NCHRP

REPORT 491

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Crash Experience Warrant for Traffic Signals

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Crash Experience Warrant for Traffic Signals

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SUBJECT AREAS
Highway Operations, Capacity, and Traffic Control

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in Cooperation with the Federal Highway Administration

TRANSPORTATION RESEARCH BOARD

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Dr. Hugh McGee of BMI was the principal investigator, assisted by Sunil Taori, Michael Obermeyer (former employee), and Chris Daily. BMI was responsible for performing the literature review; planning, collecting, and assembling all traffic and crash data into a database from field and highway agencies across the United States, and preparing the reports.

Dr. Bhagwant Persaud of Ryerson University served as a consultant and was responsible for performing all the analyses and developing the recommended warrant. He was assisted by Craig Lyon and Dominique Lord. Ryerson University provided data for Toronto sites as a subcontractor. Also, Dr. Ezra Hauer consulted throughout the study.

The authors are thankful to all the state and local highway agencies and individuals in these agencies who assisted in providing critical data required for the completion of this study. BMI also acknowledges the assistance of several of their staff members in the data collection and compilation effort.

FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

This report describes a process for estimating the safety impacts of installing or removing traffic control signals and recommends an improved Crash Experience warrant for the *Manual on Uniform Traffic Control Devices (MUTCD).* The estimation process can be used during the engineering study to determine if a traffic signal will improve the overall safety of the intersection. The report will be useful to traffic engineers determining the most appropriate traffic control device for an intersection.

Traffic signals are often seen by the public and elected officials as a cure-all for operational and safety problems at intersections. Although signals have been used for many years, very little is actually known about their impact on safety. The Crash Experience warrant in the *Manual on Uniform Traffic Control Devices* (*MUTCD*) (one of eight warrants that set minimum thresholds for considering installation of a traffic signal) is not well supported and does not consider crash severity. The *MUTCD* specifies that an engineering study "should indicate a traffic signal will improve the overall safety and/or operation of the intersection" before a signal is installed; however, there are no tools to help the traffic practitioner determine the likely impact on safety from installing a traffic signal. Past studies have yielded contradictory results and suffered from a number of serious deficiencies.

Sometimes changes in traffic conditions can eliminate the need for an existing traffic signal. Practitioners need a way to analyze the safety impact of removing such a signal. This information can be used to alleviate the public concern that usually blocks signal removal.

Under NCHRP Project 17-16, BMI and their subcontractors reviewed previous research evaluating crash experience at signalized intersections and those controlled by stop signs. They then developed and carried out a data collection and analysis plan to support development of a model to estimate the number, severity, and types of crashes expected at signalized and stop-controlled intersections and the changes expected from installation or removal of a traffic signal. Using that model, they identified conditions under which signal installation or removal is likely to improve or degrade safety. Lastly, they recommended an improved Crash Experience warrant suitable for inclusion in the *MUTCD.*

CONTENTS

CRASH EXPERIENCE WARRANT FOR TRAFFIC SIGNALS

SUMMARY

The *Manual on Uniform Traffic Control Devices (MUTCD)* provides standards and guidance concerning the design and use of traffic control devices on all public roadways. For one of these devices, the traffic control signal, the *MUTCD* requires that an engineering study be performed to determine whether installation of a traffic control signal is justified at a particular intersection. Further, the *MUTCD* provides eight warrants, any one of which could be used to determine the need for the traffic signal.

One of those warrants—Warrant 7, Crash Experience—is intended for application where the severity and frequency of crashes are the principal reasons to consider installing a traffic signal. The following are the criteria for this warrant:

1. Adequate trial of alternatives has failed to reduce crash experience;
2. Five or more crashes of types susceptible to correction by a traffic control signal have occurred within a 12-month period; and
3. The traffic and pedestrian volumes are not less than 80 percent of the required levels for Warrant 1, Eight-Hour Volume, and Warrant 4, Pedestrian Volume.

The Crash Experience warrant is considered insufficient because it does not provide an engineer with a means to determine what changes in safety can be anticipated from installing a traffic signal. In addition, it is not clear that the current threshold of five or more crashes of the type correctable by signal control is based on a logical and scientific approach for determining changes in intersection safety. To address this issue, this project was established with the objectives to develop an improved Crash Experience warrant for traffic signals and to provide a model to estimate the safety impacts of installing traffic signals.

A historical review of the *MUTCD* was conducted to establish the origin of the warrant and what changes were made with various editions. The review could not establish the empirical rational for the warrant, which changed slightly with each edition. The review of the literature that documented studies of crash changes with signalization showed somewhat mixed findings, but, in general, angle crashes were reduced and rear-end crashes on the main street increased with signalization. However, many of the findings would be considered suspect in light of current state-of-the-art crash analysis methods that were not followed in those studies.

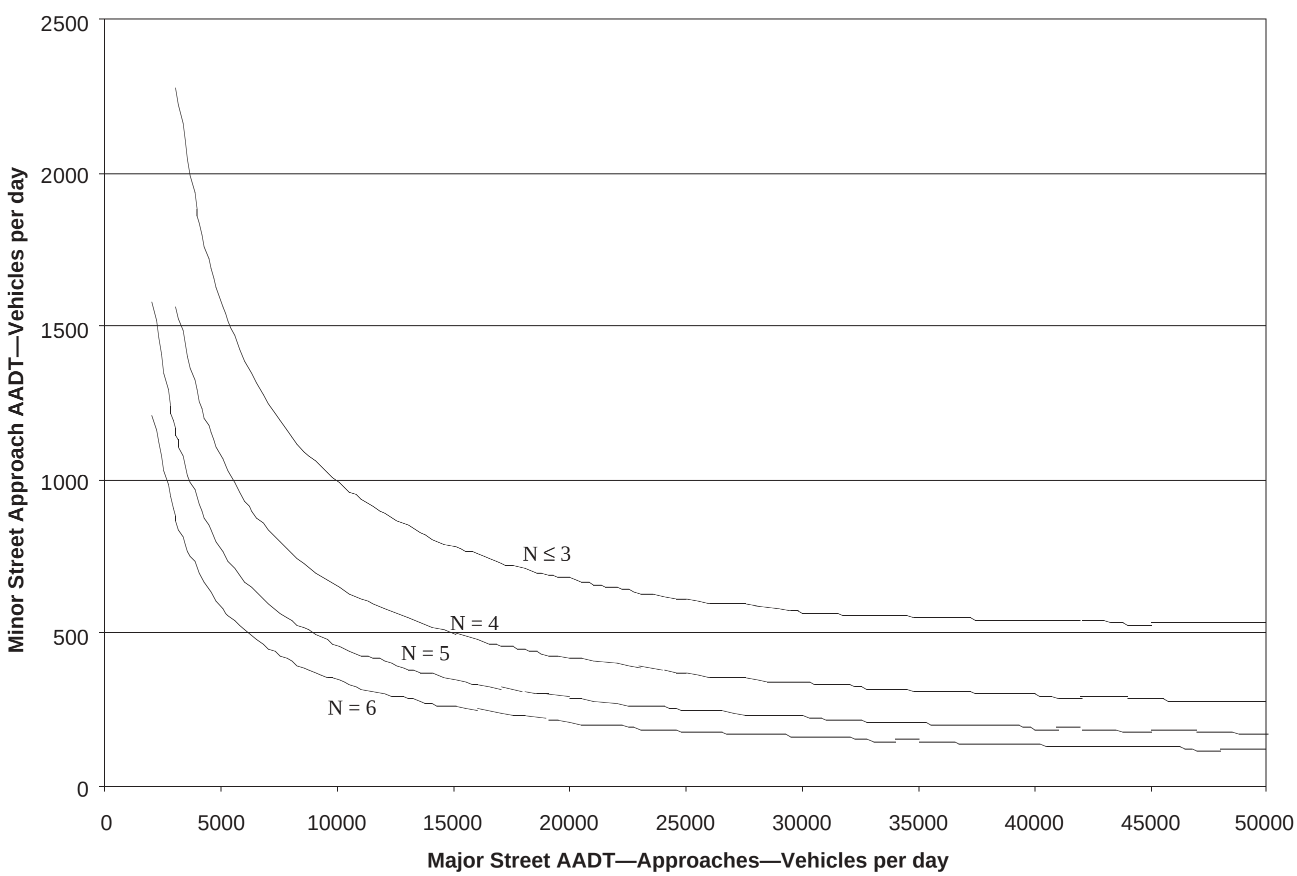
There were two principle questions that this study sought to answer through various empirical studies:

1. How can one estimate the change in accident frequency expected with the installation or removal of a traffic signal?
2. How can one use the knowledge on the safety impact of traffic signal installation to make decisions on where signals might be justified?

To effectively answer these questions required the undertaking of three fundamental analytical tasks:

1. Development of accident prediction models for stop-controlled and signalized intersections,
2. A study of the safety effect of signals already installed, and
3. Use of the results of (1) and (2) to develop decision-making tools.

These tasks required the assembly of an extensive database consisting of traffic volume and geometric and crash data for several years for three sets of intersections: (1) those converted from stop to signal controlled, (2) a reference group of signalized intersections, and (3) a reference group of stop-controlled intersections. These data were collected or acquired for 140 3-leg intersections and 395 4-leg intersections within five



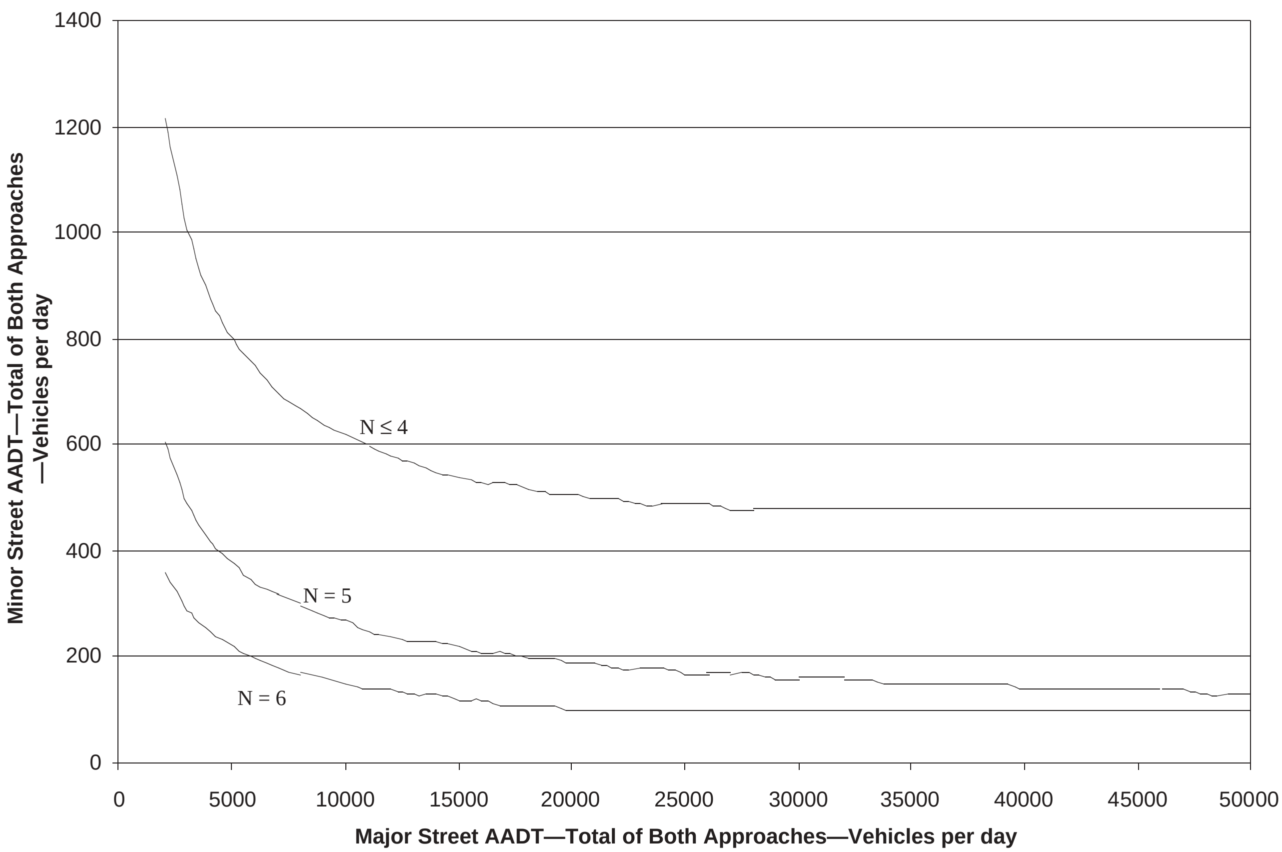
(N = number of non-rear-end injury crashes in the previous 3-year period, not involving pedestrians).

Figure 1. Recommended warrant chart for 3-leg intersections.

states—California, Florida, Maryland, Virginia, and Wisconsin—and Toronto, Canada. Additionally, separate data from HSIS for California became available later in the project and were used in the analysis. HSIS is a multistate database of linked crash and highway data maintained by FHWA.

After several trials and grouping of various explanatory variables and model forms, the analytical effort resulted in the development of crash prediction models for both stop-controlled and signal-controlled intersections, with 3- and 4-leg approaches, estimating crashes as functions of the annual average daily traffic (AADT) entering the intersection through major-street and minor-street approaches. Empirical Bayes (EB) techniques for estimating safety effects of signalizing an intersection were applied for corroborating the crash prediction models with before-and-after data and eventually developing the revised warrant.

A revision to the current warrant was recommended that takes into account the effect of signalization at an intersection based primarily on the crash history at the intersection, the number of approaches (3- or 4-leg), and the total approach volumes for the major and minor streets. The graphs shown in Figures 1 and 2 were developed for 3- and 4-leg intersections, respectively, as part of the warrant. In essence, the current warrant's requirement of "five or more crashes of types susceptible to correction by a traffic signal within a 12-month period" is replaced with the requirement to conduct a safety analysis if the plotted value determined by the major and minor approach volumes is greater than the threshold values for various levels of non-rear-end injury plus



(N = number of non-rear-end injury crashes in the previous 3-year period, not involving pedestrians).

Figure 2. Recommended warrant chart for 4-leg intersections.

fatal crashes observed over the previous 3 years. If the plotted value is below the appropriate curve, then it can be assumed that there will be a safety deficiency with signal installation.

The report provides a six-step process for conducting the safety study that requires the agency to develop crash prediction models for signalized and stop-controlled intersections within its jurisdiction and then use these models to predict the change in crashes that would occur with signalization at the subject intersection. Further, the process suggests that standard engineering economic analysis tools be used to establish the monetary benefits and costs considering the value of crashes forestalled and the direct and indirect costs of signalization.

This study has resulted in a recommended revised Crash Experience warrant, which is believed to be an improvement to the existing warrant because it includes an empirical-based methodology for considering crash changes with signalization. While the recommendations are specifically related to the Crash Experience warrant where a signal is being considered primarily to address a safety problem, it is suggested that the safety analysis procedure presented in the report be followed for any signalization consideration.

CHAPTER **1**

INTRODUCTION

BACKGROUND

The *Manual on Uniform Traffic Control Devices (MUTCD)* (*1*) provides standards and guidance concerning the design and use of traffic control devices on all public roadways. For one of these devices, the traffic control signal, the *MUTCD* requires that an engineering study be performed to determine whether installation of a traffic control signal is justified at a particular intersection. Further, the *MUTCD* provides eight warrants, any one of which could be used to determine the need for the traffic signal. However, it is cautioned that satisfying a traffic signal warrant shall not in itself mean the installation of a traffic control signal is required.

One of those warrants—Warrant 7, Crash Experience—is intended for application where the severity and frequency of crashes are the principal reasons to consider installing a traffic signal. The following are the criteria for this warrant:

1. An adequate trial of alternatives has failed to reduce crash experience;
2. Five or more crashes of types susceptible to correction by a traffic control signal have occurred within a 12-month period; and
3. Traffic and pedestrian volumes are not less than 80 percent of the required levels for Warrant 1, Eight-Hour Volume, and Warrant 4, Pedestrian Volume.

The Crash Experience warrant is insufficient because it does not provide an engineer with a means to determine what changes in safety can be anticipated from installing or removing signal control. In addition, it is not clear that the current threshold of five or more crashes of the type correctable by signal control is based upon a logical and scientific approach for determining changes in intersection safety.

Sometimes changes in traffic conditions eliminate the need for an existing traffic signal. As with signal installation, traffic practitioners need a way to analyze the safety impact of removing such a signal.

OBJECTIVES AND SCOPE

To addresses these issues, this project was established with the objectives to develop an improved Crash Experience warrant for traffic signals and to provide a methodology to estimate the safety impacts of installing or removing traffic signals. These objectives were to be achieved through the following work program:

Task 1. Review previous research evaluating crash experience at signalized intersections and those controlled by stop signs and identify crash data sources that may be suitable for this study.

Task 2. Develop a data collection and analysis plan.

Task 3. Prepare an interim report that documents the findings from these two tasks.

Task 4. Execute the approved data collection plan.

Task 5. Develop a model to estimate the number, severity, and types of crashes expected at signalized and stop-controlled intersections and the changes expected from installation or removal of a traffic signal.

Task 6. Develop an improved Crash Experience warrant and related materials suitable for inclusion in the *MUTCD*.

Task 7. Prepare a final report.

Because of the scarcity of data for sites at which signals were removed, it was decided early in the project to focus on developing tools for assessing the safety effects of signal installation. It is assumed that, since these tools essentially estimate the safety of stop- and signal-controlled conditions, they could be adapted (in effect, reversed) to assess the safety of traffic signal removal.

REPORT CONTENTS

This report documents the entire work program and presents the findings and conclusions. The remaining chapters are organized as follows:

Chapter 2, Findings from the Literature Review, presents the summary findings of the literature review including the relevant sections of the *MUTCD* and the *Traffic Control Devices Handbook* (*TCDH*) (*2*).

Chapter 3, Study Methodology and Database, discusses the research methodology followed and presents the data in summary format.

Chapter 4, Analytical Basis of the Revised Crash Experience Warrant, presents the findings from the analysis of the data, including the development of crash estimation models to estimate crash changes when converting from stop control to signal control and development of the revised crash warrant for the *MUTCD*.

Chapter 5, Procedure for Estimating Safety Impacts of Signal Installation in a Detailed Engineering Study, provides a procedure for conducting an engineering study to assess the safety impact of a proposed traffic signal with an illustrative example.

Chapter 6, Recommended Revisions to the *MUTCD* Crash Experience Warrant, offers a recommended revised warrant for the *MUTCD*.

Chapter 7, Conclusions, Application to Practice, and Further Research, provides concluding remarks, discusses the applicability of current research to practice, and provides recommendations for additional research that will be needed to further improve the recommended warrant.

In addition to a reference section, there are four appendixes. Appendix A provides a history of the Crash Experience (Accident) warrant in the *MUTCD*. Appendix B provides the complete documentation of the literature review. Appendix C provides a schematic description of the types of crashes. Appendix D provides a detailed illustration of recalibrating crash prediction models for use in the engineering study.

CHAPTER 2

FINDINGS FROM THE LITERATURE REVIEW

MUTCD AND *TCDH* REVIEW

The *MUTCD* provides standards and guidance concerning the design and use of traffic control devices, which include traffic signal control. By providing these standards and guidance, the *MUTCD* gives a common ground for implementing and using traffic control devices.

The most recent version of the *Traffic Control Devices Handbook* (*TCDH*) (*2*) was published by the Institute of Transportation Engineers to augment the *MUTCD*. It provides additional background and information to assist in traffic control device applications.

This section provides a review of these two documents as they relate to the Crash Experience (Accident) warrant. It covers the installation of a traffic signal and the removal of a traffic signal.

Installing a Traffic Signal

In the Millennium edition of the *MUTCD*, the standards and guidance for justifying a traffic control signal are found in Chapter 4C. There are two sections in the *MUTCD* that address this issue: (1) Section 4C.01—Studies and Factors for Justifying Traffic Control Signals and (2) Section 4C.08—Warrant 7, Crash Experience. Relevant portions of these sections are shown below as they appear in the *MUTCD*.

Section 4C.01 <u>Studies and Factors for Justifying Traffic Control Signals</u>

Standard:

An engineering study of traffic conditions, pedestrian characteristics, and physical characteristics of the location shall be performed to determine whether installation of a traffic control signal is justified at a particular location.

The investigation of the need for a traffic control signal shall include an analysis of the applicable factors contained in the following traffic signal warrants and other factors related to existing operation and safety at the study location:

Warrant 1, Eight-Hour Vehicular Volume.
Warrant 2, Four-Hour Vehicular Volume.
Warrant 3, Peak Hour.
Warrant 4, Pedestrian Volume.
Warrant 5, School Crossing.
Warrant 6, Coordinated Signal System.
Warrant 7, Crash Experience.
Warrant 8, Roadway Network.

The satisfaction of a traffic signal warrant or warrants shall not in itself require the installation of a traffic control signal.

Guidance:

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.

Option:

Engineering study data may include the following:

G. A collision diagram showing crash experience by type, location, direction of movement, severity, weather, time of day, date, and day of week for at least 1 year.

Section 4C.08 <u>Warrant 7, Crash Experience</u>

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 traffic signal control, 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.

Table 4C-1 referred to above is provided below as Table 1. The reference to "80 percent of the requirements specified in the Pedestrian Volume warrant" would mean that there would have to be at least 80 pedestrians crossing the major street for each of any 4 hours or at least 152 during any 1 hour.

Appendix A provides the history of how this warrant has been treated starting with the first edition in 1935.

Chapter 10 of the *TCDH* deals with traffic signals. The following are excerpts from that chapter that are relevant to this project.

1. General

b. Purpose of Traffic Control Signals

If a traffic control signal is being considered to address a safety issue, a careful study should be made to determine whether the traffic control signal would indeed solve the type of accident problem being experienced. Accident experience frequently increases at unwarranted traffic control signals or at locations where only minimum warrants are met and where the installation was not based on sound engineering analysis. Accidents related to traffic control signals can develop during periods of comparatively low volume and result from rear-end collisions, blind spots in the driver's field of vision and drivers either willfully or unintentionally running red lights. In many cases, the most severe and damaging accidents occur at traffic control signalized intersections.

i. Advantages and Disadvantages of Traffic Control Signals

Traffic control signals are often considered by the media and public as a panacea for all traffic problems at intersections. . . . The most misleading aspect regarding traffic control signals is the common belief that a traffic control signal is safer than other forms of intersections control. This belief is often not supported by facts. Intersections experiencing the highest frequency of crashes are very likely operated with traffic control signals. One

TABLE 1 ***MUTCD*** **Warrant 1—Eight-hour vehicular volume**

Condition A—Minimum Vehicular Volume							
Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total of both approaches)			Vehicles per hour on higher-volume minor-street approach (one direction only)		
Major Street	Minor Street	100%[a]	80%[b]	70%[c]	100%[a]	80%[b]	70%[c]
1…………	1…………	500	400	350	150	120	105
2 or more..	1…………	600	480	420	150	120	105
2 or more..	2 or more..	600	480	420	200	160	140
1…………	2 or more..	500	400	350	200	160	140

Condition B—Interruption of Continuous Traffic							
Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total of both approaches)			Vehicles per hour on higher-volume minor-street approach (one direction only)		
Major Street	Minor Street	100%[a]	80%[b]	70%[c]	100%[a]	80%[b]	70%[c]
1…………	1…………	750	600	525	75	60	53
2 or more..	1…………	900	720	630	75	60	53
2 or more..	2 or more..	900	720	630	100	80	70
1…………	2 or more..	750	600	525	100	80	70

[a] Basic minimum hourly volume.
[b] Used for a combination of Conditions A and B after an adequate trial of other remedial measures.
[c] May be used when the major-street speed exceeds 70 km/h (40 mph) or in an isolated community with a population of less than 10,000.

Source: Reference 1.

should not assume that an accident occurring at an intersection with STOP sign control could have been prevented if a traffic control signal had been operating in lieu of the STOP sign signs. Accidents are usually caused by driver or pedestrian error, not traffic control devices. . . .

2. Determining the Need for a Traffic Control Signal

 a. Warrants and Justifications

  2. Commonly Asked Questions on the Warrants

   f. *Does the number of injury accidents or accident severity provide a basis for adjusting the warrants for crash experience?* No, although some jurisdictions consider the accident severity as a factor in the establishment of installation priorities.

3. Warrant Considerations

Warrant 7 Crash Experience

The purpose of this warrant is to consider a traffic control signal for those locations where it would be beneficial in reducing the frequency and/or severity of collisions at an intersection.

The engineering study should address analyzing alternatives that are less restrictive than a traffic control signal. The less restrictive measures do not necessarily have to be in place at least 12 months to provide accident data relative to their effectiveness.

Note that the reducible property damage collisions must have damage exceeding the minimum statutory limits in the local ordinances or state law. This also provides some assurance of enforcement investigation and a more detailed collision report for analysis.

Typical examples of reducible and non-reducible collisions at an intersection with a traffic control signal include the following:

Reducible	Non-reducible
Right-angle vehicle collisions	Rear-end collisions
	Side-swipe collisions
Left-turn collisions	Head-on collision
Right-angle	
Pedestrian collisions	
Parking collisions	

The selection of other types of collisions as being susceptible to reduction with a traffic control signal installation should be done using engineering judgment, after reviewing the collision reports.

Removing a Traffic Signal

The only guidance found in the *MUTCD* concerning the removal of a traffic signal is in Section 4B.02 Basis of Installation or Removal of Traffic Control Signals, where it states under Guidance the following:

> If changes in traffic patterns eliminate the need for a traffic control signal, consideration should be given to removing it and replacing it with alternative traffic control devices, if any are needed.

The *TCDH* provides a little more guidance where it states the following in section 1. General, c. Basis for Removal of Traffic Control Signals:

> . . . If it is contemplated that a traffic control signal should be removed, an engineering study is recommended to establish and document the basis for the removal. . . . The following items are appropriate to consider in the study: . . .
>
> - Projected collision problems with and without the signal; . . .

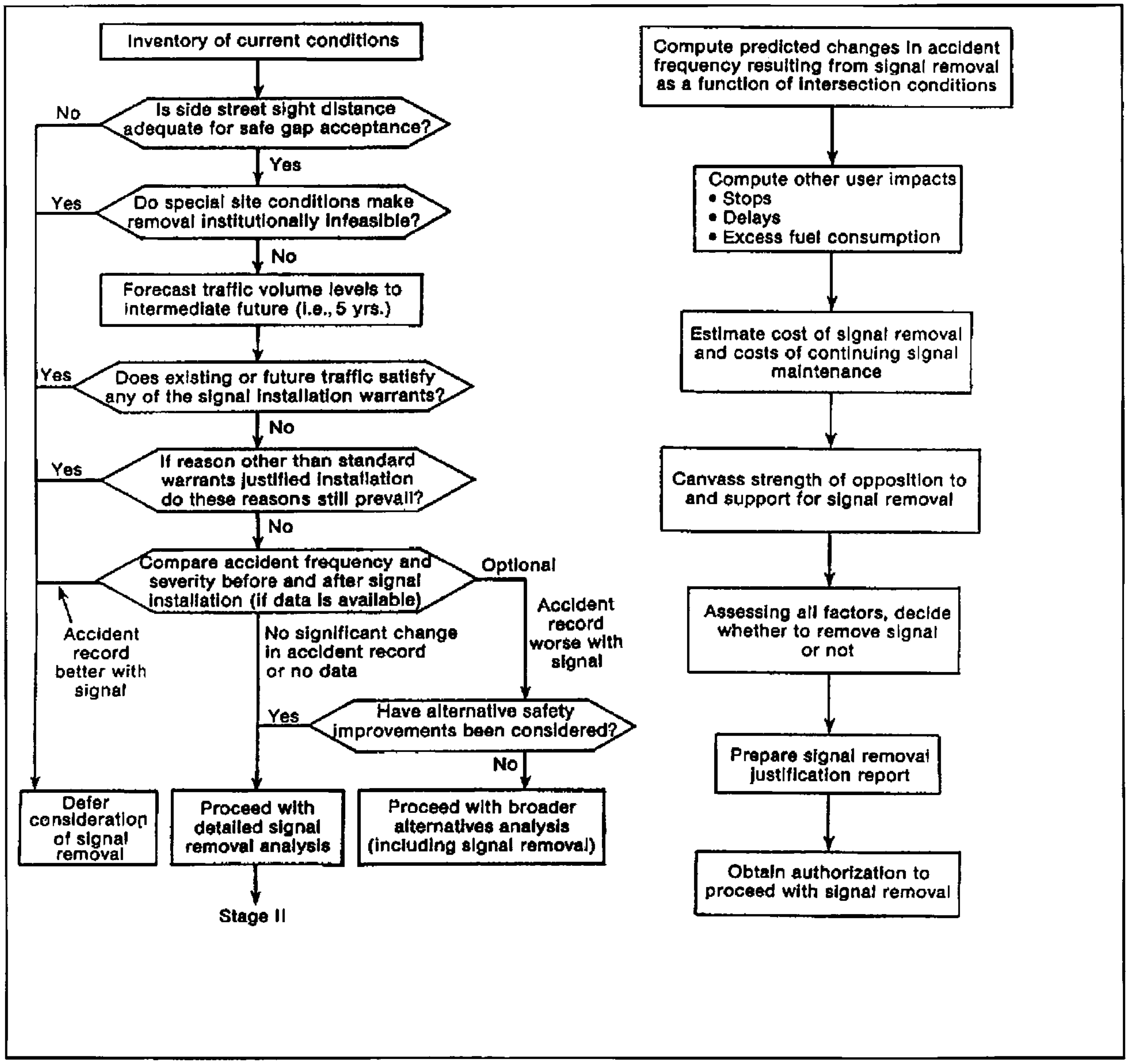
The previous edition of the *TCDH* (*3*), which is no longer in print, provided more guidance on signal removal by providing the criteria recommended by Kay et al. (*4*) in 1980 for the removal of a traffic signal. The following are the criteria:

- Traffic performance.
- Accidents impacts.
- Fuel consumption.
- Pollution reduction.

With these criteria, two types of analysis are suggested to determine if a signal should be removed. The first analysis is a preliminary screening to decide if a more in depth analysis should be performed. In this analysis, sight distance, forecasted traffic volumes, accident frequency, and so forth are examined to make a timely decision as to whether the signal should remain, or whether a more detailed analysis should be performed. The second analysis is more detailed and is concerned with “estimating the major technical and social impacts of removing a signal including accidents, fuel consumption, related costs, and public opposition.”(*3*). The answers to the preliminary analysis are yes/no and the detailed analysis requires many calculations. A flow chart of this methodology is shown in Figure 3.

SUMMARY OF FINDINGS FROM THE LITERATURE REVIEW

Appendix B provides a complete discussion of the literature review, which focused on studies that (1) evaluated



Source: Reference 3.

Figure 3. Signal removal—preliminary screening and detailed analysis.

the safety effect on installing or removing traffic signals and (2) examined relationships of crash occurrence with intersection control. The literature dealing with analytical methodologies and statistical procedures relevant to this project were reviewed and are presented in Appendix B as well. This general review of pertinent methodology guided the assessment of the studies on the safety of traffic signal and other intersection control and the knowledge derived there from. The following provides a summary of the results of those studies, *without regard for or discussion of any methodological difficulties that may have affected the outcomes*. The full review in Appendix B provides that type of critical discussion.

Safety Effect of Installing Traffic Signals

Overall Frequency. The literature review showed that most previous research (*5*, *6*, *7*, *8*), with a few exceptions (*9*), supports the commonly held opinion that signal installation reduces the number of crashes.

Right-Angle Frequency. Research (*5*, *6*, *7*, *9*) found that the number of right-angle crashes decreased at an intersection when the traffic control device was changed from a stop sign to a traffic signal. Agent (*8*) found a decrease in the right-angle crash rate when a rural stop-controlled intersection with a beacon was converted to a traffic signal. However,

TABLE 2 Summary of safety impacts from studies of signal installation/removal

Signal Installed				Signal Removed		
Increase	Decrease	No Change	Crash Types	Increase	Decrease	No Change
9	5, 6, 7, 8		Overall		10	4
8[2]	5, 6, 7, 9, 8[1]		Right-Angle	4	10	
5, 6, 9	7		Rear-End		4, 10	

The numerals in the table represent the reference number of the study cited.
8[1]: conversion from a rural stop sign with a beacon to a traffic signal.
8[2]: conversion from a rural stop sign without a beacon to a traffic signal.

when similar intersections without a beacon were converted, he noted that the right-angle crash rate increased.

Rear-End Frequency. Some research (*5*, *6*, *9*) showed a rise in rear-end crash frequency when signalization occurs. Datta and Dutta (*5*) showed an increase of 53 percent with signalization. Other research (*7*) showed a reduction in rear-end crash frequency with signalization.

Removal of Traffic Signals

Overall Frequency. Kay et al. (*4*) research found that the overall crash frequency did not change when traffic signals were removed while research from Persaud et al. (*10*) showed a decrease in crash frequency for their sample.

Right-Angle Frequency. Research by Kay et al. (*4*) showed an increase in right-angle crashes when traffic signals were removed. Persaud et al. (*10*) found a decrease in right-angle crashes for their sample.

Rear-End Frequency. Persaud et al. (*10*) and Kay et al. (*4*) found a decrease in rear-end crashes when traffic signals were removed and observed that this decrease in rear-end crashes is the reverse of what typically happens when signals are installed.

A summary of studies reporting safety impacts of signal installation/removal is presented in Table 2.

Other Findings

Agent (*8*), Bhesania (*11*), and Hanna (*12*) have shown that more angled accidents occurred at stop-controlled intersections (as compared with signal-controlled) and that more rear-end accidents occurred at signal-controlled intersections (as compared with stop-controlled intersections).

The state of the art with regard to evaluating the safety effects of a change in a traffic control feature has changed several times over the last 20 years or so, with advances in the statistical methodology and improvements to data availability that allow for better modeling of crash occurrence. These advances culminated in the landmark book by Hauer (*13*) that was the source of much of the methodology used in this research project.

CHAPTER 3

STUDY METHODOLOGY AND DATABASE

OVERALL METHODOLOGY

The fundamental objective of the study was to develop an improved safety warrant for traffic signal installation for the *MUTCD*, and in so doing provide guidance for assessing the safety implications of traffic signal removal. In achieving this objective, there were two principle questions that this study sought to answer:

1. How can one estimate the change in crash frequency expected with the installation or removal of a traffic signal?
2. How can one use the knowledge on the safety impact of traffic signal installation to make decisions on where signals might be justified?

To effectively answer these questions required the undertaking of three fundamental analytical tasks:

1. Development of crash prediction models for stop-controlled and signalized intersections.
2. A study of the safety effect of signals already installed.
3. Use of the results of tasks 1 and 2 to develop decision-making tools.

These tasks required the assembly of an extensive database consisting of traffic volume and geometric and crash data for several years for three sets of intersections: (1) those converted from stop to signal control, (2) a reference group of signalized intersections, and (3) a reference group of stop-controlled intersections.

As noted earlier, the scarcity of data for sites at which signals were removed required that the focus be on developing tools for assessing the safety effects of signal installation. It is assumed that, since these tools essentially estimate the safety of stop- and signal-controlled conditions they could be extended to assess the safety of traffic signal removal.

Using the assembled data, the crash prediction models were then estimated and an EB procedure, as recommended by Hauer (*13*), was used to develop the decision-making tools. This procedure is needed to account for changes in crash occurrence due to regression-to-the-mean (a phenomenon whereby unaltered sites with randomly high crashes in one period will on average experience fewer crashes in a subsequent period, and vice versa) and changes in traffic volumes, environmental factors, crash reporting, and other factors. In a study to determine the safety effects of conversion to all-way stop control, Persaud et al. (*10*) showed that by removing the regression-to-the-mean bias from the data, using an EB method, different results are obtained—typically a reduced safety benefit. For example, the biased estimate in Persaud's study reported a 54 percent reduction in total crashes while the unbiased estimate showed a reduction of 43 percent. In the case of traffic signal installation, analysis of safety impacts is particularly vulnerable to the regression-to-the-mean bias. Due to this bias, sites selected for signal installation on the basis of a high crash count (e.g., those which meet the existing *MUTCD* Crash Experience warrant) will on average show a reduction in crash counts in a simple before-after comparison even if the signal had no safety effect. Hence, the regression-to-the-mean effect may somewhat exaggerate the effectiveness of signalization, particularly where a short (e.g., 1 year) "before" period is used in the evaluation. Increasing the length of the before period helps reduce this bias as the relative size of the regression-to-the-mean diminishes but, as Hauer and Persaud (*14*) show, a significant bias can exist even with before periods of up to 6 years.

Fundamental to the development of the tools is the estimation of the change in safety at a stop-controlled intersection if it were to be signalized. The approach taken is essentially as follows:

(i) Use the crash counts and traffic volumes for a recent period to estimate the expected number of crashes of various affected types that would occur if the intersection *was not* signalized. Crash prediction models for stop-controlled intersections are used here in the EB procedure.

(ii) Estimate the expected number of crashes that would occur if the intersection *was* signalized, using prediction models for signal-controlled intersections.

(iii) Estimate the expected change in safety as the difference between estimates in (i) and (ii).

It is proposed that, as a logical extension, a similar approach be applied for the estimation of the change in safety at a signal-controlled intersection if the signal were to be removed. The difference would be that the starting point would be a *signalized intersection*, crash prediction models for *signalized intersections* would be used in the EB procedure, and the expected number of accidents that would happen afterward would be estimated from prediction models *for stop-controlled intersections*. It should be noted, however, that this extension of the developed procedure has not been validated in this research.

The approach to (ii) is a departure from that used by Harwood et al. (*15*) in which a crash modification factor is applied to the estimate from (i) to obtain the expected number of crashes in the after period in the absence of the treatment. It is, however, convenient and practical, in that a comprehensive set of crash modification factors, which would be required for a large number of conditions, is simply not available and is difficult to obtain. The proposed approach, however, required a fundamental assumption that the safety of a newly signalized intersection can be estimated from a prediction model developed on the basis of intersections signalized previously. This assumption was untested, so the conduct of a before-after study of signal installations was essential to ensure that the expected change in safety estimated for an installation in part (iii) of the suggested approach would be consistent with that from a before-after study. This corroboration exercise was a fundamental part of this project.

In summary, the analysis undertaken for this research entailed a number of activities. Each aspect is described in more detail as it is presented in this report. The following are the specific analysis activities:

1. Development of crash prediction models for stop-controlled and signalized intersections using a multi-jurisdiction database.
2. Use of these models and data for signal installations in several jurisdictions in an EB observational before-after study of the safety effect of signals already installed.
3. Testing to ensure that the expected change in safety estimated for an installation in part (iii) of the suggested approach would be consistent with that from a before-after study.
4. Use of the accident prediction models developed in the specification and illustration of a detailed engineering study procedure for estimating the likely safety impact of a contemplated installation.
5. Use of the crash prediction models in developing a "warrant" procedure for deciding whether or not a detailed engineering study of possible signal installation may be required for an intersection under investigation.

DATABASE

Locations

Several jurisdictions were chosen to provide the sample intersections. They were selected based on their willingness to participate and the availability of the needed data. Also, the budget available for data acquisition controlled the ultimate number of locations and sites. Table 3 shows the locations and the number of sites by type of intersection—3 or 4 leg; and type of intersection control—stop, signal, and converted from stop to signal control.

The use of a non-U.S. database from Toronto was a matter of convenience. This database was comprehensive and easily accessible and key members of the study team (from the Toronto area) already had experience using this database for purposes closely related to the objectives of the study.

At a late stage in the project, data from the Highway Safety Information Service (HSIS) for California became available and were assembled for urban unconverted intersections. This dataset was used to explore the development of improved accident prediction models for application in the engineering study procedure and in the development of the crash warrant.

Crash Data

Crash data were received in the form of police reports or data records (either in hard copy or as an electronic file). From

TABLE 3 Location and number of sites used in the analysis

State or Jurisdiction	Intersection Type	Intersection Control		
		Stop	Signal	Converted
California	3-leg	2	1	2
	4-leg	11	16	20
Florida	3-leg	2	3	1
	4-leg	15	5	13
Maryland	3-leg	3	0	2
	4-leg	18	5	10
Virginia	3-leg	3	2	5
	4-leg	15	11	10
Wisconsin	3-leg	2	0	2
	4-leg	31	30	1
Toronto	3-leg	87	13	10
	4-leg	109	29	26
Total	3-leg	99	19	22
	4-leg	199	96	100

that source the data was coded into a database. For each crash, the following key information was coded into the database:

- Type of crash—i.e., single vs. multivehicle; head-on, side-swipe, rear-end, angle, right-turn, left-turn, and other;
- Severity level—fatal, injury, property-damage-only;
- Date and time;
- Direction of first vehicle and second vehicle (or pedestrian/bicycle); and
- Movement of first and second vehicle (or pedestrian/bicycle).

Traffic Volume Data

For each location the desire was to have an AADT for each turning movement for each year corresponding to the years of crash data. This became a difficult chore due to the lack of volume counts at the agencies. There was a wide variety of volume data available ranging from a minimum of a "tube" count for one or more of the approaches for 1 or more of the study years to a desirable 8- or 12-hour turning movement count for 1 or more of the study years. Where necessary, a turning movement count was made by the research staff during the field visit. Figure 4 shows a sample data entry screen for traffic volume data from a database program developed for this project.

Expansion factors were used to create AADT values for each turning movement for each year. As would be expected, most sites did not have data for 1 or more years. An extrapolation program was used to fill the voids.

Geometric Data

Except for the HSIS data from California, all sites were visited by the research staff. At each site the following data were collected:

- Street names and route numbers,
- Functional classification,
- Major or minor route,

Figure 4. Sample data entry form for entering traffic volume data.

- Type of control (date of conversion, if appropriate),
- Type of left-turn phasing,
- Width of median, if any,
- Number of lanes by type for each approach,
- Approach speed—posted speed limit,
- Approach grade—up, down, or flat,
- Horizontal alignment for each approach—curved or not,
- Sight distance for each quadrant, and
- Angle of intersecting roads.

Figure 5 shows the data collection entry screen used to enter the geometric data directly into a laptop computer at the site or later at the office.

DATA SUMMARY

A summary of the database is provided in several tables that follow. Table 4 shows a summary of the data for the reference group of intersections that remained (i.e., were not converted) stop-controlled through the analysis period; there are separate tables for 3-leg (T-intersection) and 4-leg intersections. For all tables, the crash rate is crashes per million vehicles entering the intersection. Table 5 shows the summary data for the sites that remained (i.e., were not converted) signal-controlled during the analysis period. Table 6 shows the summary data for the sites that were converted from stop-controlled to signal-controlled within the analysis period. Finally, Table 7 shows a summary of the data for the California HSIS database for intersections for which the traffic control was not changed whether stop-controlled or signal-controlled. As noted earlier, this database became available late in the project and was used in an attempt to improve results based on data assembled for this research. It should be noted that property-damage-only crashes were not included in the analysis, which accounts for crash frequencies that appear to be low at first glance.

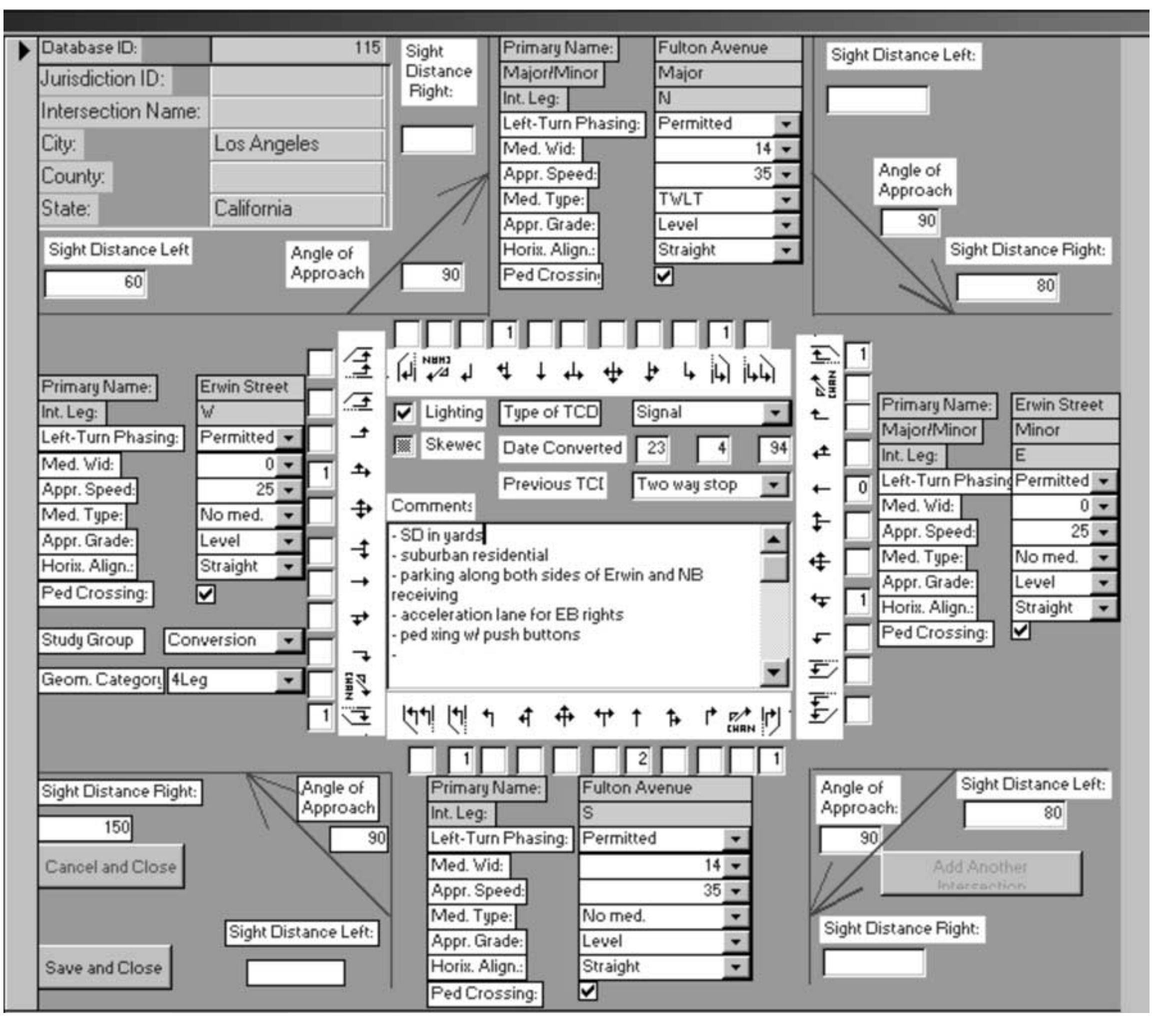


Figure 5. Sample data entry form for entering geometric data.

TABLE 4 Data summary: unconverted stop-controlled intersections

3-Leg Intersection

Location	# Sites	Yrs. Data	Avg. ADT		Injury Crashes				Avg. Annual Crashes Per Site	Avg. Annual Crash Rate Per Site (CR/MV)
			Major	Minor	All	RE	RA	LT		
California	2	4	23532	1069	10	2	0	4	1.25	0.14
Florida	2	6	21374	1265	26	7	4	11	2.17	0.26
Maryland	3	10	27070	1050	57	7	13	3	1.90	0.19
Virginia	3	8	25063	1933	32	13	0	16	1.33	0.14
Wisconsin	2	8	32198	1983	33	7	12	13	2.06	0.17
Toronto	87	7	19908	1503	451	156	110	47	0.74	0.09
TOTAL	99				609	192	139	94		
						Total Average			0.86	0.10

4-Leg Intersection

Location	# Sites	Yrs. Data	Avg. ADT		Injury Crashes				Avg. Annual Crashes Per Site	Avg. Annual Crash Rate Per Site (CR/MV)
			Major	Minor	All	RE	RA	LT		
California	11	4	18553	1300	62	11	17	11	1.41	0.19
Florida	15	6	21869	1610	130	22	18	53	1.44	0.17
Maryland	18	10	28859	1226	234	51	46	92	1.30	0.12
Virginia	15	8	19686	1513	100	16	40	38	0.83	0.11
Wisconsin	31	8	20072	2549	361	80	143	128	1.46	0.18
Toronto	109	7	18301	1834	766	178	324	58	1.00	0.14
TOTAL	199				1653	358	588	380		
						Total Average			1.14	0.14

TABLE 5 Data summary: unconverted signalized intersections

3-Leg Intersection

Location	# Sites	Yrs. Data	Avg. ADT		Injury Crashes				Avg. Annual Crashes Per Site	Avg. Annual Crash Rate Per Site (CR/MV)
			Major	Minor	All	RE	RA	LT		
California	1	4	25109	2697	4	1	0	2	1.00	0.10
Florida	3	6	29241	2622	82	40	1	19	4.56	0.39
Maryland	0	10	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Virginia	2	8	22870	3831	42	17	21	3	2.63	0.27
Wisconsin	0	8	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Toronto	13	7	32647	1464	162	52	37	20	1.78	0.14
TOTAL	19				290	110	59	44		
						Total Average			2.27	0.19

4-Leg Intersection

Location	# Sites	Yrs. Data	Avg. ADT		Injury Crashes				Avg. Annual Crashes Per Site	Avg. Annual Crash Rate Per Site (CR/MV)
			Major	Minor	All	RE	RA	LT		
California	16	6	18690	6656	167	30	0	59	1.74	0.19
Florida	5	6	20235	7559	145	38	14	65	4.83	0.48
Maryland	5	10	30524	4099	219	58	28	33	4.38	0.35
Virginia	11	8	18969	5196	194	64	37	62	2.20	0.25
Wisconsin	30	8	16989	7100	706	229	141	333	2.94	0.33
Toronto	29	7	25762	3060	481	166	130	40	2.37	0.23
TOTAL	96				1912	585	350	592		
						Total Average			2.66	0.28

TABLE 6 Data summary: converted intersections

3-Leg Intersection

Location	# Sites	Yrs. Data	Avg. ADT		Injury Crashes				Avg. Annual Crashes Per Site	Avg. Annual Crash Rate Per Site (CR/MV)
			Major	Minor	All	RE	RA	LT		
California	2	4	31265	2084	16	8	0	5	2.00	0.16
Florida	1	6	42046	911	18	10	0	5	3.00	0.19
Maryland	2	10	11739	1483	19	7	2	5	0.95	0.20
Virginia	5	8	21438	2269	75	30	14	25	1.88	0.22
Wisconsin	2	8	19768	3952	76	30	3	35	4.75	0.55
Toronto	10	7	24584	1276	80	38	11	3	1.14	0.12
TOTAL	22				284	123	30	78		
						Total Average			1.78	0.20

4-Leg Intersection

Location	# Sites	Yrs. Data	Avg. ADT		Injury Crashes				Avg. Annual Crashes Per Site	Avg. Annual Crash Rate Per Site (CR/MV)
			Major	Minor	All	RE	RA	LT		
California	20	4	18363	2700	110	30	19	30	1.38	0.18
Florida	13	6	15852	2409	223	53	39	71	2.86	0.43
Maryland	10	10	12661	3129	124	17	57	25	1.24	0.22
Virginia	10	8	18473	3373	142	29	42	62	1.78	0.22
Wisconsin	21	8	14970	3277	473	102	200	125	2.82	0.42
Toronto	26	7	22382	3628	362	97	126	36	1.99	0.21
TOTAL	100				1434	328	483	349		
						Total Average			2.06	0.28

TABLE 7 Data summary: California HSIS unconverted intersections

Traffic Control	Type	# Sites	Yrs. Data	Avg. ADT		Injury Crashes				Avg. Annual Crashes	Avg. Annual Crash Rate (CR/MV)
				Major	Minor	All	RE	RA	LT		
2-way stop	3-leg	939	8	23045	836	5148	1811	588	1349	0.69	0.08
	4-leg	479	8	19776	1275	4275	1083	1221	1087	1.12	0.15
Signalized	3-leg	170	8	34798	4560	2632	1373	185	492	1.94	0.13
	4-leg	629	8	33988	7893	14481	6634	2333	2623	2.88	0.19
TOTAL		2217				12055	4267	1994	2928		
							Total Average			0.44	0.04

TABLE 8 Data summary—all sites

Control Type	Intersection Type	Average Annual Injury Crashes		Average Annual Injury Rate	
		All but CA Sites	CA Sites	All but CA Sites	CA Sites
Unconverted Stop	3-leg	0.86	0.69	0.10	0.08
	4-leg	1.14	1.12	0.14	0.15
Converted	3-leg	1.78	N/A	0.20	N/A
	4-leg	2.06	N/A	0.28	N/A
Unconverted Signal	3-leg	2.27	1.94	0.19	0.13
	4-leg	2.66	2.88	0.28	0.19

Table 8 contains a summary of these data for all sites. From the data in that table, the following is observed:

- Average annual crashes were higher for 4-leg vis-à-vis 3-leg intersections, regardless of the type of control; this is as would be expected. Also, the average annual crash rates were higher, which may be indicate that the rates increase with increasing total intersection volume rather than conclude that 4-leg intersections are less safe.
- Average annual crashes increased from always (unconverted) stop-controlled to converted to always signal-controlled; this is as would be expected. For the average annual crash rates, the converted and always signal-controlled sites had nearly twice the rate as the always (unconverted) stop-controlled sites, but they were essentially equal within their 3- and 4-leg grouping. Again caution should be exercised in reading too much into crash rate comparisons because differences in crash rates may be due to changes in traffic volumes and not necessarily to changes in safety.

CHAPTER 4

ANALYTICAL BASIS OF THE REVISED CRASH EXPERIENCE WARRANT

Effectively addressing the objectives of this research to develop a revised Crash Experience warrant required the undertaking of three fundamental analytical tasks:

1. Development of crash prediction models for stop-controlled and signalized intersections,
2. A study of the safety effect of signals already installed, and
3. Use of the results of tasks 1 and 2 to develop decision-making tools.

The results of these analytical tasks are described in this chapter.

Based on experience with the quality of property damage crash data, a decision was made early in the project that the development of models and all subsequent analysis would be based on injury (fatal plus non-fatal) crashes. In so doing, it was expected that difficulties that arise from the transferability of the models and the procedure across jurisdictions and over time would be minimized. This is because injury (including fatal) crashes are much less likely than property damage crashes to exhibit significant reporting differences across time and space. Even so, the models can be recalibrated if such differences exist and are not unduly substantial. A procedure for doing so is also presented as part of the set of tools provided.

DEVELOPMENT OF CRASH PREDICTION MODELS

This section describes the calibration of the crash prediction models used in the before-after study and in the proposed engineering study procedure and warrant.

Development of the models involved determining which explanatory variables should be used, whether and how variables should be grouped, and how variables should enter into the model, that is, the best model form. Distinctions of area type, intersecting volumes, sight distance, turn lanes and so forth were explored for their relevance in explaining collision count and severity observations. Generalized linear modeling was used to estimate model coefficients using the software package GENSTAT and assuming a negative binomial error distribution, all consistent with the state of research in developing these models. In specifying a negative binomial error structure, a parameter, *K*, that relates the mean and variance of the regression estimate is iteratively estimated from the model and the data. The value of *K*, which is the inverse of the overdispersion parameter of the negative binomial distribution, is such that the larger the value of *K*, the better a model is for a given set of data.

Conduction of the before-after study of converted intersections required the development of models for unconverted stop-controlled intersections. These models were also used in the procedure for conducting an engineering study to assess whether or not a contemplated signal installation might be warranted. Models for unconverted signalized intersections were also developed for use in the engineering study procedure and warrant.

MODELS FOR UNCONVERTED STOP-CONTROLLED INTERSECTIONS

The reference group data summarized in Table 4 were used to develop regression models for stop-controlled intersections. The inclusion of variables such as sight distance and approach speed did not significantly affect the fit. This is not surprising for the following reasons: (1) there was insufficient variation in these factors and (2) as previous research has shown, much of the variation in accident experience is explained by the volume of traffic entering an intersection.

The results of the regression modeling are presented in Tables 9 and 10 for 3-leg and 4-leg intersections, respectively. The first row after the column headings shows the form of the regression equation for the specific dependent variable, which is shown as the heading for each column. For example, the model for predicting Total Injury Crashes (TIC) per year is as follows:

$$TIC = \alpha(F1)^b(F2)^c$$

The explanation of the abbreviations in this equation and the subsequent tables is:

F1 = entering AADT on a major road,
F2 = entering AADT on a minor road, and
(s.e.) = standard error of the estimate.
K is a calibrated parameter relating the mean and variance that is used in the EB estimation procedure for the before-after analysis and for the detailed engineering procedure to be presented in Chapter 5.

TABLE 9 Models for injury crashes/year at unconverted 3-leg stop-controlled intersections

	TOTAL	RIGHT-ANGLE	REAR-END	LEFT-TURN
Model Form	$\alpha(F1)^b(F2)^c$	$\alpha(F1)^b(F2)^c$	$\alpha(F1+F2)^d$	$\alpha(F1)^b(F2)^c$
K	6.10	2.20	2.90	3.80
Ln(α) U.S. sites (s.e.)	-13.33 (1.45)	-15.69 (2.84)	-14.62 (2.31)	-12.24 (3.13)
Ln(α) Toronto sites (s.e.)	-13.84 (1.46)	-15.91 (2.86)	-14.73 (2.33)	-13.91 (3.14)
b (s.e.)	0.968 (0.124)	1.012 (0.239)		0.536 (0.268)
c (s.e.)	0.558 (0.078)	0.582 (0.152)		0.844 (0.177)
d (s.e.)			1.337 (0.224)	

TABLE 10 Models for injury crashes/year at unconverted 4-leg stop-controlled intersections

	TOTAL	RIGHT-ANGLE	REAR-END	LEFT-TURN
Model Form	$\alpha(F1)^b(F2)^c$	$\alpha(F1)^b(F2)^c$	$\alpha(F1+F2)^d$	$\alpha(F1)^b(F2)^c$
K	2.30	1.40	1.50	1.80
Ln(α) U.S. sites (s.e.)	-7.76 (1.14)	-9.01 (1.62)	-8.99 (1.48)	-11.48 (1.95)
Ln(α) Toronto Sites (s.e.)	-8.04 (1.15)	-8.91 (1.63)		-13.20 (1.96)
b (s.e.)	0.499 (0.088)	0.218 (0.122)		0.797 (0.151)
c (s.e.)	0.430 (0.082)	0.799 (0.118)		0.380 (0.131)
d (s.e.)			0.763 (0.148)	

The value of *K* is such that $VAR\{TIC\} = TIC^2/K$, indicating that the larger the value of *K*, the smaller the variance of the model estimate and therefore the better the model.

These models were used in the before-after study of the converted intersections. The results, specifically the estimated value of the coefficient α, indicate that there is little or no difference between Toronto and the U.S. sites taken together. While there was an indication that there were some differences among U.S. sites, those differences were statistically insignificant and likely due to the small sample sizes.

The California HSIS data were used in an attempt to develop improved stop-controlled models for use in the engineering procedure and warrant. This attempt failed in that the models were deemed to be no better than those already calibrated from the reference group data. Therefore the reference group models as presented in Table 9 and Table 10 were adopted for the engineering procedure and warrant. The models using California HSIS data for 3-leg and 4-leg intersections are shown in Table 11 and Table 12, respectively.

MODELS FOR UNCONVERTED SIGNALIZED INTERSECTIONS

The data summarized in Table 5 were used to develop regression models for signalized intersections. Again, the inclusion of variables such as sight distance and approach speed did not significantly affect the fit.

Table 13 shows the results of the regression modeling. The number of 3-leg intersections was relatively small, which meant that the datasets had to be combined. An attempt was made to estimate a different constant (α) for 3- and 4-leg intersections using the number of legs as a dummy variable (0 and 1 for 3- and 4-leg, respectively). However, the constant term (α) was almost identical for the two intersection types; therefore, a single constant term was calibrated, although separate *K* values were calculated for 3- and 4-leg intersections.

TABLE 11 Models for injury crashes/year at California HSIS 3-leg stop-controlled intersections

	TOTAL	RIGHT-ANGLE	REAR-END	LEFT-TURN
Model Form	$\alpha(F1)^b(F2)^c$	$\alpha(F1)^b(F2)^c$	$\alpha(F1+F2)^d$	$\alpha(F1)^b(F2)^c$
K	2.1	0.7	1.1	0.9
Ln(α) (s.e.)	-8.688 (0.468)	-9.200 (1.010)	-13.006 (0.753)	-9.299 (0.819)
b (s.e.)	0.7032 (0.0483)	0.5010 (0.1040)		0.5407 (0.0850)
c (s.e.)	0.2011 (0.0271)	0.2618 (0.0573)		0.3524 (0.0472)
d (s.e.)			1.1456 (0.0746)	

TABLE 12 Models for injury crashes/year at California HSIS 4-leg stop-controlled intersections

	TOTAL	RIGHT-ANGLE	REAR-END	LEFT-TURN
Model Form	$\alpha(F1)^b(F2)^c$	$\alpha(F1+F2)^d$ $(F2/(F1+F2))^e$	$\alpha(F1+F2)^d$	$\alpha(F1)^b(F2)^c$
K	1.9	0.8	1.2	1.3
Ln(α) (s.e.)	-7.986 (0.656)	-4.180 (1.07)	-13.970 (1.040)	-9.814 (0.935)
b (s.e.)	0.6188 (0.0653)			0.6597 (0.0932)
c (s.e.)	0.2946 (0.0377)			0.3066 (0.0535)
d (s.e.)		0.415 (0.1130)	1.2720 (0.1040)	
e (s.e.)		0.3493 (0.0620)		

TABLE 13 Models for injury crashes/year at 3- and 4-leg unconverted signalized intersections

	TOTAL	RIGHT-ANGLE	REAR-END	LEFT-TURN
Model Form	$\alpha(F1)^b(F2)^c$	$\alpha(F1)^b(F2)^c$	$\alpha(F1+F2)^d$	$\alpha(F1)^b(F2)^c$
K 3-leg	1.7	0.6	1.1	0.8
K 4-leg	3.2	3.7	2.1	1.2
Ln(α) (s.e.)	-10.82 (1.69)	-7.06 (2.15)	-11.25 (2.30)	-12.73 (2.86)
b (s.e.)	0.719 (0.140)	0.346 (0.178)		0.434 (0.236)
c (s.e.)	0.562 (0.080)	0.368 (0.102)		0.965 (0.137)
d (s.e.)			1.070 (0.221)	

Again, the California HSIS data was used in an attempt to improve the models. The best models are shown in Table 14 and Table 15 for 3-leg and 4-leg intersections, respectively. Attempts at including other explanatory variables did not improve the models sufficiently for these variables to be included.

Based on a comparison of the standard errors and the *K* values for the models in Table 13 for data assembled for this project and the models in Tables 14 and 15 for the California HSIS data, and considering that separate models could be calibrated for 3- and 4-leg intersections using the California HSIS data, it was decided to adopt the California HSIS *signalized* intersection models for the purposes of this research. However, left-turn volumes were unavailable for the California HSIS data, and therefore could not enter the model. For this reason, the left-turn models for signalized intersections are not very strong (low *K* value and large standard error for the major road AADT). Given that these models were not very strong for stop-controlled intersections either, and the difficulties in designating crashes as left-turn, it was decided that

TABLE 14 Models for injury crashes/year at California HSIS 3-leg signalized intersections

	TOTAL	RIGHT-ANGLE	REAR-END	LEFT-TURN
Model Form	$\alpha(F1)^b(F2)^c$	$\alpha(F1)^b(F2)^c$	$\alpha(F1+F2)^d$	$\alpha(F1)^b(F2)^c$
K	3.0	1.4	2.3	1.4
Ln(α) (s.e.)	-7.510 (1.300)	-11.940 (2.770)	-9.790 (1.600)	-5.350 (2.330)
b (s.e.)	0.6370 (0.1240)	0.8070 (0.2620)		0.2650 (0.2260)
c (s.e.)	0.1901 (0.0413)	0.1896 (0.0872)		0.1914 (0.0779)
d (s.e.)			0.9270 (0.1520)	

TABLE 15 Models for injury crashes/year at California HSIS 4-leg signalized intersections

	TOTAL	RIGHT-ANGLE	REAR-END	LEFT-TURN
Model Form	$\alpha(F1)^b(F2)^c$	$\alpha(F1+F2)^d$ $(F2/(F1+F2))^e$	$\alpha(F1+F2)^d$	$\alpha(F1)^b(F2)^c$
K	3.1	1.7	2.4	1.6
Ln(α) (s.e.)	-5.751 (0.539)	-3.773 (0.874)	-10.988 (0.697)	-2.700 (0.865)
b (s.e.)	0.4911 (0.0516)			0.0901 (0.0838)
c (s.e.)	0.1975 (0.0229)			0.1323 (0.0356)
d (s.e.)		0.3287(0.0819)	1.0587 (0.0657)	
e (s.e.)		0.2454 (0.0409)		

the engineering procedure and the warrant, at least for the interim, should focus on rear-end, right-angle, and all crashes combined.

APPLICATION OF SIGNALIZED INTERSECTION MODELS TO CONVERSION SAMPLE

The conversion dataset consisted of 386.68 site-years of data for which the intersections were signalized. The number of crashes for these site-years was compared to that predicted by both the reference group models and the California HSIS signalized intersection models in Tables 13 through 15. The purpose was to test if converted intersections in the sample behaved similarly after conversion to other signalized intersections in the model calibration datasets in terms of the relationship between crashes and traffic volume.

The results, shown in Table 16, are mixed. Excellent results are obtained for total and right-angle injury crashes using the California HSIS model, while those for the reference group model are not good for all crash classes.

It could be concluded with caution that the close correspondence between the observed and predicted total injury crashes using the California HSIS model is ample indication that converted intersections in the sample behave similarly to other signalized intersections in terms of the relationship between crashes and traffic volume. On this basis, it was decided that the California HSIS signalized intersection models were adequate for the procedure for conducting an engineering study to assess whether or not a contemplated signal installation is warranted. Similarly, these models could also be used in developing the Crash Experience warrant. This analysis further confirmed the wisdom of the decision to adopt the California HSIS signalized intersection models in preference to those estimated from the reference group database.

BEFORE-AFTER ANALYSIS OF CONVERTED INTERSECTIONS

The preferred approach for estimating the likely safety effect of a contemplated signal installation requires a fundamental assumption that the safety of a newly converted intersection can be estimated from a model developed on the basis of intersections converted previously. The conduct of a before-after study of converted intersections was essential to corroborate this assumption. This corroboration exercise was a fundamental part of this study.

Basics of the Empirical Bayes Before-After Study

The EB methodology as documented by Hauer (*13*) and as applied by Persaud et al. (*16*) was used in these analyses. Given these detailed references and the fact that the before-after analysis was peripheral to the thrust of the research, only the gist of the methodology is documented here. The application required the use of regression models for stop-controlled intersections and crash counts before signal installation to estimate the expected number of crashes in the after period had the intersection not been converted. These estimates, along with the actual crash counts after signal installation, are summed over all converted intersections, using data for the conversion sample that are summarized in Table 6.

The changes in safety, expressed as an index of effectiveness, θ, is estimated as follows:

$$\theta = A/\{E\{B\}[1 + (VAR\{B\}/E\{B\}^2)]\}$$

where:

A = sum of crash frequencies recorded after signal installation in the sample and
E{B} = sum of expected crash frequencies without signal installation in the sample.

This methodology accounts for possible regression-to-the-mean effects, changes in traffic volume, and time trends in collision counts. The rudiments of EB estimation are presented in Chapter 5, including how the methodology is applied in an engineering procedure to estimate the expected number of crashes without signalization, that is, $(E\{B\}_i)$ with a variance, $VAR\{B_i\}$at an intersection (i) being considered for signalization. For an actual before-after study of a set of intersections

TABLE 16 Crashes at converted signalized intersections (based on 386.68 intersection years of after period data)

Injury Crash Type	Basis for after period crashes	Crashes in after period
Right-angle	Observed	120
	Estimated by reference group model	182.8
	Estimated by California model	123.1
Rear-end	Observed	210
	Estimated by reference group model	244.8
	Estimated by California model	274.3
All	Observed	707
	Estimated by reference group model	810.2
	Estimated by California model	692.9

already converted, which is of interest here, the values of E{B}and VAR{B}in the previous equation are obtained by summing the values of $(E\{B\}_i)$ and VAR$\{B_i\}$over all installation sites, with some modification if the AADT with signals is different than assumed in the engineering procedure and if more than 1 year of after period data are available.

To illustrate, consider the results for one 4-leg stop-controlled intersection in the study database that was converted to signal control. This intersection experienced 13 and 10 total injury crashes, respectively, in before and after periods of 2.75 and 4.08 years. The EB estimate of crashes expected in the after period on the basis of the before period data (using the procedure described in Chapter 5) is 3.80 crashes per year. The adjustment factor for the length of the after period and for differences in traffic volume between the before and after period was calculated as 3.84. This factor was calculated from the crash prediction model for 4-leg stop-controlled intersections. This indicates that in the after period one would have expected $E\{B\}_i = 3.80 \times 3.84 = 14.60$ crashes had the intersection remained stop-controlled. This compares to the A_i of 10 crashes actually recorded to indicate an improvement in safety. VAR$\{B_i\}$ was estimated at 13.93 for this intersection. Summing overall 4-leg intersections, A = 584, E{B} = 756.73 and VAR{B} = 1,009.48. Using the previous equation, the value of θ was computed to be 0.77 for total injury crashes. It should be noted that a value of θ = 0.77 is equivalent to a reduction in crashes of 23 percent [100(1 − 0.77)].

Estimates of the Safety Effect of Conversions and Analysis of Results

Estimates of the index of effectiveness, θ, are given in Table 17 for the 3- and 4-leg intersections. The results show that there is a reduction in right-angle crashes (e.g., for 4-leg, θ = 0.33 represents a reduction of 67 percent [100(1 − 0.33)]) and an increase in rear-end injury crashes (e.g., for 4-leg, θ = 1.38 represents an increase of 38 percent [100(1.38 − 1)]), both effects are in accordance with conventional wisdom. The net of these disaggregate effects is a modest and marginally significant decrease for all impact types combined at 3-leg intersections and a somewhat larger and highly significant decrease for 4-leg intersections.

Further disaggregation of the safety effects for 4-leg intersections is presented in Table 18 for informational purposes. The low number of 3-leg intersections did not allow for disaggregation of those results. Caution should be exercised in mak-

TABLE 17 Estimates of the safety effect of conversions on injury crashes

	3-leg (22 conversions)			4-leg (100 conversions)		
	All	Right-angle	Rear-end	All	Right-angle	Rear-end
EB estimated after-period expected crashes without conversion (s.e.)	142.37 (11.32)	22.13 (3.62)	35.02 (3.87)	756.73 (31.77)	314.72 (19.84)	113.22 (8.20)
Injury crashes in the after period	123	15	53	585	105	157
Index of effectiveness θ	0.86	0.66	1.50	0.77	0.33	1.38
VAR{θ}	0.10	0.20	0.26	0.05	0.04	0.15

TABLE 18 Disaggregate estimates of the safety effect of 4-leg conversions

INTERSECTION CLASS (No. of Sites)	TOTAL		RIGHT-ANGLE		REAR-END	
	θ	VAR{θ}	θ	VAR{θ}	θ	VAR{θ}
AADT ≥ 20,000	0.92	0.08	0.48	0.08	1.38	0.19
AADT < 20,000	0.63	0.05	0.23	0.04	1.37	0.22
Inadequate SD[1]	0.67	0.05	0.27	0.04	1.14	0.16
Adequate SD	0.94	0.09	0.44	0.08	1.76	0.30
All Injury Accs./year ≥ 5	0.59	0.08	0.12	0.04	0.59	0.35
All Injury Accs./year < 5	0.84	0.06	0.41	0.05	1.43	0.16
Major speed ≥ 40	0.85	0.06	0.25	0.04	1.99	0.28
Major speed < 40	0.68	0.06	0.42	0.07	0.89	0.15
Toronto (26)	0.77	0.10	0.58	0.13	0.95	0.20
California (20)	0.84	0.17	0.23	0.13	0.89	0.33
Florida (13)	0.74	0.10	0.17	0.06	1.79	0.43
Maryland (10)	0.46	0.09	0.24	0.09	0.21	0.15
Virginia (10)	0.91	0.18	0.33	0.15	0.67	0.31
Wisconsin (21)	0.82	0.08	0.26	0.05	2.68	0.49
All U.S. (74)	0.77	0.05	0.24	0.04	1.63	0.20

[1] Sight Distance along mainline from the stop-controlled leg (<120m for 2-lane road, <136m for 4-lane road, and <152m for 6-lane road).

ing inferences from these disaggregate results, particularly where the variances are relatively high and where there may be other differences between two groups other than the disaggregate factor isolated. In any case, making such inferences is immaterial for the purposes of this study. The one disaggregate result of particular interest is that the effects estimated for each jurisdiction supports the overall conclusion that the signal installation was accompanied by a reduction in *total* crashes, and that that is composed mainly of a reduction in *right-angle* crashes.

Viability of the Proposed Engineering Study Procedure

Recall that the viability of the proposed procedure for conducting an engineering study depends on whether differences in safety predicted by models for stop- and signal-controlled intersections would be corroborated by the results of the before-after study. To this end, the number of crashes for the converted intersections was estimated using the stop-controlled and the signalized intersection models described previously. These estimates are presented in Table 19. It can be seen that the direction of the differences in safety effect indicated by the estimates in Table 17 is the same as for the differences in predictions from the stop- and signal-controlled models (i.e., more rear-end crashes and fewer right-angle crashes at signalized intersections).

These results provide further evidence that the models can be used as part of the proposed approach for developing the Crash Experience warrant and in the suggested procedure for conducting an engineering study to assess whether or not a contemplated signal installation is warranted.

The conclusion from this before-after analysis is that in estimating the likely safety effect of installing signals at an intersection, the proposed approach can be used. In this, an EB estimate of the expected number of crashes without signalization is compared with the number of accidents expected with signalization, the latter estimated from a regression model for signalized intersections.

DEVELOPMENT OF THE RECOMMENDED CRASH EXPERIENCE WARRANT

Based on the analyses of data and the crash prediction models developed, a revised Crash Experience warrant was devised and is being recommended for inclusion in the *MUTCD*. Figures 1 and 2 form the basis of the proposed warrant procedure. In these figures, the appropriate line is used for the level of non-rear-end injury crashes (i.e., all injury crashes except rear-end types of crashes) not involving pedestrians in the most recent 3-year period. As noted earlier, fatal crashes are included in the total injury crashes.

The lines in Figures 1 and 2 demarcate a boundary between those regions where installation of a signal is expected to or is not expected to result in a net safety benefit for a given combination of entering traffic volumes and crash history. If the plotted point representing the two traffic volume levels is below the line indicated by the previous 3-year crash experience then it can be said that signal installation is not expected to result in net safety benefits of significance or even in a deterioration in safety hence, further detailed analysis is not needed, assuming *none of the other MUTCD warrants are met*. But, if the plotted point is above the relevant line, then further detailed analysis is needed to estimate the likely safety benefits of installing a signal and its significance. If any of the other warrants is met, then further detailed analysis is needed to assess the safety benefits or disbenefits in light of the operational benefits. The next chapter documents a procedure to perform such analysis and illustrates the application of that approach for considering safety in signal installation decisions. It should be noted that these figures inherently imply that if the number of non-rear-end injury crashes in the previous 3 years total more than 6, then a detailed engineering analysis of expected safety effects must be conducted.

For developing the proposed warrant represented in Figures 1 and 2, the steps outlined in the next chapter for conducting a detailed engineering analysis to estimate the net safety effects of installing traffic signals have been carried out for a large number of hypothetical situations to identify and specify those in which signals are likely to cause a deterioration in safety. A spreadsheet was developed to use that procedure to compute the expected safety effect of signal installation for a large number of possible combinations of major and minor road traffic volume levels and crash history. The lines in the figures were drawn to represent the combinations of these variables for which there is little or no expected safety benefit in terms of reductions in non-rear-end injury crashes not involving pedestrians.

TABLE 19 Injury crash predictions at intersections converted from stop-controlled to signal-controlled

NUMBER OF LEGS	NUMBER OF SITE-YEARS	RIGHT-ANGLE CRASHES		REAR-END CRASHES	
		Stop-controlled	Signalized	Stop-controlled	Signalized
3	75.33	26.6	7.1	29.8	54.4
4	311.35	205.0	116.0	81.2	219.9

For the application of the figures for a contemplated signal installation, one needs to know the following:

- Number of non-rear-end injury accidents in the most recent 3-year period,
- Average daily entering traffic volume on the major street (both approaches combined), and
- Average daily entering traffic volume on the minor street (both approaches combined).

The potential application of these are illustrated through the following cases:

Case 1: Consider a 3-leg intersection with major and minor streets entering AADTs of 20,000 and 500, respectively, and 3 non-rear-end injury crashes in the previous 3 years. None of the volume warrants are met but residents are concerned about safety issues. The plotted point representing the coordinates (20,000 and 500) falls below the line for $N \leq 3$ in Figure 1. The interpretation is that this intersection need not be subjected to the detailed engineering procedure because none of the other warrants is met and because it is likely that there will be either deterioration in safety or no significant safety benefit following signal installation.

Case 2: Consider the same intersection as for Case 1 in which 4 non-rear-end injury crashes occurred (instead of 3) in the previous 3 years. The plotted point representing the coordinates (20,000 and 500) now falls above the appropriate crash experience line (i.e., for $N = 4$). The interpretation is that this intersection should be subjected to the detailed engineering analysis procedure because a net safety benefit following signal installation can be expected. The estimated net benefit should then be considered in the light of other impacts, negative and positive, of installing a signal.

Case 3: Consider the same intersection as for Case 1 but with a larger major street entering AADT of 35,000. The minor street entering AADT of 500 is the same as for Case 1, and 4 non-rear-end injury crashes occurred in the previous 3 years. Suppose that, unlike Cases 1 and 2, one of the traffic volume warrants is now satisfied. The plotted point representing the coordinates (35,000 and 500) falls above the appropriate crash experience line (i.e., for $N = 4$). The interpretation is that it is likely that there will be a net safety benefit following signal installation. Because a signal is already warranted for rational reasons, it would be tempting to think of the safety benefits as a bonus and to eliminate a detailed engineering study. However, in accordance with the spirit of the *MUTCD*, a detailed study is still strongly recommended for the following reasons:

1. Quantifying the net safety and operational benefits provides a basis for prioritizing the installation of warranted signals.
2. An engineering study provides a more precise estimate of the net safety effect than that on which Figures 1 and 2 are based in that it would be more tailored to local conditions and would consider a longer crash history.

Case 4: Consider a similar intersection to Case 3, with the same entering AADTs but with 3 non-rear end-injury crashes in the previous 3 years. As for Case 3, one of the traffic volume warrants is satisfied. However, the plotted point representing the coordinates (35,000 and 500) now falls below the line in Figure 1 for N (3 non-rear-end injury crashes in the previous 3 years. The interpretation is that this intersection must be subjected to the engineering procedure to quantify the change in safety expected to result from signalization. This change in safety can then be compared with the operational benefits.

CHAPTER 5

PROCEDURE FOR ESTIMATING SAFETY IMPACTS OF SIGNAL INSTALLATION IN A DETAILED ENGINEERING STUDY

Ideally the decision to install or not to install a traffic signal would involve a detailed engineering study, with a benefit-cost analysis that considers safety and other impacts. Indeed, the *MUTCD* cautions that satisfying a warrant does not in itself justify the decision to install a signal and 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."

What appears to be required, given the expressed intent of the *MUTCD*, is a procedure that would be used as part of an engineering study to estimate the impact on safety of signal installation. This estimate could then be assessed in the light of estimates of the other impacts of signal installation—delay, energy consumption, and so on. However, in many situations, a quick answer is desired, particularly for cases where signal installation is unlikely to be warranted, and for this purpose it is useful to have a warrant procedure in the *MUTCD*. Thus, the revised crash experience presented in Chapter 4 was devised. The proposed warrant, as presented in Figures 1 and 2, can be used to screen whether further analysis is needed to determine if the signal should be installed. This chapter documents and illustrates the engineering study procedure to be applied for cases in which the Crash Experience warrant recommends such a study.

OVERALL PROCEDURE

A six-step process for estimating the safety (i.e., crash) impacts of a contemplated signal installation is described below.

STEP 1: Assemble the following for stop-controlled and signalized intersections:

Step 1(a): Assemble the crash and traffic data as follows:

– For the past, say 5 years (the procedure will work for any length of crash history as long as traffic and crash data are available and the intersection was fundamentally unchanged), obtain the count of total, rear-end, and right-angle injury crashes (crash types are as defined in Appendix C);
– For the same period obtain or estimate the entering AADTs on major and minor road approaches for each year; and
– Estimate the major and minor road entering AADTs that would have prevailed had a signal been present/installed during the last full analysis year.

Step 1(b): Assemble the Crash Prediction Models and Parameters

– Identify default crash prediction models and
– If suitable data are available and the need exists, modify the default crash prediction models, with multipliers for each year of the analysis period.

STEP 2: Use the EB procedure and the information in Step 1 to estimate the expected annual number of rear-end, right-angle, and other injury crashes that would occur without conversion. (The EB estimate for "other" injury crashes is the EB estimate for the total minus the sum of the EB estimates for rear-end and right-angle injury crashes.)

STEP 3: Use the signalized intersection models in Tables 13 and 14 and the volumes from Step 1 to estimate the expected number of rear-end, right-angle, and other injury crashes that would occur if the intersection were converted. (The estimate for "other" injury crashes is the estimate for the total minus the sum of the estimates for rear-end and right-angle injury crashes.)

STEP 4: Obtain for rear-end, right-angle, and other injury crashes, the difference between the estimates from Steps 2 and 3. If there is a net *decrease* in total accidents, check that there is an expected decrease in right-angle crashes and that this change is statistically significant for a signal to be warranted. If there is a net *increase* in total accidents, check that there is an expected increase in rear-end crashes and that this change is statistically significant.

STEP 5: Applying suitable severity weights and dollar values for rear-end, right-angle, and other injury crashes, determine whether signal installation would result in a net benefit.

STEP 6: Compare the net safety benefit with the cost, considering other impacts as desired, and using conventional economic analysis tools.

ILLUSTRATION

A 4-leg stop-controlled intersection, similar to an actual one in the database, is being considered for signal installation in 1999. AADT and crash data for this intersection are available for a period from January 1996 to August 2000. Steps to performing the detailed analysis are shown below and data and results of the analysis are summarized in Tables 20, 21, and 22. *The calculations, though seemingly complex, can be greatly simplified with the use of a spreadsheet that can be developed with minimal resources and salvaged for use in additional studies. Such a spreadsheet has been used in providing these illustrative calculations. It is reiterated here that the data needs are not extensive.*

STEP 1: Assemble data and crash prediction models.

Step 1(a): Crash and traffic data.

Crash Data

The counts of total, right-angle, and rear-end injury crashes in each year of the analysis period are shown in the second row of Tables 20 through 22. The intersection had 23 crashes in the analysis period, of which 3 were rear-end and 12 were right-angle crashes.

AADT Data

Entering AADTs for the major and minor roads for each year are shown in the third and fourth rows of Tables 20 through 22. It is recognized that actual counts are typically not available for each year; however, in most jurisdictions trend factors are available that could be applied to estimate AADTs for each year. A separate process can be used to provide the best estimate of the AADT after signalization, considering traffic that might be present at the intersection in the future. In the absence of such an estimate, the AADT expected after signalization can be assumed to be same as that in the previous year.

Step 1(b): Crash prediction models.

Base Models

For this illustration, these are required for 4-leg stop-controlled intersections for each of the years from 1996 to 2000 and for signalized 4-leg intersections for the last full year, in this case, 1999. Ideally each jurisdiction would have its own set of applicable models that are used generally in the safety management process for identifying hazardous intersections, and for developing and evaluating countermeasures. If these models do not exist, they can be calibrated using methods and software outlined in sources such as (*17*) and (*18*), but considerable statistical expertise is required to do so, especially in the selection of the model form and the independent variables.

Recognizing that this desideratum of having jurisdiction-specific models is not achievable in most cases, at least at

TABLE 20 Summary of results for all injury crashes

1) Year (y)	**1996**	**1997**	**1998**	**1999**	**01-08 2000**	**1999 (signal)***
2) CRASHES IN YEAR (X)	4	6	3	6	4	
	Sum = $\mathbf{X_b}$ = 23					
3) MAJAADT	41309	42169	43460	43891	44321	48441
4) MINAADT	3596	3671	3783	3821	3858	4295
5) Recalibrated $\alpha \times 10^{-4}$	4.26	4.40	4.01	4.20	4.36	4.30
6) Parameter K	2.30	2.30	2.30	2.30	2.30	3.1
7) Model Prediction $E\{\kappa_y\}$	2.897	3.049	2.858	3.021	2.110	3.337
8) $C_{i,y} = E\{\kappa_y\}/ E\{\kappa_{99}\}$	0.959	1.009	0.946	1	0.698	1.105
9) Comp. Ratio for period	Sum = C_b = 4.613					C_a=1.105
10) Expected annual crashes without signalization (and variance) [based on the last full year (1999)]	$\kappa(99) = C_a(K + X_b)/\{[K/E\{\kappa_{99}\}] + C_b\}$ $= 1.105(2.30 + 23)/\{(2.30/3.021) + 4.613) = 5.202$ $\mathrm{Var}\{\kappa(99)\} = C_a(K + X_b)/[\{K/E\{\kappa_{99}\} + C_b\}^2] = 0.968$					
11) Expected annual crashes after signalization (and variance)[from model in Table 14 (based on 1999)]	$E\{\kappa_{99}\}_{signal} = \exp(-5.751)(48441)^{0.4911}(4295)^{0.1975}$ $= 3.318$ $\mathrm{Var}\{\kappa_{99}\}_{signal} = E\{\kappa_{99}\}^2/K = 3.318^2/3.1 = 3.551$					

* Estimates based on stop-controlled model using anticipated volumes if the intersection had been signalized in 1999.

TABLE 21 Summary of results for right-angle injury crashes

1) Year (y)	**1996**	**1997**	**1998**	**1999**	**01-08 2000**	**1999 (signal)***
2) CRASHES IN YEAR (X)	2	4	1	3	2	
	Sum = $\mathbf{X_b}$ = 12					
3) MAJAADT	41302	42169	43460	43891	44321	48441
4) MINAADT	3596	3671	3783	3821	3858	4295
5) Recalibrated $\alpha \times 10^{-4}$	1.21	1.40	1.03	1.10	1.15	1.33
6) Parameter K	1.4	1.4	1.4	1.4	1.4	1.7
7) Model Prediction $E\{\kappa_y\}$	0.852	1.006	0.763	0.823	0.580	0.924
8) $C_{i,y} = E\{\kappa_y\}/ E\{\kappa_{99}\}$	1.034	1.222	0.927	1	0.704	1.123
9) Comp. Ratio for period	Sum = C_b = 4.887					C_a=1.123
10) Expected annual crashes without signalization (and variance) [based on the last full year (1999)]	$\kappa(99) = C_a(K + X_b)/\{[K/E\{\kappa_{99}\}] + C_b\}$ $= 1.123(1.4 + 12)/\{(1.4/0.823) + 4.887) = 2.284$ $Var\{\kappa(99)\} = C_a(K + X_b)/[\{K/E\{\kappa_{99}\} + C_b\}^2] = 0.347$					
11) Expected annual crashes after signalization (and variance)[from model in Table 14 (based on 1999)]	$E\{\kappa_{99}\}_{signal} = \exp(-3.773)(48441 + 4295)^{0.3287}[4295/(48441 + 4295)]^{0.2454}$ $= 0.443$ $Var\{\kappa_{99}\}_{signal} = E\{\kappa_{99}\}^2/K = 0.443^2/1.7 = 0.115$					

*Estimates based on stop-controlled model using anticipated volumes if the intersection had been signalized in 1999.

TABLE 22 Summary of results for rear-end injury crashes

1) Year (y)	**1996**	**1997**	**1998**	**1999**	**01-08 2000**	**1999 (signal)***
2) CRASHES IN YEAR (X)	0	2	0	1	0	
	Sum = $\mathbf{X_b}$ = 3					
3) MAJAADT	41302	42169	43460	43891	44321	48441
4) MINAADT	3596	3671	3783	3821	3858	4295
5) Recalibrated $\alpha \times 10^{-4}$	1.24	1.45	1.12	1.20	1.30	1.36
6) Parameter K	1.5	1.5	1.5	1.5	1.5	2.4
7) Model Prediction $E\{\kappa_y\}$	0.440	0.522	0.413	0.446	0.324	0.481
8) $C_{i,y} = E\{\kappa_y\}/ E\{\kappa_{99}\}$	0.987	1.172	0.926	1	0.728	1.078
9) Comp. ratio for period	Sum = C_b = 4.813					C_a=1.078
10) Expected annual crashes without signalization (and variance) [based on the last full year (1999)]	$\kappa(99) = C_a(K + X_b)/\{[K/E\{\kappa_{99}\}] + C_b\}$ $= 1.078(1.5 + 3)/\{(1.5/0.446) + 4.813) = 0.593$ $Var\{\kappa(99)\} = C_a(K + X_b)/[\{K/E\{\kappa_{99}\} + C_b\}^2] = 0.073$					
11) Expected annual crashes after signalization (and variance)[from model in Table 14 (based on 1999)]	$E\{\kappa\ 99\}_{signal} = \exp(-10.988)(48441 + 4295)^{1.0587}$ $= 1.687$ $Var\{\kappa_{99}\} = E\{\kappa_{99}\}^2/K = 1.687^2/2.4 = 1.186$					

* Estimates based on stop-controlled model using anticipated volumes if the intersection had been signalized in 1999.

present, the next best option is to recalibrate the default base models provided in Chapter 3 for the jurisdiction and time period of interest. For 4-leg stop-controlled intersections, the default base models are shown in Table 10 while those for signalized intersections are shown in Table 15. For example, the following is the default base model for total injury crashes at 4-leg stop-controlled intersections (from Table 10):

$$\text{Total Injury Crashes/year} = \alpha\,(\text{major road AADT})^b \times (\text{minor road AADT})^c$$

where:

$\alpha = 0.000426$ (i.e., $e^{-7.76}$ or $Ln(\alpha) = -7.76$)
$b = 0.499$
$c = 0.430$

Model Recalibration

It is recommended that these models be recalibrated for each jurisdiction and for each year of the analysis period. To the extent that these models can be used for several aspects of safety management, it seems generally worthwhile for a jurisdiction to devote the effort and resources required to obtain them. The recalibration procedure used in this illustration has been adopted from Harwood et al. (*15*) and is illustrated in Appendix D. The value of α in the default model equation above is recalibrated for each year, while the rest of the equation remains the same as for the default model.

These recalibrated values of α for the current illustration are shown in row 5 of Tables 20 through 22. A similar recalibration process can be done to adjust the α parameter for the signalized intersection model for the year 1999. In this example, it was assumed that this adjustment was not necessary.

The values of the calibrated parameter *K* that are used in the analysis are taken from Table 9 and shown in row 6 of Tables 20 through 22.

STEP 2: Estimate crashes without conversion.

Step 2(a): Estimate the expected number of crashes per year using the recalibrated crash prediction model. For example, for 1996,

$$E\{\kappa_{1996}\}_{\text{total}} = 0.000426(41302)^{0.499}(3596)^{0.430} = 2.897$$

$$E\{\kappa_{1996}\}_{\text{right-angle}} = 0.000121(41302)^{0.218}(3596)^{0.799} = 0.852$$

$$E\{\kappa_{1996}\}_{\text{rear-end}} = 0.000124(41302 + 3596)^{0.763} = 0.440$$

These estimates are shown in row 7 of Tables 20 through 22. Note that for the last full year, 1999 in this case, an estimate is also done for the anticipated volumes if the intersection were to be signalized (still using the stop-controlled model).

Step 2(b): Calculate the comparison ratio ($C_{i,y}$) of the model estimate for a given year divided by the model estimate for 1999. These ratios are shown in row 8 of Tables 20 through 22 and summed in row 9.

Step 2(c): Using the values in the previous rows and the formula shown in the tables, estimate the expected average annual number of crashes (and variance) without signalization for the last full year (1999). These values are shown in row 10 of Tables 20 through 22.

STEP 3: Use the signalized intersection model from Table 14 to estimate the number of crashes per year if the intersection were signalized using the expected annual AADTs after signalization (shown in the last column of Tables 20 through 22). (Recall that, for this example, it was assumed that a recalibration of this default base model was not required.)

$$E\{\kappa_{99}\}_{\text{signal/total}} = \exp(-5.751)(48441)^{0.4911}(4295)^{0.1975} = 3.318$$

$$\begin{aligned} E\{\kappa_{99}\}_{\text{signal/right-angle}} &= \exp(-3.773)(48441 \\ &\quad + 4295)^{0.3287}[4295/(48441 + 4295)]^{0.2454} \\ &= 0.443 \end{aligned}$$

$$E\{\kappa_{99}\}_{\text{signal/rear-end}} = \exp(-10.988)(48441 + 4295)^{1.0587} = 1.687$$

STEP 4: Estimate change in crashes due to conversion.

Step 4(a): Estimate the change in crashes per year if the intersection was converted to a signalized intersection as follows:

Total = 3.318 − 5.202 = −1.884 (decrease)

Rear-end = 1.687 − 0.593 = 1.094 (increase)

Right-angle = 0.443 − 2.284 = −1.841 (decrease)

Other = −1.884 − (1.094 + (−1.841)) = −1.137 (decrease)

Step 4(b): Test for significance of the changes in major crash types. If there is a net decrease in total crashes, check that there is an expected decrease in right-angle crashes and that this change is statistically significant. If there is a net increase in total crashes, check that there is an expected increase in rear-end crashes and that this change is statistically significant. If the expected changes do not materialize or are not statistically significant at the 10 percent level, then safety should not be used in evaluating the impacts of signalization.

In this case, there is a net decrease in total crashes and an expected decrease of 1.841 right-angle crashes/year. The variance of this change in right-angle crashes is equal to the sum of the variances of the two numbers that yielded this value (from Table 21).

$$\begin{aligned} &= \text{Var}\{\kappa(99)_{\text{right-angle}}\} + \text{Var}\{\kappa(99)_{\text{signal/right-angle}}\} \\ &= 0.347 + 0.115 = 0.462 \end{aligned}$$

The standard deviation is 0.680, which means that the decrease of 1.841 is statistically significant because a value of zero lies outside of 1.64 standard deviations (for a 10 percent significance level). A more precise test can be conducted using a more sophisticated procedure that is outlined by Hauer (*19*).

STEP 5: Consider relative severities and costs of rear-end, right-angle, and other injury crashes.

One of the best published works on severity weights at the moment is a paper by Hall (*20*) that reported the costs per collision for various accident types and locations. It is also worth mentioning that the National Safety Council (NSC) upgrades annual safety figures in terms of costs by accident types. The National Highway Traffic Safety Administration (NHTSA) also provides some guidelines on crash costs. Some states may have their own estimates that may reflect the local conditions better than the national averages. Users may consult any of these sources as deemed appropriate for their analyses. This illustration uses Hall's estimates. The costs given for multiple vehicle intersection crashes were used to estimate an average cost for right-angle, rear-end, and other crashes, as defined for this project. This re-estimation of accident costs and conversion to 2002 values produced costs per accident as follows:

Right-angle = \$60,000

Rear-end = \$25,000

Other = \$40,000

Using these numbers, the estimated net annual safety benefit of signal installation at this intersection is as follows:

$$1.841(60,000) + 1.137(40,000) - 1.094(25,000) = \$128,950$$

STEP 6: Compare the cost of signal installation with the benefits, considering operational benefits as well. How this is done is very jurisdiction specific and conventional methods of economic analysis can be applied after obtaining estimates of the economic values of changes in delay, fuel consumption, and other traffic operational impacts. Traffic engineering studies can be conducted and tools such as simulation can be used to estimate the changes in operational parameters, such as delay times, stops, fuel consumption, emissions, and so forth. In computing the costs and benefits of signal installation, it should be recognized that there are several components to costs and benefits. Along with the operational benefits, there may be operational cost considerations, such as maintenance of traffic signals. There may be intersection geometry improvement costs associated with the signal installation. Traffic analysis should be used to determine whether the signal installation would benefit the traffic operations or add to the cost in terms of some of the operational measures mentioned above. These factors should be considered when performing the cost-benefit analysis consistent with local practice.

Conclusions

For this illustrative example, it has been shown that there is a net safety benefit in terms of an estimated reduction in crashes. These reductions were statistically significant. Moreover, the projected annual savings in costs as a result of the estimated reduction in crashes are also quite significant. If the jurisdiction found that these benefits can offset the costs involved with signal installation and maintenance at this intersection, then a traffic signal can be justified even if other *MUTCD* warrants are not met.

CHAPTER **6**

RECOMMENDED REVISIONS TO THE *MUTCD* CRASH EXPERIENCE WARRANT

The current Crash Experience warrant in the *MUTCD* provides a measurable standard that is easily understood by traffic engineers. However, the current standard is too general. It is not sensitive to the type of intersection, that is, 3-leg or 4-leg, under consideration for signal installation, and the warrant generalizes the types of crashes by using "types susceptible to correction by a traffic control signal," where describing many of these types may very difficult. Also, it is unclear that the "magic" number of five "correctible" crashes per year has any basis in empirical evidence. In addition, using a crash count as a selection criterion is now known to be problematic in that sites with a randomly high crash count may be wrongly considered for signalization, and vice versa, because of the regression-to-the-mean phenomenon.

On the basis of the analysis of available data for this project, a recommended warrant has been developed that addresses some of the issues that the current warrant does not adequately address. The concept for the recommended Crash Experience warrant and the recommended revisions to the *MUTCD* are discussed in the following section.

RECOMMENDATION FOR REVISIONS TO THE *MUTCD*

If the signal warrant based on crash experience as recommended in this study is adopted, then the current Warrant 7 in the *MUTCD* must be revised. The text for the current warrant is presented with recommended additions shown underlined and recommended deletions shown as strikeouts. Please note that Figures 4C-5 and 4C-6 referenced in the recommended text are shown as Figures 1 and 2 from this report, respectively.

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;

B. ~~Five or more reported crashes, of types susceptible to correction by traffic signal control, 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~~ The plotted point representing the annual average daily traffic (AADT) entering on the major street (total of both approaches) and the AADT entering on the minor street (total of both approaches for a 4-leg intersection) falls above the applicable curve in Figure 4C-5 for a 3-leg intersection or in Figure 4C-6 for a 4-leg intersection. Each curve represents the number of non-rear-end injury crashes not involving pedestrians, in the most recent 3-year period; 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.~~ An analysis of expected changes in injury crashes has estimated a net safety benefit after signal installation.

The support statement of the existing standard for Warrant 7 is recommended to be used without any changes. However, it is noted that the crash analysis referred to in the recommended standard section would be appropriate even if signal installation is being considered for operational reasons and not solely for crash experience.

In the Standard section, the recommended warrant states that the first action should be to try other measures, both engineering and enforcement, to see if the crash frequency (and presumably severity) can be reduced. This action seems reasonable, and therefore no change is recommended for paragraph A. However, this implies that one or more measures are installed and that a suitable time is allowed to observe if crash frequency (severity) is reduced. This implies that an appropriate crash analysis is performed to insure that the observed change is indeed due to the countermeasure.

Paragraph B is the second criterion and would be applied after the first action was taken. It becomes a screening criterion to determine if further study is needed. If the plotted value is below the appropriate curve, then it is likely that installing a signal will result in safety deterioration, that is, an increase in crashes. No further analysis is needed if other warrants are not met. Presumably, the crash experience should be monitored for changes and other countermeasures should be considered.

If the plotted value is above the appropriate curve, then paragraph C mandates performing a safety analysis to establish if a net safety benefit can be expected as a result of signal installation. Keeping with the content format of the *MUTCD*, the “safety analysis” is not described in the warrant. The engineer or analyst must be aware of the appropriate procedures to follow. This report provides the procedure, and this or a similar procedure hopefully will be contained in the Highway Safety Manual, which is under development, and in future revisions to the *TCDH*.

Finally, the reference to the lower volume levels in existing paragraph C is deleted because traffic volumes are already considered in the application of the plots in paragraph B.

CHAPTER 7

CONCLUSIONS, APPLICATION TO PRACTICE, AND FURTHER RESEARCH

CONCLUSIONS

Based on the analysis of available data for this project, several conclusions can be drawn. These conclusions include those that enforce the current understanding of the types of crashes that are impacted as a result of signalization and others that address some the issues that the current *MUTCD* Crash Experience warrant does not adequately address, such as the regression-to-the-mean problem in using crash counts as the main screening criterion. These conclusions are briefly discussed here.

The data collected and analyzed for this study clearly show that the safety benefit of signalizing an unsignalized intersection is a function of the crash history, the traffic entering the intersection on the major and minor approaches, and whether the intersection is a 3-leg (T-intersection) or a conventional 4-leg intersection. The available data indicated that total injury crashes can be reduced by signalizing an intersection with certain levels of crash frequency and traffic volumes. Although individual intersections may yield contrary results, the data for this study showed that signalizing 4-leg intersections would generally yield different safety benefits than signalizing 3-leg intersections in terms of a reduction in total injury crashes. Hence, different crash experience thresholds for the signal warrant are required for these two intersection types. In addition, the use in the proposed warrant of crash counts and traffic volumes in effect addresses the regression-to-the-mean difficulty and also the reality that safety benefits depend on both crash counts and traffic volumes as well as the number of approach legs.

While the results of this study strongly support the *TCDH* guidance and conventional wisdom that right-angle crashes can be reduced by signalization and an increase in rear-end crashes can be expected after signalization, there was no strong evidence to support the contention that the left-turn collisions are "reducible" types of crashes after signalization, as suggested by *TCDH*. However, this lack of support may be a result of the difficulty of categorizing left-turn crashes—various jurisdictions may interpret different types of crashes as left-turn crashes—and the corresponding instability in the crash prediction models and the effect on the estimates of safety. Until more research can be done on this issue, using the types of crashes that have more "uniform" definition across jurisdictions for the purpose of signal warrant analysis seems sensible because this may be more useful to practitioners.

The results of the engineering study may indicate that signal installation is justified based on a consideration of safety benefits. This should not be taken to mean that a signal should be installed, because (a) other measures at the same or other sites may have higher priority in terms of cost effectiveness, (b) safety benefits will need to be assessed in light of other signal installation impacts, and (c) other locations may be more deserving of a signal installation. In other words, the results of the engineering study should be fed into the safety resource allocation process.

APPLICATION TO PRACTICE

The warrant, if implemented, would be set in the *MUTCD* for some period of time. Since it has been developed from crash prediction models that are still emerging, a conservative approach was required. This means that the actual proposed *MUTCD* warrant procedure is merely a pre-screen to identify clear-cut situations in which more detailed study might be unnecessary. Conversations with traffic engineers suggest that this is perhaps the most common use of the crash warrant.

The detailed study converges in the form of an economic assessment, encompassing the engineering safety estimate models, to assess the safety effects of signalizing an intersection that also ties into the operational benefits. Such a study seems most appropriate for making the ultimate decision on installation of a signal at the subject intersection. This study outlines a methodology that provides step-by-step guidance on developing such models and applying them in economic assessments.

The overall concept developed, that is, a pre-screen followed by a detailed study of "sites with promise," is a practical one that sets the stage for other warrants for geometric and traffic engineering improvements to be developed along these lines. The results of this study can be used in making decisions on removing "unwarranted" signals in that the safety implications can be assessed using the models and procedure presented in this report.

FURTHER RESEARCH

The procedure for the detailed engineering study could be enhanced with the application of better models as they become available and as the quality of data available to develop and apply them improves. It was already mentioned that individual jurisdictions may estimate their own models, or at least, estimate an adjustment factor for the default models. Major research efforts are underway that would likely provide better models in the not too distant future. These include major FHWA research projects for Interactive Highway Safety Design Model (IHSDM) and for the development of a Comprehensive Highway Safety Improvement Model (CHSIM) (now called *SafetyAnalyst*) and NCHRP research related to the development of a Highway Safety Manual, for example, NCHRP 17-26, "Methodology to Predict the Safety Performance of Urban and Suburban Arterials." With the availability of better models and appropriate before-after data, the engineering study procedure can be used to estimate the safety implications of removing traffic signals. Further research can be done on applying the economic approach as suggested for the Crash Experience warrant in this study to other MUTCD warrants. That is, there is some merit to exploring the possibility of tying the economic analysis to the ultimate decision of whether or not to install or remove a traffic signal control. In that respect, to include the safety as well as the operational benefits and costs of installation or removal of traffic signals, several volume and crash warrants may be consolidated into more comprehensive warrants.

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APPENDIX A

HISTORY OF THE CRASH EXPERIENCE WARRANT IN THE *MUTCD*

The following are sections from the various editions of the *MUTCD* (*1*) related to the Crash Experience warrant, which up until the Millennium edition was referred to as the Accident warrant. After the 1935 edition, each new edition highlights (by bolding) those areas that changed from the previous edition.

1935 Edition (1st Edition)

Section 307—Accident Hazard Warrant for Fixed-Time Signals

A fixed-time traffic control signal which would not be justified under any of the preceding warrants may be warranted where:

(a) Five or more reported accidents of types susceptible of correction by a traffic control signal have occurred within a 12-month period, each accident involving personal injury or property damage to an apparent extent of $50 or more; and
(b) Adequate trial of less restrictive remedies with satisfactory observance and enforcement has failed to reduce the accident toll.

Any fixed-time traffic control signal installed because of accident hazards should be operated on the shortest possible cycle length which will serve traffic approaching during the heaviest traffic hour.

The installation of a traffic control signal because of a spectacular or much-publicized accident, or because of a small number of accidents, is strongly condemned. The larger the number of accidents before signalization, the greater is the likelihood of the accidents being reduced by the signal.

Thorough analysis of the accident experience is important. Accident history can usually be obtained from police accident records or from accident reports made by vehicle operators involved. Without thorough analysis of such reports for the intersection in question, it is impossible to determine upon the most suitable remedial measures.

Experience has proved that the following four types of analysis are very helpful in determining what should be done:

(a) A summarized statistical table for all recorded accidents at the intersection.
(b) Analysis of physical characteristics at and near the intersection.
(c) Analysis of traffic flow characteristics secured by methods and forms described above.
(d) Analysis of a collision diagram.

A study of these analyses will generally reveal a number of significant facts. For example, the types of accidents have a very important bearing on the appropriateness of signalization. A traffic control signal, when obeyed, can be expected to eliminate or reduce materially the number and seriousness of the following types of accidents:

(a) Those involving collisions between vehicles on intersecting streets which will move on separate GO intervals.
(b) Those involving pedestrians and vehicles which will move during different GO intervals—PROVIDED PEDESTRIANS OBEY THE SIGNALS.
(c) Those between straight moving and left turning vehicles where these are to move on separate GO intervals.
(d) Those involving excessive speed in cases where coordination restricts speed to a reasonable rate.

On the other hand, traffic control signals cannot be expected to reduce the following types of accidents:

(a) Rear-end collisions, which often increase after signalization.
(b) Collisions between vehicles proceeding in the same or opposite directions, one of which makes a turn across the path of the other.
(c) Accidents involving pedestrians and turning vehicles, both moving on the same GO interval.
(d) Other types of pedestrian accidents, IF PEDESTRIANS DO NOT OBEY THE SIGNALS.

If none of the warrants except the hazard warrant is fulfilled, the initial presumption should be against signalization. It is preferable to institute (with proper education and enforcement) other remedial measures which delay and inconvenience traffic less and cost less, such as caution, slow, stated speed and STOP signs or signals; laning or otherwise organizing traffic movements; safety zones; and traffic islands. If analysis indicates that one or a combination of these other remedial measures is adapted to conditions, it should be given a fair trial of at least six months (preferably a year). Following the trial period, a restudy should be made, and if satisfactory results have not been achieved, such additional steps should be taken as are indicated by the study.

1948 Edition

Section 212—Accident Hazard

If none of the warrants except the **accident-hazard** warrant **described below** is fulfilled, the initial presumption should be against signalization. The installation of a traffic control signal because of a spectacular or much-publicized accident, or because of a small number of accidents, is strongly condemned. **The full accident record of the location should be carefully investigated before any installations are made under this warrant. Such study and experience may show at once that the hazard existing cannot be corrected by a device less restrictive than a signal. In general, however, a fixed-time signal may be considered warranted only where:**

1. Adequate trial of less restrictive remedies with satisfactory observance and enforcement has failed to reduce the **accident frequency**; and
2. Five or more reported accidents of types susceptible of correction by a traffic control signal have occurred within a 12-month period, each accident involving personal injury or property damage to an apparent extent **of $25 or more**; and
3. **There exists a volume of vehicular and pedestrian traffic not less than 50 percent of the requirements specified in the minimum vehicular volume warrant, the interruption of continuous traffic warrant, or the minimum pedestrians volume warrant.**

Any fixed-time signal installed because of accident hazard should be operated on the shortest cycle length that **will adequately** serve traffic approaching during the heaviest traffic hour.

Thorough analysis of accident experience **in advance of making installation under this warrant** is important. Accident history can usually be obtained from police accident records or from accident reports made by vehicle operators involved. Without **a careful** analysis of such **records** it is impossible to determine upon the most suitable remedial measures.

The following four steps are very helpful in determining what should be done:

1. **Analyze** summarized **statistics** of all recorded accidents at the intersection.
2. **Analyze** physical characteristics at and near the intersection.
3. **Analyze** traffic flow characteristics.
4. **Analyze** the collision diagram.

A **review** of these **data** will **frequently** reveal a number of significant facts. For example, types of accidents have a very important bearing on the appropriateness of signalization. A traffic control signal, when obeyed **by drivers and pedestrians**, can be expected to eliminate or reduce materially the number and seriousness of the following types of accidents:

1. Those involving **substantially right-angle** collisions **or conflicts, as occur between vehicles on intersecting streets.**
2. **Those involving conflicts between straight-moving vehicles and crossing pedestrians.**
3. Those between straight-moving and left-turning vehicles **approaching from opposite directions, particularly if an independent time interval is allowed during the signal cycle for the left-turn movement.**
4. Those involving excessive speed, in cases where **signal** coordination **will restrict** speed to a reasonable rate.

On the other hand, traffic control signals cannot be expected to reduce the following types of accidents:

1. Rear-end collisions, which often increase after signalization.
2. Collision between vehicles proceeding in the same or opposite directions, one of which makes a turn across the path of the other, **particularly if no independent signal interval is provided for these turn movements.**
3. Accidents involving pedestrians and turning vehicles, when both move on the same Go interval.
4. Other types of pedestrian accidents, if pedestrians do not obey the signals.

As an alternate to installing traffic signals arbitrarily at intersection locations that appear to be hazardous, it is desirable to institute, with proper education and enforcement, remedial measures which cause less delay and inconvenience to traffic. **Warning, Advisory Speed, and** Stop signs; **marking of lanes or otherwise organizing traffic movements; pedestrian and traffic islands; fixed street or highway lighting; removal of view obstructions; and proper regulation of parking are examples.** If **studies** indicate that one or a combination of these other remedial measures is adapted to conditions, it should be given a fair trial for at least 6 months, and preferably for a year. Following the trial period, a restudy should be made, and if satisfactory results have not been achieved, such additional steps should be taken as are indicated by the study.

1961 Edition

3D-8 Warrant 5, Accident Experience

The common opinion of the general public that signals materially reduce the number of accidents is rarely substantiated by experience. Not infrequently there are more accidents with signals in operation than before signal

installation. Hence, if none of the warrants except the accident experience warrant described below is fulfilled, the initial presumption should be against signalization. Signals should not be installed on the basis of a single spectacular accident or on the basis of unreasonable demands and dire predictions of accidents which allegedly might occur. The accident-experience warrant is satisfied when:

1. Adequate trial of less restrictive remedies with satisfactory observance and enforcement has failed to reduce the accident frequency; and
2. Five or more reported accidents of types susceptible of correction by a traffic control signal have occurred within a 12-month period, each accident involving personal injury or property damage to an apparent extent **of $100 or more**; and
3. There exists a volume of vehicular and pedestrian traffic not less than **80 percent** of the requirements specified in the minimum vehicular-volume warrant, the interruption of continuous traffic warrant, or the minimum pedestrian-volume warrant; and
4. **The signal installation will not seriously disrupt progressive traffic flow.**

Any signal installed solely on the accident experience warrant should be semi-traffic-actuated with control devices which provide proper coordination if installed at the intersection within a coordinated system, and normally should be full traffic-actuated if installed at an isolated intersection.

A traffic control signal, when obeyed by drivers and pedestrians, can be expected to eliminate or reduce materially the number and seriousness of the following types of accidents:

1. Those involving substantially right-angle collisions or conflicts, such as occur between vehicles on intersecting streets.
2. Those involving conflicts between straight-moving vehicles and crossing pedestrians.
3. Those between straight-moving and left-turning vehicles approaching from opposite directions, if an independent time interval is allowed during the signal cycle for the left-turn movement.
4. Those involving excessive speed, in cases where signal coordination will restrict speed to a reasonable rate.

On the other hand, traffic control signals cannot be expected to reduce the following types of accidents:

1. Rear-end collisions, which often increase after signalization.
2. Collisions between vehicles proceeding in the same or opposite directions, one of which makes a turn across the path of the other, particularly if **no independent signal interval is provided for these turn movements.**
3. Accidents involving pedestrians and turning vehicles when both move during the **same interval.**
4. Other types of pedestrian accidents, if pedestrians or drivers do not obey the signals.

1971 Edition

4C-7 Warrant 5, Accident Movement

The Accident Experience warrant is satisfied when:

1. Adequate trial of less restrictive remedies with satisfactory observance and enforcement has failed to reduce the accident frequency; and
2. Five or more reported accidents, of types susceptible of correction by traffic signal control, have occurred within a 12-month period, each accident involving personal injury or property damage to an apparent extent of $100 or more; and
3. There exists a volume of vehicular and pedestrian traffic not less than 80 percent of the requirements specified either in the minimum vehicular volume warrant, the interruption of continuous traffic warrant, or the minimum pedestrian volume warrant; and
4. The signal installation will not seriously disrupt progressive traffic flow.

Any **traffic** signal installed solely on the Accident Experience warrant should be semi-traffic-actuated (with control devices which provide proper coordination if installed at an intersection within a coordinated system) and normally should be fully traffic-actuated if installed at an isolated intersection.

1988 Edition

4C-8 Warrant 6, Accident Experience

The Accident Experience warrant is satisfied when:

1. Adequate trial of less restrictive remedies with satisfactory observance and enforcement has failed to reduce the accident frequency; and
2. Five or more reported accidents, of types susceptible of correction by traffic signal control, have occurred within a 12-month period, each accident involving personal injury or property damage **apparently exceeding the applicable requirements for a reported accident**; and
3. There exists a volume of vehicular and pedestrian traffic not less than 80 percent of the requirements specified either in the Minimum Vehicular Volume warrant, the Interruption of Continuous Traffic warrant, or the Minimum Pedestrian Volume warrant; and
4. The signal installation will not seriously disrupt progressive traffic flow.

Any traffic signal installed solely on the Accident Experience warrant should be semi-traffic-actuated (with control devices which provide proper coordination if installed at an intersection within a coordinated system) and normally should be fully traffic-actuated if installed at an isolated intersection.

Millennium Edition

Note: In this edition, the *MUTCD* was re-written to provide Standard, Guidance, Option, and Support statements. The term “accident” was changed to “crash” to reflect the safety community’s feeling that the term “crash” was a more appropriate term to use because it was better associated with what happened—a vehicle crashed with another vehicle, other road user, or object—and that “accident” implies that the event happened by chance and could not have been avoided.

4C.07 Warrant 7, Crash Experience

Support:

The Crash Experience 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 traffic signal control, 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.

APPENDIX B

LITERATURE REVIEW

This literature review identified (1) prior studies of the accident warrant; (2) prior studies of accidents at signalized and unsignalized intersections, specifically as they relate to installing or removing a signal for a safety purpose; (3) experimental methodologies to be followed or avoided; and (4) potential databases.

Studies of Changes in Crashes after Installing Signals

The most recent study of the crash changes after the installation of traffic signals uncovered through the literature search was that performed by Thomas and Smith of Iowa State University in 2001 (*21*). They conducted an evaluation of 94 traffic safety projects to determine the crash reduction factors and benefit-cost ratios for seven different improvement categories. Two of those categories included installing a traffic signal with no other improvement and installing a traffic signal with one or more turning lanes. (It is not stated under what warrant the signals were installed.) Using Iowa's statewide crash database, they compared crashes by severity and type for 3 years before installation with those crashes occurring 3 years after installation. They also used two sets of costs-per-crash values to conduct a before-after benefit-cost ratio analysis. The dollar value equivalents used were as follows for the first set:

Fatality	$800,000
Major Injury	$120,000
Minor Injury	$ 8,000
Possible Injury	$ 2,000
Property Damage Only	Actual value

For the second set, they treated the first fatality at an individual intersection as a major injury, but any additional fatalities were given the full $800,000 value. No clear justification was given for this assignment.

For new traffic signals alone, there were 16 locations. Table B-1 shows the before-and-after crash count by type of crash for these locations. The authors cite an overall crash reduction of 29 percent for new traffic signal projects. The following are other results:

- Right-angle crashes were reduced at all 16 locations and averaged 71 percent.
- Rear-end crashes increased at 8 of the 16 locations. The 44 percent average increase is influenced by one location that increased by 228 percent.
- Left-turn crashes increased at seven locations for an average of 41 percent.
- Five of the locations experienced an increase in total crashes.

While some additional analyses were performed, which will be shown subsequently, there are methodological deficiencies with this analysis. This is a simple before-after with no consideration of change in traffic volumes, control-comparison sites, or regression-to-the-mean effects. The authors recognized these considerations in their early discussion of alternative analysis methods, but then chose not to account for them.

A subsequent analysis involved developing 90 percent confidence intervals for the crash reduction factors and the benefit/cost (B/C) ratio using the *t*-statistic. The results are shown in Table B-2. The results showed that considering all crashes, the mean crash reduction factor was a 4 percent increase in crashes, but that the confidence interval was wide, going from a decrease of 53.2 percent to an increase of 61.2 percent. The researchers note that there were outliers that might be affecting this result and that they should be taken out of the database. The results of the confidence interval analysis with the outliers removed showed that there was a 27 percent decrease for all crashes with a 90 percent confidence interval ranging from a 7 to a 47 percent decrease.

The second group analyzed was 11 intersections where one or more turn lanes were added in addition to the traffic signal. (It is not stated if the turn lanes were for left or right turns and how many of the approaches received turn lanes.) The before-after crash count is shown in Table B-3. As indicated in the table, the overall reduction in crashes was 29 percent; however, this finding is subject to the same methodology criticism noted above. The following is observed from the table:

- Reductions in right-angle crashes occurred at all locations and averaged 71 percent.
- An increase in rear-end crashes occurred at 7 of the 11 locations.
- Four of the 11 locations showed an overall increase in crashes.

The 90 percent confidence interval analysis was performed with the overall finding that there was a mean value decrease in total crashes of 20 percent, but that the interval ranged from a 12 percent increase to a 51 percent reduction. The authors concluded that the installation of a signal and turn lane(s) does not result in a decrease in total crashes, but does reduce right-angle and left-turn crashes. It is noteworthy that

TABLE B-1 Number of crashes by crash type—new traffic signals

#	Right-Angle Before	Right-Angle After	Rear-End Before	Rear-End After	Left-Turn Before	Left-Turn After	Other Before	Other After	TOTAL Before	TOTAL After	TOTAL After-Before
1	4	1	8	10	0	5	4	5	16	21	5
2	6	2	5	1	3	2	13	3	27	8	-19
3	12	4	7	6	2	7	10	4	31	21	-10
4	17	4	3	4	3	8	5	4	28	20	-8
5	26	13	2	3	0	0	5	4	33	20	-13
6	8	5	7	23	2	1	27	16	44	45	1
7	4	1	0	4	5	11	4	8	13	24	11
8	2	5	0	0	0	5	1	7	3	17	14
9	4	0	2	1	1	0	6	2	13	3	-10
10	29	5	2	0	8	5	8	3	47	13	-34
11	3	0	4	7	8	2	18	20	33	29	-4
12	8	2	2	6	0	7	6	2	16	17	1
13	19	2	2	2	1	2	11	1	33	7	-26
14	5	3	3	2	1	1	8	4	17	10	-7
15	13	2	4	4	9	7	13	9	39	22	-17
16	10	0	8	12	6	6	6	6	30	24	-6
Total	170	49	59	85	49	69	145	98	423	301	-122
Before/After Change		-71%		44%		41%		-32%		-29%	

TABLE B-2 Confidence intervals—new traffic signals

CRASH CATEGORY		MEAN	COUNT	Standard Deviation	90% Confidence Interval Lower	90% Confidence Interval Upper
TOTAL		-4%	16	131%	-61.2%	53.2%
SEVERITY	Fatal	N/A	0	N/A	N/A	N/A
	Major	43%	7	98%	28.8%	114.5%
	Minor	8%	16	114%	42.3%	57.3%
	Possible	-44%	13	113%	99.8%	12.3%
	PDO	0%	16	137%	60.0%	60.5%
TYPE	RA	61%	16	59%	34.6%	86.7%
	RE	-28%	14	94%	-71.9%	16.9%
	LT	-27%	12	108%	-82.4$	29.2%
	Other	-9%	16	165%	-81.4$	62.8%
B/C RATIO	Method 1	0.8	16	16.9	-6.6	8.2
	Method 2	5.1	16	16.3	-2.1	12.2

Source: Reference 21.

TABLE B-3 Number of crashes by crash type—new traffic signals and turn lane(s)

#	Right-Angle Before	Right-Angle After	Rear-End Before	Rear-End After	Left-Turn Before	Left-Turn After	Other Before	Other After	TOTAL Before	TOTAL After	TOTAL After-Before
1	12	0	5	0	4	2	11	4	32	6	-26
2	5	4	4	5	9	16	10	12	28	37	9
3	13	2	4	6	2	1	15	3	34	12	-22
4	4	3	2	7	2	3	5	10	13	23	10
5	5	1	8	23	4	6	8	14	25	44	19
6	7	3	5	7	8	1	11	8	31	19	-12
7	9	3	17	9	6	0	18	12	50	24	-26
8	12	3	2	1	6	3	11	5	31	12	-19
9	9	2	3	6	2	0	8	2	22	10	-12
10	4	3	6	10	2	1	10	9	22	23	1
11	6	1	7	4	4	1	8	5	25	11	-14
Total	86	25	63	78	49	34	115	84	313	221	-92
Before/After Change		-71%		24%		-31%		-27%		-29%	

Source: Reference 21.

left-turn crashes were reduced on the average when a turn lane was installed (although it is not clear from the documentation that it was a left-turn lane that was added), whereas they increased on the average, when a signal was installed without a turn lane.

Research by Datta and Dutta (*5*), and Datta (*6*) used a before-and-after analysis of 102 intersections in Michigan that had signals installed between 1978 and 1983. In both studies, crash frequency rates were used to describe various types and severity levels of crashes (total, personal injury, property damage, right-angle, left-turn head-on, rear-end, and other). Datta and Dutta's (*5*) study showed that mean crash rates (number of crashes per million entering vehicles) for the before-and-after periods showed a statistically significant difference. Sample sizes did not allow for further analysis based on geometric variations. Overall, it was determined that after signalization, the mean crash rate of all studied intersections decreased. They concluded that signal installation increased rear-end but lowered right-angle crashes. A cross-classification analysis was performed by examining intersections that had no geometric changes during the study period, which yielded similar results.

Datta (*6*) performed additional studies on the same dataset in 1991. This research focused on the relationship between left-turn lanes and crash rates. The methodology had intersections divided into three groups (exclusive left-turn lane, no left-turn lane, and intersections with left-turn lanes added with the signal installation). The researchers used paired *t*-tests to evaluate the categorical data. The conclusions of this research were that signalization and the addition of a left-turn lane significantly reduced the number of total crashes, and reduced the number of right-angle crashes, but increased the number rear-end crashes.

The New York State DOT (*7*) performed a study that dealt with 39 intersections in its jurisdiction in 1982. Their literature review found that rear-end type crashes increased with signalization. However, in conducting their own before-and-after study, the conclusion reached was that the frequency of rear-end type crashes decreased with signalization. Reductions in overall and right-angle crashes matched their literature review findings, however, the fatal/injury rate showed a slight increase. In looking at intersection geometry, it was found that total crashes decreased at T-intersections, decreased slightly at 4-way divided intersections, and increased slightly at 4-way undivided intersections. The final recommendation of the report was that traffic signals should not be installed for the sole purpose of significantly reducing intersection crash rates.

In 1988, Agent (*8*) performed a before-and-after analysis on 65 rural intersections in Kentucky. The results showed a decrease in crash rate when converting to signal control from a stop-controlled intersection with a beacon (from 1.4 to 1.1 crashes per million vehicles [crashes/mv]). However, if the converted intersection did not have a beacon, the crash rate increased from 1.3 to 1.8 crashes/mv. It was suggested that providing the driver with adequate warning of the intersection was of primary importance. Providing stop bars and adequate sight distance were also deemed critical.

Before-and-after studies were performed by King and Goldblatt (*9*) in 1975 on more than 250 intersections across the United States. Hypothesis testing, analysis of variance, and multiple linear regression analysis were used on the before-and-after study results. Five outcomes were found:

1. Signalization lowered right-angle and increased rear-end crashes.
2. Signalized intersections had higher crash rates, but this was usually offset by less disutility per accident, which led to no significant change in total crash related disutility. Disutility was defined as the product of the accident evaluation index and accident rate, and can be construed as an index of net economic loss because accidents are normalized for traffic-flow levels.
3. There was no clear-cut justification for lowering numerical crash warrant minimums for rural intersections.
4. Right-angle frequency appeared to be insensitive to expected improvements due to signalization.
5. Flashing beacons appeared to lessen the crash frequency at stop-controlled intersections.

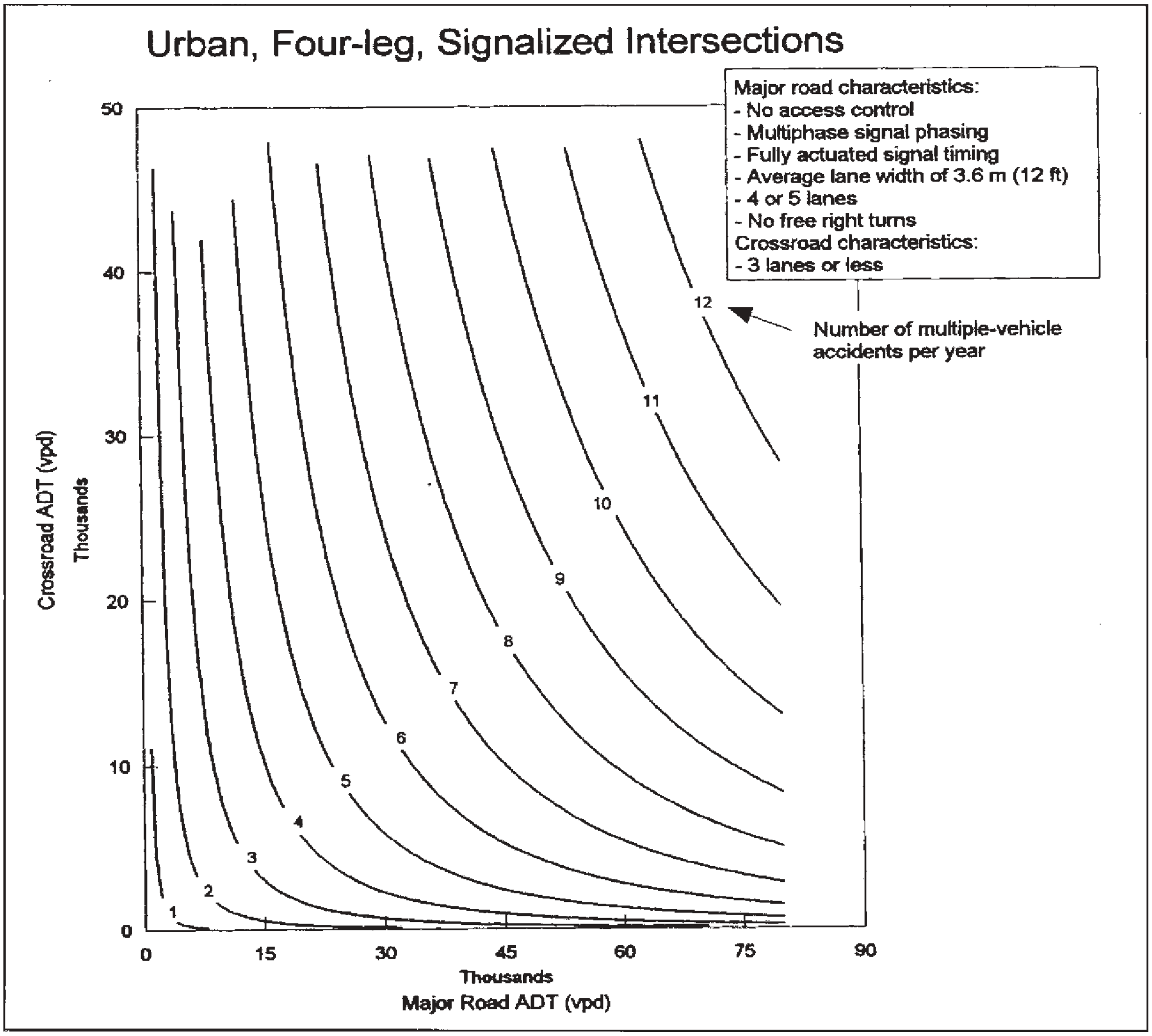
Studies of Intersection Crash Relationships

One of the more recent studies of the relationships between intersection crashes and geometric elements was reported by Bauer and Harwood (*22*). The analyses used three years of accident data from 10,652 intersections in California disaggregated as follows:

1. Rural, 4-leg, stop-controlled: 1,581
2. Rural, 3-leg, stop-controlled: 2,907
3. Urban, 4-leg, stop-controlled: 1,475
4. Urban, 3-leg, stop-controlled: 3,256
5. Urban, 4-leg, signalized: 1,433

The statistical modeling approaches used included Poisson, lognormal, negative binomial, and logistic regression, as well as discriminant and cluster analysis. Regression models of the relationships between accidents and intersection geometric design, traffic control, and traffic volume variables were found to explain only between 16 and 39 percent of the variability, with most of that variability explained by the traffic volume variables. Nomographs similar to Figure B-1 were developed for each of the five intersection types using cross road and major road average daily traffic volume as the primary variables. However, the authors concluded that the models ". . . do not appear to be appropriate for direct application by practitioners," because the goodness of fit was not as high as would be desired and some of the effects of geometric variables are in a direction opposite to that expected.

Using negative binomial regression and lognormal distribution models, they found the following variables to be statistically significant:



Source: Reference 22.

Figure B-1. Number of multiple accidents per year as a function of traffic volumes for typical urban, 4-leg, signalized intersections.

Variable	Negative Binomial	Lognormal
Left-Turn Prohibition		✓
Presence of Left-Turn Lanes	✓	
Right-Turn Channelization	✓	✓
Number Lanes, Major Road	✓	✓
Average Lane Width, Major Road	✓	✓
Median on Major Road	✓	
Outside Shoulder Width, Major Road	✓	✓
Access Control on Major Road	✓	✓
Intersection Lighting		✓
Design Speed on Major Road	✓	
Signal Timing		✓
Signal Phasing	✓	

In 1996, Williams and Ardekani (*23*) studied 68 intersections across Texas identified by Texas DOT as marginally warranted for traffic signal installation; some intersections were signalized, some were not. The mean number of crashes per year, based on accident data were created for high-low approach speeds at rural-urban intersections and related to severity of the accident. Simple statistical procedures using the 15th and 85th percentile values were used to create upper and lower boundaries of confidence bands. These bands established normal and abnormal ranges of crashes for signalized versus unsignalized intersections. It was recommended that signalization occur at marginally warranted intersections with an approach speed less than 40 mph in a rural setting if the intersection has experienced more than 2.0 crashes per year or 0.8 right-angle crashes per year over the past 5 years.

Another safety measure is the traffic conflict, considered to be a surrogate of crashes. In 1992, Migletz et al. (*24*) established a relationship between traffic conflicts and accidents by using traffic conflict, crash, and volume data from 46 urban intersections located in Kansas City. Expected and abnormal conflict rates (accidents per year) under various conflict circumstances were calculated. Migletz concluded that using regression analysis or correlation coefficients led to mixed, poor results and these were not an appropriate way to use traffic conflicts. Instead, the proper use of conflicts would be to estimate an expected rate of accidents, as opposed to predicting the actual number that might occur in a particular year. The overall conclusion was that particular types of traffic conflicts (i.e., medium and low volume opposing left turns at signalized and unsignalized intersections), do make good surrogates of accidents by producing average accident rates just as precise as those produced from historical accident data.

Studies on Safety Impacts of Signal Removal

A study by Kay et al. (*4*) in 1980 investigated the removal of traffic signals at more than 200 urban intersections throughout the country. These intersections were converted to two-way stop control and the results showed a 51 percent increase in right-angle crashes, but a 49 percent decrease in rear-end crashes. It was noticed that little difference occurred in the overall number of crashes at the intersections. However, for intersections converted to all-way stop control, there was a statistically significant decrease in the accident frequency.

Kay found that three intersection condition descriptors were significant in the impact on accidents: minor street corner sight distance, the number of hours the *MUTCD* Warrant 1—Minimum Vehicular Volume—is satisfied (60 percent values), and the "before" accident frequency. Furthermore, he established that three variables had significant effect when converting traffic signal control to two-way stop control:

- Side-street sight distance (as defined in the *Transportation and Traffic Engineering Handbook* [*25*]).
- Intersection volume magnitude, (as measured by the number of hours per day that volumes satisfy at least 60 percent of the *MUTCD* signal installation Warrant Number 1—Minimum Vehicular Volume).
- Average annual frequency of total accidents (per intersection with traffic signal control in effect, that is, before signal removal).

In 1982, Persaud et al. (*10*) showed with 222 intersections of one-way streets in Philadelphia that a reduction occurred in the total number of accidents when unwarranted signals were removed. In this study, Persaud removed the bias caused from the regression-to-the-mean (a temporal accident change phenomenon discussed later) from the data by using an EB method. The data used in the study were previously collected and analyzed by a before-and-after analysis that compared the intersections' accident frequency. For example, the biased estimate reported a 54 percent reduction in total accidents, while Persaud's unbiased estimate showed a reduction of 43 percent. While this and other differences between the unbiased and biased estimates are small, they are not negligible.

In these before-and-after studies, simple statistical procedures were used, with the exception of the Persaud study (*10*). These comparisons did not account for the bias associated with the regression-to-the-mean and their results may somewhat exaggerate the effectiveness of signalization. The work done by Persaud showed that when regression-to-the-mean is taken into account, different results are obtained.

In reviewing the literature that deals with downgrading an intersection's traffic control devices, conflicting results are given as to what these changes do to accident frequency. An NCHRP study by McGee and Blankenship (*26*) dealt with the conversion of stop-controlled intersections to yield-controlled, and found that there was an increase in the accident frequency. Research by Bhesania (*11*) shows that intersections with signal control have more accidents than intersections with stop, yield, or no traffic control devices. Unfortunately, this study does not mention what warrants the studied signals met.

Other Relevant Findings

In 1983, Council et al. (*27*) discussed vehicle exposure for various intersection and vehicle collision possibilities—single or multiple vehicle, stop- or signal-controlled, and type of accident. Equations for various exposure rates were developed to be used in conjunction with accident frequencies to calculate accident rates. These rates would be used to help the engineer or administrator answer questions when identifying safety problems at intersections.

In 1994, Epps (*28*) developed a computer program to evaluate the removal of state maintained traffic signals. A total of 141 intersections were evaluated using the SIGEVALl program in Mississippi. The program was designed to aid the evaluation of the all-way stop and signalized intersection based on the *MUTCD* traffic signal warrants, perform capacity analyses of the intersections for alternative stop-controlled schemes of traffic control, and determine the cost benefits of replacing unwarranted signal systems with the most applicable stop-control alternative.

In 1994, Kostival (*29*) provides background information in her thesis concerning the *MUTCD* and ideas on accident analysis. She recommends an accident warrant that would be based on the multiplicative accident score model. This model is based on work performed for the Federal Highway Administration in 1977 and uses data inputs (accident frequency, accident rate, accident severity, traffic conflicts) to calculate the hazardousness index. Advantages to this model include the following:

- Different types of accidents, vehicle exposure to risk, type of intersection, and accident severity are all considered.

- Changes in accident patterns after signalization are considered by calculating three accident scores per intersection, (one for right-angle, head-on left-turn, and rear-end accidents).
- The model is flexible because not all of the data inputs need to be used to calculate an accident score. The traffic conflict input allows an agency with an incomplete database to use conflicts counts in place of another input to evaluate the intersection.

Hauer et al. (*30*) performed a study on 145 intersections in Metropolitan Toronto. In this study, three insights were obtained:

- Logically sound models require that the frequency of collisions be related to the traffic flows to which the colliding vehicles belong and not to the sum of the entering flows.
- It is necessary to categorize collisions by the movement of the vehicles before the collision and not by the initial impact type.
- The relationship between collision frequency and the related traffic flows is at times unexpected in form.

From Hauer's third point above, it is not correct to use intersection accident rates on the basis of the sum of entering volumes for the comparison of the safety of two different intersections or their exposure in before-and-after studies. Also, given the traffic flow for a signalized intersection, the method can predict how many and what kinds of accidents should be expected to occur. The probability density function (PDF) of the estimate can also be shown. This will allow the engineer to determine what an unusually high number of accidents would be on such an intersection.

Hauer et al. (*31*) used data from ten intersections in Michigan to study the effect of conversion from two-way to four-way stop control. This 1984 study looked at before-and-after periods of unequal lengths, which varied from site to site, to determine the likelihood of an accident. By using the averages of the mean estimates of an accident, likelihoods were created that equated the unequal periods. The results concluded that when the difference between the biased and unbiased estimates was small, the error was not serious. However, if there was a large difference between the two estimates, the error was serious.

Statistical Procedures

There are numerous statistical procedures for analyzing accidents. Therefore, the literature was reviewed for the purpose of identifying statistical procedures that may be appropriate for this project.

Bauer and Harwood (*22*) used several statistical modeling approaches in their analyses of 10,652 intersections in California, including Poisson, lognormal, negative binomial, and logistic regression, as well as discriminant and cluster analysis. They concluded the following:

- Traditional multiple linear regression is generally not an appropriate statistical approach to modeling because accidents are discrete, non-negative events that often do not follow a normal distribution.
- Poisson, negative binomial, lognormal, and logistic distributions appear to be better suited to the modeling of accident relationships.
- Other statistical approaches, including modeling within specific ADT classes, discriminant analysis, and cluster analysis did not provide results that were preferable to those obtained from the negative binomial, lognormal, and logistic regressions.

Persaud (*32*) reviewed past traffic signal installation studies and determined that most research contains one of two types of error, either regression-to-the-mean or incorrect inferences from cross-section studies. A three-step plan was developed to improve the status of knowledge by creating a method to (1) quantify the likely safety impact of a contemplated installation, (2) classify circumstances under which signalization is likely to be good or bad for safety, and (3) incorporate this knowledge into signal warrants or a cost-benefit resource allocation procedure for signals.

Hauer and Persaud's work (*14*) explain the bias associated with before-and-after comparisons by giving a detailed understanding of the regression-to-the-mean. Hauer and Persaud stated that the pre-installation accident record of an intersection may not give clear insight to the safety impact of a proposed traffic signal. This is due to the belief that the number of accidents at an intersection follows a regression-to-the-mean. They stated that increasing the length of the before period from 1 year to 3 to 5 years would help reduce this bias. In the study, they discovered that as the before period was extended from 2 years to 6 years, the relative size of the regression-to-the-mean diminishes. It was noted that having a before period of 6 years still has the regression-to-the-mean being far from negligible. The corrected estimations supported the validity of the procedure, when taking into account the variations of the data and the possible change in conditions of the before-and-after periods. The authors also suggested an EB approach to improve accuracy when using a small number of accidents.

Griffin (*33*) devised an alternative method of using before-and-after accident data in 1989. The investigation used data from a previous 1986 study of 20 intersections in New York. This method used statistical procedures that assumed that non-random errors (confounding variables, selection bias, etc.) were not at play. In the methodology, a procedure for evaluating the effectiveness of a project (e.g., lane widening) was explained, and an example of the method was given using a previously collected dataset. The original analysis of the data showed a reduction in accidents of 19 percent; with

Griffin's method, a reduction of 18.9 percent was realized. It is difficult to say whether Griffin's assumptions were correct because the calculated results were not very different from the results of the original analysis.

In 1995, Jia and Parsonson (*34*) created expected values of accidents based on 157 intersections in Atlanta. The expected values were calculated for various volumes based on the normal distribution using the 90th and 95th percentiles. Four tables were created on the basis of signal control (if a traffic signal was present) and geometric layout (3- or 4-leg intersection). With these tables, a quick method was created for an engineer to look up and determine what an intersection's expected number of accidents should be.

While Jia and Parsonson used the normal distribution, others (*35, 36*) maintain that this is not the correct distribution to be used, and that different distributions are much better suited to model intersection accident rates. The main argument against the normal distribution is the fact that accident counts are discrete and non-negative, and therefore do not follow the normal distribution.

In 1992, Kulmala (*35*) used 1,762 Finnish intersections with accident reports dating from 1983–1987 to develop accident rates that model the safety of an intersection, by using the expected number of accidents at an intersection (the average number of accidents if all road, traffic, and other relevant characteristics of the location were to remain unchanged for a long period of time, e.g., 20 years). An intersection was defined as the road area within 200 m of the center of the intersection. Both Poisson and negative binomial distributions were used for the model development. The Poisson was used for testing the various variables and their intersections, and in testing the goodness-of-fit of the model. Kulmala concluded that when studying occurrences such as accidents, which can only have non-negative discrete variables and are nearly Poisson distributed, it is proper to use a logarithmic link function. Kulmala's data showed that the risk of accidents increased as the proportion of traffic from the minor road increased.

Safety effects of additional lanes for turning vehicles from the main road were found to vary with the traffic flow according to Kulmala. With a high percentage of vehicles entering the intersection from the minor road, intersections with a major approach left-turn lane had lower accident rates. Rear-end accident rates decreased at intersections that included a left- or right-turn lane on the major approach. For minor road vehicles crossing straight through the intersection, higher accident rates were found for those intersections with left-turn lanes on the main road.

High approach speeds and early advanced observations on the minor road were found by Kulmala to have a negative effect on safety. Straight and wide approaches that allow the driver to make premature observations have high accident rates. When looking at speed and sight distance, it was found that long intersection sight distances and short sight distances had higher accident rates.

Accident prediction on sections of roadway was researched because there is the possibility of using some of its prediction concepts on intersections. The 1992 research by Persaud and Dzbik (*36*) appeared to be the most useful, by showing that the use of the negative binomial distribution is more suited for accident counts. With accident data from the Ontario Ministry of Transportation, they determined the number of accidents on a 25-km long roadway. This accident prediction model identified light conditions and seasonal variables that may be of use in accident studies at intersections. In looking at accident prediction models in general, four errors with current accident prediction were discussed:

1. Models tend to be macroscopic.
2. Models assume that accidents are a linear function of traffic volume.
3. Regression models traditionally assume that the dependent variable has a normal error structure.
4. It is impossible for regression models to account for all of the factors that affect accident occurrence.

Persaud and Dzbik used a negative binomial error structure for their regression model. When the observed accident data was short-term, it was combined with a regression prediction of accidents through an EB technique. Also examined was the issue of how accident risk is related to the quality of traffic flow. These results showed that congestion is associated with a considerably higher risk of total and severe accidents than high volume is with uncongested operations.

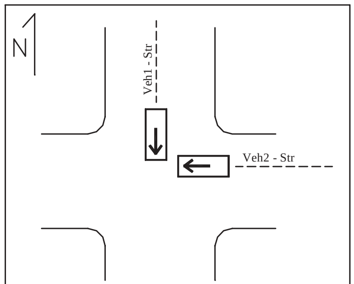
In reviewing the current literature, it was found that various types of studies have been performed in the past. As research progresses, it is becoming evident that certain methods are not as accurate as others, and that statistical models are becoming more common. Some studies have shown that the normal distribution is not as good a model as the negative binomial distribution for accident counts. Other studies have brought to light problems with using accident data, such as the regression-to-the-mean. Nevertheless, the majority of work cited uses accident data to either compare or predict accident frequencies.

APPENDIX C

ILLUSTRATION OF CRASH TYPES

Right-Angle Crashes

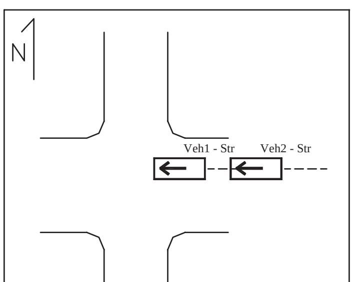
Vehicles 1 and 2 are initially traveling in perpendicular directions and both proceeding straight through the intersection.



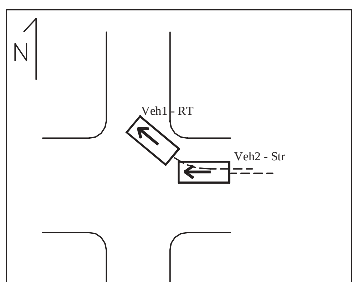
Right-Angle crash type.

Rear-End Crashes

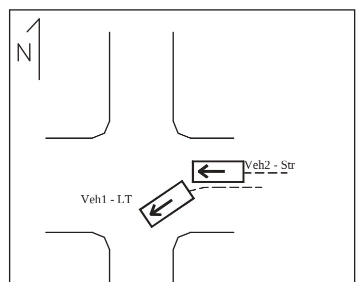
Vehicles 1 and 2 approach the intersection from the same direction.



Typical rear-end crash, both vehicles heading straight.

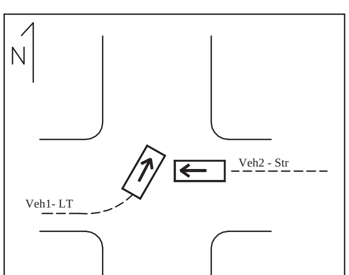


Typical rear-end crash, leading veh. turning right.

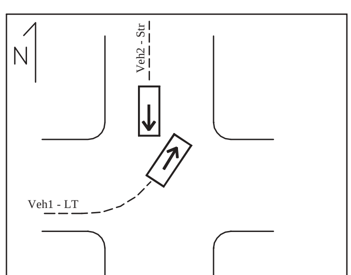


Typical rear-end crash, leading veh. turning left.

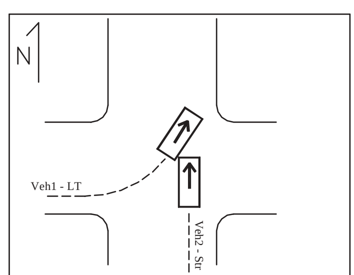
Left-Turn Crashes



Left-Turn crash, second vehicle opposite direction heading straight.



Left-Turn crash, second vehicle perpendicular direction heading straight.



Left-Turn crash, second vehicle perpendicular direction heading straight.

APPENDIX D

ILLUSTRATION OF THE PROCEDURE FOR RECALIBRATING THE DEFAULT MODEL

Two cases are presented. Case 1 recalibrates models for each year of the analysis period in the jurisdiction. It should be undertaken as long as sufficient data are available, say a dataset of 50 accidents of interest (e.g., rear-end accidents) per year at a sample of intersections of relevance (e.g., 4-leg stop-controlled). Case 2 applies data aggregated for all years of the analysis period for datasets with fewer than 50 accidents per year and recalibrates a common model for the jurisdiction to apply to each year of the analysis period.

Case 1: Recalibration for Each Year

To do this requires yearly crash counts and AADTs for a sample of 4-leg stop-controlled intersections in the jurisdiction that are typical of those considered for signal installation. The default base model is used to estimate crashes each year for each intersection in the sample. For each year, the sum of the observed counts divided by the sum of the model estimates gives a calibration factor that is applied to the model to obtain a recalibrated value of α.

For the current illustration, assume that data are available in the subject jurisdiction for 100 urban 4-leg intersections with the following crash history:

1996: 105 total accidents,
1997: 119 total accidents,
1998: 95 total accidents,
1999: 101 total accidents, and
2000 (January to August): 70 total accidents.

The default base model from Chapter 3, as applied in the illustration in Chapter 5, is as follows:

$$\text{Accidents/year} = \alpha \times (\text{Major Road AADT})^{0.499} \times (\text{Minor Road AADT})^{0.430}$$

where the calibrated multiplier α has a value of 0.000426.

Step 1: Apply the default base model to estimate the number of accidents separately for each year at each of the 100 intersections. Use the AADTs for the respective year.

For example, a site with major and minor entering AADTs of 37,200 and 3,026, respectively, would be expected to have, according to the base model, 0.000426 × 37200$^{0.499}$ × 3026$^{0.430}$ = 2.552 accidents in 1996.

Step 2: For each year, calculate a yearly calibration factor, C_i, by dividing the sum of the actual number of accidents in that year by the sum of the yearly predicted number of accidents:

$$C_i = \frac{\sum \text{observed}_i}{\sum \text{predicted}_i}$$

In this case, suppose the sums of the yearly estimated crashes for the 100 intersections were as follows:

1996: 105.00 total accidents,
1997: 115.21 total accidents,
1998: 100.92 total accidents,
1999: 102.44 total accidents, and
2000: 68.39 total accidents.

therefore,

C_{1996} = 105/105.00 = 1.000,

C_{1997} = 119/115.21 = 1.033,

C_{1998} = 95/100.92 = 0.941,

C_{1999} = 101/102.44 = 0.986, and

C_{2000} = 70/68.39 = 1.024.

Step 3: Apply the calibration factors to the default model multiplier α to obtain a recalibrated α for each year. For example, for the year 1998,

$$\alpha_{1998} = 0.000426 \times 1.10 = 0.000401$$

Thus, the following becomes recalibrated model:

$$\text{Accidents in 1998} = 0.000401 \times (\text{Major Road AADT})^{0.499} \times (\text{Minor Road AADT})^{0.430}$$

Case 2: Recalibration of a Common Model for All Years

This applies when there are fewer that 50 accidents per year in the available database. The procedure is conceptually similar to that for Case 1:

(a) Accidents in the sample are tallied over all years in the analysis period. Suppose this sum equals 192 crashes for a sample of 4-leg stop-controlled intersections for a 5-year analysis period.

(b) The default model is still applied for each year of the analysis period for each intersection in the sample. The estimates so obtained are aggregated over all intersections and analysis period years. Suppose this sum equals 210 accidents for the sample for the 5-year period.

(c) The calibration factor is the sum in (a) divided by the sum in (b):

$$C_{all} = 192/210 = 0.914$$

(d) Apply the calibration factor to the default model multiplier α to obtain a common recalibrated α that is applicable for all years. For the example,

$$\alpha_{\text{all years}} = 0.000426 \times 0.914 = 0.000389$$

Thus, the following becomes recalibrated model:

$$\text{Accidents per year} = 0.000389 \times (\text{Major Road AADT})^{0.499} \times (\text{Minor Road AADT})^{0.430}$$

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation