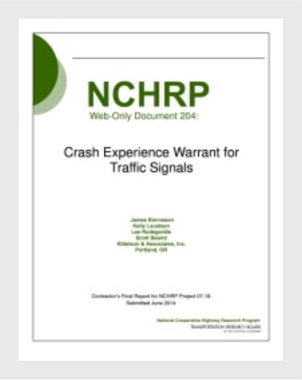

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Crash Experience Warrant for Traffic Signals

Crash Experience Warrant for Traffic Signals

DETAILS

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Abstract

The crash experience warrant in the *Manual on Uniform Traffic Control Devices* (MUTCD) specifies three criteria that must be met before a traffic signal can be considered for installation at an intersection. One of these criteria requires that five or more crashes of a type susceptible to correction by a signal must have occurred during a one-year period. Research was undertaken to evaluate the validity of this criterion and, if needed, to develop a crash experience warrant that is based on safety science and is consistent with the *Highway Safety Manual* (HSM).

A procedure was developed for quantifying the safety effect of signal installation. It is based on the predictive methods in the HSM. The procedure considers the effect of signal installation on intersection crash frequency and crash severity. The procedure was used to develop revised content for the crash experience warrant. The minimum number of crashes was found to vary by area type, intersection legs, and number of lanes on each intersection approach. A revised crash experience warrant was prepared and recommended for inclusion in the MUTCD.

Executive Summary

Introduction

The crash experience warrant in the *Manual on Uniform Traffic Control Devices* (MUTCD) specifies three criteria that must be met before a traffic signal can be considered for installation at an intersection (FHWA, 2009). One of these criteria requires that five or more crashes of a type susceptible to correction by a signal must have occurred at the subject intersection during a one-year period. The basis of this threshold of five or more crashes is not known, although it has been used for many years. This lack of historical reference has led some practitioners to consider the threshold number to be arrived at arbitrarily. The MUTCD also states that, "A traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection." However, there is no guidance offered in the MUTCD as to how the overall safety impact of the signal can be quantified.

The objective of this research is to recommend an improved crash experience traffic signal warrant that is suitable for inclusion in the MUTCD, based on research and consistency with the *Highway Safety Manual* (HSM). If the current crash experience traffic signal warrant is sufficient, then this research should validate the warrant.

The research approach was focused on the development of a procedure for evaluating the safety of stop-controlled and signal-controlled intersections. This procedure was then used to evaluate the change in safety associated with signal installation. The findings from this evaluation were used to develop the proposed crash experience warrant. The safety evaluation procedure incorporated the safety prediction methodology documented in Part C of the HSM.

Conclusions and Recommendations

Section 4C.01 of the MUTCD states that, "A traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection." However, there is no guidance offered in the MUTCD as to how the overall safety impact of the signal installation can be quantified so as to ascertain whether safety has been improved.

The MUTCD provides a crash experience warrant that serves as a first step of the engineering study process. Satisfaction of the crash experience warrant is an indication of likely safety improvement through signal installation. Once the warrant is met, the subsequent steps of the engineering study are then undertaken to confirm that signal installation will improve overall safety. The HSM is being used by some practitioners during the engineering study to confirm whether signal installation will improve overall safety. Specifically, the HSM is being used to quantify the reduction in expected crash frequency and severity associated with the signal installation.

A procedure was developed for quantifying the safety effect of signal installation. This procedure can optionally be used as part of the engineering study process. It is based on the predictive methods in the HSM. Observed crash data for one or more recent years can be used with the procedure to obtain a more reliable result. The procedure can be applied using a hand calculator, but it was also incorporated in a spreadsheet tool to facilitate implementation. The procedure considers total intersection crashes and crash severity.

The aforementioned procedure was used to develop revised content for Criterion B of the crash experience warrant. Application of the procedure to a range of typical intersection conditions indicated that there is a threshold value of observed crashes beyond which signal installation is likely to improve safety. However, the threshold value was found to vary by area type, intersection legs, and number of lanes on each intersection approach. As a result, a table of threshold values was prepared to include different values for logical combinations of area type, legs, and lanes.

It is recommended that the proposed crash experience documented in Chapter 5 be incorporated into the next edition of the MUTCD.

CHAPTER 1

Introduction

The crash experience warrant in the *Manual on Uniform Traffic Control Devices* (MUTCD) specifies three criteria that must be met before a traffic signal can be considered for installation at an intersection (FHWA, 2009). One of these criteria requires that five or more crashes of a type susceptible to correction by a signal must have occurred at the subject intersection during a one-year period. The basis of this threshold of five or more crashes is not known, although it has been used for many years. This lack of historical reference has led some practitioners to consider the threshold number to be arrived at arbitrarily. The MUTCD also states that, "A traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection." However, there is no guidance offered in the MUTCD as to how the overall safety impact of the signal can be quantified.

The aforementioned concerns have led to the conclusion that research is needed to confirm the validity of the existing warrant threshold, or develop a safety-based warrant. The research would provide the practitioner with the tools necessary to estimate the effectiveness (and determine the safety impacts of) installing traffic signals under this warrant. The basis for the crash experience warrant would take into account all available research, and ensure consistency with the *Highway Safety Manual* (HSM) (AASHTO, 2010).

Research Objective and Scope

The objective of this research is to recommend an improved crash experience traffic signal warrant that is suitable for inclusion in the MUTCD, based on research and consistency with the HSM. If the current crash experience traffic signal warrant is sufficient, then this research should validate the warrant.

The products of this research project are intended to be used to: (1) determine whether installation of a traffic control signal at a specified intersection will improve its overall safety and (2) estimate the safety impacts of installing a traffic control signal at this intersection. The intersection may be located in an urban or rural area. The focus was on typical intersection forms where (1) the through traffic movements cross at about a right angle and (2) STOP signs control the minor roadway.

Research Approach

The research approach was focused on the development of a procedure for evaluating the safety of stop-controlled and signal-controlled intersections. This procedure was then used to evaluate the change in safety associated with signal installation. The findings from this evaluation were used to develop the proposed crash experience warrant. The safety evaluation procedure incorporated the safety prediction methodology documented in Part C of the HSM. The work tasks that were undertaken are identified in the following list:

- Task 1 – Conduct Literature Review
- Task 2 – Survey Practitioners
- Task 3 – Develop Proposed Framework for Estimating Safety Impacts

- Task 4 – Develop Procedure and Tool to Estimate Safety Impacts
- Task 5 – Develop Content of Proposed Crash Experience Warrant
- Task 6 – Submit Draft Final Report and Guidebook
- Task 7 – Submit Final Report and Guidebook

The main products of the research are: (1) the proposed crash experience warrant, (2) spreadsheet tool that implements the safety evaluation procedure, and (3) safety evaluation guidebook and spreadsheet user manual. The spreadsheet tool and safety evaluation guidebook are available on the TRB website (www.trb.org).

Organization of This Report

This report presents the results of the research undertaken to develop an improved crash experience traffic signal warrant. Chapter 2 documents the findings from a review of the literature on the safety effect of signal installation. Chapter 3 summarizes the findings from a practitioner survey focused on experience with the crash experience warrant and potential opportunities to improve it. Chapter 4 documents the development of an intersection safety evaluation procedure. Chapter 5 describes how the safety evaluation procedure is used to develop the proposed crash experience warrant and presents the proposed warrant and other recommendations from the research. Chapter 6 provides the conclusions and recommendations derived from the research.

CHAPTER 2

Literature Review

Introduction

The *Manual on Uniform Traffic Control Devices* (MUTCD) provides standards and guidance for the use of traffic control signals (FHWA, 2009). It indicates that the selection and use of a traffic control signal at an intersection should be based on an engineering study of roadway, traffic, and other conditions. One component of this study includes the examination of one or more of the nine warrants listed in Section 4C.01 of the MUTCD.

Section 4C.01 of the MUTCD states that, “A traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection.” However, there is no guidance offered in the MUTCD as to how the overall safety impact of the signal installation can be quantified so as to ascertain whether safety has been improved.

This chapter describes the findings from a review of the literature on topics related to intersection safety and the safety effect of signal installation. The review is focused on research conducted since 2002. Research conducted prior to 2002 is documented in Appendix B of the report by McGee et al. (2003).

Background

MUTCD Warrant

Warrant 7, Crash Experience in the 2009 MUTCD specifies three criteria that, if met, justify further consideration of the need for a traffic control signal. This warrant is intended for application where the frequency and severity of crashes is the principal reason for considering the installation of a traffic control signal. The MUTCD indicates that the need for a traffic control signal shall be considered if all of the following criteria are met:

A. Adequate trial of alternatives with satisfactory observance and enforcement has failed to reduce the crash frequency, and

B. Five or more reported crashes, of types susceptible to correction by a traffic control signal, have occurred within a 12-month period, each crash involving personal injury or property damage apparently exceeding the applicable requirements for a reportable crash, and

C. For each of any 8 hours of an average day, the vehicles per hour (vph) given in both of the 80 percent columns of Condition A in Table 4C-1 (see Section 4C.02), or the vph in both of the 80 percent columns of Condition B in Table 4C-1 exists on the major-street, and the higher-volume minor-street approach, respectively, to the intersection, or the volume of pedestrian traffic is not less than 80 percent of the requirements specified in the Pedestrian Volume warrant. These major-street and minor-street volumes shall be for the same 8 hours. On the minor street, the higher volume shall not be required to be on the same approach during each of the 8 hours.

If the speed limit or the 85th percentile speed on the major street exceeds 40 mi/h, or if the intersection lies within the built-up area of an isolated community, the traffic volumes in the “56-percent” column in Table 4C-1 may be used in place of those in the “80-percent” column.

The need for five or more crashes in Criterion B has been with the MUTCD since 1935 (FHWA, 1937). The basis for this criterion is not indicated in the MUTCD, nor is it found in the research literature.

Hadayeghi et al. (2006) point out that the warrant does not does not address all crash types (just those susceptible to correction by a traffic control signal), nor is it sensitive to the number of intersection legs. They point out that the frequency of rear-end crashes may increase following signal installation, and that the determination of whether the signal will improve the overall safety of the intersection should be based on consideration of all crash types. They also note that intersection safety, and the effect of signal installation, is a function of the number of intersection legs.

The crash warrant in the *Ontario Traffic Manual* is similar to Warrant 7 in the MUTCD (OMT, 2001). However, the Ontario warrant states that the intersection has to experience at least 15 crashes that are susceptible to correction during the most recent three years (i.e., an average of five crashes per year).

Traffic Control Devices Handbook

The *Traffic Control Devices Handbook* (TCDH) indicates that a common belief is that a signal is safer than other forms of intersection control (ITE, 2001). However, the handbook also indicates that crashes frequently increase at an intersection following the installation of a traffic control signal when the installation was not based on a sound engineering analysis, and one or more of the following conditions holds: (1) one or more MUTCD warrants were not met, or (2) only minimum warrants were met.

The TCDH states that the installation of a traffic control signal may result in an increase in crash frequency (especially rear-end crashes). The TCDH indicates that the purpose of Warrant 7 – Crash Experience is to identify intersections where a traffic control signal would be beneficial in reducing crash frequency or making crashes less severe.

Satisfaction of the crash experience warrant implies that one or more alternatives to the traffic control signal have been tried at the subject unsignalized intersection. The following list summarizes the safety-related alternatives identified in the TCDH. The safety effect of several of these alternatives is summarized in a subsequent section.

- Install warning signs on the major street approach to alert drivers of crossing movements.
- Improve sight distance at the intersection (e.g., relocate the stop line).
- Install a flashing beacon at the intersection.
- Add one or more lanes on a minor-street approach.
- Install roadway lighting.
- Restrict one or more turn movements, perhaps on a time-of-day basis.
- Install multi-way Stop sign control.
- Install a roundabout.

If the trial of alternatives is unsuccessful, then the crash experience warrant indicates the need to examine the crash history of the intersection. The purpose of the examination is to determine if there are five or more crashes of a type that is susceptible to correction by a traffic control signal. The TCDH provides the following examples of crashes that are susceptible to correction (and those that are not).

Susceptible to Correction	Not Susceptible to Correction
Right-angle vehicle crash	Rear-end crash
Right-angle pedestrian crash	Sideswipe crash
Left-turn crash	Head-on crash
Parking crash	

The 1935 MUTCD clarifies that left-turn-opposed crashes are most susceptible to correction when the subject left-turn movement is provided a left-turn phase or, more generally, when it is served at a different time in the cycle than the opposing through movement (FHWA, 1937). It also indicates that crashes involving pedestrians and turning vehicles served at the same time in the cycle are not susceptible to correction. This language was removed for later editions of the MUTCD.

Survey of Practitioners

Carlson and Hawkins (1998) surveyed city and state traffic engineers on their use of the traffic control signal warrants in the 1988 MUTCD (which was the current version of the MUTCD at the time of the survey). The survey inquired about agency use of the warrants, and requested ideas for potential improvements to the warrants. All 50 state Departments of Transportation (DOTs) and the transportation agency responsible for the street system in 152 cities were included in the survey. Responses to the survey were received from 27 DOTs and 50 city agencies. The survey findings that address the crash experience warrant are described in this subsection.

The survey findings are summarized in Table 1. The information in the table indicates that the crash experience warrant is used infrequently to justify a signal (i.e., 6 percent for state DOTs and 11 percent for cities). In contrast, the eight-hour vehicular volume and the peak hour warrants combined were used to justify signal installation for about 75 percent of those intersections that met one or more warrants (78 percent for state DOTs, 68 percent for cities).

Most notable of the survey findings is that geometric improvements were often implemented at the intersection in conjunction with the signal installation. This practice makes it difficult to quantify the safety effect of the signal installation separately from that of the geometric improvements.

There is general agreement about the crash types that are susceptible to correction by a signal installation. About 80 percent of the state DOT respondents and 65 percent of city respondents indicated that angle, or right-angle, crashes are correctable. There is less of a consensus on left-turn crashes. This crash type was specifically identified by only 41 percent of the respondents. Most of those that identified left-turn crashes indicated that these crashes were considered correctible only if the signal installation included a protected left-turn phase.

Many of the respondents were unlikely to specifically consider crash severity when conducting a warrant analysis. Their concerns were varied but tended to reflect the many factors that can result in a fatality that are unrelated to the intersection and its control (e.g., size of involved vehicles, lack of seat belt use). The underlying issue is whether a fatal or severe crash should override the findings of the engineering study regarding signal justification. These concerns are noted to be related to the direct use of an intersections' fatal crash history in the warrant analysis, as opposed to the use of a model-based estimate of the intersection's long-run expected fatal crash frequency.

Table 1. Findings from a survey of practitioners.

Question	Response	
	State DOTs	**City Agencies**
Does your city use signal warrants that are different from those in the 1988 MUTCD?	No. However, one state DOT indicated that it did not require the use of the Criterion C (i.e., the volume-based criterion of the crash experience warrant).	No. One city indicated that they supplement the crash experience warrant with a conflict warrant.
Indicate the percentage intersections for which the crash experience warrant was used to justify installation of a signal.	6%	11%
What percentage of intersections at which signals were installed also had geometric improvements added as part of the upgrade?	24% (705 of 2936)	45% (346 of 763)
What crash types are susceptible to correction by traffic signal control?	44% - angle 37% - right angle 41% - left turn 4% - rear end 4% - all crash types	6% - angle 59% - right angle 41% - left turn 0% - rear end 0% - all crash types
What type of crash data are considered when evaluating the crash experience warrant?	76% - crash frequency 83% - crash type (e.g., rear-end) 28% - crash severity	80% - crash frequency 82% - crash type 31% - crash severity
How is crash severity considered?	If severity is used, it is used as an aide to determine other factors (e.g., priority, causation) or to push a nearly-warranted signal over the threshold.	If severity is used, it is used to determine if a signal should be given priority among all those signals that satisfy a warrant. One city uses only fatal-and-injury crashes because property-damage-only crash reporting is incomplete and inconsistent by their police department.
Should the crash experience warrant be modified or removed?	5% - modified 0% - removed The language regarding adequate trial of alternatives should be softened, or make it more specific.	8% - modified 0% - removed Need to be sensitive to crash severity. Use crash rate instead of crash frequency.

Procedures for Quantifying the Safety Effect of Signal Installation

This section describes two procedures that have been developed to predict the change in safety associated with the installation of a traffic control signal. Both procedures were specifically developed for use during the engineering study of an intersection being considered for signalization.

The two procedures are similar in many ways. Each procedure includes two sets of safety performance functions (SPF). One set of SPFs is used (with crash history data) to estimate the predicted crash frequency for the existing intersection. A second set of SPFs is used to estimate the predicted crash frequency for the intersection should the traffic control signal be installed. The difference between these two predicted values is an indication of the change in crash frequency due to the signal installation.

The procedure is used to evaluate one intersection being considered for conversion to traffic signal control. It is re-applied for each intersection that is being considered for this type of conversion.

In practice, only one of the procedures would be used for the evaluation of intersection safety. Both are described in this section to illustrate their different perspectives on the process of safety evaluation.

NCHRP Report 491 Procedure

This subsection describes the procedure developed by McGee et al. (2003) and documented in *NCHRP Report 491: Crash Experience Warrant for Traffic Signals*. The SPFs in this report apply to urban intersections. Subsequent research by Harkey et al. (2008) developed rural-intersection SPFs to be used with this procedure. Initially, the SPFs needed for the procedure are described. Then, the input data are summarized. Finally, the six steps associated with the procedure are outlined.

SPF Requirements

The procedure requires two sets of SPFs. They are identified in the following list.

- SPFs corresponding to intersections with stop-control on the minor street.
  - Three-leg intersections in urban areas.
    - SPF for fatal-and-injury (FI) crashes, all crash types.
    - SPF for FI rear-end crashes.
    - SPF for FI right-angle crashes.
  - Four-leg intersections in urban areas.
    - SPF for FI crashes, all crash types.
    - SPF for FI rear-end crashes.
    - SPF for FI right-angle crashes.
- SPFs corresponding to intersections with signal control.
  - Three-leg intersections in urban areas.
    - SPF for FI crashes, all crash types.
    - SPF for FI rear-end crashes.
    - SPF for FI right-angle crashes.
  - Four-leg intersections in urban areas.
    - SPF for FI crashes, all crash types.
    - SPF for FI rear-end crashes.
    - SPF for FI right-angle crashes.

A total of 12 SPFs are identified in the preceding list. The agency using the procedure may use SPFs they developed, or they may use the default SPFs are provided in NCHRP Report 491. Tables 9 and 10 in Report 491 describe the default SPFs for three-leg and four-leg stop-controlled intersections, respectively. Tables 14 and 15 in Report 491 describe the default SPFs for three-leg and four-leg signalized intersections, respectively.

All of the SPFs are calibrated to predict fatal-and-injury crash frequency. Property-damage-only (PDO) crash frequency is not considered in the procedure. McGee et al. (2003) indicate that this decision was made to improve the transferability of the default SPFs across jurisdictions. They observed that PDO crash frequency varied widely among jurisdictions due to differences in reporting threshold, which reduced the accuracy with which PDO crash frequency could be predicted.

The default SPFs are specific to an intersection with stop-control on the minor street. However, the procedure is equally applicable to intersections with another type of traffic control (e.g., multi-way stop control). However, the analyst would need to provide the SPFs appropriate for the other type of control.

Input Data

The procedure requires several types of input data. These data are described in the following paragraphs. The data are categorized as “minimum” and “desirable.” The minimum input data represents the essential data elements needed to conduct the safety evaluation. The desirable input data are more numerous and require more effort to acquire. However, their use in the procedure is intended to provide a more reliable estimate of the expected change in crash frequency due to signal installation.

Minimum Input Data

- Crash history – count of intersection-related fatal-and-injury crashes for most recent one-year period.
- Annual Average Daily Traffic (AADT) volume for the major street for same year as crash history.
- AADT volume for the minor street for same year as crash history.

Desirable Input Data

- Crash history – count of intersection-related fatal-and-injury crashes for each year of most recent two- to five-years.
- AADT volume for the major street for each year represented in the crash history.
- AADT volume for the minor street for each year represented in the crash history.
- Estimate of AADT volume for the major street that would prevail immediately after signal installation.
- Estimate of AADT volume for the minor street that would prevail immediately after signal installation.
- Local calibration factor for the SPFs corresponding to the traffic control at the existing intersection.
- Local calibration factor for the SPFs corresponding to signalized intersections.

Guidance

The crash history data must represent crashes that occur at the intersection, or are considered to be related to the intersection's presence. The data should have sufficient information to categorize each crash as rear-end, right-angle, or "other." Appendix C of NCHRP Report 491 describes these crash types to facilitate this categorization.

There should be no changes in the geometry of, or traffic control features at, the subject intersection during the time period represented by the input data. This period should extend backward in time from the most recent year to the last year for which it is known that no changes occurred. The time period should not exceed five years.

If the AADT volume is available for one or more years, but it is not available for all years, then it can be estimated for the missing years using the available AADT and judgment regarding annual changes in traffic volume at nearby intersections.

After the signal is installed, the major-street and minor-street AADTs at the intersection may increase more rapidly than can be explained by historic increases in traffic volume. Desirably, the analyst will estimate these two AADTs using the available AADTs and adjustment factors obtained from the AADTs of other intersections at which a signal was installed. If the Minimum Input Data approach is used, then the estimate of AADT that would prevail after signal installation can be assumed to equal the AADT associated with the most recent year for which crash data are available.

One local calibration factor is used with each SPF to insure that the predicted crash frequency is representative of all intersections in the jurisdiction within which the subject intersection is located. A procedure for computing this factor is described in Appendix D of NCHRP Report 491. If this factor is not used, then the implication is that the SPFs are representative of the intersections in the jurisdiction without further re-calibration.

Procedure Steps

Step 1. Assemble Input Data and Models.

Determine whether the desirable input data are available. If they are available, obtain them. Otherwise, obtain the minimum input data. Obtain the two sets of SPFs.

Step 2. Estimate the Expected Crash Frequency for the Existing Intersection.

Use the set of SPFs corresponding to the existing intersection with the empirical Bayes (EB) procedure (described in Table 20 of NCHRP Report 491) to estimate the expected crash frequency for the existing intersection. One estimate is obtained for each of the following categories: all crash types combined (i.e., total crashes), rear-end crashes, and right-angle crashes.

Step 3. Estimate the Predicted Crash Frequency for the Intersection if a Signal was Installed.

Use the set of SPFs corresponding to signalized intersections to estimate the predicted crash frequency for the average signalized intersection that is otherwise similar to the existing intersection. One estimate is obtained for each of the following categories: total crashes, rear-end crashes, and right-angle crashes.

Step 4. Determine if there is a Significant Change in Crash Frequency due to Signal Installation.

Using the estimates from Steps 2 and 3, compute the change in crash frequency for total crashes (i.e., change = estimate from Step 3 – estimate from Step 2). Use the following rules to determine if the change in crash frequency is statistically significant.

- If there is a decrease in total crashes (i.e., the change is negative) then,
  - Compute the change in right-angle crashes and the standard deviation of this change. Compare the change with the standard deviation to determine if the result is statistically significant.
  - If there is a statistically significant decrease in right-angle crashes, then the signal installation is likely to improve safety. Otherwise, safety should not be used to evaluate the impacts of signalization.
- Otherwise (i.e., there is an increase in total crashes),
  - Compute the change in rear-end crashes and the standard deviation of this change. Compare the change with the standard deviation to determine if the result is statistically significant.
  - If there is a statistically significant increase in rear-end crashes, then the signal installation is likely to degrade safety. Otherwise, safety should not be used to evaluate the impacts of signalization.

Step 5. Determine if there is a Net Safety Benefit Associated with the Signal Installation.

This step is applied if it was determined in Step 4 that there is a statistically significant change in crash frequency.

The estimates from Steps 2 and 3 are used to quantify the change in road-user cost due to signal installation. Comprehensive crash costs are used for this purpose. The use of these costs is rationalized to be an appropriate method for calculating the overall impact of signalization. The costs used are specific to key crash types. Harkey et al. (2008) indicate that these costs can be obtained from a report by Council et al. (2005).

Use the estimates from Step 2 to compute the comprehensive annual crash cost for the existing intersection. Similarly, use the estimates from Step 3 to compute the annual crash cost for the intersection if a signal is installed. The cost change is computed by subtracting the cost associated with Step 2 from that for Step 3.

If the difference between the two costs is negative, it indicates that signalization represents a decrease in road-user cost and that signalization provides a net safety benefit. If the difference is positive, then it indicates that signalization represents an increase in road-user cost.

Step 6. Assess Overall Benefits and Costs

This step is applied if it was determined in Step 4 that there is a statistically significant change in crash frequency.

The change in road-user cost is combined with the results from similar evaluations of operational impact and other impacts using conventional economic analysis procedures. The total benefit from all impacts can then be compared with the construction and right-of-way costs to determine the benefit-cost ratio of the proposed signal installation.

Ontario Procedure

This subsection describes the procedure developed by Hadayeghi et al. (2006) for Ontario, Canada. The procedure is similar to that described in the previous subsection. The description in this subsection is focused on highlighting the differences between the two procedures.

SPF Requirements

The procedure includes two sets of SPFs. They are identified in the following list.

- SPFs corresponding to intersections with stop-control on the minor street.
  - Three-leg intersections
    - SPF for FI+PDO crashes, crash types susceptible to correction by a traffic control signal.
    - SPF for FI+PDO crashes, crash types *not* susceptible to correction by a traffic control signal.
  - Four-leg intersections
    - SPF for FI+PDO crashes, crash types susceptible to correction by a traffic control signal.
    - SPF for FI+PDO crashes, crash types *not* susceptible to correction by a traffic control signal.
- SPFs corresponding to intersections with signal control.
  - Three-leg intersections
    - SPF for FI+PDO crashes, crash types susceptible to correction by a traffic control signal.
    - SPF for FI+PDO crashes, crash types *not* susceptible to correction by a traffic control signal.
  - Four-leg intersections
    - SPF for FI+PDO crashes, crash types susceptible to correction by a traffic control signal.
    - SPF for FI+PDO crashes, crash types *not* susceptible to correction by a traffic control signal.

A total of eight SPFs are identified in the preceding list. Default SPFs are provided by Hadayeghi et al. (2006) for Ontario, Canada.

The SPFs are not specific to crash type (e.g., rear-end), as they are for the previous procedure. Rather, one SPF is used to predict the frequency of all crashes that are susceptible to correction by a traffic control signal. The other SPF predicts the frequency of crashes that are not correctable by a signal. Hadayeghi et al. indicate that correctable crashes include: angle, left-turn, and right-turn crashes. Non-correctable crashes include: sideswipe, rear-end, and approaching crashes.

All of the SPFs are calibrated to estimate the predicted crash frequency for all severity categories combined (i.e., FI+PDO). In contrast, the SPFs for the previous procedure predict FI crash frequency.

Input Data

The input data needed for the procedure are identified in the following list:

- Crash history – count of intersection-related crashes (all severities) for the most recent 3-year period.
- AADT volume for the major street, average for same three years as crash period.
- AADT volume for the minor street, average for same three years as crash period.

Procedure Steps

Step 1. Assemble Input Data and Models.

This step is the same as for the NCHRP Report 491 procedure.

Step 2. Estimate the Expected Crash Frequency for the Existing Intersection.

This step is the same as for the NCHRP Report 491 procedure. However, the SPFs used are those described by Hadayeghi et al. (2006), and they are used to estimate the expected crash frequency for each of the following categories: crashes susceptible to correction by signal, and crashes that are not correctable by signal.

Step 3. Estimate the Predicted Crash Frequency for the Intersection if a Signal was Installed.

Use the set of SPFs corresponding to signalized intersections to estimate the predicted crash frequency for the average *signalized* intersection that is otherwise similar to the existing intersection. One estimate is obtained for each of the following categories: crashes susceptible to correction by signal, and crashes that are not correctable by signal. The remaining parts of this step are fundamentally different from Step 3 of the NCHRP Report 491 procedure

Use the set of SPFs corresponding to stop-controlled intersections to estimate the predicted crash frequency for the average *stop-controlled* intersection that is otherwise similar to the existing intersection. One estimate is obtained for each of the following categories: crashes susceptible to correction by signal, and crashes that are not correctable by signal.

Compute a crash modification factor using the results from the signalized intersection SPFs and the stop-controlled SPFs. The factor is computed for each crash-type category by dividing the predicted crash frequency for the average signalized intersection by the predicted crash frequency for the average stop-controlled intersection. For example, if the average signalized intersection is estimated to have 9 crashes/yr and the average stop-controlled intersection is estimated to have 10 crashes/yr, then the factor is computed as 0.90 (= 9/10).

Multiply the factor by the result from Step 2 to obtain an estimate of the expected crash frequency for the existing intersection after signal installation. One estimate is obtained for each of the following categories: crashes susceptible to correction by signal, and crashes that are not correctable by signal.

Hadayeghi et al. (2006) acknowledged that this factor is not used in the procedure developed by McGee et al. (2003), as described previously. Hadayeghi et al. noted that the procedure by McGee et al. compared the result from Step 2 directly with the average signalized intersection predicted crash frequency. Hadayeghi et al. believe this comparison is inappropriate because there is no reason to believe that the installation of a signal at the existing intersection would alter its overall character such that it could be reasonably assumed to have a level of safety similar to that of the average signalized intersection.

Step 4. Determine if there is a Significant Change in Safety due to Signal Installation.

This step is fundamentally different from Step 4 of the NCHRP Report 491 procedure. The two crash-type estimates from Step 2 are multiplied by a safety index that converts them into an equivalent PDO crash frequency for the existing intersection. Default safety index values for this calculation were developed by Hadayeghi et al. (2006). Similarly, the two estimates from Step 3 are multiplied by a safety index that converts them into an equivalent PDO crash frequency for the intersection if it were signalized.

The net change in safety is computed as the difference between the two equivalent PDO crash frequencies (i.e., change = equivalent frequency from Step 3 – equivalent frequency from Step 2). A positive change indicates that installation of a signal would likely result in safety deterioration for the subject intersection. In contrast, a negative change indicates that a net safety benefit would likely occur if the intersection was signalized.

Hadayeghi et al. (2006) indicate that this procedure does not include crash costs because these costs "are quite arbitrary and subjective."

Comparison of Procedures

Hadayeghi et al. (2006) applied their procedure, and that documented in NCHRP Report 491, to 17 intersections. There were eight three-leg intersections, and nine four-leg intersections. The major-street AADT ranged from 8,300 to 46,700 veh/d. It was noted that none of these intersections had a sufficient number of crashes susceptible to correction by signal to satisfy the crash experience warrant.

Both procedures indicated that safety would be improved with the installation of a signal at the same five intersections. The NCHRP Report 491 procedure identified two additional intersections that would be improved with the installation of a signal. The two procedures agreed that signal installation was not beneficial from a safety perspective at ten intersections (based on their respective decision criteria).

Factors Influencing Intersection Safety

This section summarizes a review of the recent literature on the topic of factors that influence intersection safety. The focus is on geometric design elements and traffic control features that have a quantified effect on safety.

The objective of the review is to demonstrate that many elements and features influence safety, and to make the point that the presence of these elements and features must be considered when quantifying the expected crash frequency for a specific intersection. This objective is achieved by reviewing four key documents, and identifying the elements and features identified in these documents.

Table 2 lists the elements and features that have a quantified effect on intersection safety. The list is categorized by area type, control type, and number of legs. Many of the elements or features are repeated for various combinations of area type and control type. This approach was taken to clearly indicate the conditions for which the associated effect has been quantified (and those for which it has not been quantified). It is recognized that the list is not complete, and other elements or features are likely to exist.

The predictive methods in Part C the HSM can be used to evaluate the safety effect of many of the elements and features listed in Table 2 (AASHTO, 2010). Each predictive method consists of an SPF and several crash modification factors (CMFs), where the CMFs quantify the safety effect of selected elements and features. Some of the elements and features in Table 2 are represented as CMFs in the HSM.

The estimate of expected crash frequency for an intersection will be more accurate when the safety effect of the intersection's elements and features are considered in the evaluation process. For example, Chapter 10 of the HSM indicates that the presence of a left-turn bay at a signalized intersection is associated with a larger CMF value than is the presence of a left-turn bay at a stop-controlled intersection. As a result, the installation of a signal at a stop-controlled intersection (with left-turn bays) will likely cause a change in safety due to the signal and, indirectly, due to the presence of the turn bay.

Table 2. Geometric design elements and traffic control features that affect intersection safety.

Area Type	Control Type	Number of Legs	Element or Feature	Trend: crash frequency decreases with…
Rural	Stop control on minor road	Any	Number of lanes on major [2]	increase in major lanes.
			Number of lanes on minor [2]	increase in minor lanes.
			Number of driveways on leg [2]	decrease in number of driveways.
			Shoulder width [2]	increase in shoulder width.
			Median width on major [1]	increase in median width.
			Flashing beacon [1, 3]	addition of beacon.
			Intersection skew angle [1]	decrease in skew angle.
			Left- or right-turn lane [1]	addition of a turn lane.
			Lighting [1]	addition of lighting.
	Signal	Any	Number of lanes on major [2]	decrease in major lanes.
			Number of lanes on minor [2]	decrease in minor lanes.
			Number of driveways on leg [2]	decrease in number of driveways.
			Left- or right-turn lane [1]	addition of a turn lane.
			Offset left-turn lanes[5]	shift of lanes to achieve positive offset.
		Four	Lighting [1]	addition of lighting.
Urban	Stop control on minor road	Any	Number of lanes on major [2]	increase in major lanes.
			Number of lanes on minor [2]	increase in minor lanes.
			Right-turn channelization [2]	removal of channelization.
			Lane width on major [2]	increase in lane width.
			Shoulder width [2]	increase in shoulder width.
			Median width on major [1]	decrease in median width.
			Left- or right-turn lane [1]	addition of a turn lane.
			Lighting [1]	addition of lighting.
	Signal	Any	Number of lanes on major [2]	decrease in major lanes.
			Number of lanes on minor [2]	decrease in minor lanes.
			Right-turn channelization [2]	removal of channelization.
			Lane width on major [2]	increase in lane width.
			Advance warning flashers [4]	addition of flashers.
			Median width on major [1]	decrease in median width.
			Left- or right-turn lane [1]	addition of a turn lane.
			Offset left-turn lanes[5]	shift of lanes to achieve positive offset.
			Lighting [1]	addition of lighting.
			Left-turn operation [1]	use of protected-only operation.
			Right-turn on red [1]	prohibition of right-turn on red.
			Red-light camera enforcement [1]	use of camera enforcement.

Notes:

Sources: 1 – AASHTO (2010). 2 – Bonneson et al. (2009). 3 – Srinivasan et al. (2007). 4 – Srinivasan et al. (2011). 5 – Persaud et al. (2009).

Safety Effect of Signal Installation

This section summarizes the findings from a review of the literature on the effect on safety of a change from stop control to signal control. The first section lists the CMFs reported in the literature. The second section summarizes the findings related to the effect found for intersections that did, and did not, satisfy the crash experience warrant. The third section summarizes the findings related to the issue of crash reporting consistency, and its possible effect on the accuracy of predicted crash frequency.

Crash Modification Factors

Many studies that focused on quantifying the effect of signalization have been conducted over the years. Persaud (1988) examined 14 studies of this type. He found that most of the studies were "…found wanting with respect to methods of analysis or inferences from the results." He identified the limitations of each study, which included one or more of the following issues in most instances: (1) no consideration given to the influence of traffic volume, (2) no consideration given to regression-to-the-mean artifacts in the crash data, or (3) no consideration given to the influence of geometric design elements or traffic control features at the intersections. After a detailed examination of the collective results from these studies, he concluded that "…there is very little substantial knowledge about the safety impact of traffic signal installation."

McGee et al. (2003) identified three studies that were conducted between 1988 and 2002. An examination of these studies indicated that most of the aforementioned limitations were still present, and the findings of limited value.

Four studies that concluded after 2002 were identified for this report. Collectively, the researchers appear to have acknowledged the aforementioned limitations by using more rigorous study designs and analysis methods. The findings from these four studies are summarized in Table 3.

The table categorizes the CMF values by area type, number of legs, crash type, and crash severity. Some researchers did not disaggregate their results by one or more of these categories, so area type includes "Mix," number of legs includes "Any," crash type includes "Total," and crash severity includes "All" so that the combined results can also be shown.

The table identifies some of the issues associated with the individual studies. Of note is that many of the studies did not control for the number of legs at the intersection. An examination of the urban intersection CMF values suggests that CMFs for intersections with four legs tend to be about 30 percent smaller than those for intersections with three legs. This trend suggests that the installation of a signal at a four-leg intersection tends to reduce crashes by a larger percentage than it would at a three-leg intersection. This trend cannot be confirmed for rural intersections because the studies of rural intersections did not distinguish between three- and four-leg intersections when developing CMF values.

Many of the studies are also noted to not have controlled for changes to geometric design elements or traffic control features (other than the signal installation). It is common for an agency to change one or more elements or features in conjunction with the signal installation, as shown in Table 1. For example, left-turn lanes may also be added to the major-road approaches, or protected-only left-turn phases may be used for the major-road left-turn movements. The information provided in Table 2 indicates that these changes can also have an effect of safety. If the study design does not control for these changes, the reported CMF values will reflect (by an unknown amount) the combined effect of both the signal installation and the other changes.

A cursory examination of the trends in the CMF values in Table 3 indicates that the rural intersections tend to have CMF values that are about 40 percent smaller than urban intersections. That is, the installation of a signal at a rural intersection tends to reduce crashes by a larger percentage than it would at an urban intersection.

The trends in Table 3 suggest that right-angle crashes, left-turn crashes, and fatal-and-injury crashes tend to decrease with the installation of a signal. The values for rear-end crashes and PDO crashes tend to increase with signal installation.

Table 3. Crash modification factors for conversion from stop control to signal control.

Area Type	Number of Legs	Crash Type	Crash Severity	CMF Value	Std. Error	N [2]	Issues [3]	Comment (Source[1])
Mix	Any	Total	All	1.00	--	518	A, C, E	Based on crash rate. (b)
			FI	0.97	--	518	A, C, E	Based on crash rate. (b)
			PDO	1.06	--	518	A, C, E	Based on crash rate. (b)
		Right angle	All	0.69	--	518	A, C, E	Based on crash rate. (b)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--
		Rear end	All	1.82	--	518	A, C, E	Based on crash rate. (b)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--
		Left turn	All	0.77	--	518	A, C, E	Based on crash rate. (b)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--
Rural	Any	Total	All	0.63	--	283	A, C	Based on crash rate. (b)
				0.56	0.03	45	A, D	(d)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--
		Right angle	All	0.23	0.02	45	A, D	(d)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--
		Rear end	All	1.58	0.14	45	A, D	(d)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--
		Left turn	All	0.40	0.05	45	A, D	(d)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--

Notes:

1 – Sources:

a – McGee et al. (2003). b – Pernia et al. (2002). c – Davis and Aul (2007). d – Harkey et al. (2008).

2 – N: number of intersections evaluated.

3 – Issues: A – number of legs not addressed. C- regression-to-the-mean artifacts not addressed. D – change in geometric design elements or traffic control features not addressed. E – influence of urban versus rural area type not addressed.

"--" - not available.

Table 3. Crash modification factors for conversion from stop control to signal control (continued).

Area Type	Number of Legs	Crash Type	Crash Severity	CMF Value	Std. Error	N [2]	Issues [3]	Comment (Source[1])
Urban	Any	Total	All	1.14	--	235	A, C	Based on crash rate. (b)
	Three	Total	All	--	--	--	--	--
			FI	0.86	0.10	22	D	(a)
			PDO	--	--	--	--	--
		Right angle	All	--	--	--	--	--
			FI	0.66	0.20	22	D	(a)
			PDO	--	--	--	--	--
		Rear end	All	--	--	--	--	--
			FI	1.50	0.26	22	D	(a)
			PDO	--	--	--	--	--
		Left turn	All	--	--	--	--	--
			FI	--	--	--	--	--
			PDO	--	--	--	--	--
	Four	Total	All	0.95	0.08	17	none	40 mi/h or more major street, protected-only left on major after signal installed. (c)
			FI	0.77	0.05	100	D	(a)
			PDO	--	--	--	--	--
		Right angle	All	0.33	0.05	17	none	40 mi/h or more major street, protected-only left on major after signal installed. (c)
			FI	0.33	0.04	100	D	(a)
			PDO	--	--	--	--	--
		Rear end	All	2.43	0.31	17	none	40 mi/h or more major street, protected-only left on major after signal installed. (c)
			FI	1.38	0.15	100	D	(a)
			PDO	--	--	--	--	--
		Left turn	All	0.74	0.20	17	none	40 mi/h or more major street, protected-only left on major after signal installed. (c)
			FI	--	--	--	--	--
			PDO	--	--	--	--	--

Notes:

1 – Sources:

a – McGee et al. (2003). b – Pernia et al. (2002). c – Davis and Aul (2007). d – Harkey et al. (2008).

2 – N: number of intersections evaluated.

3 – Issues: A – number of legs not addressed. C- regression-to-the-mean artifacts not addressed. D – change in geometric design elements or traffic control features not addressed. E – influence of urban versus rural area type not addressed.

“--”- not available.

Warranted versus Unwarranted Signals

Persaud et al. (1997) examined the crash history for 426 intersections in Philadelphia at which the signal was removed. The intersections selected were those that did not meet volume-based signal warrants. Most were three-leg intersections in urban areas. Multi-way stop control was typically installed following signal removal. A before-after study design was used with the EB procedure to estimate the effect of the signal removal on safety. They computed a CMF for this change of 0.766, corresponding to a 23.4 percent crash reduction in total crashes (all severities).

Stamatiadis et al. (2008) examined the crash history for 25 intersections for which a signal was recently installed. The intersections were located on the Kentucky state highway system. They applied the MUTCD signal warrants to each signal. They found that four of the intersections did not satisfy any of the warrants, and seven of the intersections satisfied the crash experience warrant. The remaining 14 intersections satisfied one or more of the volume warrants. Each of the four intersections with unwarranted signals experienced an increase in crash rate. Each of the seven intersections that satisfied the crash experience warrant experienced a decrease in crash rate. The decrease ranged from 23.0 to 88.7 percent.

Crash Reporting Consistency

The safety evaluation procedure developed by McGee et al. (2003) (described in a previous section) is based only on the evaluation of fatal-and-injury crashes (i.e., PDO crashes are not considered). They indicate that this decision was made to improve the transferability of the default SPFs across jurisdictions. They observed that PDO crash frequency varied widely among jurisdictions due to differences in reporting threshold. They were concerned that this variability would reduce the accuracy of PDO-based SPFs developed using data from two or more jurisdictions.

Evidence of the variability in PDO crash frequency among jurisdictions is provided by Zegeer et al. (1998). Their examination of rural freeway crashes in four states found that the percentage of PDO crashes varies from 60 to 77 percent. Slightly smaller variation was found for urban freeways. They speculated that this variation is due to differences in reporting threshold, as opposed to differences in freeway safety among states.

Hauer and Hakkert (1989) found that crashes of all severities are under-reported due to a variety of reasons (e.g., diligence of officer on scene, willingness of motorist to report injury to an officer or self-report a PDO crash, motorist uncertainty of legal requirements regarding reporting, improved ability of doctors to keep patients alive longer than the legal deadline for crash-related death designation, etc.). However, the degree of under-reporting is greatest for PDO crashes because of the aforementioned reasons, plus officers and motorists have difficulty assessing the cost of the property damage associated with a crash. Hauer and Hakkert showed that the proportion of PDO crashes varies year-by-year within a jurisdiction. They demonstrated how this variability reduced the accuracy of CMFs developed using PDO crash data.

Safety Predictive Methods

Safety predictive methods are documented in Part C of the HSM. Each predictive method consists of an SPF and several CMFs, where the CMFs are used to quantify the safety effect of selected geometric design elements and traffic control features (AASHTO, 2010). Each predictive method is developed to provide an estimate of the expected crash frequency of specific crash types and crash severity categories (e.g., fatal-and-injury, PDO).

A predictive method is used to estimate the safety of an intersection *having specified elements and features represented by the CMFs*. This intersection could represent an existing intersection of interest, or a planned intersection for construction in a future year.

A general-purpose SPF, such as that developed by McGee et al. (2003) and Hadayeghi et al. (2006), is used to estimate the safety of an intersection *having a typical combination of elements and features*. Unlike the result from a predictive method, the general-purpose SPF does not include CMFs. As a result, the predicted average crash frequency obtained from a general-purpose SPF is likely to be less reliable than that obtained from a predictive method.

This section summarizes the findings from a review of the predictive methods in Part C of the HSM. The first subsection describes the features of the predictive methods. The second subsection compares the predictive methods for stop control and signal control.

Highway Safety Manual

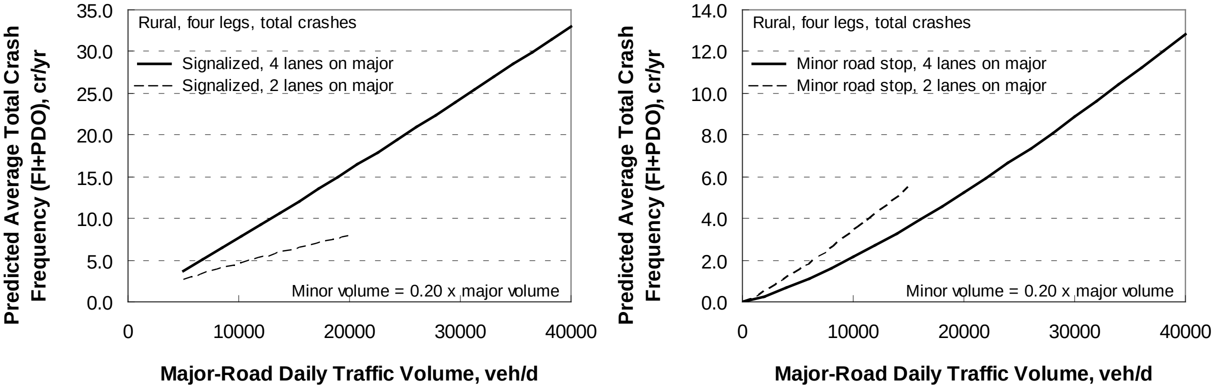
The predictive methods in Part C of the HSM are described in Table 4. A total of ten methods are listed. The HSM does not address rural, three-leg signalized intersections. As a result, it cannot be used to support the safety evaluation of signal installation at a rural, three-leg intersection. It is also shown in the table that the predictive method for rural, four-leg signalized intersections does not include any CMFs.

Table 4. HSM predictive methods.

Area Type	Control Type	Number of Legs	Major-Road Lanes	SPF Provided in HSM	Number of CMFs Provided in HSM
Rural	Stop control on minor road	3	2	Yes	4
			4	Yes	4
		4	2	Yes	4
			4	Yes	4
	Signal	3	2	No	0
			4	No	0
		4	2	Yes	3
			4	Yes	0
Urban	Stop control on minor street	3	2 or 4	Yes	3
		4	2 or 4	Yes	3
	Signal	3	2 or 4	Yes	6
		4	2 or 4	Yes	6

The number of lanes on the major-road is indicated in the table as defining separate predictive methods for rural intersections. This treatment recognizes that the number of major-road lanes has an important influence on the average crash frequency. This influence was previously noted in Table 2 as being applicable to both rural and urban intersections.

The influence of “number of lanes” is shown in Figure 1 using the predictive methods for rural, four-leg intersections. The trend in Figure 1a indicates that signalized intersections with four lanes on the major road have *more* crashes than those with two lanes, for the same traffic volume. In contrast, Figure 1b indicates that stop-controlled intersections with four lanes on the major road have *fewer* crashes than those with two lanes. Both trends are consistent with those reported in Table 2.



a. Signal control. ***b. Stop control on minor road.***

Figure 1. Relationship between number of lanes and total crash frequency.

The CMFs indicated in the last column of Table 4 (and identified by name in Table 2) allow the estimate of average crash frequency to accurately reflect the geometric design elements and traffic control features present at the existing intersection, or at a proposed intersection after signal installation. The presence of these elements or features at an intersection will vary on a case-by-case basis. The effect that they can have on the estimate of average crash frequency is shown in Figure 2.

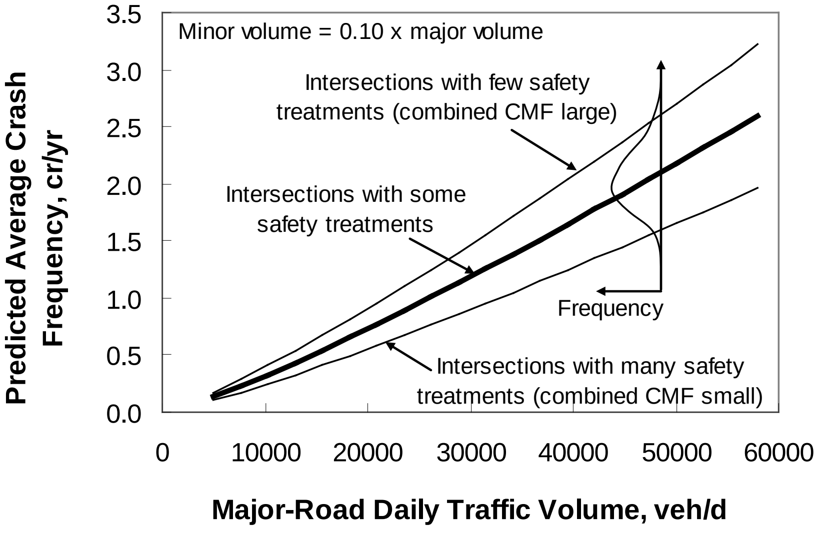


Figure 2. Variation in average crash frequency among intersections.

Figure 2 is based on the urban, three-leg signalized intersection predictive method; however, the trends shown are typical of all of the predictive methods. The thick bold line in the figure illustrates the relationship between predicted average crash frequency and traffic volume for an intersection with some safety treatments (e.g., turn lanes on some approaches, but not all). Many intersections are rationalized to be represented by this line, as suggested by the frequency distribution shown in the figure. Those intersections with a major-road AADT of 26,000 veh/d (and minor-road AADT of 2,600 veh/d) will have a predicted average crash frequency of 1.0 crashes/yr.

The thin line above the bold line in Figure 2 illustrates the relationship for an intersection with few safety treatments (e.g., no turn bays, no lighting, permissive-only left-turn operation). Only a few intersections are rationalized to be represented by this line. Those intersections with a major-road AADT of 26,000 veh/d will have a predicted average crash frequency of 1.25 crashes/yr (i.e., 25 percent more crashes than the intersection with some safety treatments.

The thin line below the bold line illustrates the relationship for an intersection with many safety treatments (e.g., turn bays on all approaches, lighting, protected-only left-turn operation, right-turn-on-red prohibited). Only a few intersections are rationalized to be represented by this line. Those intersections with a major-road AADT of 26,000 veh/d will have a predicted average crash frequency of 0.76 crashes/yr (i.e., 24 percent fewer crashes than the intersection with some safety treatments.

The spread in the trend lines in Figure 2 illustrates the wide range in average crash frequency that may exist at an intersection based on the safety treatments present. This range demonstrates the importance of using a predictive method in the safety evaluation of a specific intersection (as opposed to general-purpose SPFs), where the safety treatments at (or envisioned for) the intersection are accounted for in the estimate of average crash frequency.

This importance of using a predictive method is further illustrated using Figure 3. The two thin trend lines in Figure 2 are reproduced in Figure 3 using thick bold lines. Two dashed lines are also shown in Figure 3. The upper and lower dashed lines represent the safety of stop-controlled intersections with few and many safety treatments, respectively. The region between line pairs represents the likely range within which a given intersection of interest will lie. The fact that the region between the solid lines and the region between the dashed lines overlaps indicates that a signal installation may increase or decrease the average crash frequency. The outcome for a specific intersection will depend on the safety treatments at the existing intersection, and those envisioned for the intersection after signal installation.

To illustrate the previous point, consider an existing stop-controlled intersection represented by the upper dashed trend line in Figure 3. This intersection has a major road with 26,000 veh/d and a minor road with 2,600 veh/d. This intersection has few safety treatments, and a relatively high predicted average crash frequency of 1.15 crashes/yr. It is identified by the small black dot on the dashed line. By comparing the location of this point with the thick bold lines, it can be found that the average crash frequency will increase (to 1.25 crashes/yr) with signal installation if no safety treatments are included with the upgrade. This change is labeled “B” in the figure. In contrast, the average crash frequency is found to decrease (to 0.76 crashes/yr) with signal installation if several safety treatments are included with the upgrade. This change is labeled “A” in the figure.

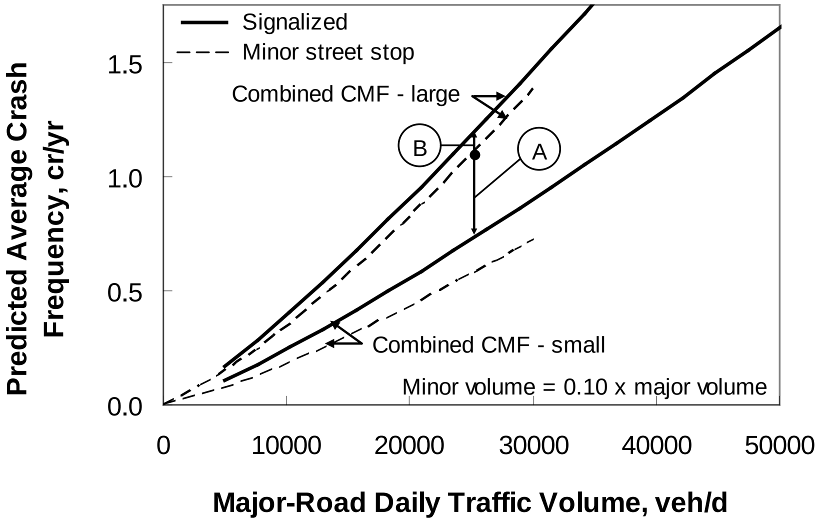


Figure 3. Examination of the effect of signal installation.

Predictive Method Comparison

This section summarizes the findings from a comparison of the predictive methods identified in Table 4. There are two comparisons being made for this discussion. One comparison is between the stop-controlled and signalized intersection predictive methods for common conditions of area type and number of legs. The objective of this comparison is to understand the likely influence of signal installation on safety, as predicted by the HSM methods.

The second comparison is between the HSM predictive methods and the SPFs developed by other researchers for common area types and number of legs. For the urban intersections, the HSM predictive methods are compared to the SPFs developed by McGee et al. (2003). For the rural intersections, the HSM predictive methods are compared to the SPFs developed by Harkey et al. (2008).

The comparisons are shown in the following four figures.

- Figure 4 - fatal-and-injury crashes at urban three-leg intersections.
- Figure 5 - fatal-and-injury crashes at urban four-leg intersections.
- Figure 6 - all crashes at rural four-leg intersections – two lanes on major road.
- Figure 7 - all crashes at rural four-leg intersections – four lanes on major road.

Figure 4a compares the HSM predictive methods for urban three-leg intersections. It suggests that there is a small increase in crash frequency associated with signal installation. However, the range in average crash frequency associated with the safety treatments is large such that the benefit of signalization could be realized if it was accompanied by additional safety treatments (e.g., the use of protected-only left-turn operation). This trend is contrary to the CMF values cited in Table 3. These CMF values suggest that signal installation will reduce crash frequency. However, it may be that the values in Table 3 include the effect of other, unknown safety treatments that were implemented along with the signal installation. This trend also underscores the importance of re-calibrating the SPFs to local conditions.

Figure 4b, Figure 4d, and Figure 4f compare the SPFs from McGee et al. (2003) with those from the HSM in Figure 4a, Figure 4c, and Figure 4e, respectively. These SPFs are specific to fatal-and-injury crashes, so fatal-and-injury crashes were also obtained from the HSM predictive methods to facilitate comparison. The trend lines in Figure 4b do not have the same curvature as those in Figure 4a. This trait is not uncommon when comparing SPFs calibrated using data from different jurisdictions, where local practice varies in terms of the use of (and volume levels associated with) different safety treatments.

The trend lines in Figure 4b cross at a major-street AADT of about 15,000 veh/d. This trend suggests that signal installation will always reduce crash frequency at high AADT volumes. This trend is not evident in Figure 4a, and it may partly reflect the fact that the SPFs in Figure 4b are based on intersections having an unknown mixture of safety treatments—treatment combinations that likely vary with volume level. This trend may also be partly due to the fact that the SPFs in both figures reflect an unknown mixture of intersections with two-lane major streets and four-lane major streets.

Figure 4c indicates that the frequency of right-angle crashes is about the same at stop-controlled and signalized intersections. In contrast, the SPFs in Figure 4d suggest that stop-controlled intersections have significantly more right-angle crashes than signalized intersections. These differences may be due to the same factors as noted for Figure 4a and Figure 4b (i.e., unknown mixture of safety treatments and number of lanes).

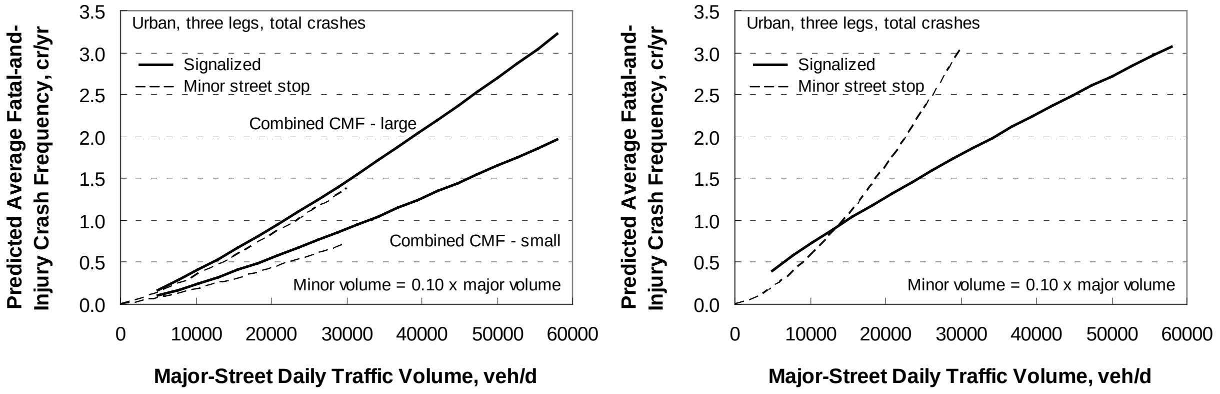
Figure 4e and Figure 4f agree that rear-end crashes at a signalized intersection are nearly twice those at a stop-controlled intersection.

The trends noted for Figure 4 are similar to those for Figure 5. However, the four-leg intersection is shown to have about twice as many crashes as the three-leg intersection.

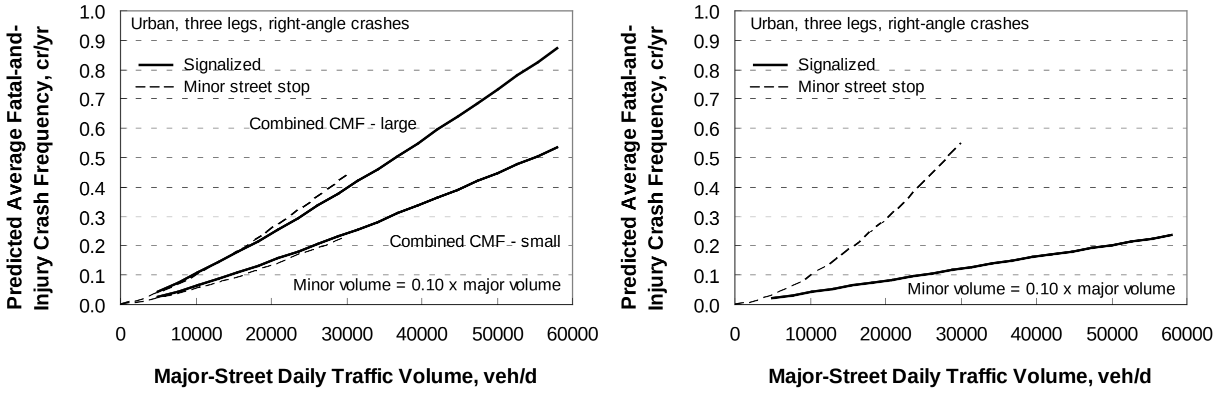
The trends noted for Figure 4 and Figure 5 are similar to those found in Figure 6 and Figure 7. CMFs were not available in the HSM for the rural four-leg signalized intersection with four lanes on the major road. As a result, the two thick bold trend lines for the signalized intersection case in Figure 7 are based on the CMFs used for rural intersections with two lanes on the major road. This modification is applied for the discussion in this chapter; it is not meant to imply that this approach should be used in practice.

Both Figure 6a and Figure 7a suggest that signal installation will significantly increase crash frequency at rural intersections. This trend is contrary to that found for the CMF values in Table 3. As noted previously, it may be that the values in Table 3 include the effect of other, unknown safety treatments that were implemented along with the signal installation.

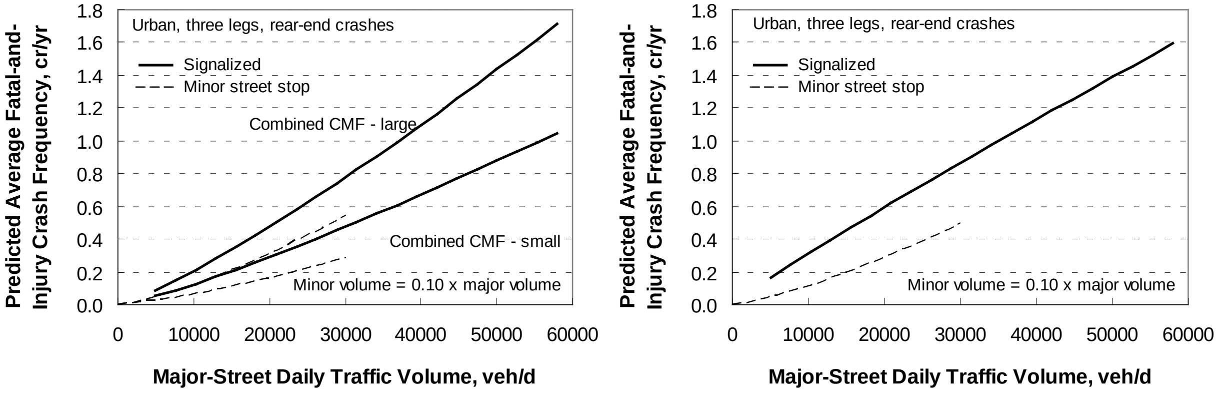
An examination of Figure 6 and Figure 7 indicates there are some inconsistencies between the estimates from the predictive method and the SPFs. For stop-controlled intersections, the predicted average crash frequency from the SPFs by Harkey et al. (2008) is similar in value to that from the HCM methods. However, the SPFs for signalized intersections from Harkey et al. (2008) produce estimates that are much lower than those from the HCM methods.



a. HSM predictive method – all crash types. *b. NCHRP Report 491 – all crash types.*

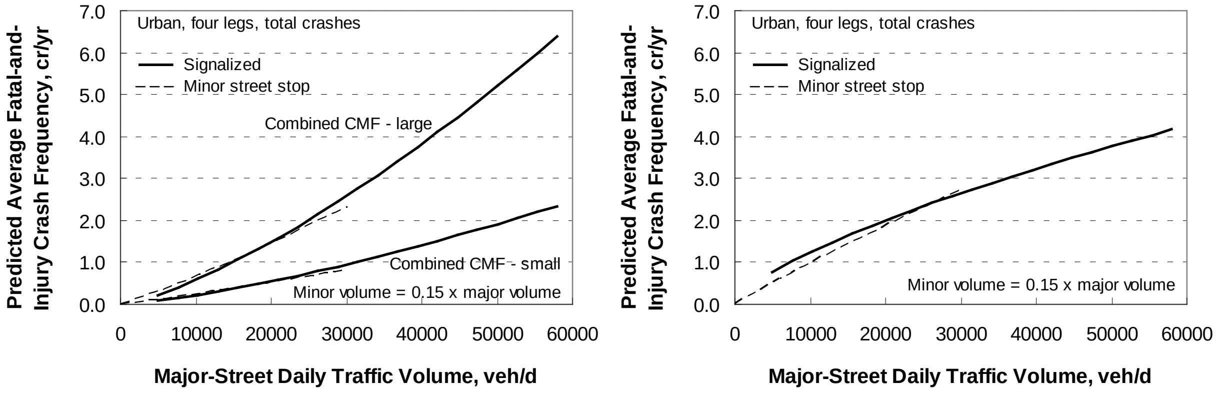


c. HSM predictive method – right-angle crashes. *d. NCHRP Report 491 – right-angle crashes.*



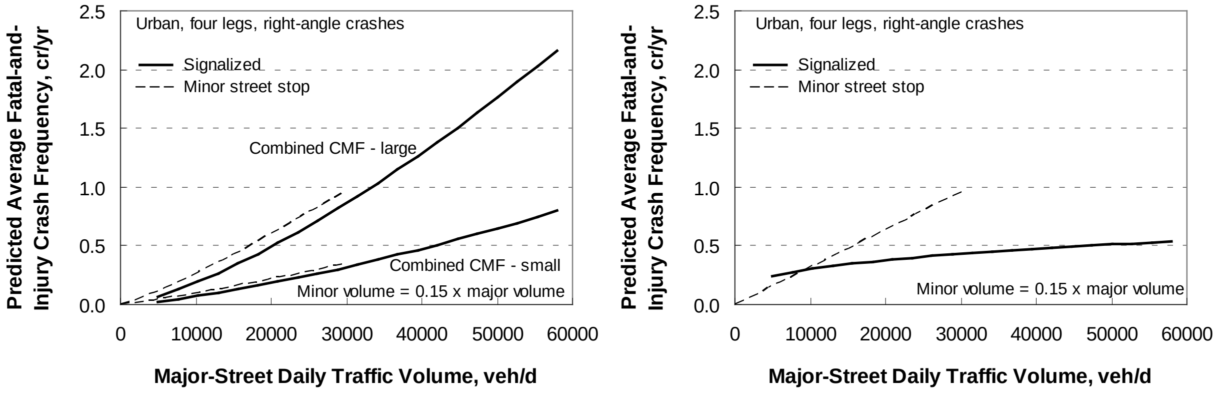
e. HSM predictive method – rear-end crashes. *f. NCHRP Report 491 – rear-end crashes.*

Figure 4. Comparison of fatal-and-injury crashes at urban three-leg intersections.



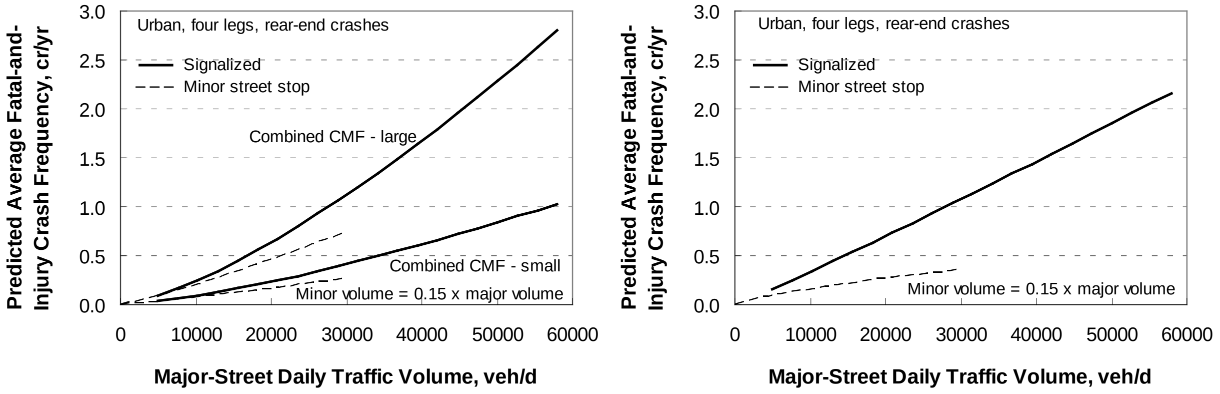
a. HSM predictive method – all crash types.

b. NCHRP Report 491 – all crash types.



c. HSM predictive method – right-angle crashes.

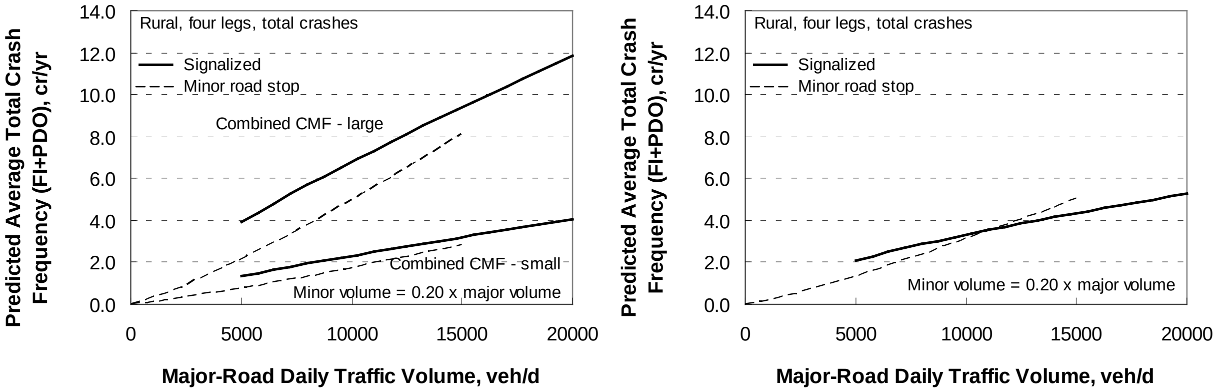
d. NCHRP Report 491 – right-angle crashes.



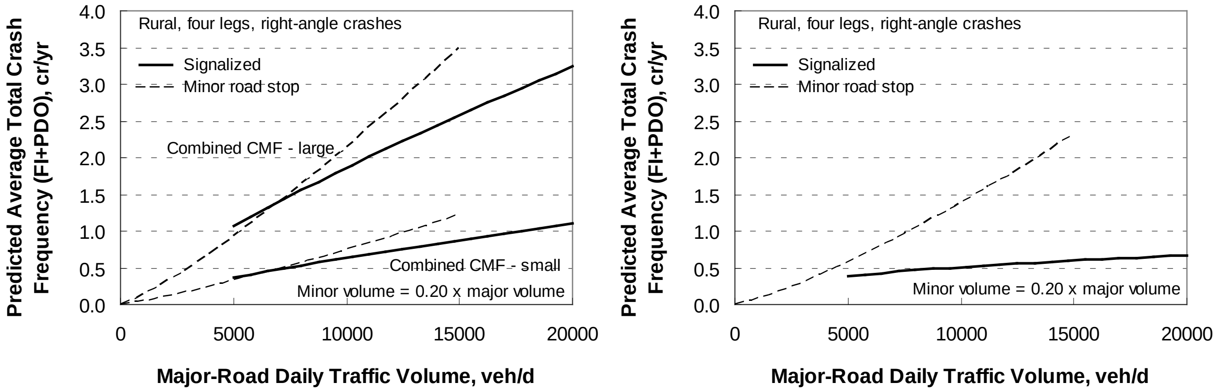
e. HSM predictive method – rear-end crashes.

f. NCHRP Report 491 – rear-end crashes.

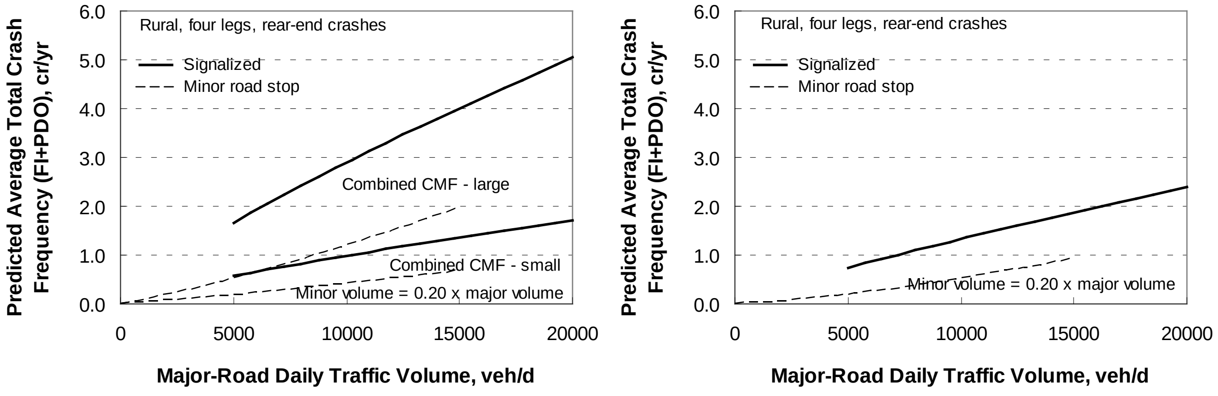
Figure 5. Comparison of fatal-and-injury crashes at urban four-leg intersections.



a. HSM predictive method – all crash types. *b. NCHRP Report 617 – all crash types.*

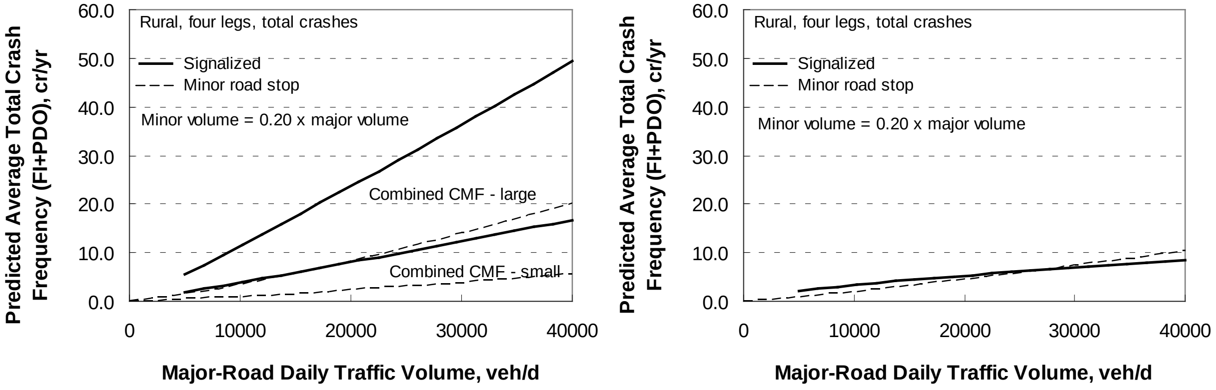


c. HSM predictive method – right-angle crashes. *d. NCHRP Report 617 – right-angle crashes.*



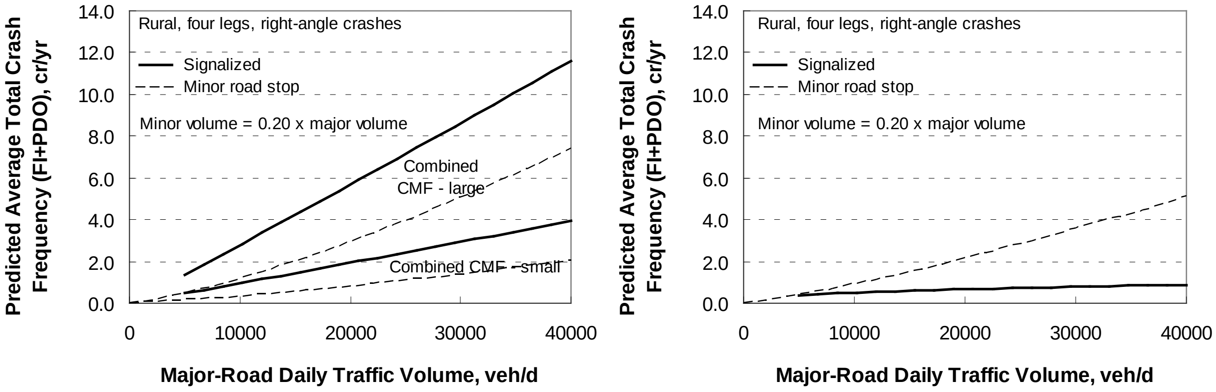
e. HSM predictive method – rear-end crashes. *f. NCHRP Report 617 – rear-end crashes.*

Figure 6. Comparison of all crashes at rural four-leg intersections – two lanes on major road.



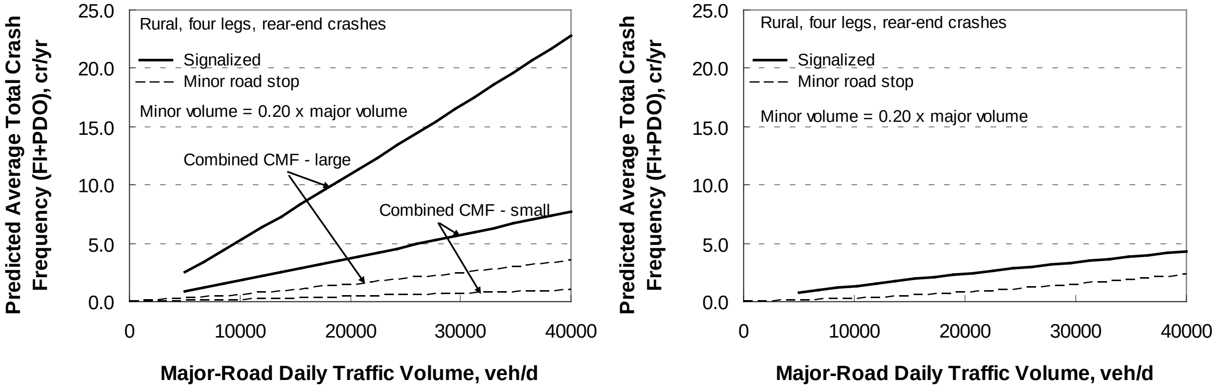
a. HSM predictive method – all crash types.

b. NCHRP Report 617 – all crash types.



c. HSM predictive method – right-angle crashes.

d. NCHRP Report 617 – right-angle crashes.



e. HSM predictive method – rear-end crashes.

f. NCHRP Report 617 – rear-end crashes.

Figure 7. Comparison of all crashes at rural four-leg intersections – four lanes on major road.

Alternatives to Signalization

There are a variety of treatments that can be considered at an unsignalized intersection as an alternative to signalization. This section discusses those treatments that address safety concerns at intersections with stop control on the minor road. The focus is on treatments with a quantified effect on safety. These treatments are summarized in Table 5.

Table 5. Alternatives to signalization.

Treatment	Effect	Comment
Transverse Rumble Strips (TRS)[1]	1% reduction in fatal-and-injury crashes and 19% increase in PDO crashes at three- and four-leg intersections.	Shift in crash types from fatal/injury to PDO observed, with unknown cause.
STOP AHEAD Pavement Markings[2]	Reduction of 31.1% in total crashes.	Likely most effective at locations with a high frequency of right-angle and rear-end collisions.
Flashing Beacons[3]	Reductions of 13.3% in angle crashes and 10.2% in fatal-and-injury crashes (point estimate).	Likely most effective at rural locations and locations with high frequency of target collisions.
Provide left-turn lanes on major road at intersection[4]	22% reduction of total crashes at three-legged intersection, and 24% reduction at four-legged intersections with addition of left-turn lane on one major road approach.	Installation of left-turn lanes on both major-road approaches expected to increase, but not quite double, the effectiveness of treatment.
Provide right-turn lanes on major road at intersection[4]	5% reduction at three-legged and four-legged intersections for a right-turn lane on one major road approach. 10% reduction for right-turn lanes on both major road approaches.	Unlikely to provide substantial safety benefits if right-turn lane is not operationally justified based on right-turning volumes or crash history.
Realign intersection to reduce or eliminate intersection skew[4,5]	For rural two-lane highways: CMF = exp(0.0040 SKEW) for three-legged intersections and CMF = exp(0.0054 SKEW) for four-legged intersections, where SKEW = 90 – intersection angle in degrees.	Most successful at intersections with crash patterns related to intersection angle (i.e., right-angle or turning collisions).
Improve visibility of the intersection by providing lighting[4]	25 to 50% reduction in the nighttime crash/total crash ratio.	Lighting makes drivers more aware of intersection, enhances available sight distances, and improves the visibility of non-motorists.
Provide all-way stop control at appropriate locations[5]	May reduce total crashes by 47% at rural intersections, and injury crashes by 70% at urban intersections.	This strategy should be used selectively at intersections with moderate and relatively balanced volumes on approaches.
Provide roundabouts at appropriate locations[5]	May reduce total crashes by 44% and injury crashes by 82%.	Construction of a roundabout would typically be a major project, and thus may be a long-term solution.
Replace direct left-turn with right-turn/U-turn[5]	May reduce total crashes by 20%, and injury crashes by 36%.	A directional median is typically used to eliminate left-turns off of the minor street.
Increase intersection median width[5]	May reduce multiple-vehicle crashes by 4% at rural unsignalized intersections. May increase multiple-vehicle crashes by 3 to 6% at urban and suburban intersections.	Data based on increasing existing median by 3-ft increments. Proportion change in crashes is multiplied for each 3-ft increase in width.

Notes:

Sources: 1 – Srinivasan et al. (2010). 2 – Gross et al. (2007). 3 – Srinivasan et al. (2010). 4 – Neuman et al. (2003). 5 – AASHTO (2010).

Some treatments are identified in the MUTCD, and are listed in the Background section. Numerous other publications identify treatments and their anticipated effectiveness. The information in these publications is summarized in this section. The intent of the discussion is to identify many of the treatments that might be considered instead of a signal, and their reported effectiveness. It is recognized that the list of treatments may not be complete.

As noted by Neuman et al. (2003), a key step in implementing effective safety treatments is first identifying and defining the safety problem to be addressed. Crash records, roadway inventories, medical data, driver-licensing data, citation history, and local knowledge can help in this process. In order to maximize the effectiveness of the treatments in Table 5, they should be applied selectively to address the identified safety problem.

Summary

Section 4C.01 of the MUTCD states that, "A traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection." However, there is no guidance offered in the MUTCD as to how the overall safety impact of the signal installation can be quantified so as to ascertain whether safety has been improved.

The MUTCD provides a crash experience warrant that serves as a first step of the engineering study process. Satisfaction of the crash experience warrant is an indication of likely safety improvement through signal installation. Once the warrant is met, the subsequent steps of the engineering study are then undertaken to confirm that signal installation will improve overall safety.

The crash experience warrant focuses on crashes that are susceptible to correction by signal installation. Table 6 provides examples of crashes that are susceptible to correction (and those that are not).

Table 6. Crashes susceptible to correction by signal installation.

Crash Types Susceptible to Correction	Crash Types Not Susceptible to Correction
Right-angle vehicle crashes	Rear-end crash
Right-angle pedestrian crashes	Sideswipe crash
Parking crashes	Head-on crash
Opposed turning vehicle crashes (if protected)[1]	Opposed turning vehicle crashes (if permissive)[1]
Turn-related pedestrian crashes (if protected)[2]	Turn-related pedestrian crashes (if permissive)[2]

Notes

1 - This crash type is correctable if the turn movement at the newly signalized intersection is served at a different time in the cycle than the conflicting through movement (e.g., protected-only turn mode). If the turn is served at the same time as the conflicting through movement, then it is not correctable (e.g., permissive-only turn mode).

2 – This crash type is correctable if the turn movement at the newly signalized intersection is served at a different time in the cycle than the conflicting pedestrian movement (e.g., protected-only turn mode). If the turn is served at the same time as the conflicting pedestrian movement, then it is not correctable (e.g., permissive-only turn mode). The conflicting pedestrian movement is that movement associated with the crosswalk that is crossed by the turning vehicle as it exits intersection (i.e., as it completes the turn).

Two procedures have been developed for quantifying the safety effect of signal installation (McGee et al. 2003; Hadayeghi et al. 2006). Both procedures require AADT data for the major and minor roads as well as crash data for one or more recent years. Both procedures can be applied using a hand calculator, but development of a spreadsheet tool that automates the procedure would likely facilitate implementation. Both procedures consider total intersection crashes and key intersection crash types. They do not focus on just those crashes that are susceptible to correction by a signal installation, unlike the crash experience warrant.

There are many geometric design elements and traffic control features that influence intersection safety. Some of these elements and features are also added or modified along with the signal installation, as shown in Table 1. The safety effect of many elements and features has been quantified through research (see Table 2). This effect is typically quantified as a crash modification factor (CMF). The predictive methods in Part C of the HSM include several of these CMFs, but not all. The safety effect of these features and elements (before and after signal installation) should be considered in the engineering study to obtain an accurate estimate of the overall change in safety following signal installation.

Many research projects have been undertaken over the last 50 years with the objective of quantifying the safety effect of signal installation. However, for a variety of reasons, there is still considerable uncertainty about this effect, especially when evaluating a specific intersection. Almost all studies have shown that signal installation reduces crash frequency; however, the researchers did not control for the regression-to-the-mean tendency or for other changes to the intersection's geometric design elements or traffic control features. As a result, most of these research results include an unknown combination of effects, such that the effect of signal installation cannot be accurately estimated.

Safety predictive methods are documented in Part C the HSM. Each predictive method consists of an SPF and several CMFs, where the CMFs are used to quantify the safety effect of selected geometric design elements and traffic control features (AASHTO, 2010). In contrast, both of the aforementioned safety evaluation procedures are based on the use of general-purpose SPFs, as opposed to predictive methods. The estimates from general-purpose SPFs are less reliable than those obtained from the predictive method because the safety effect of the elements and features of the existing and proposed signalized intersection are not represented in the calculations (i.e., by CMFs, or other methods).

The HSM predictive methods do not address rural, three-leg signalized intersections. As a result, the HSM cannot be used for a safety evaluation of signal installation at a rural, three-leg intersection. Also, the predictive method for rural, four-leg signalized intersections does not include any CMFs.

CHAPTER 3

Practitioner Survey Summary

Introduction

This chapter summarizes the findings from a practitioner survey focused on experience with the crash experience warrant and potential opportunities to improve it. Practicing engineers were surveyed about their experience with the crash experience warrant and its potential for improvement. This chapter provides an interpretation of the survey results, specifically related to findings that were used in Chapter 4 to develop the proposed crash experience warrant. A complete listing of the survey results is provided in Appendix A.

The survey consisted of three parts. The first part examined the factors considered during the typical engineering study. The second part focused on practitioner experience using the crash experience warrant. The third part inquired about potential improvements to the warrant. The findings associated with each part are separately described in the next three sections of this chapter. SurveyMonkey, an online tool, was used to conduct the survey and collect responses.

The survey was distributed to over 250 individuals, who were selected to represent a broad range of agencies and geographies. Three or more engineers in each of the 50 states were selected. These engineers were primarily affiliated with a local or state agency; however, some consulting engineers were also included in the distribution.

The candidate survey participants were contacted on July 1, 2013 and requested to provide a completed survey by July 26, 2013. A total of 129 responses were received. Seventy-eight of the respondents identified the agencies with whom they are affiliated, which include approximately 25 state DOTs, 5 counties, and 30 cities and towns.

Engineering Study for Signal Installation

The first part of the survey collected information about the engineering study that is undertaken when considering traffic control signal installation. The need for this study is specified in Part 4 of the MUTCD. This document advises that a traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection (FHWA, 2009).

Agency-Specific Guidance for Engineering Study

Fifteen of 116 survey respondents indicated that the agency for whom they work has a document that describes the steps involved in the engineering study process. Several agencies cited their use of the process in state-specific versions of the MUTCD (such as Texas, California, and Minnesota). Others cited their use of *NCHRP 457, Evaluating Intersection Improvements: An Engineering Study Guide* (Bonneson and Fontaine, 2001) and the HSM (AASHTO, 2010). The agency-specific documents were reviewed, with particular attention devoted to guidance related to the crash experience warrant. Common themes addressed by the agency documents are identified in the following list.

- Identification of crash types susceptible (and not susceptible) to correction by a traffic signal;
- Additional warrants for traffic signals beyond those in the MUTCD;
- Need for quantitative safety evaluation, e.g. using HSM or other crash predictive methods; and
- Process for conducting and documenting the traffic signal warrant analysis.

Several of the documents cited by agencies are discussed in the following sections.

Intersection Control Evaluation (Minnesota DOT)

The Minnesota DOT has developed the Intersection Control Evaluation (ICE) process to identify the best intersection control through a "comprehensive analysis and documentation of the technical (safety and operational), economic, and political issues of viable alternatives" (Minnesota DOT, 2007). The complete ICE process includes the following phases:

1. Scoping
2. Alternative Selection
3. Approval & Report

The Minnesota DOT provides additional mitigating factors beyond the warrants in the MUTCD to consider when determining if a signal installation is justified, such as access spacing guidelines and lane geometrics. In addition, it recommends an estimate of crash frequency be completed for each traffic control alternative to determine the impact of each alternative as accurately as possible. The estimate of future crashes should be obtained using crash rates or a more thorough crash reduction methodology.

Traffic Operations Handbook (City of Phoenix)

The City of Phoenix Street Transportation Department has designed a software program named SIGWAR as a tool to help "duplicate engineering judgment and compare multiple candidate locations on a relatively consistent basis" (City of Phoenix, 2009). The purpose of the tool is to evaluate and rank intersections on their potential for signalization based on the factors in the MUTCD. The tool refines some MUTCD warrants to consider such conditions as "proximity of schools, traffic volumes in excess of MUTCD minimum values, correctable crashes exceeding MUTCD criteria, intersection spacing for synchronization, speeds, and other factors deemed relevant" (City of Phoenix, 2009). The City of Phoenix traffic operations handbook stresses that meeting a warrant does not mean that a signal should be installed, but that the location deserves further consideration and study.

California Manual on Uniform Traffic Control Devices (Caltrans)

The California DOT (i.e., Caltrans) adopted the California MUTCD to provide uniform standards and specifications for all traffic control devices in California (Caltrans, 2012). The California MUTCD includes the FHWA's 2009 MUTCD, as well as policies specific to California. Section 4B of the document includes California policies that require the development of a project report for locations where a new traffic signal is to be installed. It recommends including the following items in the project report:

- Traffic counts for the average day (vehicular and pedestrian)
- Collision diagram (for a three-year period)
- Condition diagram (showing existing intersection roadway conditions)
- Improvement diagram (showing existing and proposed signals, phasing, and channelization)
- Cost estimate (and proposed method of funding)
- Other specialized data (e.g., classification of vehicles, critical speed, time-space diagram)

Section 4C of the California MUTCD includes the traffic signal warrants from the FHWA's MUTCD, with slight modifications. It also includes criterion for school crossing traffic signals, a bicycle signal warrant, and a traffic signal warrants worksheet.

Safety Effect of Signalization

The crash experience warrant in the 2009 MUTCD specifies criteria that, if met, justify further consideration for a traffic signal. This further consideration includes an engineering study that is used to determine whether the signal installation will improve the overall safety and/or operation of the intersection.

The survey asked respondents about the data or techniques used to assess the safety effect of installing a signal that are in addition to the check of the crash experience warrant. The survey responses indicate that just over 44 percent of respondents use additional data or techniques. The following list characterizes the most common kinds of comments received from respondents who identified the data or techniques used:

- Consider the distribution of crash types, including those types that may increase with a signal (9 responses).
- Produce a collision diagram and/or look for patterns in crash locations. (6 responses)
- Use the HSM or typical crash rates to compute predicted crash frequency. (6 responses)
- Perform a site visit to identify potential crash causes. (5 responses)
- Read crash narratives to determine crash location and type. (5 responses)
- Assess intersection sight lines. (5 responses)

Respondents most commonly cited considering the distribution of crash types, specifically to assess whether a signal will address the prevailing crash types or whether a different mitigation is more appropriate considering the context of the intersection. Six respondents noted that they produce a collision diagram or look for patterns in crash location, which was also recommended by several of the agency-specific guidance documents cited in the survey.

The use of crash modification factors and the HSM was cited by several respondents as a tool to assess the likely safety impacts of installing a traffic signal.

To further assess the viability of a signal, several respondents indicated that they perform a site visit or read the individual crash narratives. Several respondents cited issues interpreting crash data, and the necessity of thoroughly assessing crash reports and narratives. As noted by one respondent, reviewing the crash narratives can help "identify the real crash causes to see if signals will improve the safety at the individual intersection."

When asked whether they experienced any difficultly determining which crashes are of a type susceptible to correction by a signal, approximately 15 percent of responses said "yes." A couple respondents indicated the need for a standardized description of the types of correctable crashes. This description is not currently available in the MUTCD. As discussed earlier, the *Traffic Control Devices Handbook* (ITE, 2001) provides a list of crashes that are susceptible to correction (and those that are not). This list was provided previously in Chapter 1.

Several of the survey responses reflected on the difficulty of using the frequency of specific crash types as a basis for evaluating intersection safety. Their comments are provided in the following list.

- "Some crashes such as rear-end incidents at a stop location may be exacerbated by installation of a signal if sight distance is limited and/or if queue [lengths] change."
- "We usually use angle and turning crashes (mostly left if we will be adding a left turn phase)"

- "Too easy to dismiss fixed-object collisions that may have been related to evasive actions taken to avoid a collision."
- "Officers typically have difficulty determining whether a crash is an angle or a left turn same road. This is critical in solving the safety issues as the solutions for these two are not similar."

These survey responses indicate the necessity of more thoroughly examining crash reports to assess the location, direction, and type of crash. Engineering judgment is frequently applied to evaluate whether a traffic signal will address the predominant crash types, and to consider any crash types that may increase.

Alternatives to Signal Installation

The survey asked practitioners about alternatives (to a traffic control signal) they have found to be most effective at improving safety at stop-controlled intersections. The options provided were taken from the guidance in the MUTCD related to alternatives to traffic control signals (in Section 4B.04). The MUTCD notes that "since vehicular delay and the frequency of some types of crashes are sometimes greater under traffic signal control than under STOP sign control, consideration should be given to providing alternatives to traffic control signals even if one or more of the signal warrants has been satisfied" (FHWA, 2009).

The alternatives identified in the MUTCD are listed in Table 7. They are listed in order, from most effective to least effective based on the responses received.

Table 7. Alternatives to signalization responses.

Treatment	Respondents that Selected
Relocating the stop line(s) and/or making other changes to improve the sight distance at the intersection	58.1% (61)
Installing a roundabout	49.5% (52)
Installing multi-way STOP sign control	46.7% (49)
Installing signs along the major street to warn road users approaching the intersection	45.7% (48)
Revising the geometrics at the intersection to channelize vehicular movements	36.2% (38)
Installing a flashing beacon at the intersection to supplement STOP sign control	35.2% (37)
Restricting one or more turning movements	35.2% (37)
Installing roadway lighting	34.3% (36)
Installing flashing beacons on warning signs in advance of a STOP sign controlled intersection on major and/or minor-street approaches	30.5% (32)
Installing measures designed to reduce speeds on the approaches	20.0% (21)
Revising the geometrics at the intersection to add pedestrian median refuge islands and/or curb extensions	20.0% (21)
Adding one or more lanes on a minor-street approach	15.2% (16)
Installing a pedestrian hybrid beacon or In-Roadway Warning Lights	11.4% (12)

The alternative to signalization that was found to be most effective by the survey respondents was "relocating the stop line(s) and/or making improvements to sight distance." Approximately half of the respondents indicated that "installing a roundabout" was found to be effective at improving safety. Just under half of respondents selected "installing multi-way STOP sign control" as an effective treatment for improving safety at two-way stop controlled intersections.

In addition to the treatment options from the MUTCD listed in Table 7, respondents were given the option to indicate other treatments they have found to be most effective. Responses are identified in the following list.

- Interactive warning systems to warn minor-street of approaching main line traffic (2 responses)
- Improving sight-distance by relocating/removing vegetation (recurring sight-distance obstruction) (2 responses)

Experience with the Crash Experience Warrant

When asked to provide any additional comments on the crash experience warrant, seven survey respondents noted that it is rarely used alone to justify a signal. This is consistent with the survey of practitioners conducted by Carlson and Hawkins (1998), as discussed in Chapter 2. Several respondents also stressed the fact that meeting a warrant is not sufficient reason to install a signal, and that engineering judgment needs to be used in addition to the MUTCD warrants. The survey asked respondents several questions related to their experience with the existing crash experience warrant. The responses to these questions are summarized in the next two subsections.

Issues with Crash Data

The survey indicated that just over a third of respondents experienced difficulty in determining which crashes are related to an intersection (and which are not). The respondents that indicated difficulty were asked the follow-up question, “Would guidance regarding the use of crash location and crash type to determine intersection relationship help here?” Approximately half the respondents indicated guidance would be helpful. The others commonly cited the following sources of difficulties in determining which crashes are related to the intersection:

- Inaccurate or incomplete data, particularly related to the crash location. (17 responses)
- Differences between how law enforcement may define a crash type and how engineers seeking a countermeasure categorize the same crash. (3 responses)

Warrant Evaluation

The survey asked respondents to assess how consistent the crash experience warrant is with practitioner’s engineering judgment. About 83 percent of the respondents indicated that the decision reached from the warrant evaluation was consistent with their judgment. Of the 17 percent of respondents that expressed inconsistencies between the crash experience warrant evaluation and their judgment, the following situations were most commonly cited as producing inconsistent results:

- The crash experience warrant does not account for “close calls,” particularly with vulnerable users (bicyclists and pedestrians). (2 responses)
- Rural/Suburban areas where the peak use periods are short. (2 responses)
- Intersections outside a 10,000 population center or with higher speed limit satisfy warrants (based on crash or volume) satisfy the warrant more often than seems reasonable.(2 responses)

Several respondents noted that, as specified in the MUTCD, meeting the crash warrant does not mean that a traffic signal should be installed, but that it should be considered. One respondent noted that “Although the MUTCD has improved the clarity of the engineering judgment requirement, we continue to educate professionals and the public whenever there is a request for a traffic signal.” Several of the agency-specific documents reviewed also stressed the importance of applying engineering judgment and/or conducting a thorough engineering study to assess the appropriateness of a traffic signal.

Potential Improvements to the Crash Experience Warrant

The survey inquired about whether the respondent believes that usefulness of the crash experience warrant could be improved. The responses received indicated that just over half of respondents think the usefulness of the crash experience warrant can be improved and 12 percent think the crash experience warrant could be made easier to apply. This finding is consistent with a similar survey of practitioners conducted by Carlson and Hawkins (1998). The next two subsections summarize the survey findings related to potential improvements.

Additional Factors to Consider in Warrant

The current MUTCD Warrant 7 – Crash Experience includes three criterion that must be satisfied. These criterion are identified in the following list.

- Criterion A that addresses the trial of non-signal alternatives,
- Criterion B that addresses crash history in terms of the crash types susceptible to correction involving injury or property damage that occur during a 12-month period, and
- Criterion C that includes the evaluation of both Warrant 1 (Eight-Hour Vehicular Volume) and Warrant 4 (Pedestrian Volume) at the 80-percent volume level.

The survey asked participants what factors should be considered in the crash experience warrant, in addition to (or instead of) those factors addressed in Criteria B and C. The responses are listed in Table 8.

Table 8. Additional factors to consider in the crash experience warrant.

Factor	Respondents that Selected
A longer crash history (e.g., 24-months, 36-months, etc.)	72.0% (77)
Average daily volume (not just during the hours specified by Warrants 1 and 4)	34.6% (37)
Heavy vehicle volume (or percentage)	34.6% (37)
Other crash types (not just those susceptible to correction)[1]	19.6% (21)
Bicycle volume	15.0% (16)
Only fatal-and-injury crashes (i.e., exclude property damage only)	11.2% (12)

Notes:

1 – Of those respondents that indicated “other crash types” should be considered, the majority indicated a preference for considering “all crash types” (i.e., those crashes that are susceptible *and* those that are not susceptible to correction by traffic control signal installation).

The most frequently selected factor was a longer crash history, with 77 of the 107 respondents selecting this response. This sentiment was also echoed later in the survey, with 18 of the 50 respondents indicating that they think the usefulness of the crash experience can be improved by evaluating multiple years of crash data (as opposed to one 12-month period). About a third of respondents indicated that annual average daily volume (AADT) and heavy vehicle volume should be included in the crash experience warrant. Respondents were also given the option to indicate other factors to consider. The most commonly cited responses are identified in the following list.

- Approach speed or roadway travel speeds (3 responses)
- 4-hour warrant and peak hour warrant (2 responses)
- Turning movements (particularly if signal would include left-turn arrow phasing) (2 responses)

Other Improvements to Warrant

The survey asked practitioners whether they think the usefulness of the crash experience warrant can be improved, with over half of respondents answering in the affirmative. Potential improvements offered by these 50 respondents are identified in the following list.

- Evaluate multiple years of crash data (18 responses).
- Provide description and examples of correctable and uncorrectable crash types (4 responses).
- Incorporate the HSM, expected crash frequency, and/or crash rate (4 responses).
- Include warrants for alternative safety treatments (i.e. installing advance beacons) (3 responses).
- Revisit the traffic volume criteria related to speeds and population (3 responses).
- Weight the crashes by severity (2 responses).

As reflected in the list above, a significant number of practitioners that responded to the survey think that the crash experience warrant should evaluate multiple years of data.

Four respondents indicated that they think using the HSM to estimate the expected crash frequency would improve the usefulness of the crash experience warrant.

Several respondents indicated that it would be useful to include warrants for alternative safety treatments. The *Traffic Engineering Manual* developed by the Pennsylvania DOT (2013) includes warrants for intersection control beacons and guidance for advanced warning beacons/flashers, internally illuminated advanced warning signs, in-roadway warning lights, and rectangular rapid flashing beacons.

Several respondents indicated that the volume threshold adjustments related to major-street speed and population (in Criterion C) should be revised when used with the crash experience warrant. Specifically, these respondents indicated that these adjustments result in volume thresholds that are too low.

Two survey respondents suggest that the crash experience warrant consider crashes by severity. This desire for consideration of crash severity in the warrant was also identified in the survey by Carlson and Hawkins (1998), as described in Chapter 2.

Summary

The findings of the survey indicate that over half of engineering practitioners believe that the crash experience warrant can be improved. Many of the respondents favored revision of the warrant to consider a longer crash history, and the entire distribution of crashes (not just those susceptible to correction). It was frequently noted that crash data are incomplete and inaccurate (relative to crash location). For this reason and others, the use of the HSM method to estimate the expected crash frequency is recognized as a viable option for the engineering study. A number of practitioners are already applying the HSM or other techniques to produce a quantitative estimate of whether a signal installation will improve the overall safety of an intersection.

CHAPTER 4

Safety Evaluation Procedure

Introduction

This chapter documents the research conducted to develop an intersection safety evaluation procedure. This procedure was developed to facilitate the evaluation of the safety effect of traffic control signal installation at a stop-controlled intersection.

The first section describes the development of a procedure for intersection safety evaluation. The second section describes the research conducted to develop the tools needed to implement the procedure.

Development of a Safety Evaluation Procedure

This section describes the development a safety evaluation procedure. The elements of the procedure were determined from a review of the literature (documented in Chapter 2), the findings from a survey of practitioners (documented in Chapter 3), discussion with the National Committee on Uniform Traffic Control Devices (NCUTCD) Signals Technical Committee, and guidance from the project panel. The procedure is based on that developed by McGee et al. (2003), but it uses the predictive methods described in Part C of the HSM (AASHTO, 2010).

The first subsection to follow outlines the approach and scope of the safety evaluation procedure. The second subsection provides an overview of the procedure in terms of its input data requirements and analysis steps.

Approach and Scope of Safety Evaluation Procedure

The safety evaluation procedure is intended to provide: (1) an estimate of the safety of an existing two-way stop-controlled intersection, and (2) an estimate of the safety of this intersection if a traffic control signal were installed. By comparing these two estimates, some insight is obtained about the effect of the signal installation on traffic safety. The estimates obtained from the procedure were used to determine appropriate criteria for the crash experience warrant.

Safety Estimation

The predictive methods in the HSM were used as the basis for the safety evaluation procedure. These methods can be used to estimate the average crash frequency of the intersection as one measure of traffic safety. Specific estimates can be obtained for a wide range of configurations, crash severity categories, and crash type categories. Each predictive method includes safety performance functions (SPFs) and crash modification factors (CMFs). The CMFs can be used to refine the estimate based on consideration of geometric elements and traffic control features that have a quantified effect on safety.

A second measure of traffic safety is the road-user crash cost. This cost is computed by summing the product of average crash frequency and average cost per crash for each crash-type and severity category. In this regard, it is recognized that a location with several severe crashes is considered less safe than a location with an equal number of crashes but none of which are severe.

Crash Categories

Several safety performance measures are obtained through application of the procedure. Specifically, estimates of average crash frequency are obtained for two crash severity categories and three crash type categories. The severity categories are defined to include fatal-and-injury (FI) and property-damage-only (PDO) crashes. Injury crashes include all crashes with an incapacitating injury, non-incapacitating injury, or possible injury. This sensitivity to crash severity recognizes that a traffic control signal installation can cause a shift in the crash severity distribution (i.e., an increase in the percentage of PDO crashes). The need for this sensitivity was identified in the survey of practitioners and in discussions with the NCUTCD Signals Technical Committee.

It is difficult to develop statistically valid models for predicting fatal or incapacitating injury crash frequency because of the relative rarity of these crashes. However, reliable models have been developed to predict the combined frequency of FI crashes. In fact, Chapter 12 of the HSM includes separate models for predicting FI crash frequency and PDO crash frequency for urban intersections (AASHTO, 2010).

The crash type categories typically influenced by signal installation include angle crashes and rear-end crashes. All other crash types are considered to be “other crashes.” This category includes all intersection-related crashes that are not angle or rear-end crashes. These crashes can be categorized as single-vehicle crashes or multiple-vehicle crashes. Single-vehicle crashes can involve a vehicle and a pedestrian, or a vehicle and a bicyclist. Angle crashes involve 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. These three crash type categories are recognized in Part C of the HSM. They are also the categories recommended by McGee et al. (2003) for evaluating the safety effect of signal installation.

The procedure’s sensitivity to crash type category recognizes that a traffic control signal installation can cause a shift in the crash type distribution. This tendency is acknowledged in the MUTCD, which indicates that only some crash types are susceptible to correction by signal installation. The literature review indicated that angle crashes and rear-end crashes are the most common crash types to show a change in distribution proportions with the installation of a signal.

The proportion of left-turn-opposed crashes may also change if a left-turn phase is included in the signal installation. However, left-turn-opposed crashes tend to be reported differently among agencies, and are difficult for enforcement officers to identify in the field (McGee et al., 2003). Also, the HSM predictive methods do not specifically address left-turn-opposed crashes. For these reasons, the procedure does not explicitly address left-turn-opposed crashes.

Crash Severity Index

The procedure described in NCHRP Report 491 includes consideration of crash cost. Crash cost is also included in the procedure was documented in Appendix B of NCHRP Report 617 (Harkey et al., 2008). The consideration of crash cost recognizes (1) that signal installation tends to influence the crash type and crash severity distributions, and (2) there are significant differences in severity associated with typical rear-end and angle crashes. The crash costs that Harkey et al. used in their analysis are summarized in the top half of Table 9 (i.e., in the rows associated with a rural area type).

The crash costs shown in Table 9 were developed by Council et al. (2005). They represent “comprehensive” costs because they include human capital costs associated with a crash (i.e., medical cost, emergency services costs, property damage costs, and lost productivity costs) plus a monetary estimate of the reduced quality of life suffered by the victim and his or her family. If a crash cost is available for each K, A, B, C, and PDO severity category, then the costs associated with FI crashes can be computed as a weighted average of the cost for the K, A, B, and C categories, where the weight used is the proportion of crashes associated with each category.

Table 9. Unit crash costs.

Area Type	Control Type	Severity Level	Crash Cost by Crash Type[1], dollars	
			Angle	Rear End
Rural (speed limit of 50 mi/h or more)	Signal	Fatal or injury	126,878	52,276
		Property damage only	8,544	5,901
	Stop	Fatal or injury	199,788	34,563
		Property damage only	5,444	3,788
Urban (speed limit of 45 mi/h or less)	Signal	Fatal or injury	64,468	44,687
		Property damage only	8,673	11,463
	Stop	Fatal or injury	80,956	56,093
		Property damage only	7,910	12,295

Note:

1 – Source: Council et al. (2005). Costs are in 2001 dollars.

The conversion of crash frequency to annual crash cost was viewed by Harkey et al. (2008) as a rational and effective method for comprehensively assessing the effect of signal installation on safety. With this approach, the estimated crash frequency associated with each crash type and severity category for the two-way stop-controlled intersection is converted into an annual crash cost. The estimated crash frequency for the proposed signalized intersection is converted in a similar manner. The difference in the annual crash costs for the existing and proposed intersections represents a single-valued indication of the change in safety associated with the signal installation.

The conversion of crash frequency into cost has some negative perception issues because it monetizes the value of human life. Nevertheless, it has been a viable basis for making investment decisions, and it is often an important component of engineering alternative analysis. Moreover, when it is used solely to provide a single-valued indication of a change in safety, the computed cost can be converted into a severity index value by dividing the cost by a constant and dropping the units of dollars from the resultant quantity. This unit-less severity index provides the same relative information as crash cost but without conveying the value placed on life and limb.

After conversion to signal control, an intersection can have an average crash frequency that is larger than that of the stop-controlled intersection prior to conversion, even with no change in traffic volume. This result can occur when the increase rear-end crashes exceeds the decrease in angle crashes associated with signal installation. However, the converted intersection may still be associated with a lower annual crash cost because rear-end crashes tend to have a lower severity and cost than angle crashes. In this regard, the conversion to signal control is still considered to have improved the safety of the intersection.

Procedure Scope

The safety evaluation procedure was developed to have a broad scope in terms of the types of intersection configurations that can be evaluated and the types of crashes considered. A broad scope was needed to ensure that the proposed crash experience warrant is applicable to most intersections. Table 10 identifies the scope elements.

Table 10. Scope elements for the safety evaluation procedure.

Element	Conditions
Control types	Two-way stop control converted to signal control
Area type	Urban, rural
Major road through lanes	2, 4
Intersection legs (and travel directions)	3, 4 (each leg serves two-way traffic)
Crash severity categories	Fatal-and-injury (FI), property damage only (PDO)
Crash type categories	Angle, rear-end, other

Several of the scope elements are dictated by the capabilities of the HSM predictive methods. Notably, the number of through lanes on the major road is currently limited to a maximum of four by the HSM.

The geometry of the intersections considered is limited to three- and four-leg intersections where each intersection leg serves two-way traffic. This limitation is dictated by the HSM. It is primarily a concern for streets in downtown areas and at freeway interchanges. Intersections in these areas often include one or more legs that have one-way traffic flow. These configurations have a unique set of conflicting movements and conflict points that justify the development of separate SPFs (and possibly complete predictive methods).

Application Overview

This subsection provides an overview of the safety evaluation procedure's application. Initially, data required to apply the procedure are summarized. Then, the six analysis steps associated with the procedure are outlined.

Data Required to Apply Procedure

The procedure will require several types of input data. These data are described in the following paragraphs. The data are categorized as "minimum" and "desirable." The minimum input data represents the essential data elements needed to conduct the safety evaluation. The desirable input data will require additional effort to acquire but, if used, should provide a more reliable estimate of the expected change in crash frequency due to signal installation.

Minimum Input Data

- Number of intersection legs.
- Number of through lanes on the major road.
- Annual Average Daily Traffic (AADT) volume for the major street for a specified analysis year.
- AADT volume for the minor street for same year as used to define the major-street AADT.
- Number of approaches with a left-turn lane (or bay).
- Number of approaches with a right-turn lane (or bay).
- Presence of intersection lighting.
- Presence of left-turn phasing (only for urban signalized intersection).
- Use of right-turn-on-red signal operation (only for urban signalized intersection).
- Use of red-light-camera enforcement (only for urban signalized intersection).

Desirable Input Data

The data described in the following list are needed along with that identified as Minimum Input Data.

- Crash history – count of crashes occurring at, or related to, the intersection during each year of the most recent two- to five-years. Categorized as FI or PDO, and as angle, rear-end, or other type.
- AADT volume for the major street for each year represented in the crash history.
- AADT volume for the minor street for each year represented in the crash history.
- Estimate of AADT volume for the major street that would prevail immediately after signal installation.
- Estimate of AADT volume for the minor street that would prevail immediately after signal installation.
- Local calibration factor for each predictive method.
- Intersection skew angle (if in a rural area; not needed if in an urban area).
- Pedestrian volume data (only for urban signalized intersection).
- Number of lanes crossed by a pedestrian (only for urban signalized intersections).
- Number of bus stops near the intersection (only for urban signalized intersections).
- Presence of a public school near the intersection (only for urban signalized intersections).
- Number of alcohol sales establishments near the intersection (only for urban signalized intersections).

Guidance

The crash history data must represent crashes that occur at the intersection, or are considered to be related to the intersection's presence. The crashes will need to be categorized as rear-end, angle, or "other." Angle crashes were defined previously in the subsection titled Crash Categories. These crash type categories are dictated by the crash types recognized in Part C of the HSM.

Crash data are considered to be "desirable," and not a minimum requirement. If they are provided, then the EB method can be used in the predictive method to obtain a more reliable estimate of the average crash frequency.

There should be no changes in the geometry of, or traffic control features at, the subject intersection during the time period represented by the input data. This period should extend backward in time from the most recent year to the last year for which it is known that no changes occurred. The time period should not exceed five years.

If the AADT volume is available for one or more years, but it is not available for all years, then it can be estimated for the missing years using the available AADT and judgment regarding annual changes in traffic volume at nearby intersections. Part C of the HSM provides rules for estimating AADT for those years for which it is not available.

After the signal is installed, the major-street and minor-street AADTs at the intersection may increase more rapidly than can be explained by historic increases in traffic volume, possibly due to the signal's more attractive operation and safety benefits. Desirably, the analyst will estimate these two AADTs using (1) traffic forecasts or (2) available AADTs and adjustment factors obtained from the AADTs of other intersections at which a signal was installed. If the Minimum Input Data approach is used, then the estimate of AADT that would prevail after signal installation can be assumed to equal the AADT associated with the most recent year for which crash data are available.

Local calibration factors are used with each predictive method to ensure that the predicted crash frequency is representative of intersections in the jurisdiction within which the subject intersection is located. A procedure for computing this factor is described in Appendix A to Part C of the HSM. If this factor is not used, then the implication is that the estimated crash frequencies are representative of the intersections in the jurisdiction without further re-calibration.

The last six items in the list of Minimum Input Data represent data used to define various CMFs that are included in a predictive method. Their inclusion in this list is consistent with guidance in Appendix A to Part C of the HSM. The use of these CMFs will improve the accuracy of the predicted crash frequency.

Procedure Steps

Step 1. Assemble Input Data and Models.

Determine whether the desirable input data are available. If they are available, obtain them. Otherwise, obtain the minimum input data. Obtain the necessary SPF coefficients and CMF values from the appropriate HSM Part C chapter for the existing intersection, and for the proposed signalized intersection.

Step 2. Estimate the Average Crash Frequency for the Existing Intersection.

Use the SPFs and CMFs corresponding to the existing intersection to compute the predicted average crash frequency for the average stop-controlled intersection that is otherwise similar to the existing intersection. If crash data are provided, use the SPFs and CMFs with the EB Method (described in Part C of the HSM) to compute the expected average crash frequency for the existing intersection.

One estimate of the average crash frequency (and its variance) is obtained for each of the following categories: FI angle crashes, FI rear-end crashes, FI other crashes, PDO angle crashes, PDO rear-end crashes, and PDO other crashes. Add all of these values to obtain an estimate of the total average crash frequency.

Compute the crash severity index for the existing intersection using the average crash frequency estimates and their corresponding crash costs. One index estimate (and its variance) is obtained for each of the aforementioned six categories. Add all of these values to obtain an estimate of the total severity index.

Step 3. Estimate the Average Crash Frequency for the Intersection if a Signal was Installed.

Use the SPFs and CMFs corresponding to the signalized intersection to compute the predicted average crash frequency for the average signalized intersection that is otherwise similar to the existing intersection.

One estimate of the average crash frequency (and its variance) is obtained for each of the following categories: FI angle crashes, FI rear-end crashes, FI other crashes, PDO angle crashes, PDO rear-end crashes, and PDO other crashes. Add all of these values to obtain an estimate of the total average crash frequency.

Compute the crash severity index for the signalized intersection using the average crash frequency estimates and their corresponding crash costs. One index estimate (and its variance) is obtained for each of the aforementioned six categories. Add all of these values to obtain an estimate of the total severity index.

Step 4. Determine if there is a Significant Change in Crash Frequency due to Signal Installation.

Using the total average crash frequency estimates from Steps 2 and 3, compute the change in total average crash frequency (i.e., average crash frequency change = estimated crash frequency from Step 3 – estimated crash frequency from Step 2). Compute the variance of the change in total average crash frequency (i.e., variance of change = variance from Step 3 + variance from Step 2).

Compare the change in total average crash frequency with the variance of this change to determine if the result is significantly significant. The statistical significance of the change in average crash frequency is determined by dividing it by the square root of the corresponding variance. The hypothesis in this test is that there is no change in safety. Hence, it is a two-tail test such that the absolute value of the computed ratio would need to exceed 1.64 (corresponding to a 0.10 significance level) to reject the hypothesis.

If there is a statistically significant change in the total average crash frequency, then the signal installation is very likely to have an effect on traffic safety. If the computed change is negative, then the signal installation is likely to improve safety. If the computed change is positive, then the signal installation is likely to degrade safety.

Note that if additional years of crash data are used with the EB method in Step 2, then the variance of the expected average crash frequency may be reduced, and a statistically significant result may be obtained.

Step 5. Determine if there is a Net Safety Benefit Associated with the Signal Installation. The total severity indices from Steps 2 and 3 are used in this step to determine if there is a net safety benefit associated with the signal indication.

Using the total severity index estimates from Steps 2 and 3, compute the change in the total severity index (i.e., index change = index from Step 3 – index from Step 2). Compute the variance of the total severity index change (i.e., variance of change = variance from Step 3 + variance from Step 2).

Compare the index change with the variance of this change to determine if the result is significantly significant. The statistical significance of the index change is determined by dividing it by the square root of the corresponding variance. The hypothesis in this test is that there is no change in safety. Hence, it is a two-tail test such that the absolute value of the computed ratio would need to exceed 1.64 (corresponding to a 0.10 significance level) to reject the hypothesis.

If there is a statistically significant change in the total severity index, then the signal installation is very likely to have an effect on traffic safety. If the computed index change is negative, then the signal installation is likely to provide a net safety benefit. If the computed index is positive, then the signal installation is likely to cause a net safety dis-benefit.

If neither the change in total average crash frequency nor the change in total severity index is statistically significant, then the safety effect of signalization is not known with sufficient degree of certainty to be the sole basis for the decision to install a signal. In this case, other factors and signal impacts (e.g., operations) will need to be evaluated to determine if signal installation is justified.

Development of Selected Models and Parameters

This section describes the research that was conducted to develop the necessary tools to support the safety evaluation procedure. Research was conducted on three topics to develop these tools. The findings for each research topic are documented in a separate subsection. The first subsection describes the development of a predictive model for selected crash type and severity categories. The second subsection describes the development of an overdispersion parameter for each predictive model. The third subsection describes the estimation of crash cost for selected crash type and severity categories.

Development of Crash-Category-Specific SPFs

The safety evaluation procedure is intended to provide an important sensitivity to angle and rear-end crash types. This sensitivity is needed to evaluate the effect of signalization because angle and rear-end crash frequency tends to be notably influenced by the presence (or absence) of a traffic control signal. For the same reason, the procedure is intended to provide an important sensitivity to crash severity. In addition, the procedure is intended to support the use of the EB Method for the existing stop-controlled intersection.

For the aforementioned reasons, a predictive model is needed for each combination of area type, number of legs, control type, crash type category, and crash severity category of interest. The crash type and severity categories of interest include: FI angle crashes, FI rear-end crashes, PDO angle crashes, and PDO rear-end crashes. However, none of the predictive models in the HSM are specific to the desired combinations of crash type or severity categories (AASHTO, 2010).

To meet the aforementioned need, the HSM predictive models were disaggregated into separate "equivalent" predictive models for each combination of crash type category (angle or rear end) and crash severity category (FI or PDO). The disaggregated methods are shown as Equation 1 to Equation 6.

Equation 1

$$N_{p,fi,ang} = N_{spf,fi,ang} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \times C$$

Equation 2

$$N_{p,fi,re} = N_{spf,fi,re} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \times C$$

Equation 3

$$N_{p,fi,other} = N_{spf,fi,other} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \times C$$

Equation 4

$$N_{p,pdo,ang} = N_{spf,pdo,ang} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \times C$$

Equation 5

$$N_{p,pdo,re} = N_{spf,pdo,re} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \times C$$

Equation 6

$$N_{p,pdo,other} = N_{spf,pdo,other} \times (CMF_1 \times CMF_2 \times \ldots \times CMF_n) \times C$$

where,
$N_{p,fi,ang}$ = predicted average FI angle crash frequency, crashes/yr;
$N_{p,fi,re}$ = predicted average FI rear-end crash frequency, crashes/yr;
$N_{p,fi,other}$ = predicted average FI other crash frequency, crashes/yr;
$N_{p,pdo,ang}$ = predicted average PDO angle crash frequency, crashes/yr;
$N_{p,pdo,re}$ = predicted average PDO rear-end crash frequency, crashes/yr;
$N_{p,pdo,other}$ = predicted average PDO other crash frequency, crashes/yr;
$N_{spf,fi,ang}$ = predicted average FI angle crash frequency for base conditions, crashes/yr;
$N_{spf,fi,re}$ = predicted average FI rear-end crash frequency for base conditions, crashes/yr;
$N_{spf,fi,other}$ = predicted average FI other crash frequency for base conditions, crashes/yr;
$N_{spf,pdo,ang}$ = predicted average PDO angle crash frequency for base conditions, crashes/yr;
$N_{spf,pdo,re}$ = predicted average PDO rear-end crash frequency for base conditions, crashes/yr;
$N_{spf,pdo,other}$ = predicted average PDO other crash frequency for base conditions, crashes/yr;
CMF_i = crash modification factor i; and
C = calibration factor.

The aggregation of the individual methods (to predict total average crash frequency) is described by the following equation:

Equation 7

$$N_{p,t} = N_{p,fi,ang} + N_{p,fi,re} + N_{p,fi,other} + N_{p,pdo,ang} + N_{p,pdo,re} + N_{p,pdo,other}$$

where,
$N_{p,t}$ = total predicted average crash frequency, crashes/yr.

The safety performance function (SPF) in Equation 1 is computed using Equation 8. Its coefficient "A" is computed from the regression coefficient a and the appropriate proportion p using Equation 9.

Equation 8

$$N_{spf,fi,ang} = \exp\left[A_{fi,ang} + b \times \ln(AADT_{maj}) + c \times \ln(AADT_{\min})\right]$$

with

Equation 9

$$A_{fi,ang} = a + \ln(p_{fi,ang})$$

where,
a, b, c = regression coefficients (provided in the HSM);
$AADT_{maj}$ = average daily traffic volume for the major road, veh/day;
$AADT_{min}$ = average daily traffic volume for the minor road, veh/day;
$p_{fi,ang}$ = proportion of FI angle crashes;
$A_{fi,ang}$ = equivalent regression coefficient for the FI angle crash SPF.

The coefficient *a* and the proportion *p* are obtained from the HSM. A variation of Equation 8 and Equation 9 can be used to obtain the SPFs used in Equation 2 to Equation 6; however, these SPFs are not shown herein.

The regression coefficients for each SPF are listed in Table 11, Table 12, and Table 13 for the FI SPFs for rural three-leg intersections, rural four-leg intersections, and urban intersections, respectively. The values for coefficient *A* are computed using Equation 9 when appropriate. Where the calculation of *A* is not shown in the table, then the HSM SPF is directly applicable and the coefficient *a* from the HSM can be substituted for *A* in the SPF. In all cases, the coefficients *b* and *c* are taken directly from the HSM.

Table 11. Coefficients for SPFs that predict FI crash frequency at rural three-leg intersections.

Area Type	Number of Legs	Control Type	Major-Road Lanes	Crash Type	Coefficient Values[1]
Rural	3	Stop control on minor road	2	All types	$A = -9.86 + \ln(P_{fi}) = -10.739$; $P_{fi} = 0.415$ $b = 0.790$ $c = 0.490$
				Angle	$A = -9.86 + \ln(P_{fi}) + \ln(P_{ang}) = -12.030$; $P_{fi} = 0.415$; $P_{ang} = 0.275$ $b = 0.790$ $c = 0.490$
				Rear-end	$A = -9.86 + \ln(P_{fi}) + \ln(P_{re}) = -12.087$; $P_{fi} = 0.415$; $P_{re} = 0.260$ $b = 0.790$ $c = 0.490$
			4	All types	$a = -12.664$ $b = 1.107$ $c = 0.272$
				Angle	$A = -12.664 + \ln(P_{ang}) = -13.661$; $P_{ang} = 0.369$ $b = 1.107$ $c = 0.272$
				Rear-end	$A = -12.664 + \ln(P_{re}) = -14.062$; $P_{re} = 0.247$ $b = 1.107$ $c = 0.272$
		Signal	2	not available	
			4	not available	

Note:

1 – Variable definitions: P_{fi} = proportion FI crashes; P_{ang} = proportion angle FI crashes; P_{re} = proportion rear-end FI crashes. Proportions obtained from HSM Tables 10-5, 10-6, and 11-9.

The SPFs provided in the HSM Chapter 12 for urban intersections are specific to either multiple-vehicle crashes or to single-vehicle crashes. SPFs for predicting total (all types) crashes are not available in Chapter 12. The HSM advises that total crashes are computed by adding the predicted multiple-vehicle crash frequency and single-vehicle crash frequency.

Table 12. Coefficients for SPFs that predict FI crash frequency at rural four-leg intersections.

Area Type	Number of Legs	Control Type	Major-Road Lanes	Crash Type	Coefficient Values[1]
	4	Stop control on minor road	2	All types	$A = -8.56 + \ln(P_{fi}) = -9.402$; $P_{fi} = 0.431$ $b = 0.600$ $c = 0.610$
				Angle	$A = -8.56 + \ln(P_{fi}) + \ln(P_{ang}) = -10.033$; $P_{fi} = 0.431$; $P_{ang} = 0.532$ $b = 0.600$ $c = 0.610$
				Rear-end	$A = -8.56 + \ln(P_{fi}) + \ln(P_{re}) = -10.962$; $P_{fi} = 0.431$; $P_{re} = 0.210$ $b = 0.600$ $c = 0.610$
			4	All types	$a = -11.554$ $b = 0.888$ $c = 0.525$
				Angle	$A = -11.554 + \ln(P_{ang}) = -12.181$; $P_{ang} = 0.534$ $b = 0.888$ $c = 0.525$
				Rear-end	$A = -11.554 + \ln(P_{re}) = -13.100$; $P_{re} = 0.213$ $b = 0.888$ $c = 0.525$
		Signal	2	All types	$A = -5.13 + \ln(P_{fi}) = -6.209$; $P_{fi} = 0.340$ $b = 0.600$ $c = 0.200$
				Angle	$A = -5.13 + \ln(P_{fi}) + \ln(P_{ang}) = -7.299$; $P_{fi} = 0.340$; $P_{ang} = 0.336$ $b = 0.600$ $c = 0.200$
				Rear-end	$A = -5.13 + \ln(P_{fi}) + \ln(P_{re}) = -7.118$; $P_{fi} = 0.340$; $P_{re} = 0.403$ $b = 0.600$ $c = 0.200$
			4	All types	$a = -6.393$ $b = 0.638$ $c = 0.232$
				Angle	$A = -6.393 + \ln(P_{ang}) = -7.548$; $P_{ang} = 0.315$ $b = 0.638$ $c = 0.232$
				Rear-end	$A = -6.393 + \ln(P_{re}) = -7.144$; $P_{re} = 0.472$ $b = 0.638$ $c = 0.232$

Notes:

1 – Variable definitions: P_{fi} = proportion FI crashes; P_{ang} = proportion angle FI crashes; P_{re} = proportion rear-end FI crashes. Proportions obtained from HSM Tables 10-5, 10-6, and 11-9.

Table 13. Coefficients for SPFs that predict FI crash frequency at urban intersections.

Area Type	Number of Legs	Control Type	Major-Road Lanes	Crash Type	Coefficient Values[1]
Urban	3	Stop control on minor street	2 or 4	All types	$a = -14.010$; $b = 1.160$; $c = 0.300$; $w = 1.000$ $x = -6.81 + \ln(P_{fi}) + 14.010 = 6.064$; $P_{fi} = 0.321$ $y = 0.160 - 1.160 = -1.000$ $z = 0.510 - 0.300 = 0.210$
				Angle	$A = -14.010 + \ln(P_{ang}) = -15.080$; $P_{ang} = 0.343$ $b = 1.160$ $c = 0.300$
				Rear-end	$A = -14.010 + \ln(P_{re}) = -14.875$; $P_{re} = 0.421$ $b = 1.160$ $c = 0.300$
		Signal	2 or 4	All types	$a = -11.580$; $b = 1.020$; $c = 0.170$; $w = 1.000$ $x = -9.750 + 11.580 = 1.830$ $y = 0.270 - 1.020 = -0.750$ $z = 0.510 - 0.170 = 0.340$
				Angle	$A = -11.580 + \ln(P_{ang}) = -12.853$; $P_{ang} = 0.280$ $b = 1.020$ $c = 0.170$
				Rear-end	$A = -11.580 + \ln(P_{re}) = -12.180$; $P_{re} = 0.549$ $b = 1.020$ $c = 0.170$
	4	Stop control on minor street	2 or 4	All types	$a = -11.130$; $b = 0.930$; $c = 0.280$; $w = 1.000$ $x = -5.33 + \ln(P_{fi}) + 11.130 = 4.866$; $P_{fi} = 0.393$ $y = 0.330 - 0.930 = -0.600$ $z = 0.120 - 0.280 = -0.160$
				Angle	$A = -11.130 + \ln(P_{ang}) = -11.951$; $P_{ang} = 0.440$ $b = 0.930$ $c = 0.280$
				Rear-end	$A = -11.130 + \ln(P_{re}) = -12.215$; $P_{re} = 0.338$ $b = 0.930$ $c = 0.280$
		Signal	2 or 4	All types	$a = -13.140$; $b = 1.180$; $c = 0.220$; $w = 1.000$ $x = -9.25 + 13.140 = 3.890$ $y = 0.430 - 1.180 = -0.750$ $z = 0.290 - 0.220 = 0.070$
				Angle	$A = -13.140 + \ln(P_{ang}) = -14.198$; $P_{ang} = 0.347$ $b = 1.18$ $c = 0.220$
				Rear-end	$A = -13.140 + \ln(P_{re}) = -13.939$; $P_{ang} = 0.450$ $b = 1.18$ $c = 0.220$

Notes:

1 – Variable definitions: P_{fi} = proportion FI crashes; P_{ang} = proportion angle FI crashes; P_{re} = proportion rear-end FI crashes. Proportions for angle and rear-end crashes obtained from HSM Table 12-11.

A generalized version of Equation 8 was developed to describe a single SPF for urban intersections that predicts same total crash frequency as would be obtained by adding the results from the multiple-vehicle and single-vehicle SPFs. The form of this generalized equation is shown in Equation 10.

Equation 10

$$N_{spf,fi} = \exp\left[a_{fi,mv} + b_{fi,mv} \times \ln\left(AADT_{maj}\right) + c_{fi,mv} \times \ln\left(AADT_{\min}\right)\right] \times F_{c,fi} \times C_{fi,mv}$$

with

Equation 11

$$F_{c,fi} = 1.0 + w_{fi} \times \exp\left[x_{fi} + y_{fi} \times \ln\left(AADT_{maj}\right) + z_{fi} \times \ln\left(AADT_{\min}\right)\right]$$

Equation 12

$$x_{fi} = a_{fi,sv} - a_{fi,mv}$$

Equation 13

$$y_{fi} = b_{fi,sv} - b_{fi,mv}$$

Equation 14

$$z_{fi} = c_{fi,sv} - c_{fi,mv}$$

Equation 15

$$w_{fi} = \frac{C_{fi,sv}}{C_{fi,mv}}$$

where,

$a_{fi,mv}$, $b_{fi,mv}$, $c_{fi,mv}$ = regression coefficients for FI multiple-vehicle crashes;
$a_{fi,sv}$, $b_{fi,sv}$, $c_{fi,sv}$ = regression coefficients for FI single-vehicle crashes;
w_{fi}, x_{fi}, y_{fi}, z_{fi} = computed coefficients for FI crashes;
$F_{c,fi}$ = correction factor for FI crashes;
$C_{fi,mv}$ = calibration factor FI multiple-vehicle crashes; and
$C_{fi,sv}$ = calibration factor FI single-vehicle crashes.

The SPFs provided in HSM Chapter 11 for multilane rural highway intersections are specific to total (all severities) and to FI crashes. SPFs for predicting PDO crashes are not available in Chapter 11. The HSM advises that PDO crashes are computed by subtracting the predicted FI crash frequency from the predicted total (all severities) crash frequency. This guidance was used to derive an equivalent SPF for PDO crashes using Equation 10, with the reported FI and total-crash SPF coefficients in Equation 11 to Equation 15.

Chapter 12 of the HSM does not provide SPF coefficients for FI single-vehicle crashes at three-leg and at four-leg stop controlled intersections. The HSM offers Equation 12-27 as an alternative means for estimating the average crash frequency for these two intersection types. Equation 12-27 is equivalent to Equation 8. The HSM indicates the proportion used for predicting FI single-vehicle crashes at three-leg and four-leg intersections is 0.31 and 0.28, respectively. These proportions are not in agreement with the corresponding proportions published in the final report for Project 17-26 (Harwood et al. 2007; Table 57). As a result, the SPFs for PDO and total single-vehicle crashes published in Chapter 12 of the HSM were used, with the average AADT values published by Harwood et al. (2007; Table 23), to estimate the desired proportions. The computed proportions for FI single-vehicle crashes at three-leg and four-leg intersections are 0.321 and 0.393, which are similar to those published by Harwood et al. (2007; Table 57). These proportions are used in Table 13 to estimate the desired coefficients for the total crash SPFs.

The process used to develop the coefficients in the previous three tables was used to estimate the PDO coefficients. These coefficients are listed in Table 14.

Table 14. Coefficients for SPFs that predict PDO crash frequency.

Area Type	Number of Legs	Control Type	Major-Road Lanes	Crash Type	Coefficients						
					A	b	c	w	x	y	z
Rural	3	Stop control on minor road	2	All types	-10.396	0.790	0.490				
				Angle	-11.957	0.790	0.490				
				Rear-end	-11.627	0.790	0.490				
			4	All types	-12.526	1.204	0.236	-1.0	-0.138	-0.097	0.036
				Angle	-14.692	1.204	0.236				
				Rear-end	-14.228	1.204	0.236				
		Signal	2	not available							
			4	not available							
	4	Stop control on minor road	2	All types	-9.124	0.600	0.610				
				Angle	-10.162	0.600	0.610				
				Rear-end	-10.448	0.600	0.610				
			4	All types	-10.008	0.848	0.448	-1.0	-1.546	0.040	0.077
				Angle	-11.930	0.848	0.448				
				Rear-end	-12.126	0.848	0.448				
		Signal	2	All types	-5.546	0.600	0.200				
				Angle	-6.964	0.600	0.200				
				Rear-end	-6.371	0.600	0.200				
			4	All types	-7.182	0.722	0.337	-1.0	0.789	-0.084	-0.105
				Angle	-9.212	0.722	0.337				
				Rear-end	-8.358	0.722	0.337				
Urban	3	Stop control on minor street	2 or 4	All types	-15.380	1.200	0.510	1.00	7.020	-0.950	0.040
				Angle	-16.719	1.200	0.510				
				Rear-end	-16.201	1.200	0.510				
		Signal	2 or 4	All types	-13.240	1.140	0.300	1.00	4.160	-0.690	0.030
				Angle	-14.830	1.140	0.300				
				Rear-end	-13.845	1.140	0.300				
	4	Stop control on minor street	2 or 4	All types	-8.740	0.770	0.230	1.00	1.700	-0.410	0.020
				Angle	-9.834	0.770	0.230				
				Rear-end	-9.723	0.770	0.230				
		Signal	2 or 4	All types	-11.020	1.020	0.240	1.00	-0.320	-0.240	0.010
				Angle	-12.431	1.020	0.240				
				Rear-end	-11.748	1.020	0.240				

Development of Estimated Overdispersion Parameters

The safety evaluation procedure is intended to support the use of the EB Method for estimating the expected average crash frequency for the existing stop-controlled intersection. For these reasons, an overdispersion parameter is needed for each of the SPFs identified in Table 11 to Table 14. Unfortunately, the parameter is not available for the SPFs in these tables with derived coefficients. This section describes the techniques used to estimate the overdispersion parameter for each SPF with derived coefficients.

The first subsection describes an analysis of the overdispersion parameters associated with FI, PDO and total (all severities) crash SPFs. The second subsection describes an analysis of the overdispersion parameters associated with angle, rear-end, and total (all types) crash SPFs. The third section describes the recommended overdispersion parameters that are derived using the findings documented in the previous two subsections.

Analysis of Parameters Describing FI and PDO Crash Frequency

This subsection describes an analysis of the parameters associated with a series of SPFs calibrated by Harwood et al., 2007. They calibrated one set of SPFs for intersections in Minnesota, and a second set for intersections in North Carolina. For multiple-vehicle crash SPFs, they reported dispersion parameters for FI, PDO, and total (all severities) crashes as well as the proportion of FI and PDO crashes. They reported the same statistics for single-vehicle crash SPFs. These values are shown in Table 15.

Table 15. Overdispersion parameters for FI, PDO, and total crash SPFs.

State	Crash Type	Variable	Crash Severity	Variable Value by Control Type and Legs			
				Stop on Minor Road		Signal	
				3 Legs	4 Legs	3 Legs	4 Legs
Minnesota	Multiple-vehicle	Overdispersion parameter	All	1.10	0.20	0.41	0.51
			FI	0.85	0.17	0.26	0.36
			PDO	1.26	0.29	0.46	0.55
		Proportion of all crashes	FI	0.350	0.352	0.372	0.329
			PDO	0.650	0.648	0.628	0.671
	Single-vehicle	Overdispersion parameter	All	n.a.	0.31	0.18	0.30
			FI	n.a.	0.15	n.a.	0.09
			PDO	n.a.	0.14	0.42	0.28
		Proportion of all crashes	FI	0.368	0.420	0.391	0.248
			PDO	0.632	0.580	0.609	0.752
North Carolina	Multiple-vehicle	Overdispersion parameter	All	0.51	0.66	0.87	0.69
			FI	0.55	0.79	0.67	0.46
			PDO	0.47	0.51	0.77	0.60
		Proportion of all crashes	FI	0.369	0.415	0.342	0.336
			PDO	0.631	0.585	0.658	0.664
	Single-vehicle	Overdispersion parameter	All	1.11	n.a.	0.53	0.11
			FI	n.a.	n.a.	0.64	0.03
			PDO	0.93	0.49	0.57	0.21
		Proportion of all crashes	FI	0.304	0.365	0.227	0.241
			PDO	0.696	0.635	0.773	0.759

Note:
n.a. – not available.

The overdispersion parameter is used to quantify the variation among intersections in terms of their average crash frequency. This variation is quantified using the following equation.

Equation 16

$$V\left[N_{p,t}\right] = k_t \times \left(N_{p,t}\right)^2$$

where,

$V[N_{p,t}]$ = variance of total predicted average crash frequency among intersections, (crashes/yr)^2; and
k_t = overdispersion parameter for total crash frequency.

Consider a group of similar intersections for which the crash history is known. An SPF can be developed to predict total average crash frequency for this group. Similarly, an SPF can be developed to predict FI average crash frequency, and an SPF can be developed to predict PDO average crash frequency. The following relationship will hold between the variance of the predicted average crash frequencies.

Equation 17

$$V\left[N_{p,t}\right] = V\left[N_{p,fi}\right] + V\left[N_{p,pdo}\right] + 2\,\rho\left(V\left[N_{p,fi}\right]V\left[N_{p,pdo}\right]\right)^{0.5}$$

where,
$V[N_{p,fi}]$ = variance of predicted FI average crash frequency among intersections, (crashes/yr)^2;
$V[N_{p,pdo}]$ = variance of predicted PDO average crash frequency among intersections, (crashes/yr)^2; and
ρ = correlation coefficient.

Substitution of Equation 16 into Equation 17 yields the following relationship between the overdispersion parameters.

Equation 18

$$k_t\left(N_{p,t}\right)^2 = k_{fi}\left(N_{p,fi}\right)^2 + k_{pdo}\left(N_{p,pdo}\right)^2 + 2\,\rho\left[k_{fi}\left(N_{p,fi}\right)^2 k_{pdo}\left(N_{p,pdo}\right)^2\right]^{0.5}$$

where,
k_{fi} = overdispersion parameter for FI crash frequency; and
k_{pdo} = overdispersion parameter for PDO crash frequency.

A similar equation can be produced for the crash type categories of interest (i.e., angle, rear-end, other). These equations can be used with the overdispersion parameters in the HSM to estimate the overdispersion parameters for the desired crash-category-specific SPFs.

Equation 18 reduces to Equation 19 when the correlation coefficient ρ equals 0.0.

Equation 19

$$k_t = k_{fi}\left(p_{fi}\right)^2 + k_{pdo}\left(p_{pdo}\right)^2$$

where,
p_{fi} = proportion FI crashes; and
p_{pdo} = proportion PDO crashes (= $1.0 - p_{fi}$).

The following variation of Equation 19 was used to develop an equation for predicting the reported overdispersion parameter for total crash frequency. The coefficient b_1 is included in the equation to compensate for the assumption that the correlation coefficient equals 0.0.

Equation 20

$$k_t = b_1\left[k_{fi}\left(p_{fi}\right)^2 + k_{pdo}\left(p_{pdo}\right)^2\right]$$

where,
b_1 = regression coefficient.

A regression analysis using the data in Table 15 indicated that the best-fit model has a coefficient b_1 equal to 1.84. It is associated with a coefficient of determination R^2 of 0.87. The fit of the model to the data is shown in Figure 8.

A supplemental analysis examined the correlation between the overdispersion parameters for FI and PDO crashes. The results of this analysis are described using the following equation.

Equation 21

$$k_{pdo} = c_1\,k_{fi}$$

where,
c_1 = regression coefficient.

A regression analysis indicated that the best-fit model has a coefficient c_1 equal to 1.11. It is associated with an R^2 of 0.58. The fit of the model to the data is shown in Figure 9.

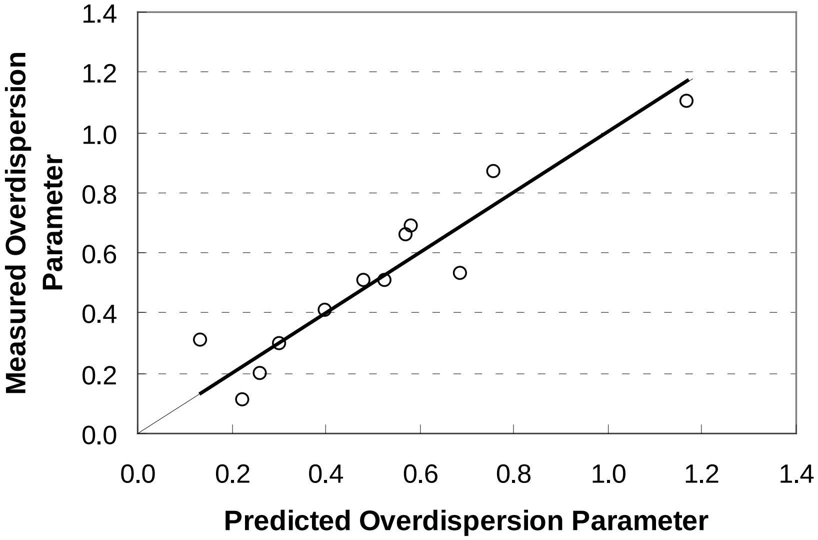


Figure 8. Comparison of predicted and measured overdispersion parameters for FI and PDO crashes.

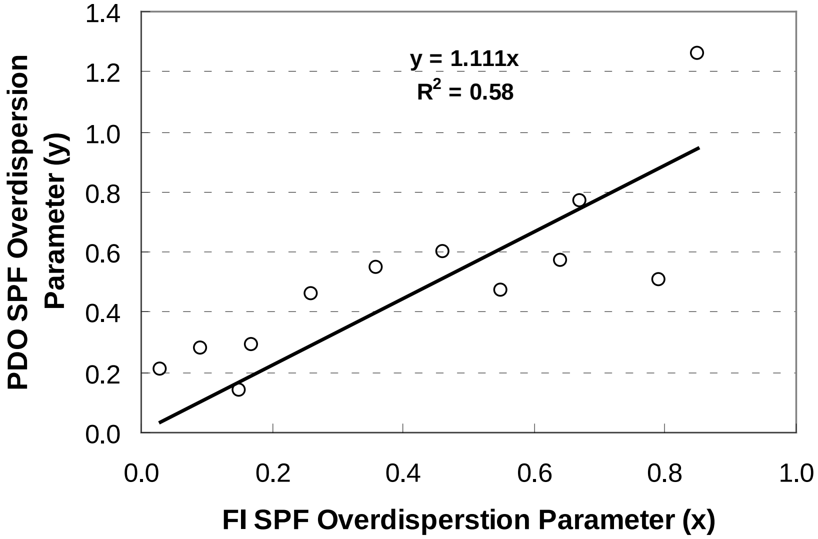


Figure 9. Relationship between overdispersion parameters for FI and PDO crashes.

Analysis of Parameters Describing Angle and Rear-End Crash Frequency

This subsection describes an analysis of the parameters associated with a series of SPFs calibrated by McGee et al. (2003) and by Harkey et al. (2008). McGee et al. (2003) calibrated a series of SPFs for FI angle and FI rear-end crashes at urban intersections. One set of SPFs was calibrated for intersections in the states of California, Florida, Maryland, Virginia, and Wisconsin. Harkey et al. (2008) calibrated a series of SPFs for total (all severities) angle and total rear-end crashes at rural intersections. One set of SPFs was calibrated for intersections in California, and a second set for intersections in Minnesota. A preliminary analysis indicated that the parameters for the Minnesota SPFs had outlier tendencies and were subsequently excluded from further analysis. All of the parameters that were used in the analysis are shown in Table 16.

Table 16. Overdispersion parameters for angle and rear-end crash SPFs.

Variable	Crash Type	Variable Value by Source and Table in Source Document										
		Harkey et al. (2008)			McGee et al. (2003) [1]							
		22	23	24	9	10	11	12	13[2]	13[3]	14	15
Overdispersion parameter	All	0.564	0.483	0.645	0.164	0.435	0.476	0.526	0.588	0.313	0.333	0.323
	Angle	1.083	1.128	1.121	0.455	0.714	1.429	1.250	1.667	0.270	0.714	0.588
	Rear-end	1.025	0.726	0.709	0.345	0.667	0.909	0.833	0.909	0.476	0.435	0.417
Proportion of all crashes	Angle	0.021	0.235	0.228	0.228	0.356	0.114	0.286	0.203	0.183	0.070	0.161
	Rear-end	0.074	0.072	0.078	0.315	0.217	0.352	0.253	0.379	0.306	0.522	0.458

Notes:

1 – McGee et al. reported the inverse dispersion parameter *K*. Overdispersion parameter *k* is computed as *k* = 1/ *K*.

2 – Values listed in this column apply to three-leg intersection data in Table 13 from McGee et al. (2003).

3 – Values listed in this column apply to four-leg intersection data in Table 13 from McGee et al. (2003).

A variation of Equation 19 was used to describe the relationship between the angle, rear-end, and total crash SPFs. The form of this equation is provided below.

Equation 22

$$k_t = k_{ang}\left(p_{ang}\right)^2 + k_{re}\left(p_{re}\right)^2 + k_{other}\left(1.0 - p_{ang} - p_{re}\right)^2$$

where,

k_t = overdispersion parameter for total crash frequency;
k_{ang} = overdispersion parameter for angle crash frequency;
k_{re} = overdispersion parameter for rear-end crash frequency;
k_{other} = overdispersion parameter for other (not angle or rear-end) crash frequency;
p_{ang} = proportion angle crashes; and
p_{re} = proportion rear-end crashes.

This variation was needed because, unlike the analysis conducted in the previous subsection, overdispersion parameters were not available for the full set of crash-type categories. As a result, the following variation of Equation 22 was used to develop an equation for predicting the reported overdispersion parameter for total crash frequency. The coefficients d_0 and d_1 are included in the equation to compensate for the missing parameters and the assumption that the correlation coefficient equals 0.0.

Equation 23

$$k_t = d_1\left[k_{ang}\left(p_{ang}\right)^2 + k_{re}\left(p_{re}\right)^2\right] + d_0\left(1.0 - p_{ang} - p_{re}\right)^2$$

where,

d_0, d_1 = regression coefficients.

A regression analysis indicated that the best-fit model has coefficients d_0 and d_1 equal to 0.729 and 2.24, respectively. The magnitude of d_1 is noted to be similar to b_1 in Equation 20 (i.e., both coefficients have a value of about 2.0). Equation 23 is associated with an R^2 of 0.78. The fit of the model to the data is shown in Figure 10.

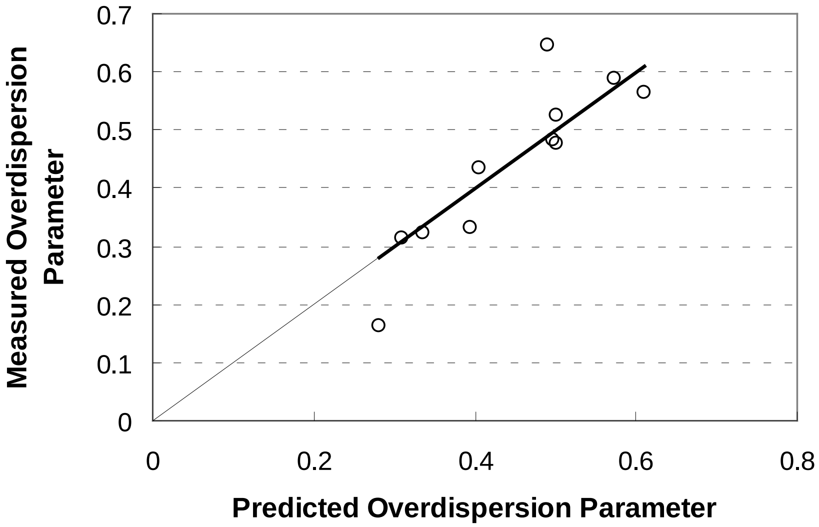


Figure 10. Comparison of predicted and measured overdispersion parameters for angle and rear-end crashes.

A supplemental analysis examined the correlation between the overdispersion parameters for rear-end and angle crashes. The results of this analysis are described using the following equation.

Equation 24

$$k_{re} = e_1 \, k_{ang}$$

where,

e_1 = regression coefficient.

A regression analysis indicated that the best-fit model has a coefficient e_1 equal to 0.673. It is associated with an R^2 of 0.51. The fit of the model to the data is shown in Figure 11.

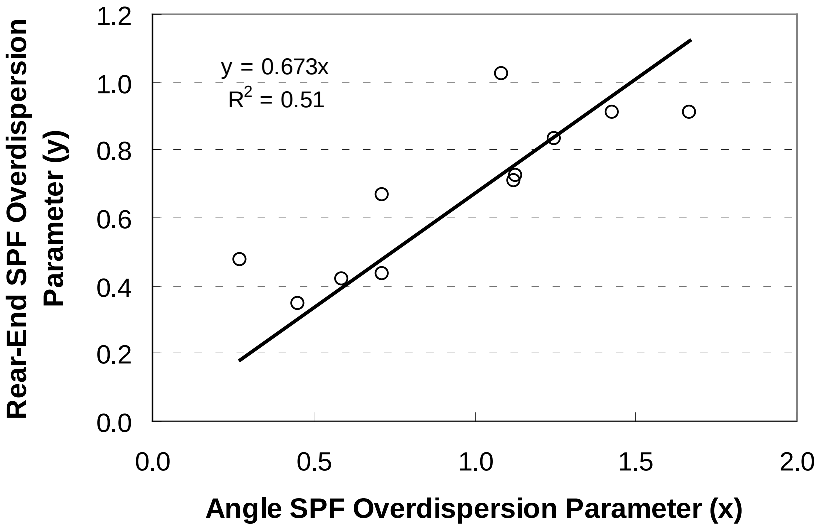


Figure 11. Relationship between overdispersion parameters for angle and rear-end crashes.

Estimated Overdispersion Parameter Values

This subsection describes the procedure used to compute the estimated overdispersion parameters. The procedure varies slightly depending on whether the underlying SPFs and parameters originated from Chapter 10, 11, or 12 of the HSM.

HSM Chapter 10

Chapter 10 describes SPFs and associated overdispersion parameters for intersections on rural two-lane highways. The SPFs and parameters in this chapter are specific to total crashes (all types and severities). These parameters were used to estimate the overdispersion parameters for the equivalent SPFs described in Table 11 to Table 14.

As a first step in the process, a parameter for the equivalent SPF for FI crashes of all types was computed by combining Equation 20 and Equation 21 and solving for k_{fi}. Then, a parameter for the equivalent SPF for PDO crashes of all types was computed using the same two equations. This step was repeated for the SPFs associated with three-leg stop-controlled intersections, the SPFs associated with four-leg stop-controlled intersections, and the SPFs associated with four-leg signalized intersections. The estimated parameters are listed in Table 17 in the rows associated with "All types" as a crash type.

Table 17. Estimated overdispersion parameters for rural two-lane highway intersections.

Area Type	Number of Legs	Control Type	Major-Road Lanes	Crash Type	Overdispersion Parameter by Severity		Proportion of Crashes by Severity[1]	
					FI	PDO	FI	PDO
Rural	3	Stop control on minor road	2	All types	0.531	0.590	0.415	0.585
				Angle	1.377	1.801	0.275	0.210
				Rear-end	0.927	1.212	0.260	0.292
		Signal	2	All types	not available			
				Angle	not available			
				Rear-end	not available			
	4	Stop control on minor road	2	All types	0.239	0.266	0.431	0.569
				Angle	0.272	0.414	0.532	0.354
				Rear-end	0.183	0.279	0.210	0.266
		Signal	2	All types	0.100	0.111	0.340	0.660
				Angle	0.101	0.086	0.336	0.242
				Rear-end	0.068	0.058	0.403	0.438

Note:

1 - Proportions obtained from HSM Tables 10-5 and 10-6.

As a second step of the process, a parameter for the equivalent SPF for angle FI crashes was computed using Equation 23, Equation 24, and the estimated parameter for FI crashes of all types. Then, a parameter for the equivalent SPF for angle PDO crashes was computed using the same equations and the estimated parameter for PDO crashes of all types. These calculations were repeated for the two SPFs for rear-end crashes. All four calculations were repeated for the three combinations of intersection legs and control type. The estimated parameters are listed in Table 17 in the rows associated with "Angle" and "Rear-end" crash types.

HSM Chapter 11

Chapter 11 describes SPFs and associated overdispersion parameters for intersections on rural multilane highways. The SPFs and parameters in this chapter are specific to total crashes (all types and severities) and to FI crashes. These parameters were used to estimate the overdispersion parameters for the equivalent SPFs described in Table 11 to Table 14.

As a first step in the process, a parameter for the equivalent SPF for PDO crashes of all types was computed using Equation 20. This step was repeated for the SPFs associated with three-leg stop-controlled intersections, the SPFs associated with four-leg stop-controlled intersections, and the SPFs associated with four-leg signalized intersections. The estimated parameters are listed in Table 18 in the rows associated with “All types” as a crash type and columns associated with PDO crashes.

Table 18. Estimated overdispersion parameters for rural multilane highway intersections.

Area Type	Number of Legs	Control Type	Major-Road Lanes	Crash Type	Overdispersion Parameter by Severity		Proportion of Crashes by Severity[1]	
					FI	PDO	FI	PDO
Rural	3	Stop control on minor road	4	All types	0.569	0.445	0.421	0.579
				Angle	1.163	1.146	0.369	0.198
				Rear-end	0.782	0.771	0.247	0.315
		Signal	4	All types	not available			
				Angle	not available			
				Rear-end	not available			
	4	Stop control on minor road	4	All types	0.742	0.334	0.499	0.501
				Angle	0.983	0.626	0.534	0.292
				Rear-end	0.662	0.421	0.213	0.240
		Signal	4	All types	0.218	0.315	0.389	0.611
				Angle	0.331	0.528	0.315	0.215
				Rear-end	0.223	0.355	0.472	0.505

Note:

1 - Proportions for angle and rear-end crashes obtained from HSM Table 11-9.

Equation 20 requires the proportion of FI and PDO crashes. However, this proportion was not available for “All Types” as a crash type from the HSM. As a result, the SPFs for FI and total crashes published in Chapter 11 of the HSM were used, with the average AADT values published by Lord et al. (2008; Tables 4.6, 4.7, and 4.12), to estimate the desired proportions. The computed proportions for FI and PDO crashes are listed in Table 18.

The second step of the process was to compute the estimated parameters for angle and rear-end crashes. The calculations for this step were the same as those described in the previous subsection for Chapter 10. The estimated parameters are listed in Table 18 in the rows associated with “Angle” and “Rear-end” crash types.

HSM Chapter 12

Chapter 12 describes the SPFs and associated overdispersion parameters for intersections on urban and suburban arterial streets. The SPFs and parameters in this chapter are specific to total single-vehicle and total multiple-vehicle crashes (all severities), as well as to FI and PDO crashes for the single-vehicle and multiple-vehicle categories. These parameters were used to estimate the overdispersion parameters for the equivalent SPFs described in Table 11 to Table 14.

As a first step in the process, a parameter for FI crashes of all types was computed using the following variation of Equation 20, as well as the overdispersion parameters for FI single-vehicle and FI multiple-vehicle crashes.

Equation 25

$$k_t = 1.84 \times \left[k_{mv} \left(p_{mv} \right)^2 + k_{sv} \left(p_{sv} \right)^2 \right]$$

where,

k_t = overdispersion parameter for total crash frequency;
k_{mv} = overdispersion parameter for multiple-vehicle crash frequency;
k_{sv} = overdispersion parameter for single-vehicle crash frequency;
p_{mv} = proportion multiple-vehicle crashes; and
p_{sv} = proportion single-vehicle crashes (= 1.0 − p_{mv}).

A parameter for PDO crashes of all types was computed using Equation 25 and the overdispersion parameters for PDO single-vehicle and multiple-vehicle crashes. This step was repeated for the SPFs associated with three-leg stop-controlled intersections, the SPFs associated with four-leg stop-controlled intersections, the SPFs associated with three-leg signalized intersections, and the SPFs associated with four-leg signalized intersections. The estimated parameters are listed in Table 19 in the rows associated with “All types” as a crash type.

Table 19. Estimated overdispersion parameters for urban and suburban arterial intersections.

Area Type	Number of Legs	Control Type	Major-Road Lanes	Crash Type	Overdispersion Parameter by Severity		Proportion of Crashes by Severity[1]	
					FI	PDO	FI	PDO
Urban	3	Stop control on minor road	2 or 4	All types	0.973	1.084	0.350	0.650
				Angle	1.756	2.288	0.343	0.262
				Rear-end	1.182	1.540	0.421	0.440
		Signal	2 or 4	All types	0.494	0.572	0.341	0.659
				Angle	0.750	0.971	0.280	0.204
				Rear-end	0.505	0.653	0.549	0.546
	4	Stop control on minor road	2 or 4	All types	0.719	0.598	0.381	0.619
				Angle	1.127	1.160	0.440	0.335
				Rear-end	0.758	0.780	0.338	0.374
		Signal	2 or 4	All types	0.549	0.707	0.326	0.674
				Angle	0.902	1.345	0.347	0.244
				Rear-end	0.607	0.906	0.450	0.483

Note:

1 - Proportions for angle and rear-end crashes obtained from HSM Exhibit 12-11.

Equation 25 requires the proportion of multiple-vehicle crashes and the proportion of single-vehicle crashes. However, these proportions were not available for “All Types” as a crash type from the HSM. As a result, the SPFs for FI and PDO multiple-vehicle and single-vehicle crashes published in Chapter 12 of the HSM were used, with the average AADT values published by Harwood et al. (2007; Table 23), to estimate the desired proportions.

The second step of the process is to compute the estimated parameters for angle and rear-end crashes. The calculations for this step were the same as those described in a previous subsection for Chapter 10.

The estimated parameters are listed in Table 19 in the rows associated with "Angle" and "Rear-end" crash types.

Development of Crash Costs

This section describes the estimation of crash cost for selected crash type and severity categories. The severity index is used to provide a single-valued indication of overall safety that reflects both the frequency and relative severity of different crash types. The following equation is used to compute this index.

Equation 26

$$I_{p,t} = \frac{c_{p,t}}{1{,}000}$$

with

Equation 27

$$\begin{aligned} c_{p,t} = {} & \left(N_{p,fi,ang} \times c_{fi,ang}\right) + \left(N_{p,fi,re} \times c_{fi,re}\right) + \left(N_{p,fi,other} \times c_{fi,other}\right) \\ & + \left(N_{p,pdo,ang} \times c_{pdo,ang}\right) + \left(N_{p,pdo,re} \times c_{pdo,re}\right) + \left(N_{p,pdo,other} \times c_{pdo,other}\right) \end{aligned}$$

where,

$I_{p,t}$ = severity index for total crashes;
$c_{p,t}$ = road-user cost associated with total crashes, \$/year;
$c_{fi,ang}$ = average cost of FI angle crash, \$/year;
$c_{fi,re}$ = average cost of FI rear-end crash, \$/year;
$c_{fi,other}$ = average cost of FI other (not angle or rear-end) crash, \$/year;
$c_{pdo,ang}$ = average cost of PDO angle crash, \$/year;
$c_{pdo,re}$ = average cost of PDO rear-end crash, \$/year; and
$c_{pdo,other}$ = average cost of PDO other (not angle or rear-end) crash, \$/year.

In Equation 27, the predicted average crash frequency variables N_p are replaced by the expected average crash frequency variables N_a when the EB Method is applied.

The variance of the severity index is computed using the following equation.

Equation 28

$$V\left[I_{p,t}\right] = \frac{V\left[c_{p,t}\right]}{1{,}000^2}$$

with

Equation 29

$$\begin{aligned} V\left[c_{p,t}\right] = {} & \left(V\left[N_{p,fi,ang}\right] \times c^2_{fi,ang}\right) + \left(V\left[N_{p,fi,re}\right] \times c^2_{fi,re}\right) + \left(V\left[N_{p,fi,other}\right] \times c^2_{fi,other}\right) \\ & + \left(V\left[N_{p,pdo,ang}\right] \times c^2_{pdo,ang}\right) + \left(V\left[N_{p,pdo,re}\right] \times c^2_{pdo,re}\right) + \left(V\left[N_{p,pdo,other}\right] \times c^2_{pdo,other}\right) \end{aligned}$$

where,

$V[I_{p,t}]$ = variance of severity index among intersections;
$V[c_{p,t}]$ = variance of road-user cost among intersections, $(\$/\text{year})^2$; and
$V[N_{p,i,j}]$ = variance of predicted average crash frequency among intersections for severity category i and crash type j, crashes/yr^2.

In Equation 29, the variance of the predicted average crash frequency variables $V[N_p]$ are replaced by the variance of the expected average crash frequency variables $V[N_a]$ when the EB Method is applied. Equation 29 does not include the variance of the crash cost estimates. This approach is used because the focus of the safety evaluation procedure is on relative changes in crash severity among alternatives for a given set of road-user costs, as opposed to the degree of certainty that can be placed on a specific estimate of crash cost.

The variance of the predicted average crash frequency is computed using the following equation.

Equation 30

$$V[N_p] = k \times (N_p)^2$$

where,

$V[N_p]$ = variance of predicted average crash frequency among intersections, (crashes/yr^2); and

k = overdispersion parameter.

The variance of the expected average crash frequency is computed using the equations described by Hauer (1997).

The crash costs used in Equation 27 and Equation 29 are based on estimates developed by Council et al. (2005). This report identifies crash costs for several crash types and severities, including FI angle, FI rear-end, PDO angle, PDO rear-end, and FI vehicle-pedestrian crashes. These costs are listed in Table 20.

Table 20. Unit crash costs.

Area Type	Control Type	Crash Severity	Crash Cost by Crash Type[1], $			
			Angle	Rear-end	Vehicle-Ped.	Other
Rural (speed limit of 50 mi/h or more)	Signal	FI	126,878	52,276	183,461	164,041
		PDO	8,544	5,901	not needed[2]	5,337
	Stop	FI	199,788	34,563	183,461	201,282
		PDO	5,444	3,788	not needed[2]	5,795
Urban (speed limit of 45 mi/h or less)	Signal	FI	64,468	44,687	169,090	121,665
		PDO	8,673	11,463	not needed[2]	5,641
	Stop	FI	80,956	56,093	169,090	113,088
		PDO	7,910	12,295	not needed[2]	5,583

Notes:

1 – Source: Council et al. (2005). Costs are in 2001 dollars.

2 – Based on guidance in HSM Chapter 12, all vehicle-pedestrian crashes are assumed to be fatal or injury.

The development of a crash cost estimate for the “other” crash category is described in this section. The crash cost estimates provided in the report by Council et al. (2005) were used for this purpose.

In addition to angle, rear-end, and vehicle-pedestrian crash costs, the report by Council et al. provides a cost for vehicle-animal, fixed-object, parked-vehicle, rollover, sideswipe, and head-on crashes. These “other” crash types were used to estimate the cost for the “other” crash category. This cost was computed as a weighted average of the crash cost for each crash type, where the weight used was the proportion of crashes associated with the specified crash type. Typical proportions for the other crash types are provided in the crash type distributions in the HSM Part C chapters.

The calculation of cost for the other crash category for rural intersections is shown in Table 21. The total proportion in column 7 is computed as the product of the proportion in column 4 and the proportion in column 6. The total proportions are used as the weighting factor in the calculation of “weighted average” crash cost. One average is computed for each combination of control type and crash severity.

The calculation of cost for the other crash category for urban intersections is shown in Table 22. It is noted that the weighted average cost for FI “other” crashes exceeds the cost of FI angle and FI rear-end crashes. This trend can be observed by comparing the cost summary in the last four columns of Table 20. The reasons for this trend are that (1) FI fixed-object and FI head-on crashes have very high crash costs, and (2) they constitute about 60 percent of the crash types listed in Table 21 and Table 22.

Table 21. Crash cost calculations for rural intersections.

Control Type	Crash Severity	Crash Type	Pro-portion	Crash Type	Pro-portion[2]	Total Pro-portion	Crash Cost[1], $	HSM Table for Proportions
Signal	PDO	Any	0.660	Animal	0.003	0.0020	5,619	10-5, 10-6
				Object	0.081	0.0535	5,565	
				Parked veh.	0.000	0.0000	6,223	
				Rollover	0.003	0.0020	13,525	
				Sideswipe	0.153	0.1010	5,762	
				Head on	0.040	0.0264	2,617	
		Weighted average:					**5,337**	
	FI	Single	0.340	Animal	0.000	0.0000	61,341	
				Object	0.032	0.0109	246,235	
				Parked veh.	0.000	0.0000	214,511	
				Rollover	0.003	0.0010	366,821	
				Sideswipe	0.051	0.0173	169,438	
				Head on	0.080	0.0272	120,118	
		Weighted average:					**164,041**	
Stop	PDO	Any	0.560	Animal	0.014	0.0080	5,619	
				Object	0.144	0.0819	5,565	
				Parked veh.	0.000	0.0000	6,223	
				Rollover	0.004	0.0023	13,526	
				Sideswipe	0.144	0.0819	5,762	
				Head on	0.025	0.0142	6,169	
		Weighted average:					**5,795**	
	FI	Single	0.340	Animal	0.006	0.0026	61,341	
				Object	0.094	0.0405	246,235	
				Parked veh.	0.000	0.0000	214,511	
				Rollover	0.006	0.0026	366,821	
				Sideswipe	0.044	0.0190	169,438	
				Head on	0.060	0.0259	151,647	
		Weighted average:					**201,282**	

Notes:

1 – Source: Council et al. (2005). Costs are in 2001 dollars.

2 – Proportions used are based on those for a four-leg intersection. Proportions used for “Object” crash type are assumed to equal those specified as “ran off road” in the HSM.

Table 22. Crash cost calculations for urban intersections.

Control Type	Crash Severity	Crash Type	Proportion[3]	Crash Type	Proportion[2]	Total Proportion	Crash Cost[1], $	HSM Table for Proportions
Signal	PDO	Single vehicle	0.046	Animal	0.002	0.0001	2,617	12-13
				Object	0.870	0.0399	5,721	
				Parked veh.	0.001	0.0000	3,738	
				Rollover	0.000	0.0000	9,697	
		Multiple vehicle	0.628	Sideswipe	0.032	0.0201	6,007	12-11
				Head on	0.030	0.0188	5,101	
		Weighted average:					**5,641**	
	FI	Single vehicle	0.016	Animal	0.002	0.0000	90,943	12-13
				Object	0.744	0.0121	202,918	
				Parked veh.	0.001	0.0000	57,980	
				Rollover	0.000	0.0000	160,218	
		Multiple vehicle	0.310	Sideswipe	0.099	0.0307	74,519	12-11
				Head on	0.049	0.0152	152,240	
		Weighted average:					**121,665**	
Stop	PDO	Single vehicle	0.067	Animal	0.026	0.0017	2,617	12-13
				Object	0.847	0.0563	5,721	
				Parked veh.	0.001	0.0001	3,738	
				Rollover	0.000	0.0000	9,697	
		Multiple vehicle	0.552	Sideswipe	0.044	0.0243	6,007	12-11
				Head on	0.030	0.0166	4,806	
		Weighted average:					**5,583**	
	FI	Single vehicle	0.043	Animal	0.001	0.0000	90,943	12-13
				Object	0.679	0.0292	202,918	
				Parked veh.	0.001	0.0000	57,980	
				Rollover	0.000	0.0000	160,218	
		Multiple vehicle	0.338	Sideswipe	0.121	0.0409	74,519	12-11
				Head on	0.041	0.0139	37,976	
		Weighted average:					**113,088**	

Notes:

1 – Source: Council et al. (2005). Costs are in 2001 dollars.

2 – Proportions used are based on those for a four-leg intersection. Proportions used for “Object” crash type are assumed to equal those specified as “fixed object” in the HSM.

3 – Proportions are computed using the HSM SPFs for four-leg intersections with average AADT values.

CHAPTER 5

Proposed Crash Experience Warrant

Introduction

This chapter describes the development of a proposed crash experience warrant. The development is based on an evaluation of the change in safety associated with the installation of a traffic control signal at a two-way stop-controlled intersection.

The chapter consists of three sections. The first section outlines the purpose and scope of the warrant content. The second section describes the activities that were undertaken to develop the warrant criteria. The third section documents the proposed warrant using language that is suitable for inclusion in the MUTCD.

Purpose and Scope of Proposed Warrant

Warrant 7 – Crash Experience in the MUTCD consists of three criteria (FHWA, 2009). All three criteria must be satisfied before the warrant is met. These criteria are identified in the following list:

- Criterion A identifies the need to try other (non-signal) alternatives to address traffic safety at the existing intersection.
- Criterion B requires that the subject intersection have a reported crash count for a 12-month period that exceeds a minimum threshold value before the warrant can be met.
- Criterion C identifies a minimum threshold volume level that must be exceeded for eight hours or more of the average day.

The provision of a science-based justification for Criterion B is the primary focus of this research. The feedback provided by the survey of practitioners and the NCUTCD Signals Technical Committee indicate that Criterion C is useful because it ensures that the intersection has sufficient volume to justify consideration of signal installation.

Purpose

Although not stated in the MUTCD, it is believed that the purpose of the crash experience warrant is to identify situations where (1) traffic safety is likely to be improved by signal installation, and (2) there is sufficient traffic volume to justify consideration of signal installation as a cost-effective treatment. At volumes lower than those specified by Criterion C, it is possible for signal installation to improve intersection safety but the number of crashes reduced may be very small (e.g., only one crash prevented in 10 or 20 years). As shown by Radwan and Sinha (1979), Criterion B and C can be used together to identify those intersections where signal installation is likely to be a viable treatment from a benefit-cost perspective (based on consideration of safety and/or operational benefits).

Scope Elements

This subsection describes the intersection elements (or variables) that were considered in the development of the proposed warrant. These elements were selected because they are considered to have the greatest influence on intersection safety. As a result, they have the potential to be helpful in defining the crash-based criterion for the proposed warrant. In fact, the threshold value for crash count in Criterion B could vary depending on the value of one or more of these elements.

The elements include: area type (urban, rural), time period for the crash history evaluation (one year, three years), crash severity (fatal-and-injury [FI], all severities), crash type (angle, all types), and number of intersection legs (3 or 4). These elements and conditions are listed in the first five rows of Table 23.

Table 23. Candidate scope elements for the proposed crash experience warrant.

Element	Conditions
Control types	Two-way stop control converted to signal control
Area type	Urban and rural
Time period for crash history	1 year, 3 years
Crash severity categories	All severities, fatal-and-injury (FI)
Crash type categories	All types, angle [a]
Intersection legs	3, 4
Major road AADT	Range: based on volumes in Warrants 1 and 7
Minor road AADT	Range: based on volumes in Warrants 1 and 7

Note:

a – 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.

The literature review indicated that intersection safety is also significantly influenced by the number of intersection legs and traffic volume (i.e., annual average daily traffic volume [AADT]). These elements are identified in the last three rows of Table 23.

The AADT elements are identified in Table 23 as having a range of values that are considered in the warrant development process. This process is described in the next section; however, it is noted here that this process considered the effect of signal installation for a *range* of AADT volumes. The lower limit of this range is based on Criterion C of Warrant 7. It specifies that the eight highest hourly volumes of the average day exceed those identified in the “80 percent” columns in Table 4C-1 of the MUTCD (FHWA, 2009). The upper limit of the range is based on the values in Table 4C-1 in the “100 percent” columns. The hourly volumes in Table 4C-1 were used to estimate equivalent AADTs. The process used to compute these estimates is described in the next section.

Four crash categories were considered for the warrant development. Total crashes (i.e., crashes of all severities and types) were considered because the guidance in the Section 4C.01 of the MUTCD indicates that a signal should not be installed unless it will improve the overall safety and/or operation of the intersection (FHWA, 2009). Consideration of total crashes is important because signal installation can influence the frequency of many crash types, not just angle and opposed-left-turn crashes. Fatal-and-injury crashes (all crash types) were considered because property-damage-only crashes are not reliably or consistently reported in some jurisdictions. Angle crashes were considered because Warrant 7 currently focuses on “crashes of a type susceptible to correction.” Angle crashes are the most predominant crash type that satisfies this criterion, and that are also addressed in the HSM predictive methods. Crashes with a pedestrian and crashes between a left-turning vehicle and an opposing through vehicle also satisfy this criterion, but the HSM does not provide a predictive model and overdispersion factor for these crash types. Fatal-and-injury angle crashes were considered for the combination of reasons cited previously for fatal-and-injury crashes and for angle crashes.

Two crash-history time periods were considered for the warrant development. The one-year period is intended to provide warrant thresholds suitable for the "quick response" identification of a relatively recent degradation in intersection safety. The three-year period is intended to provide thresholds suitable for identifying intersections for which signal installation will have a more subtle effect on safety—an effect that is only detectable using a longer evaluation period.

Development Process

This section describes the process used to develop the proposed content for the crash experience warrant. The first subsection describes the rules used to define the threshold values for the proposed Criterion B. The second subsection describes the sensitivity analysis used to quantify the change in safety associated with signal installation. The third subsection describes the findings from the sensitivity analysis.

Rules to Define Warrant Criterion

The decision rules were established to indicate when the frequency of target crashes is likely to be reduced by signal installation. These rules were applied to the results of the safety evaluation procedure during the sensitivity analysis to identify appropriate threshold values for Criterion B. The rules are described in Table 24 for each of four crash categories.

Table 24. Decision rules to define warrant criterion.

Crash Category	Decision Rule
Total crashes (all types and severities)	1. Relative to the existing stop control, the signal produces a significant decrease in total average crash frequency; or 2. Relative to the existing stop control, the signal produces a significant decrease in the total severity index.
Fatal-and-injury crashes (all types)	1. Relative to the existing stop control, the signal produces a significant decrease in average fatal-and-injury crash frequency.
Angle crashes (all severities)	1. Relative to the existing stop control, the signal produces a significant decrease in average angle crash frequency.
Fatal-and-injury angle crashes	1. Relative to the existing stop control, the signal produces a significant decrease in average fatal-and-injury angle crash frequency.

The Total Crashes category in Table 24 uses two decision rules. The first rule considers total crash frequency and the second rule considers the total severity index. Both performance measures are important indicators of safety performance. Consideration of total crashes is important for the reasons cited in the previous paragraph. The total severity index is important when evaluating alternatives that influence the crash severity distribution (e.g., signal installation).

Rule 1 for each crash category is checked by completing the first four steps of the safety evaluation procedure described in Chapter 4. By completing these steps, the analyst produces an estimate of the average crash frequency (and its variance) for subject crash category. This estimate is produced for the existing stop-controlled intersection and for this same intersection after a proposed signal is installed.

The change in average crash frequency is determined by computing the difference of the two estimates (change in crash frequency = signal-control crash frequency – stop-control crash frequency). If the change is negative, then the statistical significance of the change is determined by dividing it by the square root of the corresponding variance.

The hypothesis test for Rule 1 is that safety did not improve (i.e., that the difference is not significantly less than zero). Hence, it is a one-tail test such that the computed ratio would need to be less than -1.64 (corresponding to a 0.05 significance level) to reject the hypothesis. If the ratio exceeds -1.64, then the change is not considered to be statistically significant and Rule 1 is not satisfied. If this ratio is less than -1.64, then the change is statistically significant and the rule is satisfied.

If the change in average crash frequency is positive then Rule 1 is not satisfied (i.e., the signal increases the average crash frequency). In this case, the test of significance is not strictly needed because the computed ratio will be positive, which will always make it exceed -1.64.

Rule 2 for the Total Crashes category is tested using the results from Step 5 of the safety evaluation procedure. The change in total severity index is computed by computing the difference of the two estimates (change in severity index = signal-control index – stop-control index). If the change is negative, then the statistical significance of the change is determined by dividing it by the square root of the corresponding variance.

The hypothesis test for Rule 2 is that there is no net safety benefit (i.e., that the difference is not significantly less than zero). Hence, it is a one-tail test such that the computed ratio would need to be less than -1.64 (corresponding to a 0.05 significance level) to reject the hypothesis. If the ratio exceeds -1.64, then the change is not considered to be statistically significant and Rule 2 is not satisfied. If this ratio is less than -1.64, then the change is statistically significant and the rule is satisfied.

If the change in total severity index is positive then Rule 2 is not satisfied (i.e., the signal causes a net safety dis-benefit). In this case, the test of significance is not strictly needed because the computed ratio will be positive, which will always make it exceed -1.64.

Sensitivity Analysis

The safety evaluation procedure described in Chapter 4 was used to conduct a sensitivity analysis of the elements listed in Table 23. For this analysis, the average crash frequency for the existing stop-controlled intersection was compared with that for the same intersection with signal control. These two estimates were computed for each element identified in Table 23.

The first three subsections to follow describe the input variables established for the analysis. The last subsection provides an overview of the analysis process.

Typical Conditions

The safety evaluation procedure is based on the predictive methods described in Part C of the HSM. As a result, it shares the same input variables as the HSM predictive methods. Typical values were selected for these input variables. They are collectively identified in the following bullet list and Table 25.

- Intersection skew (stop-control): 0.0 degrees
- Red-light camera enforcement (signal control): no
- Number of approaches with right-turn-on-red prohibition (signal control): 0
- Left-turn operational mode (signal control): permissive
- Right-turn bay: none
- Lighting presence: not present
- Bus stops (signal control): 0
- Public schools nearby (signal control): 0
- Alcohol sales establishments nearby (signal control): 0

Table 25. Input variable values.

Area Type	Number of Legs	Control Type	Major-Road Lanes[a]	Pedestrian Volume, ped/h	Left-Turn Bays	Lanes Crossed by Pedestrian
Rural	3	Stop control on minor road	2,4	0	Major: 0	0
		Signal	2, 4	0	Major: 1 Minor: 0	0
	4	Stop control on minor road	2, 4	0	Major: 0	0
		Signal	2, 4	0	Major: 2 Minor: 0	0
Urban	3	Stop control on minor road	4	400	Major: 1	5
		Signal	4	400	Major: 1 Minor: 1	5
	4	Stop control on minor road	4	700	Major: 2	5
		Signal	4	700	Major: 2 Minor: 2	5

Note:

a – Major-road lanes include all lanes serving through movements at the intersection on the major-road approaches (total of both approaches).

The values in the preceding list and Table 25 are considered typical of most intersections. As a result, they are appropriate for developing the threshold values for Criterion B. The use of input variable values that are different from the typical values will produce different results in the sensitivity analysis. However, it is expected that the collective effect of any differences will be small, and offsetting.

Crash Distribution

The EB Method used in the safety evaluation procedure requires the observed crash count for the subject stop-controlled intersection. In fact, the safety evaluation procedure was developed to accept the observed crash count categorized by crash type and severity. Typical crash distribution proportions are provided in Part C of the HSM. These proportions are listed in Table 26. The proportions in this table total 1.0 for each combination of area type, lanes, and legs (i.e., for each column). In some cases, the values in the table had to be computed from the proportions published in the HSM because those published in the HSM did not conform to the desired combinations.

Equivalent AADTs

The volumes used in the sensitivity analysis were based on AADTs estimated from the hourly volumes associated with Table 4C-1 in the MUTCD (FHWA, 2009). The AADT estimates were computed using a typical distribution of hourly volume (expressed as a proportion of AADT). These distributions were obtained from a report by Hallenbeck et al. (1997) who aggregated continuous count station data from 19 states. Separate distributions were established for urban streets and for rural highways. The eighth-highest hourly volume was found to be 0.060 and 0.055 of the AADT on urban streets and rural highways, respectively.

Table 26. Crash distribution for intersections with stop control on the minor road.

Severity	Crash Type	Proportion Crashes by Area Type, Major-Road Lanes, and Intersection Legs					
		Rural				Urban	
		2 Lanes[a]		4 Lanes[a]		2 or 4 Lanes[a]	
		3 Legs	4 Legs	3 Legs	4 Legs	3 Legs	4 Legs
Fatal and injury (FI)	Angle [b]	0.116	0.230	0.140	0.228	0.105	0.149
	Rear end	0.110	0.091	0.094	0.091	0.128	0.114
	Other	0.196	0.111	0.146	0.108	0.117	0.118
	Total	0.421	0.431	0.381	0.428	0.350	0.381
Property damage only (PDO)	Angle [b]	0.122	0.201	0.123	0.167	0.145	0.185
	Rear end	0.169	0.151	0.195	0.137	0.244	0.207
	Other	0.288	0.216	0.302	0.268	0.260	0.227
	Total	0.579	0.569	0.619	0.572	0.650	0.619

Note:

a – Major-road lanes include all lanes serving through movements at the intersection on the major-road approaches (total of both approaches).

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.

The equivalent AADTs associated with the “100 percent” and “70 percent” columns of MUTCD Table 4C-1 are provided in Table 27. Table 4C-1 is included in Warrant 1 – Eight-Hour Vehicular Volume. Those AADTs associated with the “80 percent” and “56 percent” columns of Table 4C-1 are provided in Table 28. These two columns are referenced in Criterion C of Warrant 7. The equation used to compute these AADTs is identified in the table footnotes.

The AADTs in Table 27 and Table 28 were used to form a target volume range for the sensitivity analysis. Specifically evaluated were major-road AADTs in the range of 5,000 and 15,000 veh/d and minor-road AADTs in the range of 1,400 and 6,000 veh/d.

Table 27. Equivalent average daily traffic volumes based on Warrant 1.

Area Type	Number of Through Lanes on Each Approach		Approximate Equivalent AADT by Condition, veh/d [a, b]			
			Basis: Warrant 1, Condition A		Basis: Warrant 1, Condition B	
	Major	Minor	Major	Minor	Major	Minor
Urban	1	1	8,333	4,545	12,500	2,272
	2+	1	10,000	4,545	15,000	2,273
	2+	2+	10,000	6,061	15,000	3,030
	1	2+	8,333	6,061	12,500	3,030
Rural[c]	1	1	6,364	3,471	9,545	1,736
	2+	1	7,636	3,471	11,455	1,736
	2+	2+	7,636	4,628	11,455	2,314
	1	2+	6,364	4,628	9,545	2,314

Notes:

a – AADT volumes are based on the Warrant 1 hourly volumes in Table 4C-1 of the MUTCD (FHWA, 2009). Those volumes for urban areas are based on the “100 percent” columns. Those volumes for rural areas are based on the “70 percent” columns.

b – Major-Road AADT = warrant vehicles per hour / f_8; Minor-Road AADT = warrant vehicles per hour / (f_8 x D); where, f_8 = eighth-highest hour volume expressed as a proportion of the AADT (= 0.060 in urban areas and 0.055 in rural areas); and D = directional distribution (= 0.55).

c – “Rural” values apply to intersections where the major-road speed exceeds 40 mi/h or intersections located in an isolated community with a population of less than 10,000.

Table 28. Equivalent average daily traffic volume based on Criterion C of Warrant 7.

Area Type	Number of Through Lanes on Each Approach		Approximate Equivalent AADT by Condition, veh/d [a, b]			
			Basis: Warrant 1, Condition A		Basis: Warrant 1, Condition B	
	Major	Minor	Major	Minor	Major	Minor
Urban	1	1	6,667	3,636	10,000	1,818
	2+	1	8,000	3,636	12,000	1,818
	2+	2+	8,000	4,848	12,000	2,424
	1	2+	6,667	4,848	10,000	2,424
Rural[c]	1	1	5,091	2,777	7,636	1,388
	2+	1	6,109	2,777	9,164	1,388
	2+	2+	6,109	3,702	9,164	1,851
	1	2+	5,091	3,702	7,636	1,851

Notes:

a – AADT volumes are based on the Warrant 1 hourly volumes in Table 4C-1 of the MUTCD (FHWA, 2009). Those volumes for urban areas are based on the “80 percent” columns. Those volumes for rural areas are based on the “56 percent” columns.

b – Major-Road AADT = warrant vehicles per hour / f_8; Minor-Road AADT = warrant vehicles per hour / (f_8 x D); where, f_8 = eighth-highest hour volume expressed as a proportion of the AADT (= 0.060 in urban areas and 0.055 in rural areas); and D = directional distribution (= 0.55).

c – “Rural” values apply to intersections where the major-road speed exceeds 40 mi/h or intersections located in an isolated community with a population of less than 10,000.

Analysis Process

The process for determining the threshold values for Criterion B consisted of a series of steps. The first step involved defining a set of AADT values that represent the range identified in Table 23. Major-road and minor-road "trial" AADTs were then selected from the low end of this range (and incrementally increased for each subsequent iteration of the process).

The second step was to identify a set of "trial" crash counts associated with specific crash type and severity categories for the stop-controlled intersection. These counts were used in the safety evaluation procedure with the EB Method to estimate the expected average crash frequency for the stop-controlled intersection. The crash distribution used for this purpose is provided in Table 26.

At the start of second step, the number of total crashes was specified. Then, the crash distribution proportions were used to compute the corresponding trial crash count for each crash type and severity category. The distribution used in this step matched that of the element combination being considered (i.e., separate distributions were prepared for two-lane highway, multilane highway, and urban arterial intersections).

This process is illustrated in Table 29 for a rural two-lane highway intersection. The first few columns of the table show the crash distribution proportions provided in Chapter 10 of the HSM. The proportions in the table are used to compute the corresponding trial crash count for each crash type and severity category. The computed values shown in the last three columns of the table illustrate the trial counts that are obtained when the total crashes are specified as 21 crashes per three years. The computed trial counts varied depending on the total crash count that is specified.

Table 29. Crash count estimation procedure for rural two-lane highway intersections.

Crash Type	Crash Distribution by Severity			Trial Crash Count, crashes/3 years		
	FI	PDO	Total	FI	PDO	Total
Angle	0.114	0.123	0.237	2	3	5
Rear end	0.114	0.164	0.278	2	4	6
Other	0.183	0.302	0.485	4	6	10
Total	0.411	0.589	1.000	8	13	21

The third step involved using one value of major-road AADT, one value of minor-road AADT, and one set of trial crash counts in the safety evaluation procedure. The results from the evaluation were then assessed using the decision rules for a specific crash category from Table 24.

The second and third steps were repeated by incrementally increasing the specified total crash count (and computing new trial crash counts). Through several iterations of these two steps, the crash counts that just satisfied the rules were found. They were considered to be candidate Criterion B values for the corresponding AADTs.

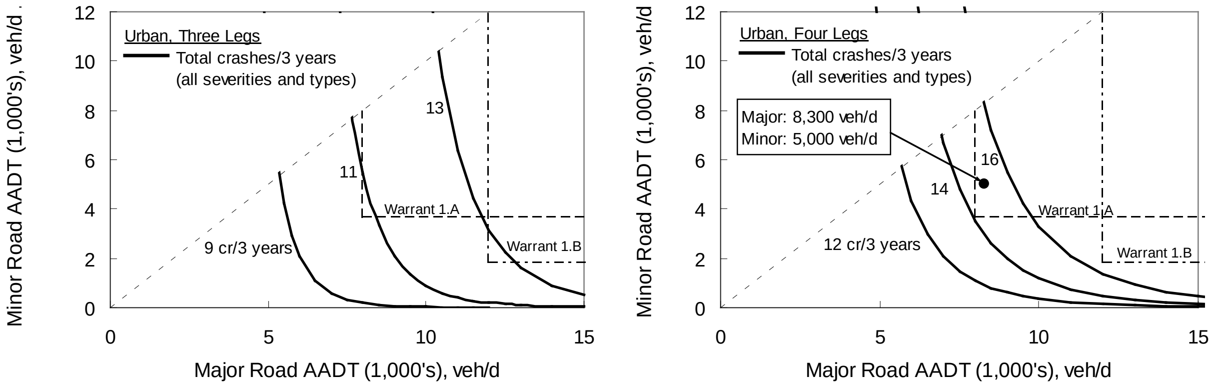
When the three steps were completed, the process was restarted with the first step wherein a new set of major-road and minor-road AADTs were selected. After all combinations of AADT values were evaluated, the results were combined to determine the recommended criterion values for the specified combination of crash category, area type (urban, rural), number of legs, and time period for crash history. The process was then repeated for each of the four crash categories identified in Table 24.

Analysis Results

The results of the sensitivity analysis were used to identify several hundred threshold values for a given crash category. Each value is associated with various combinations of area type, major-road lanes, intersection legs, time period for crash history, and AADT. The number of values identified is largely a function of the number of trial AADTs. The number of values increases when smaller intervals are used to define specific AADTs within the specified range. The AADT interval size used was established to produce a desired minimum sample size for each combination.

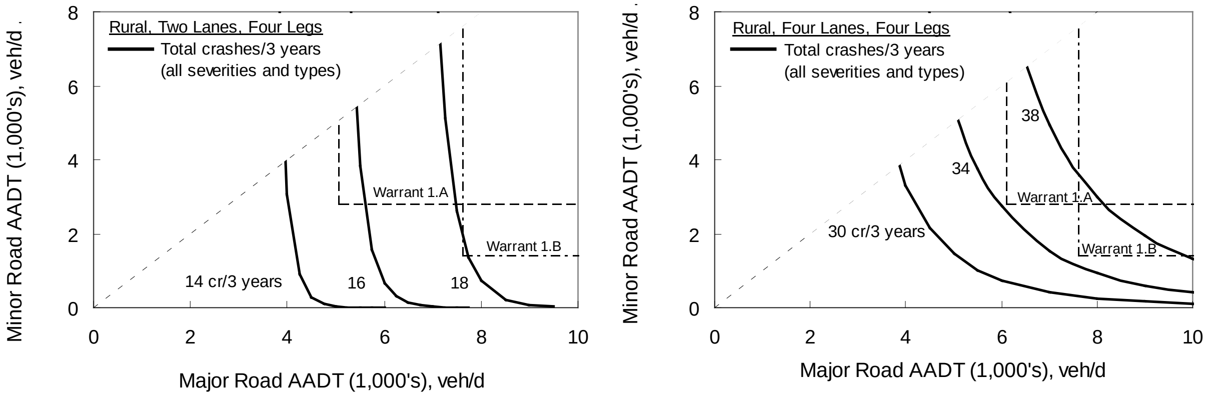
For each combination of area type, lanes, legs, and time period, the threshold values were examined using regression analysis to quantify the influence of AADT. A log-linear model (i.e., ln[threshold] = b_0 + b_1 ×ln[Major AADT] + b_2 ×ln[Minor AADT], where ln[x] equals the natural log of x) was used for the analysis. One model was calibrated for each combination. The coefficient of determination R^2 was found to vary from 0.95 to 0.99, depending on the combination.

The calibrated models for total crashes (all crash types and severities) and a three-year crash history are illustrated in Figure 12. Similar trends were obtained for total crashes with a one-year crash history, and for the other crash categories. However, the threshold values were smaller for these other combinations.



a. Urban three-leg intersections (2 or 4 lanes).

b. Urban four-leg intersections (2 or 4 lanes).



c. Rural four-leg intersections (2 lanes).

d. Rural four-leg intersections (4 lanes).

Figure 12. Total-crash thresholds as a function of major-road and minor-road AADT.

Three thick bold trend lines are shown in each figure. Each trend line is associated with a specific threshold value of “total crashes per three years.”

Also shown in Figure 12 are dashed lines associated with the AADTs listed in Table 28. With one exception, the AADTs used in the figures are associated with two through lanes on each major-road approach and one through lane on each minor-road approach. The one exception to this rule is that the dashed lines in Figure 12c are associated with one through lane on each major-road approach.

The diagonal dashed line is a logical boundary for the AADT region of interest. Volume combinations that lie above this line imply that the minor-road AADT exceeds the major-road AADT.

To illustrate the use of Figure 12b, consider an urban four-leg intersection with a major-road AADT of 8,300 veh/d, and a minor-road AADT of 5,000 veh/d. These two AADTs intersect at a point that is half-way between the “14-cr/3years” and “16-cr/3years” trend lines. This point is shown in the figure. By interpolation, the threshold value is determined to be 15 cr/3 years for these AADTs. The fact that the two AADT’s intersect at a point above and to the right of the dashed lines suggests that these AADTs are likely to correspond to hourly volumes that satisfy Criterion C of the existing crash experience warrant. The crash history at this intersection would need to include 15 or more reported crashes (any crash type or severity) during the previous three years before safety could be improved by signal installation.

Threshold Definition

The three thick bold trend lines in Figure 12 indicate that the threshold crash count decreases with decreasing AADT. By projecting this trend to the lower left in each figure, it implies that intersections with very small AADTs could realize improved safety (with signal installation) when there are only one or two reported crashes. On the other hand, AADT combinations intersecting above and to the right of the dashed lines identify situations where there is likely to be sufficient traffic volume to justify consideration of signal installation as a cost-effective treatment. Therefore, it is rationalized that the trend line associated with the fewest reported crashes that just intersects the dashed line region should be used to define the appropriate threshold value for Criterion B. This threshold should identify intersections where the engineering study will likely indicate that traffic safety will be improved by signal installation, and that there are a sufficient number of crashes to justify a more detailed evaluation of signal installation as part of the engineering study.

Proposed Thresholds

Examination of the aforementioned threshold definition indicated that the trend line with the fewest crashes that just intersects the dashed line region is consistently defined by the Condition A AADTs in Table 28. As a result, these AADTs were used to compute the Criterion B reported crash thresholds that satisfied the decision rules (described in Table 24). The proposed thresholds are listed in Table 30 to Table 33 for each combination of crash category and crash-history time period considered.

The values in Table 30 and Table 32 apply to a one-year time period for crash history. Those in Table 31 and Table 33 apply to a three-year time period for crash history. The thresholds for the one-year period are suitable for the “quick response” identification of a relatively recent degradation in intersection safety. The thresholds for the three-year period are suitable for which signal installation will have a more subtle effect on safety—an effect that is only detectable using a longer evaluation period.

Table 30 and Table 31 apply to all crash types combined. The “Total Crashes” thresholds can be used to identify intersections where signal installation is likely to improve the overall safety of the intersection, based on consideration of crash frequency and severity. The “Fatal-and-Injury” thresholds can be used to identify intersections where signal installation is likely to reduce fatal-and-injury crash frequency. The overall safety of the intersection is also likely to be improved if the proportion of property-damage-only crashes at the subject intersection is consistent with that for typical intersections.

Table 30. Reported crash threshold for use with Criterion B of Warrant 7 based on one-year crash history and considering all crash types.

Area Type	Number of Through Lanes on Each Approach		Minimum Number of Reported Crashes in One-Year Period			
			Total Crashes (all types and severities)		Fatal-and-Injury (all types)	
	Major	Minor	Four Legs	Three Legs	Four Legs	Three Legs
Urban	1	1	8	6	5	5
	2+	1	9	7	5	5
	2+	2+	9	7	5	5
	1	2+	8	6	5	5
Rural[a]	1	1	8	6	5	5
	2+	1	18	14	11	11
	2+	2+	18	14	11	11
	1	2+	8	6	5	5

Notes:

a – "Rural" values apply to intersections where the major-road speed exceeds 40 mi/h or intersections located in an isolated community with a population of less than 10,000.

Table 31. Reported crash threshold for use with Criterion B of Warrant 7 based on three-year crash history and considering all crash types.

Area Type	Number of Through Lanes on Each Approach		Minimum Number of Reported Crashes in Three-Year Period			
			Total Crashes (all types and severities)		Fatal-and-Injury (all types)	
	Major	Minor	Four Legs	Three Legs	Four Legs	Three Legs
Urban	1	1	12	9	6	6
	2+	1	14	10	7	7
	2+	2+	14	10	7	7
	1	2+	13	10	6	6
Rural[a]	1	1	15	11	8	8
	2+	1	34	25	21	21
	2+	2+	35	26	21	21
	1	2+	15	11	8	8

Notes:

a – "Rural" values apply to intersections where the major-road speed exceeds 40 mi/h or intersections located in an isolated community with a population of less than 10,000.

Table 32 and Table 33 apply to angle crashes. The "Angle Crashes" thresholds can be used to identify intersections where signal installation is likely to reduce angle crash frequency. Similarly, the "Fatal-and-Injury Angle Crashes" thresholds can be used to identify intersections where signal installation is likely to reduce fatal-and-injury angle crash frequency. For both sets of thresholds, the overall safety of the intersection is also likely to be improved if the distribution of the "other" crashes (i.e., those not addressed by the stated crash category) at the subject intersection is consistent with that for typical intersections.

In each table, values for all crash severities and values for fatal-and-injury crashes are provided. The thresholds for fatal-and-injury crashes may be more useful to those practitioners who suspect that property-damage-only crashes in the subject jurisdiction are not reliably or consistently reported.

Table 32. Reported crash threshold for use with Criterion B of Warrant 7 based on one-year crash history and considering angle crashes.

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

Notes:

a – "Rural" values apply to intersections where the major-road speed exceeds 40 mi/h 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.

Table 33. Reported crash threshold for use with Criterion B of Warrant 7 based on three-year crash history and considering angle crashes.

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

Notes:

a – "Rural" values apply to intersections where the major-road speed exceeds 40 mi/h 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.

The threshold values for a one-year period exceed those for a three-year period when the latter are expressed on a "per year" basis. This trend reflects the fact that counts averaged over longer time periods reduce the uncertainty associated with the estimate of average crash frequency, and they increase the reliability of the results.

Application

Table 30, Table 31, Table 32, or Table 33 can be used in application. Satisfaction of the values from one table is sufficient to satisfy Criterion B. Within a table, the satisfaction of a threshold value for either the "All severities" category or the "FI" category is sufficient to satisfy Criterion B.

To illustrate the use of Table 31, consider an urban four-leg intersection with a four-lane major-road (2 lanes on each approach) and a two-lane minor-road (1 lane on each approach). Table 31 indicates that the "total-crash" threshold value is 14 cr/3 years. The trend line in Figure 12b confirms the intent of the threshold definition because the "14-cr/3years" trend line just intersects the two dashed trend lines associated with Warrant 1, Condition A. The crash history at this intersection would need to include 14 or more reported crashes (any crash type or severity) during the previous three years to satisfy Criterion B. If all three warrant criterion are met, then the implication is that there is sufficient evidence of the need for a more detailed evaluation of signal installation as part of the engineering study process. This study would then confirm whether the signal installation provides an overall safety improvement.

Discussion

The safety evaluation procedure used to develop the threshold values is not able to evaluate rural three-leg signalized intersections. This deficiency stems from the fact that the necessary safety prediction models for rural three-leg intersections are not available in the HSM. The threshold values shown in Table 30 to Table 33 for rural three-leg intersections were estimated as equal to the rural four-leg threshold values multiplied by the ratio of urban three-leg to urban four-leg values. This approach is based on the assumption that the trend associated with intersection legs at urban intersections is the same for rural intersections.

An examination of trends in Table 30 to Table 33 indicates that the values for urban three-leg intersections are often lower than those for urban four-leg intersections. This trend follows that obtained from the underlying safety prediction models, as shown in Figure 4 and Figure 5. The reason for this trend is that three-leg intersections have fewer conflict points than four-leg intersections and fewer crashes, all other factors being the same. As a result, the minimum number of crashes needed to indicate that a three-leg intersection can be improved by signal installation is correspondingly lower than that for a four-leg intersection.

The thresholds associated with rural intersections having two or more through lanes on each major-road approach are much higher than those for an urban intersection with similar geometry. This trend reflects the fact that the rural signalized intersections on multilane highways have a predicted average crash frequency that is about three times larger than that for rural stop-controlled intersections on multilane highways (as shown in Figure 7). As a result, the rural stop-controlled intersection must experience many crashes in a given time period before its expected average crash frequency will exceed that of the rural signalized intersection (i.e., before signalization will offer a safety benefit). This trend is not reflected for urban intersections or rural intersections on two-lane highways. It likely reflects the high speed associated with multilane highways and the infrequent occurrence (i.e., wide spacing) of signalized intersections.

Of the two decision rules used to establish the thresholds for the "Total Crashes" category, the rule that was typically met first was dependent on area type. The thresholds associated with urban intersections were dictated by Rule 1 (i.e., a significant decrease in total average crash frequency). In contrast, the thresholds associated with rural intersections were dictated by Rule 2 (i.e., significant decrease in total severity). This trend reflects the tendency for crashes at rural intersections to be more severe than those at urban intersections. It also reflects the fact that a severe crash has a higher road-user cost than a property-damage-only crash.

Table 30 and Table 31 do not include values for specific crash types (e.g., crashes susceptible to correction by signal installation). This omission is intended to focus the warrant evaluation on *overall* intersection safety. This approach is consistent with the general approach in the MUTCD to consider overall intersection safety in the engineering study, and as the basis for justifying the use of a traffic control signal. Also, the literature review and the survey of practitioners indicated that it is sometimes difficult to determine which crashes are susceptible to correction, especially for agencies with crash records that have limited information about crash type or manner of collision.

It is also recognized that some crash types are unlikely to be influenced by signal presence. A warrant threshold that is based on consideration of all crash types could occasionally be met when the subject intersection has a large number of these “uninfluenced” crashes. The Signals Technical Committee of the NCUTCD expressed a desire to avoid this undesirable outcome. Therefore, to avoid this outcome, the proposed warrant (described in the next section) includes only the thresholds associated with angle crashes.

In addition to angle and left-turn-opposed crashes, the *Traffic Control Devices Handbook* indicates that pedestrian crashes are also susceptible to correction by signal installation (ITE, 2001). However, it is not possible to explicitly develop thresholds for pedestrian crashes because the HSM does not provide a predictive model and overdispersion factor for pedestrian crashes at stop-controlled intersections. Harwood et al. (2008) report that pedestrian crashes at urban intersections represent less than 2 percent of all intersection crashes. Chapter 10 of the HSM indicates that pedestrian crashes are less than 0.1 percent of all intersection crashes at rural intersections. Given these small percentages, it is rationalized that the scope of Table 32 and Table 33 could be expanded to include pedestrian crashes without further adjustment to the threshold values.

Proposed Warrant Content

The text for the proposed warrant is provided in this section. The new text is shown underlined and the recommended deletions are shown as strikeouts.

Section 4C.08 Warrant 7, Crash Experience

Support:

The Crash Experience signal warrant conditions are intended for application where the severity and frequency of crashes are the principal reasons to consider installing a traffic control signal.

Standard:

The need for a traffic control signal shall be considered if an engineering study finds that all of the following criteria are met:

- **A. Adequate trial of alternatives with satisfactory observance and enforcement has failed to reduce the crash frequency; and**
- **B. ~~Five or more reported crashes, of types susceptible to correction by a traffic control signal, have occurred within a 12-month period, each crash involving personal injury or property damage apparently exceeding the applicable requirements for a reportable crash; and~~**
- **B. One of the following conditions apply to the reported crash history (where each reported crash considered is related to the intersection and apparently exceeds the applicable requirements for a reportable crash):**
  - **a. The number of reported angle crashes and pedestrian crashes within a one-year period equals or exceeds the threshold number in Table 4C-2 for total angle crashes and pedestrian crashes (all severities); or**
  - **b. The number of reported fatal-and-injury angle crashes and pedestrian crashes within a one-year period equals or exceeds the threshold number in Table 4C-2 for total fatal-and-injury angle crashes and pedestrian crashes ; or**

c. **The number of reported angle crashes and pedestrian crashes within a three-year period equals or exceeds the threshold number in Table 4C-3 for total angle crashes and pedestrian crashes (all severities); or**

d. **The number of reported fatal-and-injury angle crashes and pedestrian crashes within a three-year period equals or exceeds the threshold number in Table 4C-3 for total fatal-and-injury angle crashes and pedestrian crashes; and**

C. **For each of any 8 hours of an average day, the vehicles per hour (vph) given in both of the 80 percent columns of Condition A in Table 4C-1 (see Section 4C.02), or the vph in both of the 80 percent columns of Condition B in Table 4C-1 exists on the major-street and the higher-volume minor-street approach, respectively, to the intersection, or the volume of pedestrian traffic is not less than 80 percent of the requirements specified in the Pedestrian Volume warrant. These major-street and minor-street volumes shall be for the same 8 hours. On the minor street, the higher volume shall not be required to be on the same approach during each of the 8 hours.**

Option:

If the posted or statutory speed limit or the 85th-percentile speed on the major street exceeds 40 mph, or if the intersection lies within the built-up area of an isolated community having a population of less than 10,000, the traffic volumes in the 56 percent columns in Table 4C-1 may be used in place of the 80 percent columns.

Table 4C-2. Reported crash value for use with Criterion B of Warrant 7 based on one-year crash history.

Area Type	Number of Through Lanes on Each Approach		Minimum Number of Reported Crashes in One-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	4	3	3
	2+	1	5	4	3	3
	2+	2+	5	4	3	3
	1	2+	5	4	3	3
Rural[a]	1	1	4	3	3	3
	2+	1	10	9	6	6
	2+	2+	10	9	6	6
	1	2+	4	3	3	3

Notes:

a – “Rural” values apply to intersections where the major-road speed exceeds 40 mi/h 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.

Table 4C-3. Reported crash value for use with Criterion B of Warrant 7 based on three-year crash history.

Area Type	Number of Through Lanes on Each Approach		Minimum Number of Reported Crashes in 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	6	5	4	4
	2+	1	6	5	4	4
	2+	2+	6	5	4	4
	1	2+	6	5	4	4
Rural[a]	1	1	6	5	4	4
	2+	1	16	13	9	9
	2+	2+	16	13	9	9
	1	2+	6	5	4	4

Notes:

a – “Rural” values apply to intersections where the major-road speed exceeds 40 mi/h 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.

CHAPTER 6

Conclusions and Recommendations

Conclusions

Section 4C.01 of the MUTCD states that, “A traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection.” However, there is no guidance offered in the MUTCD as to how the overall safety impact of the signal installation can be quantified so as to ascertain whether safety has been improved.

The MUTCD provides a crash experience warrant that serves as a first step of the engineering study process. Satisfaction of the crash experience warrant is an indication of likely safety improvement through signal installation. Once the warrant is met, the subsequent steps of the engineering study are then undertaken to confirm that signal installation will improve overall safety. The HSM is being used by some practitioners during the engineering study to confirm whether signal installation will improve overall safety. Specifically, the HSM is being used to quantify the reduction in expected crash frequency and severity associated with the signal installation.

There are many geometric design elements and traffic control features that influence intersection safety (e.g., turn bay presence, protected left-turn phase, etc.). Some of these elements and features are often added or modified along with the signal installation. The safety effect of these features and elements (before and after signal installation) should be considered in the engineering study to obtain an accurate estimate of the overall change in safety following signal installation.

Many research projects have been undertaken over the last 50 years with the objective of quantifying the safety effect of signal installation. However, for a variety of reasons, there is still considerable uncertainty about this effect, especially when evaluating a specific intersection. Almost all studies have shown that signal installation reduces crash frequency; however, the researchers did not control for the regression-to-the-mean tendency or for other changes to the intersection’s geometric design elements or traffic control features. As a result, most of these research results include an unknown combination of effects, such that the effect of signal installation cannot be accurately estimated.

A procedure was developed for quantifying the safety effect of signal installation. This procedure can optionally be used as part of the engineering study process. It is based on the predictive methods in the HSM. It requires AADT data for the major and minor roads. Observed crash data for one or more recent years can be used with the procedure to obtain a more reliable result. The procedure can be applied using a hand calculator, but it was also incorporated in a spreadsheet tool to facilitate implementation. The procedure considers total intersection crashes and crash severity. It does not focus on just those crashes that are susceptible to correction by a signal installation, unlike the crash experience warrant. This approach is consistent with similar procedures developed by other researchers (McGee et al. 2003; Hadayeghi et al. 2006). It is also consistent with the preferences of many practitioners.

The aforementioned procedure was used to develop revised content for Criterion B of the crash experience warrant. Application of the procedure to a range of typical intersection conditions indicated that there is a threshold value of observed crashes beyond which signal installation is likely to improve safety. However, the threshold value was found to vary by area type, intersection legs, and number of lanes on each intersection approach. As a result, a table of threshold values was prepared to include different values for logical combinations of area type, legs, and lanes.

An examination of trends in the threshold values indicates that the values for urban three-leg intersections are often lower than those for urban four-leg intersections. The reason for this trend is that three-leg intersections have fewer conflict points than four-leg intersections and fewer crashes, all other factors being the same. As a result, the minimum number of crashes needed to indicate that a three-leg intersection can be improved by signal installation is correspondingly lower than that for a four-leg intersection.

The thresholds associated with rural intersections having two or more through lanes on each major-road approach are much higher than those for an urban intersection with similar geometry. This trend reflects the fact that the rural signalized intersections on multilane highways have a predicted average crash frequency that is about three times larger than that for rural stop-controlled intersections on multilane highways. As a result, the rural stop-controlled intersection must experience many crashes in a given time period before its expected average crash frequency will exceed that of the rural signalized intersection (i.e., before signalization will offer a safety benefit). This trend is not reflected for urban intersections or rural intersections on two-lane highways.

Recommendations

The following recommendations have been developed based on the research conducted for this project.

- The proposed crash experience documented in Chapter 5 should be incorporated into the next edition of the MUTCD.
- The safety evaluation procedure documented in Chapter 4 should be extended to include roundabouts, all-way stop-controlled intersections, and crossroad ramp terminals (at interchanges). This extended procedure should then be used to develop crash experience warrants for these intersection types.
- Additional research is needed to extend the HSM predictive methods so that they can be used to estimate the average frequency of left-turn-opposed crashes. These extended methods should be incorporated in the safety evaluation procedure and used to develop a crash experience warrant for a protected left-turn phase.

CHAPTER 7

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APPENDIX A

Survey of Practitioners

Introduction

This appendix documents a survey of practitioners on their experience with the crash experience warrant and its possible improvement. The survey contained a total of ten questions; some questions were follow-up questions based on the response received to a previous question. The survey was divided into three main sections. The first section focused on how agencies evaluate intersection safety and consider alternative treatments to signalization. The second section explores agency experience with the existing crash warrant. The third section examines potential improvements to the warrant. A fourth section was used to identify the respondent's responsibilities, and to solicit open-ended comments about the crash experience warrant. SurveyMonkey, an online tool, was used to conduct the survey and collect responses.

The survey was distributed to over 250 individuals, who were selected to represent a broad range of agencies and geographic locations. Three or more engineers in each of the 50 states were selected, with a mix of local and state agencies represented. In addition, the Institute of Transportation Engineers (ITE) sent the survey request to about 215 of its U.S. members that work for local agencies.

The survey participation request was sent in an e-mail announcement. The e-mail included information about the project and a link to the survey website. The e-mail was sent out on July 1st, 2013. Responses were requested by July 26th. A total of 129 responses were received. Seventy-eight of the respondents identified the agencies they represent, which include approximately 25 state DOTs, 5 counties, and 30 cities and towns. A list of the agencies and consultants participating in the survey is provided in Table A-1.

The next section provides the text of the survey and the individual responses received. Due to the quantity of responses received for open-ended questions, the responses were grouped and summarized to capture general themes.

Table A-1. Agencies and consultants participating in the survey.

Alabama DOT	Kane County, Illinois
Arkansas State Highway & Transportation Dept	Kansas DOT
Athens-Clarke County, Georgia	Lake Havasu City, Arizona
California DOT	Louisiana DOT
City of Alexandria, Virginia	Maryland Transportation Authority
City of Ann Arbor, Michigan	Mississippi DOT
City of Baton Rouge, Louisiana	Missouri DOT
City of Burlington, Ontario, Canada	Nevada DOT
City of Davis, California	New Hampshire DOT
City of Dublin, Ohio	New Jersey DOT
City of Farmington, Connecticut	North Carolina DOT
City of Federal Way, Washington	North Dakota DOT
City of Gainesville, Georgia	Palm Beach County, Florida
City of High Point, North Carolina	Pennsylvania DOT
City of Idaho Falls, Idaho	Puerto Rico Highway and Transportation Authority
City of Kennewick, Washington	Sedgwick County, Kansas
City of Kent, Washington	Stantec Consulting Inc., Duluth, Georgia
City of Lincoln, Nebraska	Suffolk County, New York
City of Milwaukee, Wisconsin	Texas DOT
City of Phoenix, Arizona	Town of Danville, California
City of Poway, California	Town of Gilbert, Arizona
City of Rochester, Minnesota	Town of Manchester, Connecticut
City of Rocky Mount, North Carolina	Utah DOT
City of Stamford, Connecticut	Virginia DOT
City of Tempe, Arizona	Washington DOT
City of Wilmington, Delaware	West Jordan City, Utah
City of Wisconsin Rapids, Wisconsin	West Virginia DOT
Delaware DOT	Wisconsin DOT
DLZ Ohio, Inc.	Woodbury County, Iowa
Illinois DOT	Wyoming DOT
Iowa DOT	

Part I – Engineering Study

Guidance in Part 4 of the MUTCD indicates that a traffic control signal should not be installed unless an engineering study indicates that installing a traffic control signal will improve the overall safety and/or operation of the intersection.

1. Does your agency have a document that describes the steps involved in the evaluation of intersection safety, as part of the engineering study process?

	Response Percent	**Response Count**
No	87.1%	101
Yes, a copy of the document will be sent to jbonneson@kittelson.com	4.3%	5
Yes, a copy of the document can be downloaded from (write Internet address):	8.6%	10

2. Other than a check of the crash experience warrant, does your agency evaluate any data (or use any technique) to determine whether the signal installation will improve the overall safety of the intersection?

	Response Percent	**Response Count**
No	55.6%	65
Yes. The data and/or techniques are described in the document identified in Question 1 above.	6.0%	7
Yes. Please briefly describe the data or techniques that are used, and how they are used:	38.5%	45

The following list characterizes the kinds of comments received from the 45 respondents who indicated they would describe the data or techniques used (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Consider the distribution of crash types, including those types that may increase with a signal. *(9)*
- Produce a collision diagram and/or look for patterns in crash locations. *(6)*
- Use the *Highway Safety Manual* or typical crash rates to compute predicted crash frequency. *(6)*
- Perform a site visit to identify potential crash causes. *(5)*
- Read crash narratives to determine crash location and type. *(5)*
- Assess intersection sight lines. *(5)*
- Consider roadway speeds. *(4)*
- Review intersection geometry. *(3)*
- Review multiple years of crash data. *(2)*
- Develop a condition diagram. *(2)*
- Review the time of crash occurrences. *(2)*
- Consider distribution of crash severities. *(1)*
- Consider distance to adjacent intersections. *(1)*
- Assess school crossing information. *(1)*
- Conduct a road safety audit. *(1)*
- Seek police or citizen input. *(1)*

3. Does your agency keep documentation of the analysis and results from the engineering study of a given location (including the crash experience warrant evaluation)?

	Response Percent	**Response Count**
No	25.0%	32
Yes	75.0%	96

3a. Can we obtain a copy of this documentation for one "typical" intersection?

	Response Percent	Response Count
No	62.5%	55
Yes, a copy of the document will be sent to the e-mail address provided	33.0%	29
Yes, a copy of the document can be downloaded from (write Internet address):	4.5%	4

4. What alternatives to a traffic control signal have you found to be most effective at improving safety at stop-controlled intersections? (check all that apply)

	Response Percent	Response Count
Installing signs along the major street to warn road users approaching the intersection	45.7%	48
Relocating the stop line(s) and/or making other changes to improve the sight distance at the intersection	58.1%	61
Installing measures designed to reduce speeds on the approaches	20.0%	21
Installing a flashing beacon at the intersection to supplement STOP sign control	35.2%	37
Installing flashing beacons on warning signs in advance of a STOP sign controlled intersection on major and/or minor-street approaches	30.5%	32
Adding one or more lanes on a minor-street approach	15.2%	16
Revising the geometrics at the intersection to channelize vehicular movements	36.2%	38
Revising the geometrics at the intersection to add pedestrian median refuge islands and/or curb extensions	20.0%	21
Installing roadway lighting	34.3%	36
Restricting one or more turning movements	35.2%	37
Installing multi-way STOP sign control	46.7%	49
Installing a pedestrian hybrid beacon or In-Roadway Warning Lights	11.4%	12
Installing a roundabout	49.5%	52
Other (please describe):	14.3%	15

Other responses include (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Interactive warning systems to warn minor-street of approaching main line traffic (Intersection Conflict Warning Systems – being studied by the Enterprise pooled fund study) *(2)*
- Improving sight-distance by relocating/removing vegetation (recurring sight-distance obstruction) *(2)*
- Offset left and right turn lanes *(1)*
- Installing stop signs with LED lights on the perimeter of the sign *(1)*
- Pavement markings and signage on minor street approach *(1)*
- Installing multiple STOP signs per approach *(1)*

Part II – Experience with Existing Warrant

For the questions to follow, consider those intersections for which the crash experience warrant was evaluated during the last three years.

5. Was there any difficulty in determining which crashes are related to the intersection (and which are not)?

	Response Percent	Response Count
No	64.2%	70
Yes	35.8%	39

5a. Would guidance regarding the use of crash location and crash type to determine intersection relationship help here?

	Response Percent	Response Count
Yes	48.7%	19
No. Please describe the source of the difficulty:	51.3%	20

The following list characterizes the sources of difficulties offered when the response was “No” (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Inaccurate or incomplete data, particularly related to the crash location. *(17)*
- Differences between how law enforcement may define a crash type and how engineers seeking a countermeasure categorize the same crash. *(3)*

6. Was there any difficulty determining which crashes are of a type susceptible to correction by a signal?

	Response Percent	Response Count
No	85.6%	89
Yes. Please describe the type of guidance that would be of help here:	14.4%	15

The following list characterizes the types of guidance offered when the answer was “Yes” (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Need to further review the crash report and narrative. *(4)*
- More description of the types of crashes correctable by a signal would be helpful. *(2)*
- Fixed object crashes may be a result of drivers making avoidance maneuvers. *(2)*
- Left-turn crashes may decrease with a signal if left-turn protection is provided. *(1)*
- Rear-end crashes may increase with a signal, especially if sight distance is limited. *(1)*

7. Was the decision reached from the crash experience warrant evaluation always consistent with your judgment (i.e., for each intersection, did the decision seem reasonable based on everything you know about the intersection)?

	Response Percent	**Response Count**
Yes	83.5%	86
No. Please describe the situations for which the results of the warrant evaluation tended to be inconsistent with your judgment:	16.5%	17

The following list characterizes the situations offered when the response was "No" (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- The crash experience warrant does not account for "close calls," particularly with vulnerable users (bicyclists and pedestrians). *(2)*
- Rural/Suburban areas where the peak use periods are short. *(2)*
- Intersections outside a 10,000 population center or with higher speed limit satisfy warrants (based on crash or volume) more often than seems reasonable.*(2)*
- Point location analyses that did not incorporate system/network impacts and effects. *(1)*
- Urban areas where queues prevent full demand counts. *(1)*
- The lowering of volume warrants for high-speed locations doesn't consider the increased severity of rear-end collisions on high-speed approaches. *(1)*
- The warrant does not consider crash rate or the effects of increasing traffic volumes. *(1)*
- The warrant used the count of correctable crash types to justify a signal, but further review of the crash narratives revealed that some crashes were not correctable. *(1)*
- The 12-month crash count was not representative of the long-run crash average. *(1)*
- Right-turn traffic volumes satisfied the warrant, but reviewing the data suggested right-turn traffic volumes may not be the cause of safety problems. *(1)*

Part III – Suggested Improvements to Warrant

The current MUTCD Warrant 7 – Crash Experience includes:

- **Criterion A** that addresses the trial of non-signal alternatives,
- **Criterion B** that addresses crash history in terms of the crash types susceptible to correction involving injury or property damage that occur during a 12-month period, and
- **Criterion C** that includes the evaluation of both Warrant 1 (Eight-Hour Vehicular Volume) and Warrant 4 (Pedestrian Volume) at the 80-percent volume level.

8. What additional factors should be considered in Warrant 7, in addition to (or instead of) those factors addressed in Criteria B and C? (check all that apply):

	Response Percent	**Response Count**
Other crash types (not just those susceptible to correction)	19.6%	21
Only fatal-and-injury crashes (i.e., exclude property damage only)	11.2%	12
A longer crash history (e.g., 24-months, 36-months, etc.)	72.0%	77
Average daily volume (not just during the hours specified by Warrants 1 and 4)	34.6%	37
Heavy vehicle volume (or percentage)	34.6%	37
Bicycle volume	15.0%	16
Other (please explain)	29.0%	31

Other responses include (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Approach speed/roadway travel speeds *(3)*
- 4-hour warrant and peak hour warrant *(2)*
- Turning movements (particularly if signal would include left-turn arrow phasing) *(2)*
- Severity risk based on approach speeds and/or vehicle types *(1)*
- Lighting *(1)*
- Intersection width *(1)*
- Average daily volume during the hours when crashes are occurring *(1)*
- Driveways/other distractions within intersection influence zone *(1)*
- "Systems" warrant (how well does this fit into the system of signals) *(1)*
- "Induced traffic" (traffic currently avoiding the intersection that will use it if a signal is installed) *(1)*
- Major road median width *(1)*
- Expected crash rate/ using HSM to estimate collision history with signalization *(1)*
- Rear-end crashes *(1)*

8a. What crash types, if any, should be considered in Warrant 7?

	Response Percent	**Response Count**
All crash types	57.9%	11
Just those crashes that are susceptible to correction by signal installation	26.3%	5
Only right-angle crashes	0.0%	0
Only right-angle and left-turn-related crashes	5.3%	1
Other. Please list the specific crash types that should be considered in the warrant:	10.5%	2[1]

[1] Both "Other" responses implied that all crash types should be considered to assess whether a signal will address the crashes.

9. Do you think the usefulness of the crash experience warrant can be improved?

	Response Percent	**Response Count**
No	49.0%	48
Yes. Please describe improvements to the crash experience warrant that you think would improve its usefulness:	51.0%	50

The list below identifies the improvements offered when the response to this question was "Yes" (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Evaluate multiple years of crash data. *(18)*
- Provide description and examples of correctable and uncorrectable crash types. *(4)*
- Incorporate the *Highway Safety Manual*, expected crash frequency, and/or crash rate. *(4)*
- Include warrants for alternative safety treatments (i.e. installing advance beacons). *(3)*
- Revisit the traffic volume criteria related to speeds and population. *(3)*
- Weight the crashes by severity. *(2)*
- Consider the presence of a median. *(1)*
- Consider peak hour volumes. *(1)*

- Provide guidance for a safety assessment or road safety audit before installing a traffic signal due to crash experience. *(1)*

10. Do you think the crash experience warrant could be made easier to apply?

	Response Percent	**Response Count**
No	88.5%	85
Yes. Please describe any improvements to the crash experience warrant that you think would improve its ease of application:	11.5%	11

The list below identifies the improvements offered when the response to this question was "Yes" (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Provide description of crashes susceptible to correction. *(1)*
- Being able to plot something on a graph would be helpful. *(1)*
- Remove Part C. *(1)*
- Consideration of signalization should carry some burden of professional analysis and judgment. *(1)*

Part IV – General Information

Please indicate the number of signalized intersections for which your agency is responsible:

69 numerical responses given, with the following statistics:

Mean	714
Median	185
Mode	200
Range	0-14,000

Use the space below to provide any additional comments on the crash experience warrant, or the engineering study process:

Responses include (the number in parenthesis following each comment indicates the number of responses that reflected a similar comment):

- Warrant 7 is rarely used alone to justify a signal. *(7)*
- Roundabouts have shown success in reducing crashes and minimizing severe pedestrian and bicyclist conflicts and should also be considered. *(3)*
- Individual crash reports need to be reviewed. *(2)*
- The crash warrant should serve as an indicator that the intersection needs to be evaluated more in depth to determine the best treatment (not justification for a signal). *(1)*
- Consider integrating the *Highway Safety Manual*. *(1)*
- The warrant should consider the crash rate/fatalities coupled with the ADT on the major street. *(1)*
- The crash warrant should consider the severity of crashes correctable by a signal. *(1)*
- The crash warrant should use a longer period of data. *(1)*
- Signals may be installed for "political reasons" even if warrants aren't met. *(1)*

- Transitioning from a “tried and true” method to something new is always rocky. The strength (and weakness) of the current methodology is its simplicity. *(1)*
- Computerized applications are increasingly necessary for warrant analysis, although engineering judgment must be applied. *(1)*
- Traffic control warrants are easier to apply since predicted traffic volumes are easier to determine. Using a crash prediction model can be difficult in areas with new development. *(1)*
- Warrant 7 has been used to justify signals when the other warrants aren’t met. *(1)*
- A predictive aspect for analyzing an existing signal for removal in predicting the change in crashes would be useful. More guidance is needed for “de-warranting” signals. *(1)*
- Need to consider the changes in signals that have occurred since developing the original warrants (i.e. a properly maintained fully actuated signal has less impact to the major street than the old pre-timed signals). *(1)*