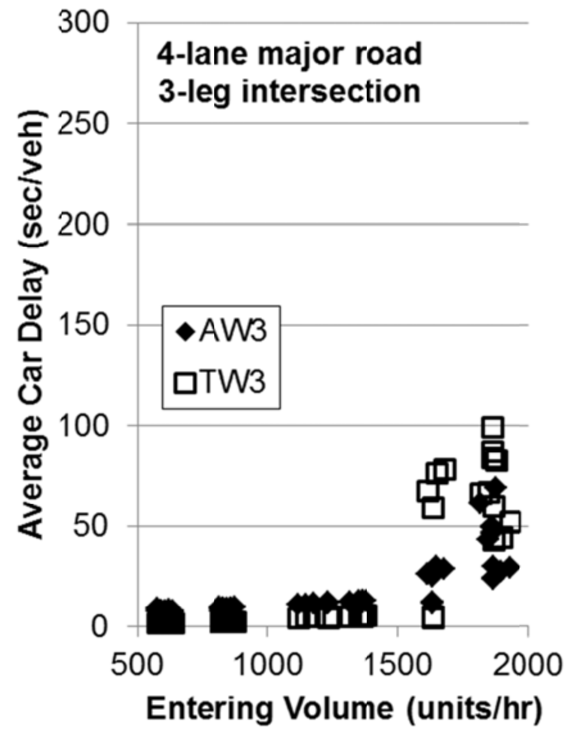
Trials	A	B	C	D	E	F	Average
Major Speed (mph)	25	40	40	55	55	55	Varies
Minor Speed (mph)	25	25	40	25	40	55	Varies
Car, Average Intersection Delay (sec/car)	6.7	7.5	7.8	7.5	7.6	7.7	7.5
Truck, Average Intersection Delay (sec/truck)	5.9	5.5	6.7	7.0	6.9	7.2	6.5
Pedestrian, Average Intersection Delay (sec/pedestrian)	4.3	6.0	5.8	6.9	7.3	7.0	6.2
Car, Average Minor Road Delay (sec/car)	18.7	21.1	22.0	20.9	21.0	21.4	20.8
Other input values: 500 veh/hr/approach on major, 250 veh/hr/ln on minor, 20 ped/hr all approaches, 0 bike/hr all approaches, TWSC, four lanes on major, two lanes on minor, four legs.							

Findings from Simulation

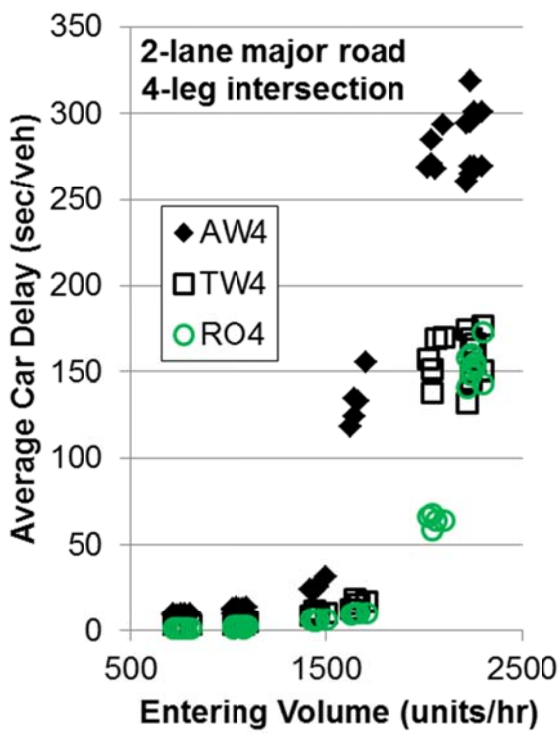
Figure 14 shows plots of the delay findings for cars, while Figure 15 shows delay results for pedestrians. The entering volume is the sum of the volume of vehicles, pedestrians, and bicycles on each approach for the hour of simulation.



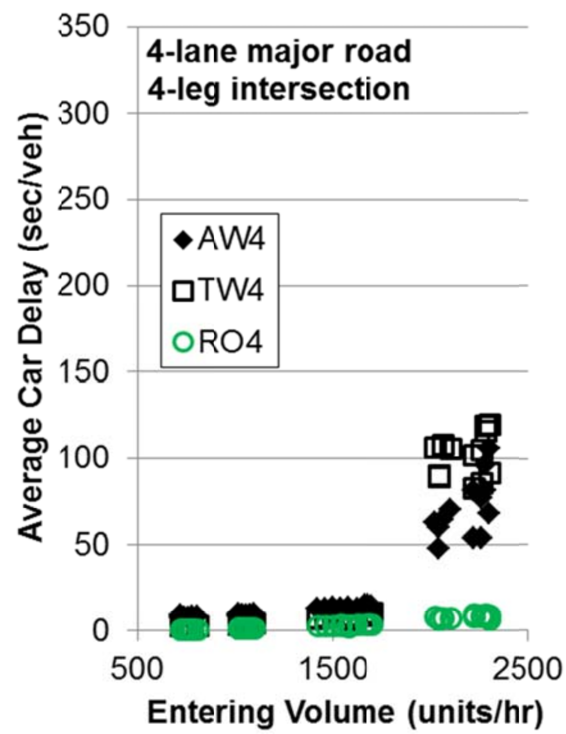
(a) Two-Lane Major Road, Three Legs



(b) Four-Lane Major Road, Three Legs



(c) Two-Lane Major Road, Four Legs



(d) Four-Lane Major Road, Four Legs

Figure 14. Car Delay Results.

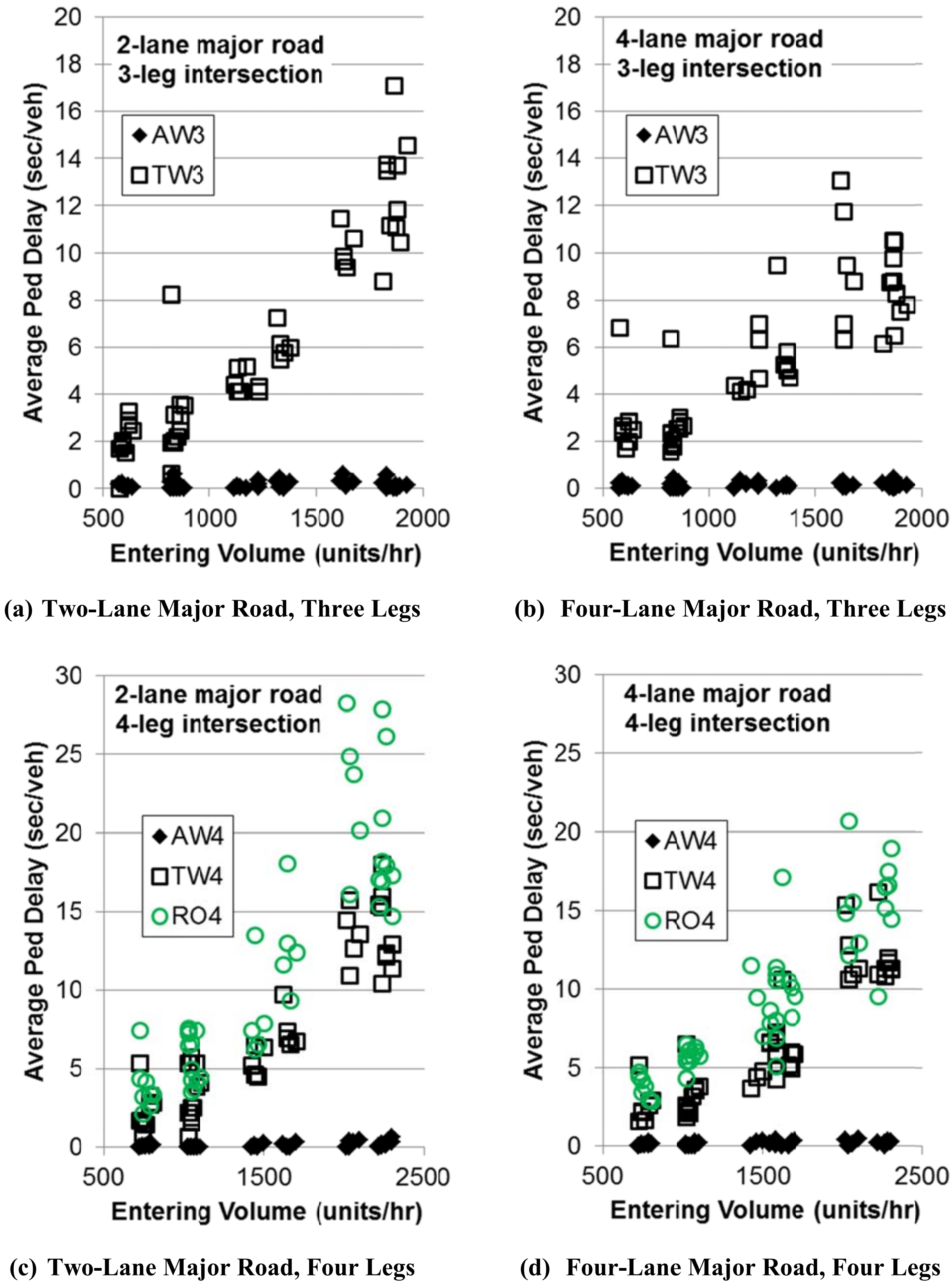


Figure 15. Pedestrian Delay Results.

For intersections with four lanes on the major road, average car delay begins to increase above 1,500 units/hr. The increase in average car delays begins at a slightly lower entering volume when there are only two lanes on the major road (i.e., one-lane approaches), as expected. As illustrated in Figure 14(a) and (c), the average per-car delay at AWSC intersections with only one-lane approaches on the major road exceeds the average per-car delay at the other intersection types (TWSC and roundabout intersections). Delay at TWSC and roundabouts also increases with higher entering volumes, but not as much as it does for the AWSC condition.

The pedestrian delay results illustrate the benefits of AWSC to pedestrians because the delay is minimal for pedestrians across all volume levels. For the higher volumes levels, the delay incurred by the pedestrians waiting for an adequate gap at the higher volume—whether at a TWSC or a roundabout intersection—can be seen in Figure 15. The average pedestrian delay is higher at roundabouts because pedestrians must search for a gap on all approaches at a roundabout, while the pedestrians at a TWSC intersection only search for a gap on two of the four approaches.

The results from the VISSIM runs were reviewed, and the volume combinations were identified where the average minor-road delay was greater than 60 sec (see Table 28). These results reflect the average vehicle delay for the minor road rather than the average vehicle delay for the entire intersection. The combinations listed in Table 28 are higher than the current peak-hour signal warrant; for example, the signal warrant is 240 units/hr on the minor approach when the major volume is assumed to be 600 veh/hr/approach or 1,200 veh/hr total for both approaches.

Table 28. Volume Combinations Used in VISSIM Resulting in More Than 35 sec or 60 sec of Minor-Road Average Vehicle Delay during the Simulated Hour.

Delay (sec)	Number of Legs	Number of Lanes on Major Approach	Major Volume (veh/hr/approach)	Minor Volume (veh/hr/approach)
>35, less than 60	3	1	500	300
>35	3	1 and 2	600	400
>35	3	1 and 2	700	400
>35	3	1 and 2	750	350
>35	3	2[a]	1,000	500
>35, less than 60	4	1	500	300
>35	4	1 and 2	600	400
>35	4	1 and 2	700	400
>35	4	1 and 2	750	350
>35	4	2[a]	1,000	500

[a] Volume combination not used with a one-lane major-road approach.

Table 28 also provides the volume combinations included in the VISSIM simulation where greater than 35 sec of delay per vehicle was observed on the minor-road approach. The value of 35 sec of delay corresponds to LOS E in the HCM (*23*). The lowest volume combination with more than 35 sec delay per veh was 500 veh/hr/approach on the major road (or 1,000 veh/hr for both approaches) and 300 veh/hr/approach on the minor road for a two-lane major road. For a four-lane major road, the lowest volume combination is 600 on the major road and 400 on the minor road. However, these volumes (500/300 or 600/400) would both plot above the relevant peak-hour signal warrant curve. For a two-lane major road, the signal warrant for 1,000 veh/hr on the major road is 200 veh/hr. For a four-lane major road, the signal warrant of 1,200 veh/hr on the major road is 225 veh/hr on the minor road.

COSTS

Based upon the review of several contributing sources, as discussed previously in this chapter, the research team selected the following costs for consideration in evaluating changes in intersection traffic control:

- User delay.
- Crash.
- Vehicle operating.
- Roundabout construction.

User Delay Costs

To evaluate the change in user delay, the results from the simulation runs were used. The delay results from the AWSC and roundabout scenarios were compared to the delay determined with only TWSC present. The intersection-wide measure of performance used was average delay per car, per truck, or per pedestrian for the network, measured in seconds. To determine the consequences of changing the intersection traffic control, the difference between the average total delay before (i.e., TWSC) and after (i.e., either the AWSC or roundabout scenario) the change was calculated. The difference could be positive or negative with the following meaning:

- Negative difference in delay means that more user delay is occurring due to the change.
- Positive difference in delay means that there is a delay savings due to the change.

For example, assume that the intersection traffic control at a four-leg intersection with four lanes on the major road was changed from TWSC to AWSC. The peak-hour volume is 300 veh/hr/approach on the major road, 200 veh/hr/approach on the minor road, 10 ped/hr/approach, and 0 bikes/hr/approach. The estimated delays per hour for the scenarios being used in this example are shown in Table 29. When TWSC is replaced with AWSC, the delay for cars and trucks becomes worse (as illustrated by the negative values in Table 29), while delay for pedestrians improves (as illustrated by the positive value in the TW4-AW4 row of Table 29).

Per-hour delays available from the simulation are converted into hours of delay per year and then multiplied by the assumed vehicle occupancy (for cars and trucks) and the assumed value of time (for cars, trucks, and pedestrians).

Table 29. Example of Delay by User.

Scenario	Car Intersection Delay[a] (sec/car) or Delay Costs/Savings ($/yr)[b]	Truck Intersection Delay[a] (sec/truck) or Delay Costs/Savings ($/yr)[b]	Pedestrian Intersection Delay[a] (sec/ped) or Delay Costs/Savings ($/yr)[b]
TW4	3.6	2.1	4.0
AW4	9.3	12.5	0.3
TW4-AW4 (Change from TW4 to AW4)	−5.7	−10.4	3.7
TW4-AW4 Costs per Year	$(155,566)	$(63,347)	$3,950

[a] Average intersection delay for four-leg intersection with four lanes on major road and when volume is 300 veh/hr/approach on the major road, 200 veh/hr/approach on the minor road, 10 ped/hr/approach, and 0 bikes/hr/approach.
[b] Average annual delay costs/savings determined using the methodology discussed in this document. The parentheses with dollars represent a negative amount and indicate that more delay is occurring due to the intersection control change for cars and trucks. Positive delay costs/savings indicate less delay is occurring for pedestrians due to the intersection control change.

Table 30. Factors Used to Convert Seconds/Vehicle Delay to Hour/Intersection Delay for a Year.

Traffic Period	Number of Hours in Weekday	Number of Hours in Weekend	Hours per Year[a]	Hourly Percent of ADT during Period[b]	Typical Hourly Volume If AADT = 1,000 veh/day
Weekday Peak Period	3	0	751	7.8	78
Weekday, Near-Peak Hour, and Weekend Typical Period	7	11	3,014	6.1	61
Weekday and Weekend Off-Peak	8	8	2,920	3.7	37
Night	6	5	2,075	0.7	7
Total	**24**	**24**	**8,760**		**1,000**

[a] Assume 52.16 weeks/year with 4.8 days having weekday traffic distribution and 2.2 days having weekend traffic distribution (the typical 5 weekdays and 2 weekend days were adjusted to reflect 10 holidays).
[b] Assumed hourly percent of traffic for given traffic period.

Delay for Entire Year

The simulation provides predictions of delay measured in seconds per user. This value needs to be converted to delay at the intersection for the entire year. To perform the conversion, the assumed number of hours along with the percent of the ADT represented by each traffic period is needed. Table 30 provides the assumptions used in this project to convert seconds-per-user delay into hours of delay for the year at the intersection. The hourly percent of ADT values was determined using hourly traffic distributions available in the *2012 Urban Mobility Report* (*78*). The distributions for non-freeway, AM and PM peak periods for both no/low congestion and moderate congestion were considered to obtain the weekday values. The non-freeway, weekend traffic distribution was used to obtain the weekend data. While hourly factors were available for each hour of the day, hours were grouped as shown in Table 30 to facilitate calculations.

Travel Time Delay Cost

The national congestion constants used in the *2012 Urban Mobility Report* (78) are shown in Table 31. The values represent 2011 dollars. The value of person-time used in the *Urban Mobility Report* is based on the value of time, rather than the average or prevailing wage rate. The average cost of time was assumed to be $16.79 per person-hour for 2011. The 2011 value of time was adjusted using the Consumer Price Index (CPI) for 2011 and 2013 available from the U.S. Bureau of Labor Statistics (*79*). The ratio of the 2013 to 2011 CPI value is 232.957 divided by 224.939, which is 1.04. The ratio 1.04 multiplied by $16.79 gives a 2013 value of time of $17.39, which represents the average cost of time per person. To convert to an average cost of time per vehicle, the cost of time per person is multiplied by the vehicle occupancy factor of 1.25 persons per vehicle. The CPI was also applied to the commercial vehicle operating cost to obtain a 2013 hourly value of $89.90. The vehicle occupancy for trucks was assumed to be 1.0.

Table 31. National Congestion Constants Used in the *2012 Urban Mobility Report* (*78*).[a]

Constant	Value
Vehicle Occupancy (Passenger Vehicles)	1.25 persons per vehicle
Average Cost of Time (2011)	$16.79 per person-hour[b]
Commercial Vehicle Operating Cost (2011)	$86.81 per vehicle-hour[b, c]

[a] Source: *2012 Urban Mobility Report* methodology, http://tti.tamu.edu/documents/mobility-report-2012-wappx.pdf.
[b] Adjusted annually using the Consumer Price Index.
[c] Adjusted periodically using industry cost and logistics data.

Crash Costs

Crash Prediction

The predicted average crash frequency for an intersection can be determined from equations in the HSM (*24*). These equations, called safety performance functions, are regression models for estimating the predicted average crash frequency of individual roadway segments or intersections for a set of specific base conditions. As discussed in the HSM, each SPF in the predictive method was developed with observed crash data for a set of similar sites. The SPFs, like all regression models, estimate the value of a dependent variable as a function of a set of independent variables. In the SPFs developed for the HSM, the dependent variable estimated is the predicted average crash frequency for a roadway segment or intersection under base conditions, and the independent variables are the AADTs of the roadway segment or intersection legs (and, for roadway segments, the length of the roadway segment).

The SPFs applicable to the rural conditions in this study are listed in Table 32, while the SPFs applicable to the urban conditions are listed in Table 33. Table 34 lists the definitions for the variables listed in Table 33. Table 35 lists the acceptable ranges for AADT for each equation. These ADT ranges were not exceeded in the evaluations.

Table 32. Safety Performance Functions for Rural Highways for Total Crashes.

Number of Lanes	Number of Legs	Equation	
Two	Three	$N_{spf\ 2\ ln,\ 3st} = \exp[-9.86 + 0.79 \times \ln(AADT_{maj}) + 0.49 \times \ln(AADT_{min})]$	(1)
Two	Four	$N_{spf\ 2\ ln,\ 4st} = \exp[-8.56 + 0.60 \times \ln(AADT_{maj}) + 0.61 \times \ln(AADT_{min})]$	(2)
Four	Three	$N_{spf\ 4\ ln,\ 3st} = \exp[-12.526 + 1.204 \times \ln(AADT_{maj}) + 0.236 \times \ln(AADT_{min})]$	(3)
Four	Four	$N_{spf\ 4\ ln,\ 4st} = \exp[-10.008 + 0.848 \times \ln(AADT_{maj}) + 0.448 \times \ln(AADT_{min})]$	(4)

Where:

$N_{spf\ 2\ ln,\ 3st}$ = estimate of intersection-related predicted average crash frequency for base conditions for a rural two-lane highway with three-leg stop-controlled intersections.

$N_{spf\ 2\ ln,\ 4st}$ = estimate of intersection-related predicted average crash frequency for base conditions for a rural two-lane highway with four-leg stop-controlled intersections.

$N_{spf\ 4\ ln,\ 3st}$ = estimate of intersection-related predicted average total crash frequency for base conditions for a rural four-lane highway with three-leg stop-controlled intersections.

$N_{spf\ 4\ ln,\ 4st}$ = estimate of intersection-related predicted average total crash frequency for base conditions for a rural four-lane highway with four-leg stop-controlled intersections.

$AADT_{maj}$ = AADT (vehicles per day) on the major road.

$AADT_{min}$ = AADT (vehicles per day) on the minor road.

Table 33. Safety Performance Functions for Urban and Suburban Arterial Intersections for Total Crashes.

Number of Legs	Crash Type	Equation	
Intersections with Stop Control on the Minor Approach			
Three	Multiple	$N_{spf\ U/S\text{-}MV,\ 3st} = \exp[-13.36 + 1.11 \times \ln(AADT_{maj}) + 0.41 \times \ln(AADT_{min})]$	(5)
Four	Multiple	$N_{spf\ U/S\text{-}MV,\ 4st} = \exp[-8.90 + 0.82 \times \ln(AADT_{maj}) + 0.25 \times \ln(AADT_{min})]$	(6)
Three	Single	$N_{spf\ U/S\text{-}SV,\ 3st} = \exp[-6.81 + 0.16 \times \ln(AADT_{maj}) + 0.51 \times \ln(AADT_{min})]$	(7)
Four	Single	$N_{spf\ U/S\text{-}SV,\ 4st} = \exp[-5.33 + 0.33 \times \ln(AADT_{maj}) + 0.12 \times \ln(AADT_{min})]$	(8)
Three	Multiple and Single	$N_{spf\ U/S,\ 3st,\ M\&S} = (N_{spf\ U/S\text{-}MV,\ 3st} + N_{spf\ U/S\text{-}SV,\ 3st}) = (5) + (7)$	(9)
Four	Multiple and Single	$N_{spf\ U/S,\ 4st,\ M\&S} = (N_{spf\ U/S\text{-}MV,\ 4st} + N_{spf\ U/S\text{-}SV,\ 4st})$	(10)
Three	Pedestrian	$N_{spf\ U/S\text{-}Ped,\ 3st} = 0.021 \times (N_{spf\ U/S,\ 3st,\ M\&S})$	(11)
Four	Pedestrian	$N_{spf\ U/S\text{-}Ped,\ 4st} = 0.022 \times (N_{spf\ U/S,\ 4st,\ M\&S})$	(12)
Three	Bike	$N_{spf\ U/S\text{-}Bike,\ 3st} = 0.016 \times (N_{spf\ U/S,\ 3st,\ M\&S})$	(13)
Four	Bike	$N_{spf\ U/S\text{-}Bike,\ 4st} = 0.018 \times (N_{spf\ U/S,\ 4st,\ M\&S})$	(14)
Three	All	$N_{spf\ U/S,\ 3st} = N_{spf\ U/S,\ 3st,\ M\&S} + N_{spf\ U/S\text{-}Ped,\ 3st} + N_{spf\ U/S\text{-}Bike,\ 3st}$	(15)
Four	All	$N_{spf\ U/S,\ 4st} = N_{spf\ U/S,\ 4st,\ M\&S} + N_{spf\ U/S\text{-}Ped,\ 4st} + N_{spf\ U/S\text{-}Bike,\ 4st}$	(16)

Note: Equations and coefficients obtained from Section 12.6.2 of the HSM (*24*). Variable descriptions are in Table 34.

Table 34. Definitions for Variables in Table 33.

Variable	Definition
$N_{spf\ U/S\text{-}MV,\ 3st}$	Estimate of multiple-vehicle predicted average crash frequency for base conditions for urban/suburban arterial three-leg intersections with stop control on the minor-road approach (3ST)
$N_{spf\ U/S\text{-}MV,\ 4st}$	Estimate of multiple-vehicle predicted average crash frequency for base conditions for urban/suburban arterial four-leg intersections with stop control on the minor-road approaches (4ST)
$N_{spf\ U/S\text{-}SV,\ 3st}$	Estimate of single-vehicle predicted average crash frequency for base conditions for urban/suburban arterial three-leg intersections with stop control on the minor-road approach
$N_{spf\ U/S\text{-}SV,\ 4st}$	Estimate of single-vehicle predicted average crash frequency for base conditions for urban/suburban arterial four-leg intersections with stop control on the minor-road approaches
$N_{spf\ U/S,\ 3st,\ M\&S}$	Estimate of multiple- and single-vehicle predicted average crash frequency for urban/suburban arterial three-leg intersections with stop control on the minor-road approach
$N_{spf\ U/S,\ 4st,\ M\&S}$	Estimate of multiple- and single-vehicle predicted average crash frequency for urban/suburban arterial four-leg intersections with stop control on the minor-road approaches
$N_{spf\ U/S\text{-}Ped,\ 3st}$	Estimate of pedestrian predicted average crash frequency for urban/suburban arterial three-leg intersections with stop control on the minor-road approach
$N_{spf\ U/S\text{-}Ped,\ 4st}$	Estimate of pedestrian predicted average crash frequency for urban/suburban arterial four-leg intersections with stop control on the minor-road approaches
$N_{spf\ U/S\text{-}Bike,\ 3st}$	Estimate of bicycle predicted average crash frequency for urban/suburban arterial three-leg intersections with stop control on the minor-road approach
$N_{spf\ U/S\text{-}Bike,\ 4st}$	Estimate of bicycle predicted average crash frequency for urban/suburban arterial four-leg intersections with stop control on the minor-road approaches
$N_{spf\ U/S,\ 3st}$	Estimate of predicted average crash frequency for urban/suburban arterial three-leg intersections with stop control on the minor-road approach
$N_{spf\ U/S,\ 4st}$	Estimate of predicted average crash frequency for urban/suburban arterial four-leg intersections with stop control on the minor-road approaches
$AADT_{maj}$	AADT (vehicles per day) on the major road
$AADT_{min}$	AADT (vehicles per day) on the minor road

Table 35. Minimum and Maximum AADT for HSM Equations.

Intersection Characteristics	Major-Approach Minimum to Maximum AADT	Minor-Approach Minimum to Maximum AADT
Rural Two-Lane Highway with Three-Leg Stop-Controlled Intersections	0 to 19,500 veh/day	0 to 4,300 veh/day
Rural Two-Lane Highway with Four-Leg Stop-Controlled Intersections	0 to 14,700 veh/day	0 to 3,500 veh/day
Rural Four-Lane Highway with Three-Leg Stop-Controlled Intersections	0 to 78,300 veh/day	0 to 23,000 veh/day
Rural Four-Lane Highway with Four-Leg Stop-Controlled Intersections	0 to 78,300 veh/day	0 to 7,400 veh/day
Urban and Suburban Arterial Intersections with Three-Leg Stop-Controlled Intersections	0 to 45,700 veh/day	0 to 9,300 veh/day
Urban and Suburban Arterial Intersections with Four-Leg Stop-Controlled Intersections	0 to 46,800 veh/day	0 to 5,900 veh/day

Figure 16 shows an illustration of predicted crash frequency at stop-controlled rural and urban arterial intersections. The graph shows the predicted crashes for a range of major-road volumes when the minor-road ADT is 2,000 veh/day. The predicted number of crashes for intersections on rural four-lane highways and rural two-lane four-leg intersections is higher than the crash prediction for urban and suburban arterials. The crash prediction in this illustration for rural four-lane three-leg intersections is similar to urban and suburban three-leg intersections for a given major-road ADT.

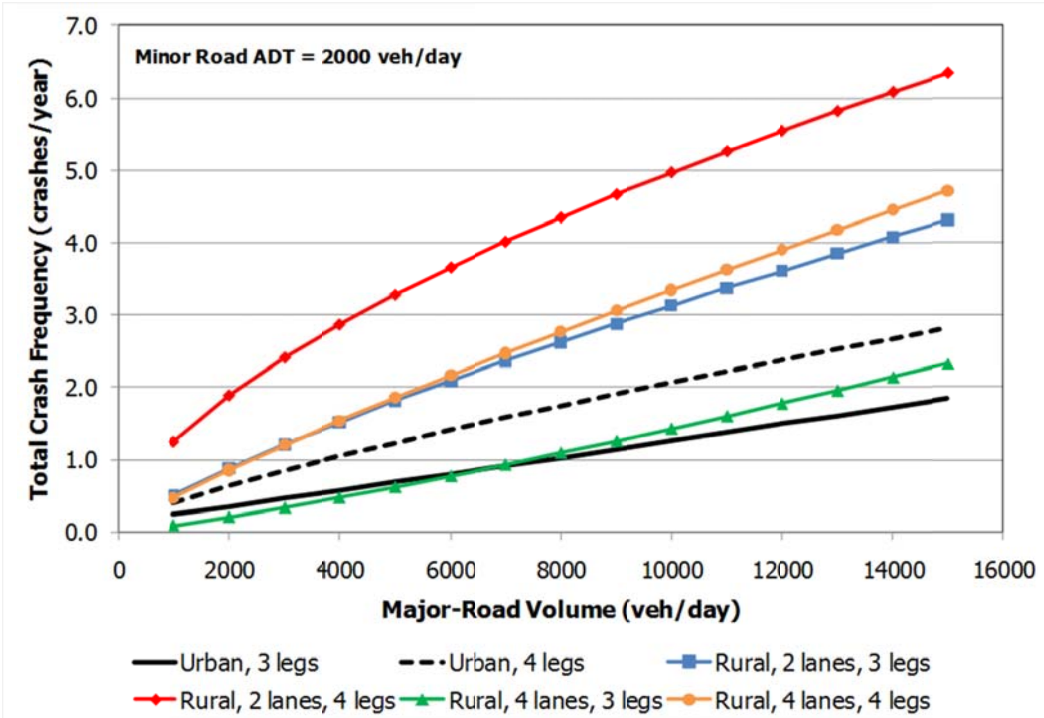


Figure 16. Illustration of Predicted Crash Frequency Using HSM Equations.

Crash Modification Factor

To obtain an estimate of the number of crashes at an AWSC intersection or a roundabout, a CMF is applied to the predicted crash frequency (total crashes) determined from the SPF. The CMFs considered for use in this analysis are listed in Table 36. The CMF for converting a minor-road stop control to AWSC available in the HSM includes a restriction that the volumes must meet the MUTCD warrants. A study by Persaud (*34*) found results that showed that the effectiveness of all-way stop conversion in urban areas is not limited to a certain range of entering volumes that follow MUTCD warrants. When analyzing total and right-angle crashes, it "can be just as effective for total entering volumes less than 6,000 per day as it is for higher volumes." The study also showed that for total and right-angle crashes, all-way stop conversion in urban areas is "no less effective when approach volumes are unbalanced as when they are equal on all approaches." Since this NCHRP study is to identify volumes for warranting a stop control and given the findings from Persaud (*34*), the researchers assumed that meeting the MUTCD warrants restriction is not critical.

An alternative is to use a CMF available on the Crash Modification Factors Clearinghouse (*29*). A study published in 2010 by Simpson and Hummer (*32*) using North Carolina data determined several CMFs. They determined a CMF of 0.393 for the conversion of TWSC (without flashing beacons) to AWSC (without flashing beacons) for intersections with four legs. The roadway characteristics present within the developed 0.393 CMF matches the characteristics being assumed for this study (e.g., urban and rural, volume range, crash type, and severity) except for the number of legs. The North Carolina data were based on four-leg intersections; therefore, an assumption was made that the 0.393 CMF would also be valid for three-leg intersections. The CMF for the Simpson and Hummer study was selected over the CMF in the HSM because the CMF in the HSM is only for injury crashes, and all severity crashes are used within the economic analysis.

For a rural setting, the assumed CMF was 0.52, which is the value available in the HSM and in the clearinghouse (see Table 36).

Table 36. CMFs Considered for This Analysis.

Treatment	Source	Setting	Crash Type (Severity)	CMF
Convert Minor-Road Stop Control to All-Way Stop Control	HSM Table 14-5 based on work by Lovell and Hauer (*33*)	Urban (MUTCD warrants are met)	All types (injury)	0.30
Convert Minor-Road Stop Control to All-Way Stop Control	HSM Table 14-5 based on work by Lovell and Hauer (*33*)	Rural (MUTCD warrants are met)	All types (all severities)	0.52
Convert Two-Way (without Flashing Beacons) to All-Way Stop Control (without Flashing Beacons)	CMF Clearinghouse (*29*) based on work by Simpson and Hummer (*32*)	All	All (all)	0.393
Convert Minor-Road Stop Control to All-Way Stop Control	CMF Clearinghouse (*29*) based on work by Harwood et al. (*43*)	Rural	All (all)	0.52
Convert Intersection with Minor-Road Stop Control to Modern Roundabout	HSM Table 14-4 based on work by Rodegerdts et al. (*80*)	Suburban (one or two lanes)	All types (all severities)	0.68
Convert Intersection with Minor-Road Stop Control to Modern Roundabout	HSM Table 14-4 based on work by Rodegerdts et al. (*80*)	Rural (one lane)	All types (all severities)	0.29

2013 Value of a Statistical Life by Crash Severity

In 2013, a memorandum was released by the U.S. Department of Transportation regarding the treatment of the economic value of a statistical life (VSL) in developmental analyses (*81*). The memorandum "identifies $9.1 million as the VSL to be used for Department of Transportation analyses assessing the benefits of preventing fatalities and using a base year of 2012." Researchers developed an estimate of the VSL in 2013 dollars by crash severity using the methodology documented in Council et al. (*82*) and subsequently implemented in the HSM. Table 37 shows the resulting comprehensive society costs by crash severity.

Table 37. 2013 Comprehensive Societal Cost Estimates (2013 Dollars).

Crash Severity	Comprehensive Societal Cost (Low)	Comprehensive Societal Cost (Mid-range)	Comprehensive Societal Cost (High)
Fatality (K)	$5,291,800	$9,260,700	$13,127,800
Disabling Injury (A)	$284,900	$498,500	$706,700
Evident Injury (B)	$104,200	$182,300	$258,500
Possible Injury (C)	$59,200	$103,600	$146,800
Property Damage Only (PDO)	$9,700	$17,100	$24,200
Note: Values are rounded after spreadsheet calculations.			

Typical Crash Cost for Unsignalized Intersections

The cost per crash at an unsignalized intersection requires knowing the distribution of crash severity for the different intersection configurations. Table 10-5 in the HSM (*24*), which is reproduced as Table 38 in this report, provides the default proportions for crash severity levels for three-leg and four-leg stop-controlled rural intersections.

Table 38. Default Distribution of Crash Severity Level at Rural Two-Lane Two-Way Intersections from the HSM (*24*).

Crash Severity Level	Percentage of Total Crashes		
	Three-Leg Stop-Controlled Intersections	Four-Leg Stop-Controlled Intersections	Four-Leg Signalized Intersections
Fatality	1.7	1.8	0.9
Incapacitating Injury	4.0	4.3	2.1
Nonincapacitating Injury	16.6	16.2	10.5
Possible Injury	19.2	20.8	20.5
Property Damage Only	58.5	56.9	66.0
Total	100.0	100.0	100.0

Also needed for the analysis is the conversion of the cost per person to a cost per crash; for that information, the number of individuals killed or injured in a crash must be known. A TxDOT study examined crashes at rural intersections. Data available for 595 rural intersections provided the distributions shown in Table 39. For the 1,198 crashes in the dataset, the number of injured persons per crash ranged from 1.22 to 2.30. The fatal crashes had 1.09 deaths per crash at the four-leg intersections and 1.46 deaths per crash at the three-leg intersections. Reflecting the multiple conflict points at an intersection, the average number of vehicles involved at a crash ranged from 1.48 to 2.36 veh/crash for rural intersections.

Table 39. Injuries or Deaths per Crash for Rural Two-Way or One-Way Stop Control Intersections.

Severity	Injuries or Deaths/Crash[a]		Number of Persons/Crash		Number of Vehicles/Crash	
	Three Legs	Four Legs	Three Legs	Four Legs	Three Legs	Four Legs
K	1.46 deaths/crash 0.31 A injuries/crash 1.15 B injuries/crash 0.00 C injuries/crash 0.31 no injuries/crash 0.15 unk. injuries/crash	1.09 deaths/crash 0.55 A injuries/crash 0.55 B injuries/crash 0.36 C injuries/crash 0.36 no injuries/crash 0.36 unk. injuries/crash	3.38	3.27	1.54	2.36
A	1.17 A injuries/crash 0.29 B injuries/crash 0.12 C injuries/crash 0.38 no injuries/crash 0.06 unk. injuries/crash	1.40 A injuries/crash 0.47 B injuries/crash 0.43 C injuries/crash 1.83 no injuries/crash 0.10 unk. injuries/crash	2.01	4.23	1.48	2.00
B	1.30 B injuries/crash 0.18 C injuries/crash 0.59 no injuries/crash 0.09 unk. injuries/crash	1.42 B injuries/crash 0.48 C injuries/crash 1.08 no injuries/crash 0.08 unk. injuries/crash	2.15	3.06	1.55	1.87
C	1.22 C injuries/crash 0.89 no injuries/crash 0.13 unk. injuries/crash	1.34 C injuries/crash 1.20 no injuries/crash 0.09 unk. injuries/crash	2.24	2.64	1.53	1.82
PDO	0.00 injuries/crash	0.00 injuries/crash	2.15	2.48	1.61	1.88

[a] Findings based on 1,189 crashes at 595 rural Texas intersections for the time period of 2003 to 2008. Unk. = unknown.

While information on crash distribution and number of persons per crash is available for rural intersections and portions are available for urban conditions (e.g., information is available for red-light running at signalized intersections [*83*]), the concern is that unsignalized intersections, especially intersections with lower speeds, would have a very different distribution.

For this analysis, researchers contacted representatives from cities of various sizes in different parts of the country to request data from their crash databases. Researchers initially requested data for the last available 7 years at all unsignalized intersections on streets with posted speed limits of 40 mph or less. Three cities were able to provide usable data within the time frame of the analysis: Bryan, Texas; Lawrence, Kansas; and Phoenix, Arizona. Only Phoenix was able to provide 7 years' worth of data, but the other cities were able to share at least 3 years. The resulting database contained information on 10,208 crashes from 6,374 unsignalized intersections; the number of crashes by city and year is shown in Table 40.

Table 40. Crashes in Database by City and Year.

City	2006	2007	2008	2009	2010	2011	2012	2013	Total
Bryan	N/A[a]	N/A	N/A	N/A	280	251	276	243	1,050
Lawrence	N/A	N/A	N/A	N/A	N/A	107	126	106	339
Phoenix	1,687	1,634	1,327	1,108	1,041	1,039	983	N/A	8,819
Total	**1,687**	**1,634**	**1,327**	**1,108**	**1,321**	**1,397**	**1,385**	**349**	**10,208**

[a] N/A = data not available for use in this study.

The cities submitted crash data for intersections with a variety of control types. Researchers assigned codes to the control types as follows:

- 0W (“zero-way” stop control, an uncontrolled intersection).
- 1W (one-way stop control, a three-leg intersection with stop control only on the minor approach).
- 2W (two-way stop control, a four-leg intersection with stop control only on the minor approaches).
- 3W (three-way stop control, a three-leg intersection with all-way stop control).
- 4W (four-way stop control, a four-leg intersection with all-way stop control).
- Y (yield control on the minor approaches).

Based on these control types, researchers determined the number of crashes per intersection per year in each of the three cities; that information is summarized in Table 41.

Researchers reviewed the crashes by severity and by type of intersection control to determine the distribution of injuries and deaths per crash in the database. In comparison to Table 38, the distribution of crash severity by intersection control is shown in Table 42. The proportion of injury and fatality crashes in the database is lower for all injury severities than the default distribution for rural intersections in the HSM. Correspondingly, the share of PDO (non-injury) crashes is higher; roughly three-fourths of the crashes in the database were non-injury crashes.

Crash data from the 6,374 intersections provided the distributions of injuries per crash shown in Table 43. For the 10,208 crashes, the number of injured persons per crash ranged between 1.00 and 1.48, not counting unknown injuries. The fatal crashes resulted in 1.14 deaths per crash at uncontrolled intersections and 1.00 death per crash at intersections with minor-road stop control. There were no fatal crashes at intersections with AWSC or yield control. In Table 44, the number of injuries per crash is summed to show the number of persons involved in each crash. Most of the crash categories on the 0W, 1W, and 2W intersections had an average number of persons per crash less than 2.0, suggesting a sizeable portion of single-vehicle crashes at those intersections.

Table 41. Crashes per Intersection for Cities in the Database.

City	Control	Number of Legs	Number of Intersections	Number of Crashes	Crashes per Intersection	Crashes per Intersection per Year
Bryan	**All**	**3 or 4**	**452**	**1,050**	**2.32**	**0.58**
	0W	3	41	50	1.22	0.30
	1W	3	192	379	1.97	0.49
	2W	4	174	536	3.08	0.77
	3W	3	4	7	1.75	0.44
	4W	4	15	45	3.00	0.75
	Y	3 or 4	26	33	1.27	0.32
Lawrence	**All**	**3 or 4**	**109**	**339**	**3.11**	**1.04**
	0W	--	0	0	--	--
	1W	--	0	0	--	--
	2W	4	89	269	3.02	1.01
	3W	3	3	8	2.67	0.89
	4W	4	17	62	3.65	1.22
	Y	--	0	0	--	--
Phoenix	**All**	**3 or 4**	**5,813**	**8,819**	**1.52**	**0.22**
	0W	3 or 4	4,237	5,691	1.34	0.19
	1W	3	552	926	1.68	0.24
	2W	4	1,004	2,131	2.12	0.30
	3W	3	8	13	1.63	0.23
	4W	4	12	58	4.83	0.69
	Y	--	0	0	--	--
All	**All**	**3 or 4**	**6,374**	**10,208**	**1.60**	**--**

Note: Yearly crashes per intersection values are based on 4 years of data in Bryan, 3 years in Lawrence, and 7 years in Phoenix.
-- = No data for the category

Table 42. Distribution of Crash Severity Level at Urban and Suburban Unsignalized Intersections in Database (Posted Speed Limit ≤ 40 mph).

Crash Severity Level	Percentage of Total Crashes							
	0W	**1W**	**2W**	**3W**	**4W**	**Y**	**All**	**Count**
Fatality	0.4	0.2	0.3	0.0	0.0	0.0	0.3	32
Incapacitating Injury	1.7	2.3	2.3	3.6	2.4	6.1	2.0	201
Nonincapacitating Injury	8.1	9.7	10.2	0.0	10.9	15.2	8.9	913
Possible Injury	9.4	13.0	15.7	14.3	13.9	6.1	11.8	1200
Property Damage Only	80.5	74.8	71.5	82.1	72.7	72.7	77.0	7862
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Count	5,741	1,305	2,936	28	165	33	10,208	10,208

Table 43. Injuries or Fatalities per Crash for Crashes in Database.

Severity[a]	Injuries or Fatalities/Crash					
	0W	**1W**	**2W**	**3W**	**4W**	**Y**
K	1.14 K 0.00 A 0.00 B 0.00 C 0.05 N 0.29 U	1.00 K 0.00 A 0.00 B 0.00 C 0.50 N 0.00 U	1.00 K 0.00 A 0.11 B 0.00 C 0.00 N 0.67 U	N/A[b]	N/A	N/A
A	1.00 A 0.00 B 0.00 C 0.01 N 0.26 U	1.00 A 0.10 B 0.20 C 0.27 N 0.17 U	1.07 A 0.01 B 0.03 C 0.25 N 0.40 U	1.00 A 0.00 B 0.00 C 0.00 N 0.00 U	1.00 A 0.00 B 0.00 C 0.75 N 0.25 U	1.00 A 0.00 B 0.00 C 1.00 N 0.00 U
B	1.01 B 0.00 C 0.01 N 0.31 U	1.13 B 0.05 C 0.69 N 0.22 U	1.22 B 0.05 C 0.61 N 0.28 U	N/A	1.17 B 0.06 C 0.72 N 0.22 U	1.20 B 0.40 C 1.00 N 0.00 U
C	1.27 C 0.01 N 0.00 U	1.32 C 0.66 N 0.01 U	1.43 C 0.59 N 0.02 U	1.25 C 0.25 N 0.00 U	1.48 C 0.17 N 0.09 U	1.00 C 2.00 N 0.00 U
PDO	0.00	0.00	0.00	0.00	0.00	0.00

[a] Crash Severity:

- K = fatal
- A = incapacitating injury
- B = nonincapacitating injury
- C = possible injury
- N = no injury
- U = unknown (not reported)

[b] N/A = not applicable; no crashes in this category.

Table 44. Number of Persons per Crash for Crashes in Database.

Severity	Number of Persons/Crash					
	0W	**1W**	**2W**	**3W**	**4W**	**Y**
K	1.48	1.50	1.78	N/A[a]	N/A	N/A
A	1.27	1.73	1.78	1.00	2.00	2.00
B	1.34	2.09	2.16	N/A	2.17	2.60
C	1.28	1.99	2.03	1.50	2.74	3.00
PDO	1.02	1.44	1.45	2.04	2.09	2.83

[a] N/A = not applicable; no crashes in this category.

Researchers calculated typical crash cost using the ranges for comprehensive societal cost for all of the urban stop-control scenarios (i.e., 1W, 2W, 3W, and 4W) and rural three-leg and four-leg intersections. As an example of the calculation process, Table 45 shows the calculations to determine the typical crash cost using the ranges for comprehensive societal cost for four-leg urban intersections with minor-road stop control (i.e., 2W intersections). A summary of crash costs for all scenarios is shown in Table 46.

Table 45. Crash Cost Calculations for Urban 2W Intersections.

Range (Cost)	Crash Severity	Injury Severity	Cost[a, b]	Convert Cost/Person to Cost/Crash[c]	Cost per Crash	Percent of Total Crashes[d]	Extension
Mid-range ($100,000)	Fatality	K	$9,260,700	1.00	$9,260,700	0.31	$28,450
		A	$498,500	0.00	$0		
		B	$182,300	0.11	$20,956		
		C	$103,600	0.00	$0		
	A	A	$498,500	1.07	$535,701	2.28	$12,357
		B	$182,300	0.01	$2,721		
		C	$103,600	0.03	$3,093		
	B	B	$182,300	1.22	$223,150	10.18	$23,255
		C	$103,600	0.05	$5,197		
	C	C	$103,600	1.43	$147,872	15.70	$23,218
	PDO	PDO	$17,100	1.00[e]	$17,100	71.53	$12,231
					Total (cost/crash)	**100.00**	**$99,511**
Low ($57,000)	Fatality	K	$5,291,800	1.00	$5,291,800	0.31	$16,257
		A	$284,900	0.00	$0		
		B	$104,200	0.11	$11,578		
		C	$59,200	0.00	$0		
	A	A	$284,900	1.07	$306,161	2.28	$7,062
		B	$104,200	0.01	$1,555		
		C	$59,200	0.03	$1,767		
	B	B	$104,200	1.22	$127,549	10.18	$13,292
		C	$59,200	0.05	$2,970		
	C	C	$59,200	1.43	$84,498	15.70	$13,268
	PDO	PDO	$9,700	1.00[e]	$9,700	71.53	$6,938
					Total (cost/crash)	**100.00**	**$56,817**
High ($141,000)	Fatality	K	$13,127,800	1.00	$13,127,800	0.31	$40,330
		A	$706,700	0.00	$0		
		B	$258,500	0.11	$28,722		
		C	$146,800	0.00	$0		
	A	A	$706,700	1.07	$759,439	2.28	$17,519
		B	$258,500	0.01	$3,858		
		C	$146,800	0.03	$4,382		
	B	B	$258,500	1.22	$316,425	10.18	$32,974
		C	$146,800	0.05	$7,365		
	C	C	$146,800	1.43	$209,532	15.70	$32,900
	PDO	PDO	$24,200	1.00[e]	$24,200	71.53	$17,309
					Total (cost/crash)	**100.00**	**$141,032**

[a] Comprehensive societal cost for fatal crash is from "Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses," Memorandum to Secretarial Officers, Modal Administrators, available at http://www.dot.gov/sites/dot.gov/files/docs/VSL Guidance_2013.pdf.
[b] Comprehensive societal cost for crash severity A, B, C, or PDO is based on distribution determined using HSM data, with costs adjusted to 2013 dollars.
[c] Factors from Table 43.
[d] From Table 42.
[e] No factor is needed. Assumption is that cost reflects cost per crash.

Table 46. Calculated Crash Costs for Intersection Scenarios.

Cost Range	Crash Severity	Urban 1W	Urban 2W	Urban 3W	Urban 4W	Rural Three-Leg	Rural Four-Leg
Mid-range	Fatality	$14,193	$28,450	$0	$0	$236,042	$189,106
	A	$12,355	$12,357	$17,804	$12,085	$25,942	$35,610
	B	$20,452	$23,255	$0	$23,830	$42,436	$49,992
	C	$17,783	$23,218	$18,500	$21,348	$24,267	$28,875
	PDO	$12,789	$12,231	$14,046	$12,436	$10,004	$9,730
	Total	**$77,572**	**$99,511**	**$50,350**	**$69,699**	**$338,690**	**$313,313**
Low	Fatality	$8,110	$16,257	$0	$0	$134,881	$108,061
	A	$7,061	$7,062	$10,175	$6,907	$14,826	$20,351
	B	$11,690	$13,292	$0	$13,621	$24,255	$28,574
	C	$10,162	$13,268	$10,571	$12,199	$13,867	$16,500
	PDO	$7,255	$6,938	$7,968	$7,055	$5,675	$5,519
	Total	**$44,278**	**$56,817**	**$28,714**	**$39,781**	**$193,504**	**$179,005**
High	Fatality	$20,119	$40,330	$0	$0	$334,610	$268,074
	A	$17,515	$17,519	$25,239	$17,132	$36,777	$50,482
	B	$29,001	$32,974	$0	$33,790	$60,171	$70,881
	C	$25,198	$32,900	$26,214	$30,250	$34,386	$40,916
	PDO	$18,099	$17,309	$19,879	$17,600	$14,157	$13,770
	Total	**$109,932**	**$141,032**	**$71,332**	**$98,772**	**$480,101**	**$444,123**

Note: Crash costs for urban 1W and 2W were used as the base condition in the economic analysis for urban scenarios; rural three-leg and four-leg values were applied to rural scenarios.

Vehicle Operating Costs

Vehicle operating costs reflect the expenses for users of the network for the operation of their vehicles. Operating costs are affected by changes in vehicle miles traveled (VMT) and user delay. The costs for VMT are calculated for the following components per HERS-ST (*75*): fuel, oil, maintenance, tires, and depreciation.

Changes in operating speed and delay also affect operating costs by changing fuel consumption efficiency. Changes to an intersection's operations impact fuel consumption based on changes in the average speed along with the number of times users must start and stop their vehicle. For example, two intersections with the same average speed but with differing numbers of starts and stops will result in different fuel consumption and different operating costs.

As noted in the NCHRP 3-110 interim report (*74*), different intersection designs are not likely to cause differences in operating costs that measure the marginal cost of driving additional distance. Users are likely to travel the same distance regardless of intersection design. What is likely to vary among changes in intersection operations is the fuel consumed as a result of user delay.

The simulation results can also be used to estimate fuel consumption. Delay is converted to minutes of delay per year and then multiplied by the number of gallons per minute rate available from the AASHTO *Red Book* and the assumed cost for fuel. Table 47 shows the amount of fuel consumption per minute as a result of delays. For cars, the gallon-per-minute rate was assumed to be an average of the small and big vehicles. The three-axle single-unit vehicle rate was assumed for trucks. Low-speed condition was assumed to be represented by averaging the 30 to 40 mph data, while high-speed was represented by averaging the 45 to 55 mph data.

The U.S. Energy Information Administration (EIA) projection, as of May 6, 2014, for the average retail price of regular-grade gasoline for May to December 2014 is $3.49 per gallon (*84*). EIA's projection, as of May 6, 2014, for the average retail price of on-highway diesel fuel for May 2014 to December 2014 is $3.83 per gallon (*85*). These values were assumed to represent 2013 values of fuel.

Table 47. Fuel Consumption (Gallons) per Minute of Delay by Vehicle Type (Table 5-6 in *73*).

Free-Flow Speed	Small Car	Big Car	SUV	2-Axle Single-Unit	3-Axle Single-Unit	Combo
20	0.011	0.022	0.023	0.074	0.102	0.198
25	0.013	0.026	0.027	0.097	0.133	0.242
30	0.015	0.030	0.035	0.122	0.167	0.284
35	0.018	0.034	0.037	0.149	0.203	0.327
40	0.021	0.038	0.043	0.177	0.241	0.369
45	0.025	0.043	0.049	0.206	0.280	0.411
50	0.028	0.048	0.057	0.235	0.321	0.453
55	0.035	0.054	0.065	0.266	0.362	0.495
60	0.037	0.060	0.073	0.297	0.404	0.537
65	0.042	0.066	0.083	0.328	0.447	0.578
70	0.047	0.073	0.094	0.360	0.490	0.620
75	0.053	0.080	0.105	0.392	0.534	0.661
Note: Values determined by ECONorthwest calculations based on HERS-ST model equations.						

From *User and Non-User Benefit Analysis for Highways*, 2010, by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by Permission.

Roundabout Construction Costs

The average construction cost of roundabouts is estimated at approximately $250,000 (*86*) as reported on a 2010 FHWA website. Roundabouts discussed in an FHWA report (*86*) ranged in cost from $194,000 to just under $500,000, depending on their size and needed right-of-way acquisitions. Using a 20-year service life and a 4 percent return, the $250,000 construction cost can be converted to an annual cost of $18,395, while the $500,000 construction cost would be represented by a $36,790 annual cost. The $18,395 was assumed to represent rural conditions, while the $36,790 annual cost was assumed to represent urban conditions in consideration of the potentially higher right-of-way costs.

Total Costs

The total cost for a change in intersection traffic control would represent the summation of the crash, user delay, and vehicle operating costs. Table 48 shows the calculated cost when TWSC is converted for a given set of volumes when three or four legs and 40 mph (urban) or 45 mph (rural) speeds are present. When the total cost for these combinations is positive, it indicates that the after treatment would be cost-effective for these conditions. For the volumes represented in Table 48, TWSC is more cost-effective as compared to AWSC except for rural (or higher-speed) scenarios. The higher crash cost for that situation justifies the higher level of control. The roundabout geometric form is more cost-effective compared to TWSC.

Table 48. Summary of Costs for an Example Where the Peak Hour Is 300 veh/hr/Approach on the Major Road and 200 veh/hr/Approach on the Minor Road.

Lanes on Major Approach	Leg	Change	Rural or Urban	Medium Crash Cost ($/yr)	Car, Truck, and Pedestrian Delay Costs ($/yr)	Car and Truck Operating Costs ($/yr)	Initial Year of Construction Cost for Roundabouts ($/yr)	Total Cost ($/Year)
2	3	TW3–AW3	Urban	$33,898	$(185,877)	$(57,513)	$ -	$(209,493)
2	4	TW4–AW4	Urban	$74,918	$(186,378)	$(58,284)	$ -	$(169,744)
2	4	TW4–RO4	Urban	$34,248	$156,702	$41,018	$(36,790)	$195,178
2	3	TW3–AW3	Rural	$113,713	$(189,284)	$(87,507)	$ -	$(163,078)
2	4	TW4–AW4	Rural	$364,723	$(189,841)	$(88,759)	$ -	$86,123
2	4	TW4–RO4	Rural	$369,933	$163,754	$61,264	$(18,395)	$576,556
1	3	TW3–AW3	Urban	$33,898	$(270,394)	$(83,552)	$ -	$(320,048)
1	4	TW4–AW4	Urban	$74,918	$(209,609)	$(65,695)	$ -	$(200,386)
1	4	TW4–RO4	Urban	$34,248	$75,222	$20,716	$(36,790)	$93,396
1	3	TW3–AW3	Rural	$393,828	$(273,076)	$(127,202)	$ -	$(6,451)
1	4	TW4–AW4	Rural	$714,467	$(212,574)	$(100,101)	$ -	$401,792
1	4	TW4–RO4	Rural	$724,674	$82,274	$30,958	$(18,395)	$819,511

Input variables: major volume = 300 veh/hr/approach, minor volume = 200 veh/hr/approach, pedestrian volume = 10 ped/hr/approach (urban) or 0 ped/hr/approach (rural), two lanes on minor (one-lane approach).

TREATMENT RECOMMENDATIONS BASED ON COST

Four-Lane Major Road

Based on the results of the simulations and calculations described in the previous section, researchers identified the recommended traffic control for each combination of variables based on total cost. When the total cost of the change was positive, the after condition (e.g., all-way stop) was recommended. If total cost was negative, the before condition (i.e., two-way stop) would be recommended. Graphs were generated to illustrate when AWSC or TWSC would be justified for a given major and minor volume. The graphs are shown for the peak hour, which was determined as 7.8 percent of the daily volume used in the cost calculations. The following figures were generated for a four-lane major road:

- Figure 17 shows the graph for three-leg urban intersections.
- Figure 18 shows the graph for four-leg urban intersections.
- Figure 19 shows the graph for three-leg rural intersections.
- Figure 20 shows the graph for four-leg rural intersections.

Within these graphs, symbols are used to indicate which type of stop control is more economical:

- TW3, shown with a blue diamond, identifies conditions where TWSC is more economical for three-legged intersections.
- AW3, shown with a red square, identifies conditions where AWSC is more economical for three-legged intersections.
- TW4, shown with a blue diamond, identifies conditions where TWSC is more economical for four-legged intersections.
- AW4, shown with a red square, identifies conditions where AWSC is more economical for four-legged intersections.

To provide a comparison between the findings from the economic analysis and the MUTCD peak-hour signal warrant, the signal warrant criteria were added to each graph (shown with a green solid line).

In all urban cases with a four-lane road when using total cost (crash, user, and vehicle operations), the intersection warrants a signal before an all-way stop.

The economic analysis approach resulted in roundabouts being a more cost-effective geometry than TWSC for all volume combinations studied when the assumed right-of-way and construction costs are less than $500,000 for the roundabout.

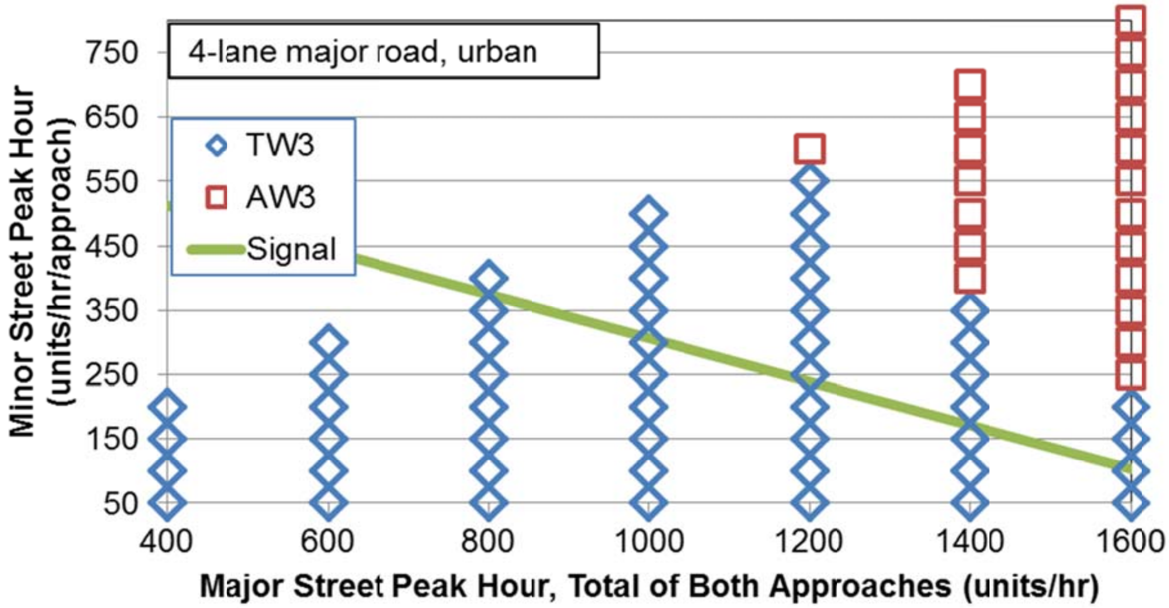


Figure 17. Recommended Unsignalized Intersection Traffic Control Based on Costs for a Three-Leg Urban Intersection on a Four-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

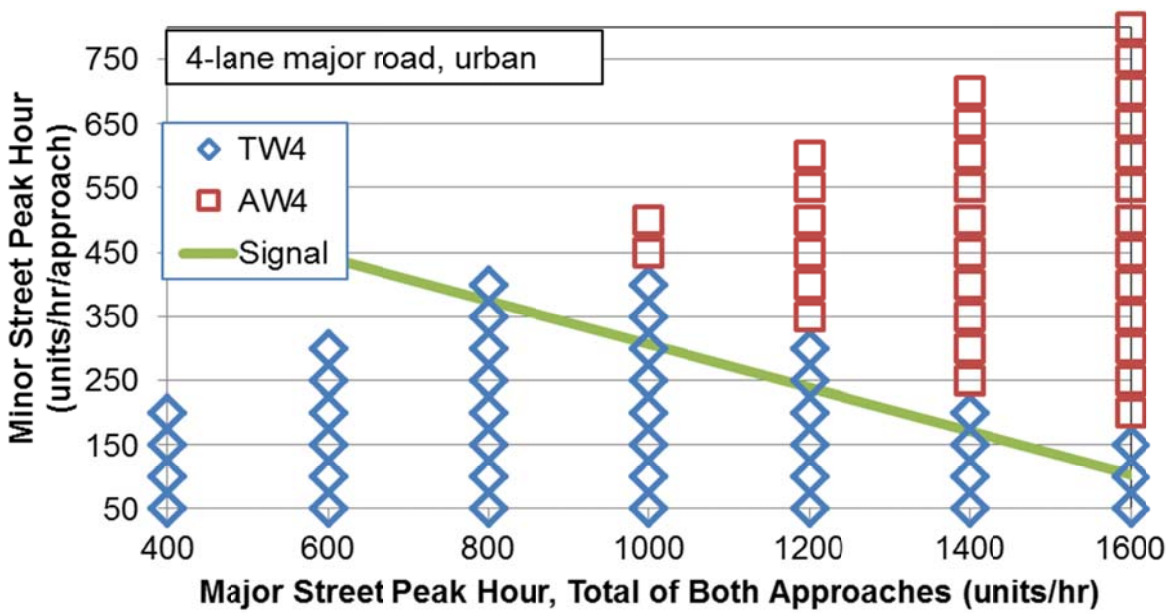


Figure 18. Recommended Unsignalized Intersection Traffic Control Based on Costs for a Four-Leg Urban Intersection on a Four-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

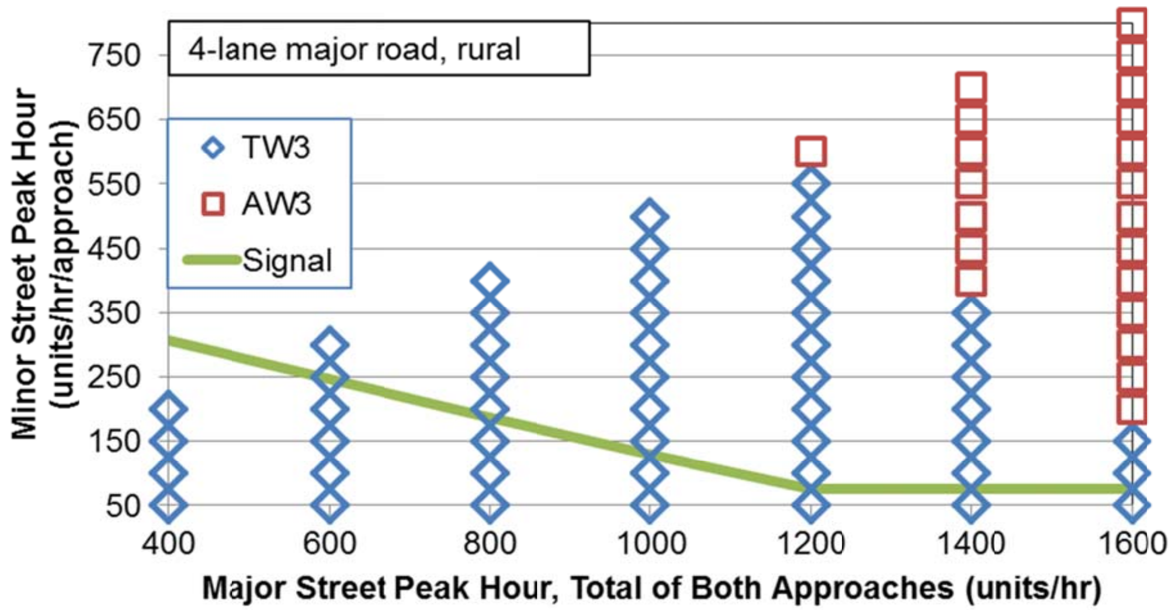


Figure 19. Recommended Unsignalized Intersection Traffic Control Based on Costs for a Three-Leg Rural Intersection on a Four-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

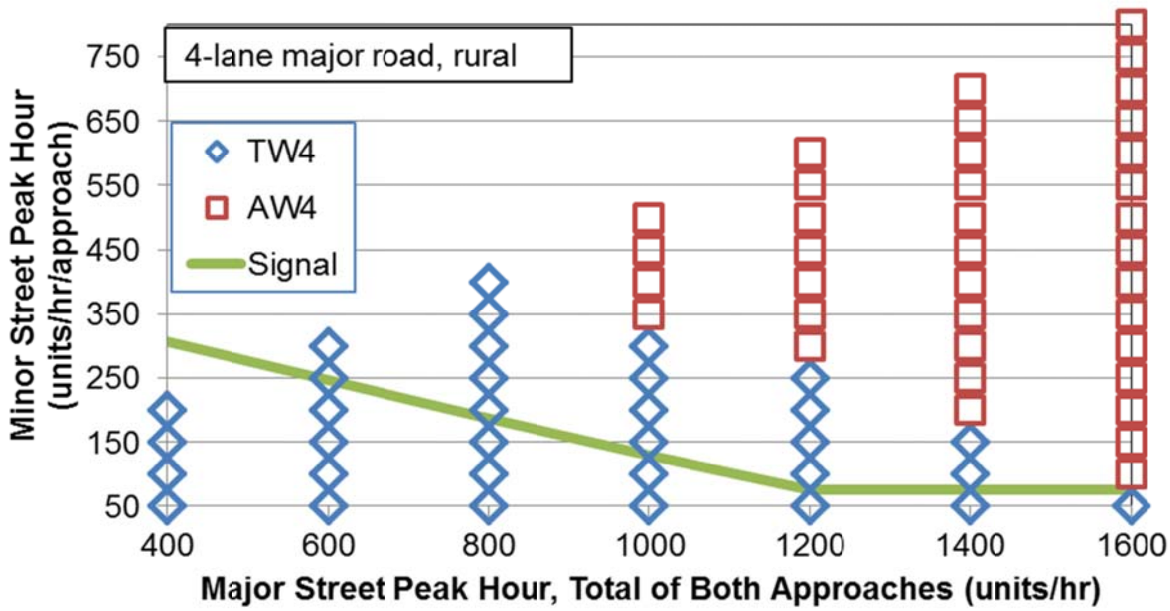


Figure 20. Recommended Unsignalized Intersection Traffic Control Based on Costs for a Four-Leg Rural Intersection on a Four-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

Two-Lane Major Road

The results of the simulations and calculations described in the previous section were also used to generate recommendations for two-lane major roads. Graphs were generated to illustrate when AWSC or TWSC would be justified for a given major and minor volume. The graphs are shown for the peak hour, which was determined as 7.8 percent of the daily volume used in the cost calculations. The following figures were generated for a two-lane major road:

- Figure 21 shows the graph for three-leg urban intersections.
- Figure 22 shows the graph for four-leg urban intersections.
- Figure 23 shows the graph for three-leg rural intersections.
- Figure 24 shows the graph for four-leg rural intersections.

Within these graphs, symbols are used to indicate which type of stop control is more economical:

- TW3, shown with a blue diamond, identifies conditions where TWSC is more economical for three-legged intersections.
- AW3, shown with a red square, identifies conditions where AWSC is more economical for three-legged intersections.
- TW4, shown with a blue diamond, identifies conditions where TWSC is more economical for four-legged intersections.
- AW4, shown with a red square, identifies conditions where AWSC is more economical for four-legged intersections.

When the major road has two lanes, an all-way stop is not justified in the urban environment for both three-leg and four-leg intersections. When fewer major road lanes are present to accommodate the volume, much higher vehicle (car and truck) delay costs are present for the AWSC scenario.

The larger number of crashes associated with rural two-lane highways along with higher crash costs for that environment due to higher speeds, resulting in more several crashes, presents a very different recommendation. All-way stops are recommended at four-leg intersections (see Figure 24), except for lower minor-road approach volumes.

Similar to the finding from four-lane roads, the economic analysis approach resulted in roundabouts being a more cost-effective geometry than TWSC for all volume combinations studied when the assumed right-of-way and construction costs are less than $500,000 for the roundabout.

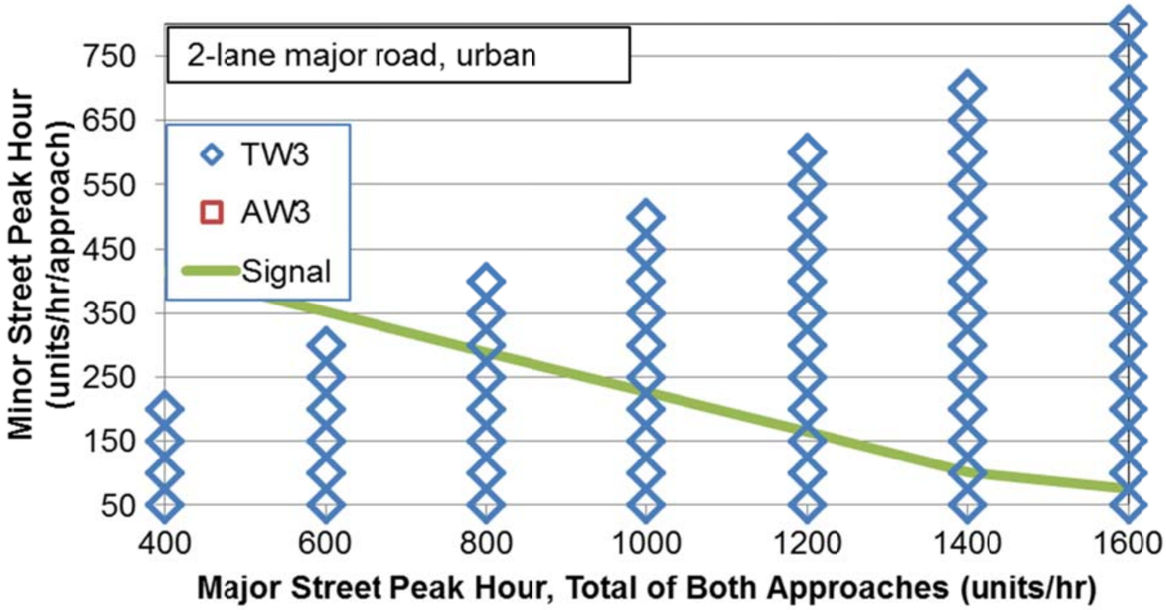


Figure 21. Recommended Unsignalized Intersection Traffic Control Based on Costs for a Three-Leg Urban Intersection on a Two-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

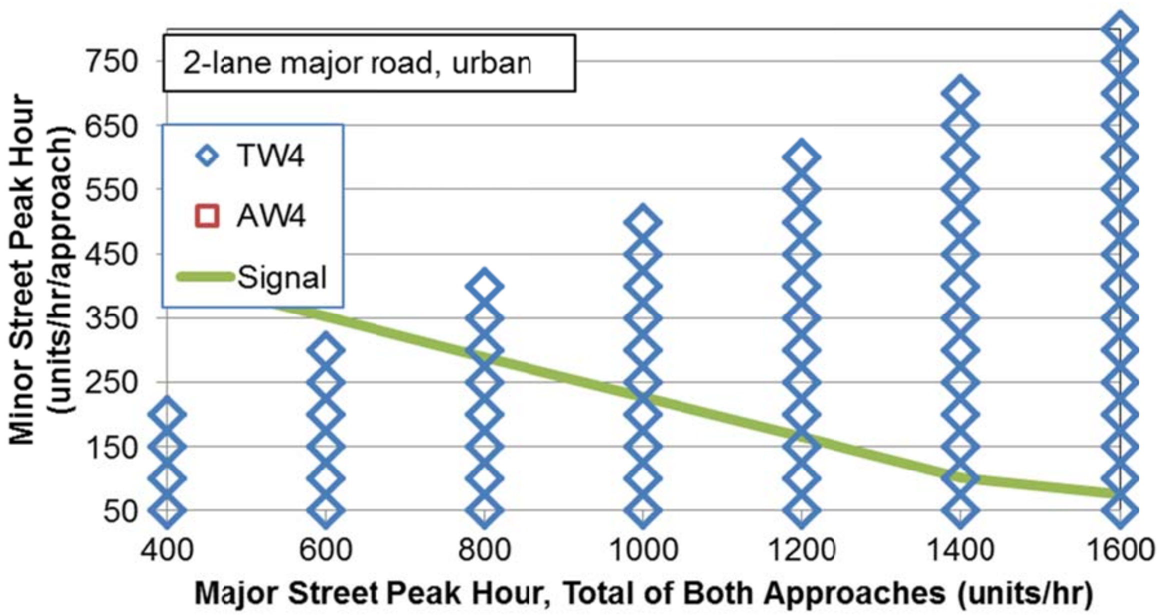


Figure 22. Recommended Unsignalized Intersection Traffic Control Based on Costs for Four-Leg Urban Intersection on a Two-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

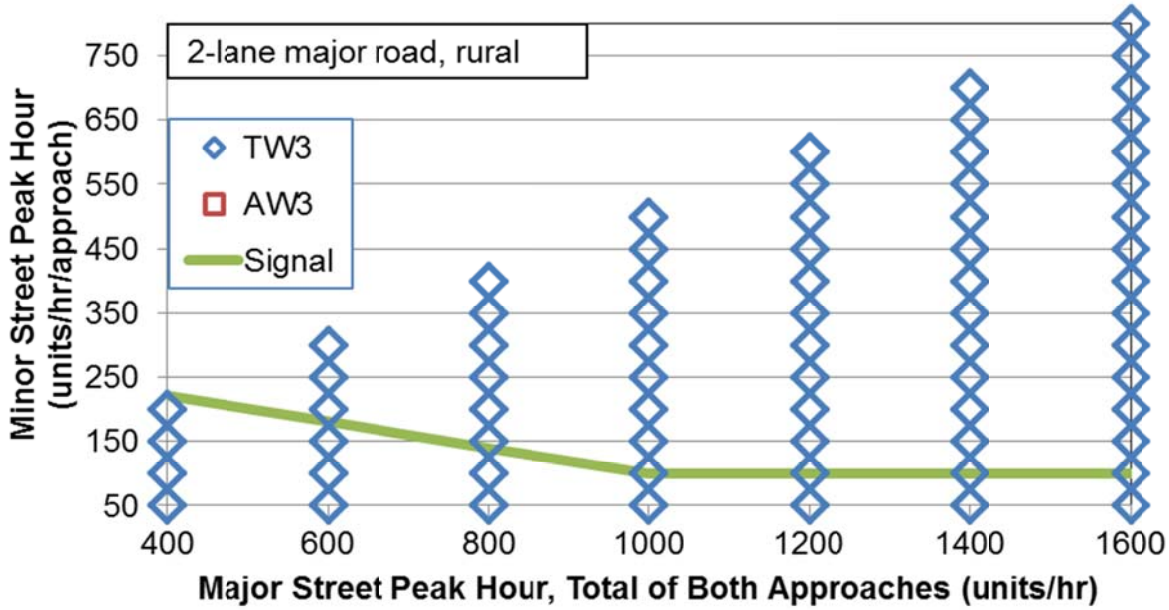


Figure 23. Recommended Unsignalized Intersection Traffic Control Based on Costs for a Three-Leg Rural Intersection on a Two-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

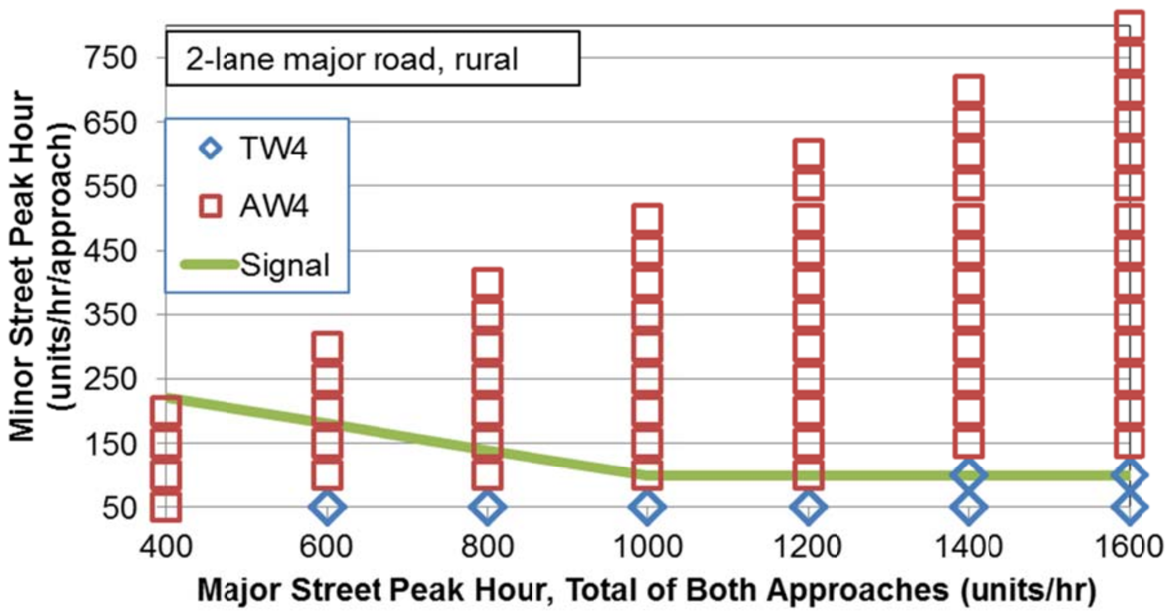


Figure 24. Recommended Unsignalized Intersection Traffic Control Based on Costs for a Four-Leg Rural Intersection on a Two-Lane Major Road; Also Shown Is the 2009 Peak-Hour Signal Warrant for When There Are Two or More Lanes on the Major Road and One Lane on the Minor Road.

Discussion Regarding Use of Speed and Number of Legs

As part of the research, the effects of speed were to be considered within the warrant development. Crash prediction equations are not sensitive to speed; however, there are different equations for the rural and urban conditions. Therefore, development environment (i.e., rural or urban) was used as a surrogate for speed. In addition, the cost of a crash is higher in rural areas due to increased severity associated with the higher speeds. Therefore, crash costs are influential in generating different results for urban (low-speed) and rural (high-speed) conditions.

Initial simulation runs did include a range of major and minor speeds; however, as was illustrated in Table 27, the variability in delay for the range of speeds and volumes being considered was minimal. The influence of speed was included in the development of vehicle operating costs because vehicles consume more fuel at higher speeds.

Previous MUTCD warrants were not sensitive to the number of legs at the intersection. Primarily due to different crash predictions for three- and four-leg intersections, the warrant criteria should also reflect the number of legs present. The economic analysis considered the number of legs at the intersection.

CHAPTER 7: OVERVIEW, CONCLUSIONS, AND RECOMMENDATIONS

OVERVIEW

As stated in the introduction of this report, the intent of this research study was to develop criteria and supporting material for the selection of appropriate right-of-way control at an unsignalized intersection, and for those criteria to be in a format that can be integrated into a future revision of the MUTCD. Within the context of this research, an unsignalized intersection is one where one of the following methods of right-of-way control is used on one or more of the approaches:

- No control: Right-of-way is based on the rules of the road where the first to arrive at the intersection has the right of way, and if two vehicles arrive at the same time, a driver yields to the vehicle to the right.
- Yield control: YIELD sign(s) are installed on the minor approach or approaches. At a roundabout intersection, YIELD signs are installed on all approaches.
- Minor-road stop control: STOP sign(s) are installed on one approach for a three-leg intersection or on two approaches for a four-leg intersection. The STOP sign is normally installed on the minor road but in some cases may be installed on the major road with no control on the minor road.
- All-way stop control: STOP signs are installed on all approaches to the intersection.

The next level of right-of-way control for an intersection is a traffic control signal, criteria for which were not included in the scope of this research.

This project was conducted within seven tasks that included a review of literature and existing policies and guidelines, identification of intersection and traffic characteristics, a critical evaluation of relevant sections of the 2009 MUTCD, an economic analysis to evaluate control alternatives, development of recommendations for revisions to the MUTCD, and the completion of this report.

Review of Policies and Guidelines

Researchers reviewed the current MUTCD and the supporting material for the guidance found therein. The research team also conducted searches of guidelines and manuals from all 50 states (available online) to review their current policies. In addition, researchers asked practitioners for information on novel approaches they were considering for selecting traffic control at unsignalized intersections. Several states provide guidance in addition to that found in the MUTCD, but in many jurisdictions, the MUTCD (or a particular state's equivalent) is the prevailing source for guidance. Much of the existing text in the MUTCD has remained largely intact for several decades.

Literature Review

The research team had a three-pronged approach to reviewing the relevant literature: key reference documents, previous literature that discussed methods for selecting traffic control at unsignalized intersections, and previous literature that discussed methods for selecting traffic control at unsignalized pedestrian crossings. Key reference documents included the *Highway Capacity Manual* (*23*), *Highway Safety Manual* (*24*), and ITE *Manual of Traffic Engineering Studies* (*25*). Literature that described the selection of traffic control included processes that considered delay, traffic volumes, number of lanes, crashes, and other variables. Some processes resulted in regression equations or charts to calculate the variables of interest, while others were based on a point system that described a recommended traffic control for a certain point score. Key intersection and traffic characteristics included in these processes are summarized in Chapter 4.

Critical Review of MUTCD

Researchers reviewed key sections of MUTCD Chapter 2B to determine which sections could have the most potential benefit from new research to support revised guidance. Numeric and non-numeric criteria for traffic control in Sections 2B.04, 2B.06, and 2B.07 were reviewed, and comments for potential revisions were made as provided in Chapter 5.

Based on the activities in the initial phase of the project, the research team, with the guidance of the project panel, conducted a study in the second phase of the project that focused on the following items:

- Set a higher priority on investigating when to go from TWSC to AWSC rather than when to go from no control to yield or TWSC.
- Develop criteria that reflect urban and rural or speed conditions.
- Develop criteria that are sensitive to the number of legs at the intersection.
- Consider roundabouts as a geometric design alternative within the evaluation.
- Consider a variety of major- and minor-road volume splits and not just when the split is "approximately equal."
- Consider the existing and ongoing revisions to relevant sections of the MUTCD, such as the changes suggested for the reorganization.

Economic Analysis Procedure

The research team used a procedure for comparing traffic control alternatives based on the relative economic costs and benefits of those alternatives for particular intersection types (three-leg or four-leg), environments (urban or rural), and volumes (varying levels of major- and minor-road volumes). Based on information from a variety of relevant sources, the research team selected user delay, crashes, vehicle operating, and construction as the four costs for consideration in the project. Researchers used microsimulation to measure the effects of delay. A multi-step process for calculating crash costs was adapted from the HSM. Vehicle operating costs were estimated using information from federal sources such as the Environmental Protection Agency and the Energy Information Administration. Roundabout construction costs were estimated from FHWA information.

Potential Criteria

Table 49 summarizes potential criteria for AWSC as identified from the literature review, from the review of policies and guidelines, or as part of the economic analysis. Table 50 summarizes criteria identified from the reviews for no control, yield control, or minor-road stop control.

Table 49. Potential Criteria for AWSC.

<table>
<tr><th>Criteria</th><th>All-Way Stop</th></tr>
<tr><td>Number of Crashes Susceptible to Correction by Intersection Control (e.g., Right-Turn, Left-Turn, or Right-Angle Crashes)</td><td>• 5 or more within 12 months (1)
• 4-leg: 5 or more within 12 months, 6 or more within 36 months, proposed crash warrant criteria for signals (49)
• 3-leg: 4 or more within 12 months, 5 or more within 36 months, proposed crash warrant criteria for signals (49)
• 5 or more preventable crashes within 12 months (21)</td></tr>
<tr><td>Peak-Hour Entering Volume</td><td>• 500 veh/hr major approach and 210 veh/hr minor approach (and 300 veh/hr major approach and 300 veh/hr minor approach) based on average delay or average queue length (54)
• Examples of volumes based on control delay determined using Highway Capacity Software with consideration of percent left turns (56) are shown below:
<table>
<tr><th>Major</th><th>% Left</th><th>Minor</th><th>% Left</th><th>Minor</th><th>% Left</th><th>Minor</th><th>% Left</th><th>Minor</th></tr>
<tr><td>200</td><td>5</td><td>50</td><td>10</td><td>50</td><td>15</td><td>50</td><td>20</td><td>50</td></tr>
<tr><td>300</td><td>5</td><td>140</td><td>10</td><td>100</td><td>15</td><td>90</td><td>20</td><td>80</td></tr>
<tr><td>400</td><td>5</td><td>NR</td><td>10</td><td>NR</td><td>15</td><td>105</td><td>20</td><td>90</td></tr>
</table>
Major and minor are veh/hr/approach. NR = not recommended.
• 500 units/hr/major approach and 300 units/hr/minor approach, values from simulation conducted as part of this research project associated with more than 35 sec/minor-road vehicle</td></tr>
<tr><td>Entering Volume per Day</td><td>• When combined ADT of 7,500 to 50,000 exist, then conduct all-way stop evaluation (16)
• Highly desirable for intersection roadways to have closely balanced ADTs, e.g., the volume of at least one minor approach is not less than 70% of higher volume of major approach (18)
• 4,000 vpd, major 65% of total (21)
• 17,000 (3-leg) or 21,000 (4-leg) vpd (values calculated using the peak-hour simulation numbers associated with more than 35 sec/minor-road delay and adjusting to a daily value)</td></tr>
<tr><td>8 hr</td><td>• 300 veh/hr entering from major and 200 units (veh and ped) from minor (1)
• 210 veh/hr entering from major and 140 units (veh and ped) from minor (i.e., minimum vehicular volume warrant is 70%) when 85th percentile major street exceeds 40 mph (1)
• 430 units/hr/major approach and 260 units/hr/minor approach (values were calculated using the peak-hour simulation numbers associated with more than 35 sec/minor-road delay and the top 8 hourly factors used in the economic analysis and then averaged for the 8 hr)</td></tr>
<tr><td>Delay (Minimum)</td><td>• 30 sec/minor-street veh (1)
• 35 sec/minor-street veh, suggested based on HCM (23) Exhibit 19-1, lowest control delay (sec/veh) for LOS E (when v/c <=1.0)</td></tr>
<tr><td>Other</td><td>• “All-way stop conversion in urban areas is not limited to a certain range of entering volumes that follow current MUTCD warrants and is no less effective when approach volumes are unbalanced as when they are equal on all approaches.” (34)
• Need to control left-turn conflicts, vehicle/ pedestrian conflicts, or multi-way stop control would improve traffic operations (1)
• Sight distance
• Engineering study</td></tr>
</table>

Table 50. Potential Criteria for No Control, Yield Control, or Minor-Road Stop Control.

Criteria	No Control	Yield Control	Minor-Road Stop
Number of Crashes Susceptible to Correction by Intersection Control	• Box (*52*) recommended fewer than 2 crashes in 1 year or 4 crashes in 3 years • Maryland MUTCD Table 2B-1a (*10*) provides guidelines for conversion from stop to yield control and recommends 2 or less reported crashes in 1 year or 4 or less in 3 years	• Box (*52*) recommended fewer than 2 crashes in 1 year or 4 crashes in 3 years • Maryland MUTCD Table 2B-1a (*10*) provides guidelines for conversion from stop to yield control and recommends 2 or less reported crashes in 1 year or 4 or less in 3 years • Fewer than 3 crashes in 2 years from NCHRP Report 320 (*36*) • 3 or more preventable crashes within 12 months (*21*)	• 3 or more within 12 months or 5 or more within 2 years (*1*) • 4-leg: 3 or more within 12 months, 6 or more within 36 months, suggested with consideration of the proposed crash warrant criteria for signals (*49*) • 3-leg: 3 or more within 12 months, 5 or more within 36 months, suggested with consideration of the proposed crash warrant criteria for signals (*49*) • 3 or more preventable crashes within 12 months (*21*)
Peak-Hour Entering Volume	• Maximum 80 units/hr (rounded calculation from the 1,000 units/day value using 7.8 percent, which is the peak-hour factor used in the economic analysis) • Box (*52*) recommended less than 100 total entering volume during peak hour	• Maximum 140 units/hr (rounded calculation from the 1,800 units/day value using 7.8 percent, which is the peak-hour factor used in the economic analysis)	• No volume criteria identified
Entering Volume per Day	• 1983 study in rural Michigan (*41*) found no statistical difference for stop-controlled and no-control intersections with major street volumes less than 1,000 vpd • 1,500 vpd from Nitzel et al. (*51*)	• Maximum 1,800 units/day from NCHRP Report 320 (*36*) • Maryland MUTCD Table 2B-1a (*10*) provides guidelines for conversion from stop to yield control: high priority: major 2,000 vpd and minor less than 200 vpd or medium priority: major 2,000–3,000 vpd and minor 200–500 vpd • 1,500 to 3,000 vpd from Nitzel et al. (*51*) • 1,000 vpd (*21*)	• Exceeds 6,000 veh/day (*1*) • 2,000 vpd (*21*)
8 hr	• No volume criteria identified	• No volume criteria identified	• No volume criteria identified
Delay	• No delay criteria identified	• No delay criteria identified	• No delay criteria identified
Other	• Adequate sight distance • Angle of intersection (*72*)	• Adequate sight distance • Merge conditions • Angle of intersection (*72*)	• Sight distance

Note: Underlined text represents values recommended by the authors; the underlining was added to aid in reading the table.

CONCLUSIONS

Caution Regarding Warrants

As criteria were being identified, examined, and considered for inclusion in the proposed new MUTCD language, a caution regarding the term "warrant" was acknowledged. The criteria eventually selected for the MUTCD do not necessarily represent the minimum requirements for installing AWSC. The criteria identify a condition that merits detailed analysis and consideration of right-of-way control through a traffic engineering study. Such a study should review the traffic data, pedestrian and bicycle volume, intersection geometrics, expected operational characteristics, and expected safety impacts to conclude whether AWSC is justified.

AWSC offers operational benefits and safety benefits under certain traffic conditions. The intent of a traffic engineering study is to document that the AWSC will improve the safety and efficiency of the intersection.

How and whether the above thoughts need to be integrated into the MUTCD are questions that FHWA or members of NCUTCD may need to consider.

Use of Findings from Economic Analysis

A portion of the research efforts focused on an economic analysis to determine when AWSC or roundabout geometric design should be considered based on cost considerations. In general, the findings from the economic analysis are:

- For roundabouts: always install a roundabout when the benefits of installation are greater than the construction costs. For the scenarios tested in this study, such as construction costs of $250,000 and $500,000, a roundabout was always justified for the volume levels studied because the delay and crash savings were greater than the construction costs.
- For all-way stop control: do not use AWSC except at rural four-leg intersections with a two-lane major highway (one lane in each direction) when you should use AWSC at all intersections with a major-road volume of 400 units/hr and greater and a minor-road approach volume of 100 units/hr/approach and greater.

The research team members do not support implementation of these findings (i.e., do not use all-way Stop on urban intersections—except as an interim measure for a signal—or use in most situations for four-leg intersections on rural two-lane highways) at this time for several reasons, including:

1. The economic analysis is based on several assumptions and calculations. Some of the assumptions are based on data from only one state (e.g., the CMFs are based on North Carolina data). The variability of other input values, such as the predicted number of crashes or the average cost of time, is not known and could have a sizable impact on the results. It is important to recognize that the findings were developed using several assumptions. Each of these assumptions could have an associated range of reasonable values, such that significantly different results could be produced when all the values' ranges or variability are considered.

2. The research results provide specific criteria for the selection of a specific type of unsignalized control, but these results do not provide an appreciation of the range of reasonable values—a limitation frequently present within a decision-making process that is based on specific criteria. Additional MUTCD language should include a caution that the criteria should be only one consideration given that a wide range of factors may impact the decision-making process.
3. The user costs for safety considerations have significantly increased in recent years. As indicated in the analysis procedure, the cost of a single fatal accident is over $9 million. This is significantly higher than safety costs that have been used in the past, and the cost of a single fatality can be much greater than other costs associated with an alternative means of providing right-of-way control. As a result, the analysis procedure used in this study may be inconsistent with the procedures used in the past to develop criteria that are currently in the MUTCD and other guidelines. Accordingly, the application of these criteria may lead to implementation results that are inconsistent with existing decision-making criteria in the MUTCD.
4. This research project has demonstrated a "disconnect" between the economic analysis approach used in this research and the existing peak-hour signal warrant in the MUTCD in that an all-way stop is not warranted until volumes are much greater than those that would warrant a traffic control signal. The team suggests that another research project should use a similar basis to examine all types of intersection traffic control so that the relationships between AWSC and the various signal warrants are consistent.
5. If the peak-hour signal warrant is used as the basis to warrant AWSC, the disparity in volumes may result in extensive delay to the major traffic volumes during other times of the day. This raises concerns that the economic analysis is not the best approach for determining AWSC warrants. The consideration of peak-hour, 4-hr, or even 8-hr traffic conditions can justify intersection traffic control that may not be needed the remaining hours of the day. The traffic control, while beneficial during the limited time frame, creates a disparity for the other hours of the day, imposing unneeded traffic regulation and intersection delay.

While the findings from the economic analysis are based on thorough research, because of the inconsistencies identified above, the differences in basis between these criteria and those that are currently in the MUTCD mean that the criteria developed from the economic analysis may not be ready for inclusion in the MUTCD until such time as the existing MUTCD criteria and warrants for traffic signals can also be reevaluated in a manner that considers the impacts of user safety costs in the same manner that this research project did. Only through the use of consistent decision-making criteria can practitioners correctly determine the most appropriate means of providing right-of-way control at an intersection.

Use of Findings from Traffic Simulation

The research team considered other approaches for determining a minimum volume recommendation for AWSC. Delays in excess of 35 sec/veh on the minor-road approach have been suggested as a tipping point due to it representing LOS E in Exhibit 19-1 of the HCM (*23*). If so, the volumes when the VISSIM runs are above 35 sec/minor-road vehicle are 500 units/hr/major approach and 300 units/hr/minor approach. Using the hourly volume distribution determined in this project, those peak-hour volumes would equate to 8-hr volumes of

430 units/hr/major approach and 260 units/hr/minor approach. (The assumed hourly volume distribution is 7.8 percent for 3 hr and 6.1 percent for 5 hr.)

RECOMMENDATIONS

Suggested Language for Next Edition of MUTCD

Using information available from reviews of existing literature, policies, guidelines, and findings from the economic analysis along with the engineering judgment of the research team and panel, recommendations were developed and are summarized in Table 51. The language proposed for the next edition of the MUTCD for unsignalized intersections developed at the conclusion of this research is provided in the appendix.

The proposed language includes introductory general considerations, discusses alternatives to changing right-of-way control, and steps through the various forms of unsignalized control from least restrictive to most restrictive, beginning with no control and concluding with AWSC. Supplemental notes are provided to suggested additions to the current text, which show the reader the source(s) of the material and/or the research team's reasoning for proposing the text.

Future Research Needs

This research project demonstrated a "disconnect" between the AWSC results produced by the economic analysis approach and the existing signal warrant in the MUTCD in that AWSC is not warranted until volumes are much greater than those that would warrant a traffic control signal. A research project is needed that would examine all types of intersection traffic control from a similar basis so that the relationships between AWSC and the various signal warrants are consistent.

The future research project should also consider the effects of left-turning vehicles along with appropriate consideration of pedestrian and bicycle travel. How should multimodal traffic needs, such as those of pedestrians and bicyclists, be considered within intersection traffic control evaluations? Should delay, perhaps using values available in the HCM (*23*), set the threshold values, or should values be a function of the setting of the intersection, for example, nearness to school or rural versus urban area.

The consideration of peak-hour, 4-hr, or even 8-hr traffic conditions can justify intersection traffic control that may not be needed the remaining hours of the day. The traffic control, while beneficial during the limited time frame, creates a disparity for the other hours of the day, imposing unneeded traffic regulation and intersection delay. The relationship of traffic volumes and intersection distribution of those volumes versus the disadvantages of the traffic control during the remaining hours needs further study. The intersection traffic control impacts under lower traffic volumes are especially onerous for AWSC because it imposes unnecessary stops on the major traffic flows. The same disadvantages have been noted relative to the traffic signal warrants based on limited time periods. It is recommended that further research be directed at variations in traffic volumes, including specific consideration of turning vehicles versus advantages and disadvantages of that intersection traffic control for both AWSC and traffic signal control.

Table 51. Recommended Criteria for Unsignalized Intersection Control.

Criteria	No Control	Yield Control	Minor-Road Stop	All-Way Stop
Number of Crashes Susceptible to Correction by Intersection Control	No crash criteria	Two or fewer reported crashes in a year[a]	4-leg: 3 or more within 12 months, 6 or more within 36 months[b] 3-leg: 3 or more within 12 months, 5 or more within 36 months[b]	4-leg: 5 or more within 12 months, 6 or more within 36 months[b] 3-leg: 4 or more within 12 months, 5 or more within 36 months[b]
Peak-Hour Entering Volume	Maximum 80 units/hr[c]	Maximum 140 units/hr[c]	No volume criteria	No volume criteria
Entering Volume per Day	Maximum 1,000 units/day[d]	Maximum 1,800 units/day[e]	No volume criteria	No volume criteria
8 hr	No volume criteria	No volume criteria	No volume criteria	1. The vehicular volume entering the intersection from the major street approaches (total of both approaches) averages at least 300 units per hour for any 8 hr of an average day; and 2. The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor-street approaches (total of both approaches) averages at least 200 units per hour for the same 8 hr; but 3. If the 85th percentile approach speed of the major-street traffic exceeds 40 mph, the minimum vehicular volume warrants are 70 percent of the values provided in Items 1 and 2.[f]
Delay	No delay criteria	No delay criteria	No delay criteria	35 sec/veh[g]
Other	Adequate sight distance One-lane approaches Angle of intersection[h]	Adequate sight distance One-lane approaches Angle of intersection[h]	Sight distance	Sight distance Engineering study

[a] Maryland MUTCD Table 2B-1a (*10*) provides guidelines for conversion from stop to yield control.
[b] Selected with consideration of the proposed crash warrant criteria for signals, NCHRP Project 07-18 (*49*).
[c] Rounded calculation from the 1,000 and 1,800 units/day value using 7.8 percent, which is the peak-hour factor used in the economic analysis.
[d] Value selected because a 1983 study in rural Michigan (*41*) found no statistical difference for stop-controlled and no-control intersections with major-street volumes less than 1,000 vpd, and the 1,000 value is less than the value selected for YIELD sign control (1,800).
[e] From NCHRP Report 320 (*36*).
[f] Values currently in 2009 MUTCD with changes of vehicular volume to units.
[g] Selected based on HCM (*23*) Exhibit 19-1, lowest control delay (sec/veh) for LOS E (when $v/c \le 1.0$).
[h] As recommended in the *Handbook for Designing Roadways for the Aging Population* (*72*).

APPENDIX: POTENTIAL MUTCD REVISIONS

INTRODUCTION

This appendix provides suggested language recommended for inclusion in the upcoming edition of the MUTCD as developed at the conclusion of the research project.

FORMATTING USED WITH REVISIONS

Recommended Language

The proposed revisions represent a substantial rewrite to Sections 2B.04, 2B.06, 2B.07, and 2B.09. Traditionally, changes are shown with strikeout deletions and underlined new text. Because of the extensive revisions, using that approach would result in multiple cross-outs. For this appendix, a different formatting structure was used that shows proposed text supplemented with notes shown in brackets. This decision was made with the intent that it would provide less confusion by showing a cleaner copy of the proposed text for these sections. The formatting styles used are:

- Black text reflects existing MUTCD text.
- Gray highlight surrounded by square brackets [ ] shows notes regarding the source of material including, if appropriate, where the text is currently within the 2009 MUTCD.
- Red underline text presents new material developed by the research team. This new material reflects proposed changes to the MUTCD.

Existing Language

Deleted text from the 2009 MUTCD is not shown for Sections 2B.04, 2B.06, 2B.07, and 2B.09 within the "Recommended Language for the MUTCD" section but rather for clarity is provided at the end of the appendix. In effect, the existing text in those sections would be removed and replaced with the text in this proposal. The existing language is provided with deletions shown so the reader can identify whether existing language is being retained. The formatting styles used within the "Existing MUTCD (2009) Language" section are:

- ~~Red strikeout~~ text reflects material that was not retained.
- Black text reflects MUTCD text retained in the recommended language proposal.
- Gray highlight surrounded by square brackets [ ] shows notes regarding where the 2009 MUTCD material is proposed to be moved.

RECOMMENDED LANGUAGE FOR THE MUTCD

[Note: Sections 2B.04, 2B.06, 2B.07, and 2B.09 are deleted and replaced with the following.]

Chapter 2B.XX Signing for Right of Way at Intersections

Section 2B.X1 General Considerations

Support:

1 Unsignalized intersections represent the most common form of intersection right-of-way control. Selection of unsignalized control type might be affected by specific requirements of state law or local ordinances.

2 Roundabouts and traffic circles are intersection designs and are not traffic control devices. The decision to convert an intersection from a traditional intersection to a roundabout is an engineering design decision and not a traffic control device decision. As such, criteria for conversion from a traditional intersection to a roundabout are not included in the MUTCD.

Guidance:

3 *The type of traffic control used at an unsignalized intersection should be the least restrictive that provides appropriate levels of safety and efficiency.*

4 *When selecting a form of intersection control, the following factors should be considered:*

- *A. Vehicular, bicycle, and pedestrian traffic volumes on all approaches.* [Note: From 2009 MUTCD Section 2B.04, Paragraph 02.] *Where the term units/day or units/hour is indicated, it should be the total of vehicular, bicycle, and pedestrian volume.*
- *B. Driver yielding behavior with regard to bicyclists and pedestrians.*
- *C. Number and angle of approaches.*
- *D. Approach speeds.*
- *E. Sight distance available on each approach.*
- *F. Reported crash experience.*[Note: From 2009 MUTCD Section 2B.04, Paragraph 02.]

5 Yield or Stop signs should not be used for speed control. [Note: From 2009 MUTCD Section 2B.04, Paragraph 05.]

Standard:

6 Because the potential for conflicting commands could create driver confusion, YIELD or STOP signs shall not be used in conjunction with any traffic control signal operation, except in the following cases:

- **A. If the signal indication for an approach is a flashing red at all times;**
- **B. If a minor street or driveway is located within or adjacent to the area controlled by the traffic control signal, but does not require separate traffic signal control because an extremely low potential for conflict exists; or**
- **C. If a channelized turn lane is separated from the adjacent travel lanes by a raised, painted, or other type island and the channelized turn lane is not controlled by a traffic control signal.** [Note: From 2009 MUTCD Section 2B.04, Paragraph 10.]

7 Except as provided in Section 2B.X6, STOP signs and YIELD signs shall not be installed on different approaches to the same unsignalized intersection if those approaches conflict with or oppose each other. [Note: From 2009 MUTCD Section 2B.04, Paragraph 11.]

8 **Portable or part-time STOP or YIELD signs shall not be used except for emergency and temporary traffic control zone purposes.** [Note: From 2009 MUTCD Section 2B.04, Paragraph 12.]

9 **A portable or part-time (folding) STOP sign that is manually placed into view and manually removed from view shall not be used during a power outage to control a signalized approach unless the maintaining agency establishes that the signal indication that will first be displayed to that approach upon restoration of power is a flashing red signal indication and that the portable STOP sign will be manually removed from view prior to stop-and-go operation of the traffic control signal.** [Note: From 2009 MUTCD Section 2B.04, Paragraph 13.]

Option:

10 A portable or part-time (folding) STOP sign that is electrically or mechanically operated such that it only displays the STOP message during a power outage and ceases to display the Stop message upon restoration of power may be used during a power outage to control a signalized approach. [Note: From 2009 MUTCD Section 2B.04, Paragraph 14.]

Section 2B.X2 Types of Unsignalized Intersection Right-of-Way Control

Support:

1 The types of right-of-way control that can exist at an unsignalized intersection are listed below in order from the least restrictive to the most restrictive.

A. No intersection control: There are no right-of-way traffic control devices on any of the approaches to the intersection.
B. Yield control: YIELD signs are placed on all approaches (for a roundabout), on opposing approaches (for a four-leg intersection), on a single approach (for a three-leg intersection), or in the median of a divided highway. The YIELD signs are typically placed on the minor road. (See Section 2B.X3 for guidance on selecting the minor road.)
C. Minor-road stop control: STOP signs are typically placed on opposing approaches (for a four-leg intersection) or on a single approach (for a three-leg intersection). The STOP signs are typically placed on the minor road. (See Section 2B.X3 for guidance on selecting the minor road.)
D. All-way stop control: STOP signs are placed on all approaches to the intersection.

Section 2B.X3 Determining the Minor Road for Unsignalized Intersections

Guidance:

1 *The selection of the minor road to be controlled by YIELD or STOP signs should be based on one or more of the following criteria:*

A. A roadway intersecting a designated through highway.
B. A roadway with the lower functional classification.
C. A roadway that is less important.
D. A roadway with the lower traffic volume.
E. A roadway with the lower speed limit.

[2] *When two roadways that have relatively equal volumes, speeds, and/or other characteristics intersect, the following factors should be considered in selecting the minor road for installation of YIELD or STOP signs:* [Note: Similar thought to 2009 MUTCD Section 2B.04, Paragraph 09.]

A. *Controlling the direction that conflicts the most with established pedestrian crossing activity or school walking routes;*
B. *Controlling the direction that has obscured vision, dips, or bumps that already require drivers to use lower operating speeds; and*
C. *Controlling the direction that has the best sight distance from a controlled position to observe conflicting traffic.* [Note: From 2009 MUTCD Section 2B.04, Paragraph 09.]

Section 2B.X4 Alternatives to Changing Intersection Right-of-Way Control

Guidance:

[1] *Before converting to a more restrictive form of right-of-way control at an unsignalized intersection, consideration should be given to the following alternative treatments to address safety, operational, or other concerns.*

[2] *Alternatives that should be considered include, but are not limited to, the following:*

A. *Where yield or stop controlled, installing STOP AHEAD or YIELD AHEAD signs on the appropriate approaches to the intersection;*
B. *Removing parking on one or more approaches;*
C. *Removing sight distance restrictions;*
D. *Installing warning signs along the major street to warn road users approaching the intersection;*
E. *Relocating the stop line(s) and making other changes to improve the sight distance at the intersection;*
F. *Installing measures designed to reduce speeds on the approaches;*
G. *Installing a flashing beacon at the intersection to supplement STOP sign control;*
H. *Installing yellow flashing beacons on warning signs in advance of a STOP-sign-controlled intersection on major- and/or minor-street approaches;*
I. *Adding one or more lanes on a minor-street approach to reduce the number of vehicles per lane on the approach;*
J. *Revising the geometrics at the intersection to channelize vehicular movements and reduce the time required for a vehicle to complete a movement, which could also assist pedestrians;*
K. *Revising the geometrics at the intersection to add pedestrian median refuge islands and/or curb extensions;*
L. *Installing roadway lighting if a disproportionate number of crashes occur at night;*
M. *Restricting one or more turning movements, perhaps on a time-of-day basis, if alternate routes are available;*
N. *Installing a pedestrian hybrid beacon (see Chapter 4F) or in-roadway warning lights (see Chapter 4N) if pedestrian safety is the major concern;*
O. *Converting to a roundabout; and*
P. *Employing other alternatives, depending on conditions at the intersection.*

[Note: Items D–P noted above were taken from 2009 MUTCD Section 4B.04.]

Section 2B.X5 No Intersection Control

Guidance:

1 *The decision not to use intersection control should be based on engineering judgment that indicates all of the following conditions exist:*

- A. *Intersection sight distance is adequate on all approaches.*
- B. *All approaches to the intersection are a single lane, and there are no separate turn lanes.*
- C. *The combined vehicular, bicycle, and pedestrian volume (existing or projected) entering the intersection from all approaches averages less than 1,000 units per day or 80 units in the peak hour.* [*Note: Value selected because (a) 1983 study in rural Michigan* (41) *found no statistical difference for stop-controlled and no-control intersections with major-street volumes less than 1,000 vpd, and (b) it is less than the value selected for yield control.*]
- D. *There are no pedestrian or bicycle traffic control devices on any approach.*
- E. *None of the approaches to the intersection are for a through highway or higher functional classification roadway.*
- F. *The angle of intersection is between 90 and 75 degrees.* [*Note: The* Handbook for Designing Roadways for the Aging Population (72) *includes the recommendation that the angle not be less than 75 degrees; therefore, it was added to this list of conditions when a stop should not be replaced with no intersection control.*]
- G. *The functional classification of the intersecting streets is either the intersection of two local streets or the intersection of a local street with a collector street.*

Support:

2 *Evaluate and consider the presence of a rail crossing near the intersection of a local street with a collector street.*

Section 2B.X6 Yield Control

Guidance:

1 *At intersections where a full stop is not necessary at all times, consideration should first be given to using less restrictive measures such as YIELD signs.* [Note: From 2009 MUTCD Section 2B.06, Paragraph 01.]

2 *Yield control should be considered when engineering judgment indicates that all of the following conditions apply:*

- A. *Intersection sight distance is adequate on the approaches to be controlled by YIELD signs.*
- B. *All approaches to the intersection are a single lane, and there are no separate turn lanes.*
- C. *One of the following crash-related criteria applies:*
  - a. *For changing from no intersection control to yield control, there have been two or more reported crashes that are susceptible to correction by installation of a YIELD sign in the previous 12 months.*
  - b. *For changing from minor-road stop control to yield control, there have been two or fewer reported crashes in the previous 12 months.*

D. *Entering intersection volume of less than 1,800 units per day or 140 units in the peak hour.* *[Note: The 1,800 units/day value was based on NCHRP 320* (36) *recommendation.]*
E. *The angle of intersection is between 90 and 75 degrees.* *[Note: the* Handbook for Designing Roadways for the Aging Population (72) *includes the recommendation that the angle not be less than 75 degrees; therefore, it was added to this list of conditions when a Stop sign should not be replaced with a Yield sign.]*
F. *The functional classification of the intersecting streets is either the intersection of two local streets or the intersection of a local street with a collector street.*

Option:

3 YIELD signs may be installed at an intersection when any of the following conditions apply:

A. At the second crossroad of a divided highway, where the median width at the intersection is 30 feet or greater. In this case, a YIELD sign may be installed at the entrance to the second roadway. [Note: From 2009 MUTCD Section 2B.09, Paragraph 1, Item B.]
B. For a channelized turn lane that is separated from the adjacent travel lanes by an island, even if the adjacent lanes at the intersection are controlled by a highway traffic control signal or by a STOP sign. [Note: From 2009 MUTCD Section 2B.09, Paragraph 1, Item C.]
C. At an intersection where a special problem exists and where engineering judgment indicates the problem to be susceptible to correction by the use of the YIELD sign. [Note: From 2009 MUTCD Section 2B.09, Paragraph 1, Item D.]
D. Facing the entering roadway for a merge-type movement if engineering judgment indicates that control is needed because acceleration geometry and/or sight distance is not adequate for merging traffic operation. [Note: From 2009 MUTCD Section 2B.09, Paragraph 01, Item E.]

Guidance:

4 The YIELD signs should be installed on opposing minor-road approaches (for a four-leg intersection) or on the minor-road approach (for a three-leg intersection). (See Section 2B.X3 for information to identify the minor road.) Yield control should be established on the approach that conflicts most with established pedestrian crossing activity or school walking routes.

Standard:

5 A YIELD sign shall be used to assign right-of-way at the entrance to a roundabout. YIELD signs at roundabouts shall be used to control the approach roadways and shall not be used to control the circulatory roadway. [Note: From 2009 MUTCD Section 2B.09, Paragraph 02.]

6 ~~Other than for all of the approaches to a roundabout,~~ YIELD signs shall not be placed on all of the approaches to an intersection, except at roundabouts. [Note: From 2009 MUTCD Section 2B.09, Paragraph 03.]

Section 2B.X7 Minor-Road Stop Control

Guidance:

[1] *Stop control on the minor-road approach or approaches to an intersection should be considered when engineering judgment indicates that one or more of the following conditions exist:*

A. *A restricted view exists that requires road users to stop in order to adequately observe conflicting traffic on the through street or highway. [Note: From 2009 MUTCD Section 2B.06, Paragraph 2B.]*
B. *Crash records indicate:*
   a. *For a four-leg intersection, there are three or more reported crashes in a 12-month period or six or more reported crashes in a 36-month period. The crashes are of a type susceptible to correction by installation of minor-road stop control.*
   b. *For a three-leg intersection, there are three or more reported crashes in a 12-month period or five or more reported crashes in a 36-month period. The crashes are of a type susceptible to correction by installation of minor-road stop control.*
C. *The intersection of a lower functional classification road with a higher functional classification road. [Note: Similar thought as in 2009 MUTCD Section 2B.04, Paragraph 03A.]*
D. *Conditions that previously supported installation of an all-way stop control, under all-way stop control warrants, no longer exist.*

Section 2B.X8 All-Way Stop Control

[Note: The term "all-way" is recommended rather than "multi-way" because "all-way" is the term used in the supplemental plaque.]

Guidance:

[1] The decision to install all-way stop control at an unsignalized intersection should be based on an engineering study accounting for the advantages and disadvantages of the control treatment. [Note: From 2009 MUTCD Section 2B.07, Paragraph 03.]

[2] The evaluation of the need for all-way stop control should include an analysis of factors related to the existing operation and safety at the study intersection and the potential to improve these conditions and the applicable factors contained in the following all-way stop control warrants:

A. *All-Way Stop Control Warrant A: Crash Experience (Section 2B.X9).*
B. *All-Way Stop Control Warrant B: Sight Distance (Section 2B.X10).*
C. *All-Way Stop Control Warrant C: Transition to Signal Control (Section 2B.X11).*
D. *All-Way Stop Control Warrant D: Peak-Hour Delay (Section 2B.X12).*
E. *All-Way Stop Control Warrant E: 8-Hour Volume (Vehicle, Pedestrians, and Bicycles) (Section 2B.X13).*
F. *All-Way Stop Control Warrant F: Other Factors (Section 2B.X14).*

Standard:

[3] **The satisfaction of an all-way stop control warrant or warrants shall not in itself require the installation of all-way stop control at an unsignalized intersection.**

Section 2B.X9 All-Way Stop Control Warrant A: Crash Experience

Option:

1 All-way stop control may be established at an intersection where an engineering study indicates that:

A. For a four-leg intersection, there are five or more reported crashes in a 12-month period or six or more reported crashes in a 36-month period. The crashes should be susceptible to correction by installation of all-way stop control.

B. For a three-leg intersection, there are four or more reported crashes in a 12-month period or five or more reported crashes in a 36-month period. The crashes should be susceptible to correction by installation of all-way stop control. [Note: Crash numbers are a reflection of the proposed signal crash experience warrant developed in NCHRP Project 07-18 (*49*).]

Section 2B.X10 All-Way Stop Control Warrant B: Sight Distance

Option:

1 All-way stop control may be established at an intersection where an engineering study indicates that sight distance on the minor-road approaches controlled by a STOP sign is not adequate for a vehicle to turn onto or cross the major (uncontrolled) road. At such a location, a road user, after stopping, cannot see conflicting traffic and is not able to negotiate the intersection unless conflicting cross traffic is also required to stop. [Note: From 2009 MUTCD Section 2B.07, Paragraph 05C.]

Section 2B.X11 All-Way Stop Control Warrant C: Transition to Signal Control

Option:

1 All-way stop control may be established at locations where all-way stop control is an interim measure that can be installed to control traffic while arrangements are being made for the installation of the traffic control signals at the intersection. [Note: Similar to 2009 MUTCD Section 2B.07, Paragraph 04A.]

Section 2B.X12 All-Way Stop Control Warrant D: Peak-Hour Delay

Option:

1 All-way stop control may be established at an intersection where an engineering study indicates that the peak-hour delay on an average day on the minor road(s) is greater than 35 sec/veh.

Section 2B.X13 All-Way Stop Control Warrant E: 8-Hour Volume (Vehicle, Pedestrians, and Bicycles)

Option:

2 All-way stop control may be established at an intersection where an engineering study indicates:

A. The volume entering the intersection from the major-street approaches (total of both approaches) averages at least 300 units per hour for any 8 hours of an average day; and
B. The volume entering the intersection from the minor-street approaches (total of both approaches) averages at least 200 units per hour for the same 8 hours; but
C. If the 85th percentile approach speed of the major-street traffic exceeds 40 mph, the minimum vehicular volume warrants are 70 percent of the values provided in Items A and B. [Note: Similar to 2009 MUTCD Section 2B.07, Paragraph 04C.]

Section 2B.X14 All-Way Stop Control Warrant F: Other Factors

Option:
3 All-way stop control may be installed at an intersection where an engineering study indicates that all-way stop control is needed due to other factors not addressed in the other all-way stop control warrants. Such other factors may include, but are not limited to, the following:

A. The need to control left-turn conflicts. [Note: From 2009 MUTCD Section 2B.07, Paragraph 05A.]
B. An intersection of two residential neighborhood collector (through) streets of similar design and operating characteristics where all-way stop control would improve traffic operational characteristics of the intersection. [Note: From 2009 MUTCD Section 2B.07, Paragraph 05D.]
C. Where pedestrian and/or bicycle movements justify the installation of all-way stop control. [Note: Similar to 2009 MUTCD Section 2B.07, Paragraph 05B.]

[Note: Sections 2B.05 (STOP sign and ALL WAY plaque), 2B.08 (YIELD sign), and 2B.10 (STOP sign and YIELD sign placement) in the existing 2009 manual do not change as a result of the proposed revisions. Those sections would be inserted before or after the proposed text or in an alternate location between the revised sections as deemed appropriate by FHWA.]

[Note: End of proposed revisions.]

EXISTING MUTCD (2009) LANGUAGE

[Note: The following text is from Sections 2B.04, 2B.06, 2B.07, and 2B.09 of the 2009 MUTCD. Deletions are shown, and notes are provided regarding the proposed location for text being moved.]

~~**Section 2B.04 Right-of-Way at Intersections**~~
~~Support:~~
~~01 State or local laws written in accordance with the "Uniform Vehicle Code" (see Section 1A.11) establish the right-of-way rule at intersections having no regulatory traffic control signs such that the driver of a vehicle approaching an intersection must yield the right-of-way to any vehicle or pedestrian already in the intersection. When two vehicles approach an intersection from different streets or highways at approximately the same time, the right-of-way rule requires the driver of the vehicle on the left to yield the right-of-way to the vehicle on the right. The right-of-way can be modified at through streets or highways by placing YIELD (R1-2) signs (see Sections 2B.08 and 2B.09) or STOP (R1-1) signs (see Sections 2B.05 through 2B.07) on one or more approaches.~~

Guidance: *[Note: Moved to Section 2B.X1.]*

02 *Engineering judgment should be used to establish intersection control. The following factors should be considered:*

A. Vehicular, bicycle, and pedestrian traffic volumes on all approaches;

B. Number and angle of approaches;

C. Approach speeds;

D. Sight distance available on each approach; and

E. Reported crash experience. *[Note: Moved to Section 2B.X1.]*

03 ~~*YIELD or STOP signs should be used at an intersection if one or more of the following conditions exist:*~~

~~*A. An intersection of a less important road with a main road where application of the normal right-of-way rule would not be expected to provide reasonable compliance with the law;*~~ *[Note: Similar thought was included in Section 2B.X7.]*

~~*B. A street entering a designated through highway or street; and/or*~~ *[Note: Similar thought in Section 2B.X7.]*

~~*C. An unsignalized intersection in a signalized area.*~~

04 ~~*In addition, the use of YIELD or STOP signs should be considered at the intersection of two minor streets or local roads where the intersection has more than three approaches and where one or more of the following conditions exist:*~~

~~*A. The combined vehicular, bicycle, and pedestrian volume entering the intersection from all approaches averages more than 2,000 units per day;*~~

~~*B. The ability to see conflicting traffic on an approach is not sufficient to allow a road user to stop or yield in compliance with the normal right-of-way rule if such stopping or yielding is necessary; and/or*~~

~~*C. Crash records indicate that five or more crashes that involve the failure to yield the right-of-way at the intersection under the normal right-of-way rule have been reported within a 3-year period, or that three or more such crashes have been reported within a 2-year period.*~~

05 *YIELD or STOP signs should not be used for speed control.* *[Note: Moved to Section 2B.X1.]*

~~Support:~~

06 ~~Section 2B.07 contains provisions regarding the application of multi-way STOP control at an intersection.~~

~~Guidance:~~

07 ~~Once the decision has been made to control an intersection, the decision regarding the appropriate roadway to control should be based on engineering judgment. In most cases, the roadway carrying the lowest volume of traffic should be controlled.~~

08 ~~A YIELD or STOP sign should not be installed on the higher volume roadway unless justified by an engineering study.~~

Support:

09 The following are considerations that might influence the decision regarding the appropriate roadway upon which to install a YIELD or STOP sign where two roadways with relatively equal volumes and/or characteristics intersect:

A. Controlling the direction that conflicts the most with established pedestrian crossing activity or school walking routes; [Note: Moved to Section 2B.X3.]

B. Controlling the direction that has obscured vision, dips, or bumps that already require drivers to use lower operating speeds; and [Note: Moved to Section 2B.X3.]
C. Controlling the direction that has the best sight distance from a controlled position to observe conflicting traffic. [Note: Moved to Section 2B.X3.]

Standard:
10 **Because the potential for conflicting commands could create driver confusion, YIELD or STOP signs shall not be used in conjunction with any traffic control signal operation, except in the following cases: [Note: Moved to Section 2B.X1.]**
A. If the signal indication for an approach is a flashing red at all times; [Note: Moved to Section 2B.X1.]
B. If a minor street or driveway is located within or adjacent to the area controlled by the traffic control signal, but does not require separate traffic signal control because an extremely low potential for conflict exists; or [Note: Moved to Section 2B.X1.]
C. If a channelized turn lane is separated from the adjacent travel lanes by an island and the channelized turn lane is not controlled by a traffic control signal. [Note: Moved to Section 2B.X1.]
11 **Except as provided in Section 2B.09, STOP signs and YIELD signs shall not be installed on different approaches to the same unsignalized intersection if those approaches conflict with or oppose each other. [Note: Moved to Section 2B.X1.]**
12 **Portable or part-time STOP or YIELD signs shall not be used except for emergency and temporary traffic control zone purposes. [Note: Moved to Section 2B.X1.]**
13 **A portable or part-time (folding) STOP sign that is manually placed into view and manually removed from view shall not be used during a power outage to control a signalized approach unless the maintaining agency establishes that the signal indication that will first be displayed to that approach upon restoration of power is a flashing red signal indication and that the portable STOP sign will be manually removed from view prior to stop-and-go operation of the traffic control signal. [Note: Moved to Section 2B.X1.]**

Option:
14 A portable or part-time (folding) STOP sign that is electrically or mechanically operated such that it only displays the STOP message during a power outage and ceases to display the STOP message upon restoration of power may be used during a power outage to control a signalized approach. [Note: Moved to Section 2B.X1.]

~~Support:~~
~~15 Section 9B.03 contains provisions regarding the assignment of priority at a shared-use path/roadway intersection.~~

~~**Section 2B.06 STOP Sign Applications**~~
Guidance:
01 At intersections where a full stop is not necessary at all times, consideration should first be given to using less restrictive measures such as YIELD signs [Note: Moved to Section 2B.X6.]
~~*02 The use of STOP signs on the minor-street approaches should be considered if engineering judgment indicates that a stop is always required because of one or more of the following conditions:*~~

~~*A. The vehicular traffic volumes on the through street or highway exceed 6,000 vehicles per day;*~~
B. A restricted view exists that requires road users to stop in order to adequately observe conflicting traffic on the through street or highway; and/or *[Note: Moved to Section 2B.X7.]*
C. ~~*Crash records indicate that three or more crashes that are susceptible to correction by the installation of a STOP sign have been reported within a 12-month period, or that five or more such crashes have been reported within a 2-year period. Such crashes include right-angle collisions involving road users on the minor-street approach failing to yield the right-of-way to traffic on the through street or highway.*~~

~~Support:~~
~~03 The use of STOP signs at grade crossings is described in Sections 8B.04 and 8B.05.~~

~~**Section 2B.07 Multi-Way Stop Applications**~~
~~Support:~~
~~01 Multi-way stop control can be useful as a safety measure at intersections if certain traffic conditions exist. Safety concerns associated with multi-way stops include pedestrians, bicyclists, and all road users expecting other road users to stop. Multi-way stop control is used where the volume of traffic on the intersecting roads is approximately equal~~
~~02 The restrictions on the use of STOP signs described in Section2B.04 also apply to multi-way stop applications.~~

Guidance:
03 The decision to install multi-way stop control should be based on an engineering study. [Note: Moved to Section 2B.X8.]
~~*04 The following criteria should be considered in the engineering study for a multi-way STOP sign installation:*~~
A. Where traffic control signals are justified, the multi-way stop is an interim measure that can be installed quickly to control traffic while arrangements are being made for the installation of the traffic control signal. [Note: Moved to Section 2B.X11.]
B. ~~*Five or more reported crashes in a 12-month period that are susceptible to correction by a multi-way stop installation. Such crashes include right-turn and left-turn collisions as well as right-angle collisions.*~~
C. Minimum volumes: [Note: Moved to Section 2B.X13 with some changes.]
1. The vehicular volume entering the intersection from the major street approaches (total of both approaches) averages at least 300 vehicles per hour for any 8 hours of an average day; and
2. The combined vehicular, pedestrian, and bicycle volume entering the intersection from the minor street approaches (total of both approaches) averages at least 200 units per hour for the same 8 hours, with an average delay to minor-street vehicular traffic of at least 30 seconds per vehicle during the highest hour; but
3. If the 85^{th}-percentile approach speed of the major-street traffic exceeds 40 mph, the minimum vehicular volume warrants are 70 percent of the values provided in Items 1 and 2.
~~*D. Where no single criterion is satisfied, but where Criteria B, C.1, and C.2 are all satisfied to 80 percent of the minimum values. Criterion C.3 is excluded from this condition.*~~

Option:

05 Other criteria that may be considered in an engineering study include:

A. The need to control left-turn conflicts; [Note: Moved to Section 2B.X14.]

~~B. The need to control vehicle/pedestrian conflicts near locations that generate high pedestrian volumes;~~ [Note: Similar to Section 2B.X14.]

C. Locations where a road user, after stopping, cannot see conflicting traffic and is not able to negotiate the intersection unless conflicting cross traffic is also required to stop; and [Note: Moved to Section 2B.X10.]

D. An intersection of two residential neighborhood collector (through) streets of similar design and operating characteristics where multi-way stop control would improve traffic operational characteristics of the intersection. [Note: Moved to Section 2B.X14.]

~~**Section 2B.09 YIELD Sign Applications**~~

~~Option:~~

~~01 YIELD signs may be installed:~~

A. ~~On the approaches to a through street or highway where conditions are such that a full stop is not always required.~~

B. At the second crossroad of a divided highway, where the median width at the intersection is 30 feet or greater. In this case, a STOP or YIELD sign may be installed at the entrance to the first roadway of a divided highway, and a YIELD sign may be installed at the entrance to the second roadway. [Note: Moved to Section 2B.X6.]

C. For a channelized turn lane that is separated from the adjacent travel lanes by an island, even if the adjacent lanes at the intersection are controlled by a highway traffic control signal or by a STOP sign. [Note: Moved to Section 2B.X6.]

D. At an intersection where a special problem exists and where engineering judgment indicates the problem to be susceptible to correction by the use of the YIELD sign. [Note: Moved to Section 2B.X6.]

E. Facing the entering roadway for a merge-type movement if engineering judgment indicates that control is needed because acceleration geometry and/or sight distance is not adequate for merging traffic operation. [Note: Moved to Section 2B.X6.]

Standard:

02 A YIELD (R1-2) sign shall be used to assign right-of-way at the entrance to a roundabout. YIELD signs at roundabouts shall be used to control the approach roadways and shall not be used to control the circulatory roadway. [Note: Moved to Section 2B.X6.]

03 Other than for all of the approaches to a roundabout, YIELD signs shall not be placed on all of the approaches to an intersection. [Note: Moved to Section 2B.X6.]

REFERENCES

1 Federal Highway Administration. 2009. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S. Department of Transportation, Washington, D.C.

2 Federal Highway Administration. 1948. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S. Department of Transportation, Washington, D.C.

3 Federal Highway Administration. 1961. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S. Department of Transportation, Washington, D.C.

4 Federal Highway Administration. 1988. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S. Department of Transportation, Washington, D.C.

5 Federal Highway Administration. 2000. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S. Department of Transportation, Washington, D.C.

6 Federal Highway Administration. 2003. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S. Department of Transportation, Washington, D.C.

7 National Committee on Uniform Traffic Control Devices. 2009. "Multiway Stop Control." NCUTCD Regulatory/Warning Signs Technical Committee, Council Approval Date: June 20, 2009.

8 Idaho Transportation Department. 2012. *Traffic Manual*. Section 100, STOP and YIELD Signs. Accessed on October 1, 2013, from http://itd.idaho.gov/manuals/Manual%20Production/Traffic/100TrafStdy.pdf.

9 Indiana Department of Transportation. 2011. *Indiana Design Manual*. Section 75-3.02 "Stop" or "Yield" Sign of Chapter 75 Traffic Design. Accessed on October 1, 2013, from http://www.in.gov/dot/div/contracts/standards/dm/2011/Part7/Ch75/ch75.htm.

10 Maryland State Highway Administration. 2011. *Maryland Manual on Uniform Traffic Control Devices*. Section 2B.04 Right-of-Way at Intersections, p. 61. Accessed on October 1, 2013, from http://www.roads.maryland.gov/mmutcd/2011_Chapters_02B.pdf.

11 Montana Department of Transportation. 2007. *Traffic Engineering Manual*. Section 18.2.1 Stop/Yield Signs. Accessed on October 1, 2013, from http://www.mdt.mt.gov/other/traffic/external/pdf/chapter_18.pdf.

12 Pennsylvania Department of Transportation. No date. *Official Traffic Control Devices.* Publication 212, p. B2-3. Accessed on October 1, 2013, from ftp://ftp.dot.state.pa.us/public/PubsForms/Publications/PUB%20212.pdf.

13 Washington Department of Transportation. 2014. *Design Manual*. M 22-01.10, p. 1300-5. Accessed on October 1, 2013, from http://www.wsdot.wa.gov/publications/manuals/fulltext/M22-01/1300.pdf.

14 Florida Department of Transportation. 2007. *Florida Intersection Design Guide*. Section 2.2.3 Traffic Control Modes. Accessed on October 1, 2013, from http://www.dot.state.fl.us/rddesign/fidg-manual/fidg2007.pdf.

15 Kentucky Transportation Cabinet. 2005. *Traffic Operations Guidance Manual.* Section TO-402-9. Accessed on October 1, 2013, from http://transportation.ky.gov/organizational-resources/policy%20manuals%20library/traffic%20operations.pdf.

16 Minnesota Department of Transportation. 2007. *Intersection Control Evaluation*. Accessed on October 31, 2013, from http://www.dot.state.mn.us/trafficeng/safety/ice/2007_ICE_Manual.pdf.

17 Wisconsin Department of Transportation. 2013. *Facilities Development Manual*. Chapter 11 Design, Section 25 Intersection at Grade. Accessed on October 1, 2014, from http://roadwaystandards.dot.wi.gov/standards/fdm/11-25.pdf.
18 Wisconsin Department of Transportation. 2007. *Traffic Guidelines Manual*. Chapter 13 Traffic Regulations, Section 26 Intersection Control, Subject 5 All-Way Stop.
19 Maze, T. H., J. L. Hochstein, R. R. Souleyrette, H. Preston, and R. Storm. 2010. *NCHRP Report 650: Median Intersection Design for Rural High-Speed Divided Highways*. National Cooperative Highway Research Program, Washington, D.C. Accessed on October 1, 2014, from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_650.pdf.
20 Minnesota Department of Transportation. 2007. *Intersection Control Evaluation (ICE)*. Accessed on October 31, 2013, from http://www.dot.state.mn.us/trafficeng/signals/worksheets/ICE.pdf.
21 City of Janesville. 1996. *Transportation Committee Procedures*. August 1977, updated 1996.
22 Fitzpatrick, K., S. Turner. M. Brewer, P. Carlson, N. Lalani, B. Ullman, N. Trout, E. S. Park, D. Lord, and J. Whitacre. 2006. *TCRP Report 112/NCHRP Report 562: Improving Pedestrian Safety at Unsignalized Crossings*. Transportation Research Board of the National Academies, Washington, D.C. Accessed on January 5, 2011, from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_562.pdf.
23 *Highway Capacity Manual.* 2010. Transportation Research Board of the National Academies, Washington, D.C.
24 American Association of State Highway and Transportation Officials. 2010. *Highway Safety Manual*. Washington, D.C.
25 Schroeder, B. J., C. M. Cunningham, D. J. Findley, J. E. Hummer, and R. S. Foyle. 2010. *Manual of Transportation Engineering Studies.* Second Edition, Institute of Transportation Engineers, Washington, D.C.
26 Pline, J. (ed.). 2001. *Traffic Control Device Handbook.* Institute of Transportation Engineers, Washington, D.C.
27 Koonce, P., L. Rodegerdts, K. Lee, S. Quayle, S. Beaird, C. Braud, J. Bonneson, P. Tarnoff, and T. Urbanik. 2008. *Traffic Signal Timing Manual*. Report No. FHWA-HOP-08-024, Federal Highway Administration, Washington, D.C.
28 *Highway Capacity Manual.* 2000. TRB, National Research Council, Washington, D.C.
29 Crash Modification Factors Clearinghouse. 2014. Crash Modification Factors Clearinghouse Website. Federal Highway Administration. Accessed on February 1, 2014, from http://www.cmfclearinghouse.org/index.cfm.
30 Sayed, T., K. El-Basyouny, and J. Pump. 2006. "Safety Evaluation of Stop Sign In-Fill Program." *Transportation Research Record: Journal of the Transportation Research Board, No. 1953*. Transportation Research Board of the National Academies, Washington, D.C., pp. 201–210.
31 El-Basyouny, K. and T. Sayed. 2010. "A Full Bayes Approach to Before-After Safety Evaluation with Matched Comparison." Presented at 89th Annual Meeting of the Transportation Research Board, Washington, D.C.

32 Simpson, C. L. and J. E. Hummer. 2010. "Evaluation of the Conversion from Two-Way Stop Sign Control to All-Way Stop Sign Control at 53 Locations in North Carolina." *Journal of Transportation Safety and Security*, Vol. 2, No. 3, pp. 239–260.

33 Lovell, J. and E. Hauer. 1986. "The Safety Effect of Conversion to All-Way Stop Control." *Transportation Research Record 1068*. TRB, National Research Council, Washington, D.C., pp 103–107.

34 Persaud, B. N. 1986. "Safety Migration, the Influence of Traffic Volumes, and Other Issues in Evaluating Safety Effectiveness—Some Findings on Conversion of Intersections to Multi-way Stop Control." *Transportation Research Record 1068*. TRB, National Research Council, Washington, D.C., pp 108–114.

35 Souleyrette, R. R., R. J. Tenges, T. McDonald, T. H. Maze, and A. Carriquiry. 2006. "Safety Effectiveness of Stop control at Ultralow-Volume Unpaved Intersections." *Transportation Research Record: Journal of the Transportation Research Board, No. 1967*. Transportation Research Board of the National Academies, Washington, D.C., pp. 58–65.

36 McGee, H. W. and M. R. Blankenship. 1989. *NCHRP Report 320: Guidelines for Converting Stop to Yield Control at Intersections.* TRB, National Research Council, Washington, D.C.

37 Stokes, R. 2000 *Analysis of Rural Intersection Accidents Caused by "Stop" Sign Violations and Failure to "Yield" the Right-of-Way.* Report No. K-TRAN: KSU-98-6, Kansas State University, Manhattan, Kansas.

38 Stokes, R. 2004. *Effectiveness of Two-Way Stop Control at Low-Volume Rural Intersections.* Report No. K-TRAN: KSU-99-5, Kansas State University, Manhattan, Kansas.

39 Mounce, J. M. 1981. "Driver Compliance with "Stop"-Sign Control at Low-Volume Intersections." *Transportation Research Record 808.* TRB, National Research Council, Washington D.C., pp. 30–37.

40 Stockton, W. R., R. Q. Brackett, and J. M. Mounce. 1981. *Stop, Yield, and No Control at Intersections*. FHWA/RD-81/084, U.S. Department of Transportation, Washington, D.C.

41 Lum, H. S. and M. R. Parker, Jr. 1983. "Intersection Control and Accident Experience in Rural Michigan." *ITE Journal*, May Issue, pp. 27–29.

42 Polus, A. 1985. "Driver Behavior and Accident Records at Unsignalized Urban Intersections." *Accident Analysis and Prevention*, Vol. 17, No. 1, pp. 25–32.

43 Harwood, D. W., F. M. Council, E. Hauer, W. E. Hughes, and A. Vogt. 2000. *Prediction of the Expected Safety Performance of Rural Two-Lane Highways.* FHWA Report No. FHWA-RD-99-207, Federal Highway Administration, Washington, D.C.

44 Hochstein, J. L., C. Albrecht, and R. R. Souleyrette. 2011. *Rural Expressway Intersection Safety Toolbox, Desktop Reference.* Iowa Department of Transportation Report No. 14690. Accessed on October 1, 2013, from http://publications.iowa.gov/14690/.

45 Briglia, P. M. 1984. "4-Way Stop Signs Cut Accident Rate 58 Percent at Rural Intersections." *ITE Journal* Vol. 54, No. 11. Institute of Transportation Engineers. Washington, D.C.

46 Abdel-Aty, M., P. Kerr, K. Haleem, and H. Huang. 2009. *Identification of Intersections' Crash Profiles/Patterns to Include Unsignalized Intersections and Expand the Safety/Traffic Database (Part I).* Report Number BD548-27.

47 Charbonneau, J. and E. Rooney. 1995. "Developing Modified MUTCD Stop Sign Warrants: The City of Portland's Experience." *65th Institute of Transportation Engineers Annual Meeting Compendium of Technical Papers,* Institute of Transportation Engineers, pp. 199–203.

48 Lee, S. B. and W. D. Berg. 1998. "Development of Safety-Based Level-of-Service Parameters for Two-Way Stop-Controlled Intersections." *Transportation Research Record 1635*, TRB, National Research Council, Washington, D.C., pp. 127–132.

49 Bonneson, J., K. Laustsen, L. Rodegerdts, and S. Beaird. 2014. *NCHRP Web-Only Document 204: Crash Experience Warrant for Traffic Signals.* Transportation Research Board of the National Academies, Washington, D.C., Tables 4C-2 and 4C-3.

50 Upchurch, J. 1983. "Guidelines for Use of Sign Control at Intersections to Reduce Energy Consumption." *ITE Journal*, Vol. 53, No. 1. Institute of Transportation Engineers. Washington, D.C.

51 Nitzel, J. J., F. G. Schattner, and J. P. Mick, Jr. 1988. "Residential Traffic Control Policies and Measures." ITE 1988 *Compendium of Technical Papers*, pp. 217–223.

52 Box, P. C. 1995. "Warrants for Traffic Control Devices at Low-Volume Urban Intersections." *ITE Journal*, Vol. 65, No. 4. Institute of Transportation Engineers. Washington, D.C.

53 Bonneson, J. A. and M. D. Fontaine. 2001. *NCHRP Report 457: Evaluating Intersection Improvements: An Engineering Study Guide.* TRB, National Research Council, Washington, D.C., Figure 3-2.

54 Marek, J. F., M. Kyte, T. Zongzhong, K. Lall, and K. Voigt. 1997. Determining Intersection Traffic Control Using the 1994 *Highway Capacity Manual*. *ITE Journal*, Vol. 67, No. 12, pp. 22–26. Institute of Transportation Engineers. Washington, D.C.

55 Elbermawy, A. E. 2004. "Development of Vehicular Volume Guidelines for Two-Way versus Four-Way Stop Controls" *ITE Journal*, Vol. 74, No. 11, pp. 16–22. Institute of Transportation Engineers. Washington, DC.

56 Han, L. D., J-M. Li, and T. Urbanik II. 2008. "Control Type Selection at Isolated Intersections Based on Control Delay under Various Demand Levels." *Transportation Research Record: Journal of the Transportation Research Board, No. 2071*, Transportation Research Board of the National Academies, Washington, D.C., pp. 109–116.

57 Jiang, T., Q. Yu, X. Deng, and Y. Zhang. 2012. "Control Type Selection at Isolated Intersections Based on Level of Service." Paper 12-2511, *Compendium of Papers, 91st Annual Meeting,* Transportation Research Board of the National Academies. Washington, D.C.

58 Wu, N. 2000. "Determination of Capacity at All-Way Stop Controlled Intersections." *Transportation Research Record: Journal of the Transportation Research Board, No. 1710*, TRB, National Research Council, Washington, D.C., pp. 205–214.

59 Brilon, W. and T. Miltner. 2005. "Capacity at Intersections without Traffic Signals." *Transportation Research Record: Journal of the Transportation Research Board, No.*

1920, Transportation Research Board of the National Academies, Washington, D.C., pp. 32–40.

60 Gard, J. T. 2001. "Estimation of Maximum Queue Lengths at Unsignalized Intersections." *2001 Compendium of Papers, ITE 2001 Annual Meeting and Exhibit*, Institute of Transportation Engineers, Chicago, Illinois, August 19–22.

61 Tian, Z. and M. Kyte. 2006. "Queue Length Models for All-Way Stop-Controlled Intersections." *Transportation Research Record: Journal of the Transportation Research Board, No. 1988*, Transportation Research Board of the National Academies, Washington, D.C., pp. 63–66.

62 Kirk, A., C. Jones, and N. Stamatiadis. 2011. "Improving Intersection Design Practices." *Transportation Research Record: Journal of the Transportation Research Board, No. 2223,* Transportation Research Board of the National Academies, Washington, D.C., pp. 1–8.

63 Arizona Department of Transportation. (Undated). *Final Pedestrian Crosswalk Warrant Study: SR 89A Dry Creek Road to Airport Road*. Phoenix, Arizona.

64 City of Phoenix Street Transportation Department. (Undated). *Draft Phoenix HAWK Beacon Priority Evaluation.* Phoenix, Arizona.

65 Arizona Department of Transportation. (Undated). *ADOT Pedestrian Hybrid Beacon (PHB) Evaluation Guidelines.* Arizona Department of Transportation. Accessed on February 12, 2015 from http://azdot.gov/docs/default-source/traffic-library/draft-pedestrian-hybrid-beacon-phb-guide.pdf.

66 ITE All Member Forum Community. 2012. "RRFB Pedestrians per Hour Threshold" conversation thread. Accessed on January 11, 2013, from http://community.ite.org/ite/communities/viewdiscussions/viewthread?GroupId=1597&MID=4296.

67 City of Boulder. 2011. *City of Boulder Pedestrian Crossing Treatment Installation Guidelines*. Boulder, Colorado. Accessed on January 30, 2015, from https://www-static.bouldercolorado.gov/docs/pedestrian-crossing-treamtment-installation-guidelines-1-201307011719.pdf.

68 Washington County Board of Commissioners. 2010. Resolution and Order No. 10-107: Approval Process for New Pedestrian Crossings at Midblock Locations and Uncontrolled Intersections. Hillsboro, Oregon. Accessed on January 24, 2013, from http://www.co.washington.or.us/lut/upload/midblock-crossing-policy-and-agenda.pdf.

69 Zegeer, C. V., J. R. Stewart, and H. Huang. 2002. *Safety Effects of Marked vs. Unmarked Crosswalks at Uncontrolled Locations: Executive Summary and Recommended Guidelines*. Report No. FHWA-RD-01-075, Federal Highway Administration, Washington, D.C.

70 Texas Department of Transportation. 2012. *Guidelines for Pedestrian Hybrid Beacon*. Austin, Texas.

71 Texas Department of Transportation. 2012. *Guidelines for Rectangular Rapid Flashing Beacon.* Austin, Texas.

72 M. A. Brewer, D. Murillo, A. Pate, D. Harkey, L. Staplin, K. Lococo, R. Srinivasan, J. Baek, M. Daul, H. McGee, and M. Tantillo. 2014. *Handbook for Designing Roadways for the Aging Population*. Report No. FHWA-SA-14-015, Federal Highway Administration,

Washington, D.C. Accessed on August 21, 2014, from http://safety.fhwa.dot.gov/older_users/handbook/.

73 American Association of State Highway and Transportation Officials. 2010. *User and Non-User Benefit Analysis for Highways.* Washington, D.C.

74 Kittelson and Associates, Inc., Eco Northwest, and Write Rhetoric. 2013. *Estimating the Life-Cycle Cost of Intersection Designs: Interim Report.* NCHRP Project 03-110, Kittelson and Associates, Reston, Virginia.

75 Federal Highway Administration. 2005. *Highway Economic Requirements System-State Version: Technical Report.* U.S. Department of Transportation, Washington, D.C.

76 Fitzpatrick, K., M. Brewer, J. S. Gluck, W. L. Eisele, Y. Zhang, H. S. Levinson, W. von Zharen, M. R. Lorenz, V. Iragavarapu, and E. S. Park. 2010. *NCHRP Web-Only Document 193: Development of Left-Turn Lane Warrants for Unsignalized Intersections.*, Transportation Research Board of the National Academies, Washington, D.C.

77 Upchurch, J. E. 1982. *Development of an Improved Warrant for Use of Stop and Yield Control at Four-Legged Intersections.* Dissertation, University of Maryland.

78 Schrank, D., B. Eisele, and T. Lomax. 2012. *2012 Urban Mobility Report.* Texas Transportation Institute, The Texas A&M University System, College Station, Texas. Accessed on June 21, 2014, from http://tti.tamu.edu/documents/mobility-report-2012-wappx.pdf.

79 U.S. Bureau of Labor Statistics. 2014. *CPI Detailed Report for February 2014.*Table 24, Historical Consumer Price Index for All Urban Consumers (CPI-U): U.S. City Average, All Items. Accessed on April 10, 2014, from http://www.bls.gov/cpi/cpid1402.pdf.

80 Rodegerdts, L. A., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and E. C. Carter. 2007. *NCHRP Report 572: Applying Roundabouts in the United States.* Transportation Research Board of the National Academies, Washington, D.C.

81 Trottenberg, P. and R. S. Rivkin. 2013. "Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analyses." Memorandum to Secretarial Officers, Modal Administrators. Accessed on April 10, 2014, from http://www.dot.gov/sites/dot.gov/files/docs/VSL Guidance_2013.pdf.

82 Council, F. M., E. Zaloshnja, T. Miller, and B. Persaud. 2005. *Crash Cost Estimates by Maximum Police Reported Injury Severity within Selected Crash Geometries.* Report No. FHWA-HRT-05-051, Federal Highway Administration, Washington, D.C.

83 Bonneson, J., K. Zimmerman, and C. Quiroga. 2003. *Review and Evaluation of Enforcement Issues and Safety Statistics Related to Red-Light Running.* Report No. FHWA/TX-04/4196-1, Texas Transportation Institute, The Texas A&M University System, College Station, Texas.

84 U.S. Energy Information Administration. 2014. "Frequently Asked Questions: What Is the Outlook for Gasoline Prices for 2014 and for 2015?" Accessed on October 1, 2014, from http://www.eia.gov/tools/faqs/faq.cfm?id=287&t=10.

85 U.S. Energy Information Administration. 2014. "Frequently Asked Questions: What Are the Projected Diesel Fuel Prices for 2014 and for 2015?" Accessed on October 1, 2014, from http://www.eia.gov/tools/faqs/faq.cfm?id=31&t=9.

86 Federal Highway Administration. 2010. "Roundabouts—The Maryland Experience, A Maryland Success Story." FHWA-SA-09-018. Accessed on June 14, 2014, from http://safety.fhwa.dot.gov/intersection/resources/casestudies/fhwasa09018/.