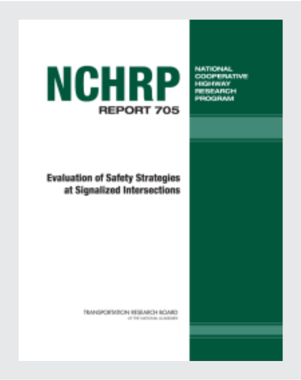

Evaluation of Safety Strategies at Signalized Intersections

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Evaluation of Safety Strategies at Signalized Intersections

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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Finally, this project would not have been possible without the help and support of members of many state and city DOTs who provided valuable data for this project.

FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report presents crash modification factors (CMFs) for safety strategies at signalized intersections. CMFs are a tool for quickly estimating the impact of safety improvements. The report will be of particular interest to safety practitioners responsible for programming and implementing highway safety improvements at intersections.

Crash modification factors (CMFs), also known as Accident modification factors, provide a computationally simple and quick way of estimating crash reductions. Many states and local agencies have a set of CMFs that are used for estimating the safety impacts of various types of engineering improvements. Typically, these factors are computed using before-after comparisons, although recent research also has suggested the use of cross-sectional comparisons.

Currently, CMFs are often used in program planning to make decisions concerning whether to implement a specific treatment and/or to quickly determine the costs and benefits of selected alternatives. CMFs are also used in project development for nonsafety as well as safety-specific projects and could be used by agencies in deciding on policies affecting general project design (e.g., context-sensitive design solutions and traffic calming). CMFs are also key components of the latest safety-estimation tools and procedures, including the Interactive Highway Safety Design Model, SafetyAnalyst, and the procedures in the AASHTO Highway Safety Manual.

NCHRP Project 17-18(3) developed a series of guides to assist state and local agencies in reducing injuries and fatalities in targeted emphasis areas. Each guide includes a brief introduction, a general description of the problem, strategies to address the problem, and a model implementation process. *NCHRP Report 500, Volume 12: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, A Guide for Reducing Collisions at Signalized Intersections* includes strategies for improving the safety of signalized intersections. However, the safety effectiveness of many of the strategies in the guide have not been rigorously evaluated.

Under NCHRP Project 17-35, "Evaluation of Safety Strategies at Signalized Intersections," researchers at the University of North Carolina Highway Safety Research Center developed reliable CMFs for a number of safety strategies outlined in *NCHRP Report 500, Volume 12.* The research team reviewed the literature and ongoing research related to CMF development, surveyed the state DOTs, and developed a priority list of treatments deemed to be important in safety decisions. The final list was determined based on the availability of data needed in CMF development.

CMFs were developed for the installing dynamic advanced warning flashers, converting signalized intersections to roundabouts, increasing clearance intervals, changing left-turn phasing, and introducing flashing yellow arrow.

Users are encouraged to consider the quality and applicability of CMFs when selecting a CMF for use in the decision-making process. Users are also encouraged to consider the measures of uncertainty (standard error or standard deviation) associated with a given CMF.

The details of each evaluation are included in the appendices. The appendices are posted on the TRB project website at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=461.

CONTENTS

Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the Web at www.trb.org) retains the color versions.

SUMMARY

Evaluation of Safety Strategies at Signalized Intersections

Background

In 1997, the American Association of State and Highway Transportation Officials (AASHTO) Standing Committee for Highway Safety along with the Federal Highway Administration (FHWA), National Highway Traffic Safety Administration (NHTSA), and the Transportation Research Board (TRB) Committee on Transportation Safety Management convened a meeting of national experts in the highway safety area to develop a Strategic Highway Safety Plan. This plan focuses on 22 highway safety challenges or emphasis areas that have an impact on highway safety. To advance the implementation of countermeasures to reduce accidents and injuries, National Cooperative Highway Research Program (NCHRP) Project 17-18(3) began the development of a series of implementation guides which were subsequently published in the form of several volumes of *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan.* Each guide addresses one of the 22 emphasis areas and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. Each strategy is designated as proven, tried, or experimental.

Objectives

Many of the strategies in *NCHRP Report 500* have not been evaluated using state of the art methods. The objective of this project was to evaluate the safety effectiveness for selected strategies identified in *NCHRP Report 500: Guidance for the Implementation of the AASHTO Strategic Highway Safety Plan, Volume 12: A Guide for Reducing Collisions at Signalized Intersections* (Antonucci et al., 2004). The intent is to develop reliable Crash Modification Factors (CMFs).

Approach

The first part of the project was a critical review of published studies for each treatment/strategy. To obtain information about ongoing or planned research, several research-in-progress databases were reviewed in addition to discussions with other highway safety researchers, and conversations with research sponsors such as FHWA and the Insurance Institute for Highway Safety (IIHS).

Following the literature review, surveys were developed and sent to two listservs, contacts in all 50 States, and several local agencies. The respondents were asked to indicate if they implemented a particular strategy/treatment and the approximate number of installations

for each strategy/treatment. In addition, they were also asked to rate the importance of knowing the Crash Modification Factor for each treatment. These ratings along with the information about the installations were used to develop a short list of treatments for further consideration. To get further information about the availability and suitability of the data for the short-listed strategies, selected agencies who responded to the original web-based survey were contacted by telephone.

Using the results of the literature and the survey of practitioners, a recommended and prioritized list of strategies for evaluation were developed along with a work plan for evaluating these strategies. The prioritized list of strategies and the work plan were discussed at the Interim Meeting with the NCHRP Panel.

At the meeting, the project team and the NCHRP Panel agreed on a set of Tier I treatments (higher priority) and a set of Tier II treatments (lower priority) for the evaluation. At the meeting, it was agreed that funds will probably not be available to address all the treatments in Tier I. In addition, if data were not available to evaluate one or more of the treatments in Tier I, treatments in Tier II could be included. The following is a list of treatments in Tier I and Tier II:

Tier I (higher priority)

- Protected phasing,
- Protected-permissive phasing,
- Modify phasing and add left-turn lane,
- Add left turn only,
- Lengthen left-turn lane,
- Dynamic advance warning flashers,
- Optimize clearance intervals, and
- Flashing yellow arrow.

Tier II (lower priority)

- Convert signalized intersections to roundabouts,
- Right-turn channelization,
- Add signal heads,
- Improving friction at approaches to intersections,
- Changing fonts, and
- Split phasing.

After the interim meeting, the project team started compiling the necessary data for evaluating the treatments in Tier I. The project team could not find sufficient data for some of the treatments in Tier I, and after discussing this issue with the panel, it was decided to include one of the treatments from Tier II (convert signalized intersections to roundabouts) for which there appeared to be a research need coupled with the availability of data for a substantial number of treatment sites. The following is the final list of treatments that were evaluated in this study:

- Install Dynamic Advanced Warning Flashers,
- Convert Signalized Intersections to Roundabouts,
- Increase Clearance Intervals,
- Change Left-Turn Phasing, and
- Introduce a Flashing Yellow Arrow.

Results

The intent was to use the state of the art empirical Bayes (EB) method for evaluating the safety impacts of these treatments. In addition, cross-sectional regression models were used to derive CMFs if the sample size for the EB evaluation was limited, and to examine the comparability of before-after and cross-sectional studies, a subject of topical interest in CMF development, for which there is little research.

To evaluate the safety of dynamic signal warning flashers (DSWF), data were compiled from North Carolina, Virginia, and Nevada. In Virginia and Nevada, flashers had been introduced when the intersections were signalized, and hence did not allow the application of a before-after method. The Virginia and Nevada data were used to develop cross-sectional regression models, and these models were used to develop the CMFs. In North Carolina, a before-after analysis was possible, but the results were not found to be reliable. Hence, the CMFs based on the results from the cross-sectional models from Virginia and Nevada data are recommended and provided in this report. These results show a consistent reduction in total crashes at intersections that had DSWF. The results also suggest that DSWF may help to reduce angle, injury, and heavy vehicle crashes. The expected safety benefits are statistically significant at the 0.05 level for all crash types except heavy vehicles.

To evaluate the safety of converting from signalized intersections to roundabouts, the before-after EB method was used to evaluate treatments in Colorado, Florida, Indiana, Maryland, Michigan, North Carolina, New York, South Carolina, Vermont, and Washington. A disaggregate analysis was conducted to identify differential effects based on specific site characteristics (e.g., traffic volume, area type, and number of approaches). There was a substantial reduction in injury and fatal crashes following the implementation of roundabouts. In terms of the effect on total crashes, the safety benefit of roundabouts appears to decrease as traffic volumes increase. The analysis also suggested that the safety benefit is larger for suburban than for urban conversions and for intersections with four approaches compared to those with three.

For evaluating the change in clearance interval, data were obtained in California from the cities of San Diego and San Francisco and in Maryland from the counties of Howard and Montgomery. The primary analysis methodology used was the EB before-after analysis as previously described. The evaluation analyzed the effects of the treatment on crash frequencies for different crash types and severities before and after the treatment. Specifically, the EB analysis was employed to investigate five specific scenarios. The following three scenarios were related to various combinations of increasing the yellow and all red time:

1. Increasing *both* the yellow and all red phases.
2. Increasing the all red phase only.
3. Increasing the yellow phase only.

Two other scenarios were investigated, comparing the total change interval to the ITE recommended practice. In both cases, the before condition was represented by signalized intersections where the total change interval was less than the ITE recommended practice. The after period was represented by signalized intersections with the following characteristics:

1. Total change interval remains less than the ITE recommended practice.
2. Total change interval is greater than the ITE recommended practice.

The analyses attempted to develop CMFs by severity (i.e., fatal/injury vs. total crashes) and by crash type (i.e., total, angle, and rear-end) for both States. The EB before-after analyses indicated a significant reduction in total, injury, and rear-end crashes under various scenarios. Specifically, the analysis indicated a statistically significant reduction (at the 0.05 level) in total crashes as a result of (1) increasing the all red phase only and (2) increasing the total change interval to be less than the ITE recommended practice. Injury crashes were significantly reduced as a result of increasing the total change interval to be less than the ITE recommended practice. Rear-end crashes were significantly reduced as a result of increasing the total change interval to be greater than the ITE recommended practice. The change in angle crashes was statistically insignificant under all scenarios investigated.

For evaluating the change from permissive to protected-permissive phasing, data from 59 intersections in Toronto and 12 intersections from urban areas in North Carolina were used. The analysis methodology was the EB before-after method. Similar results were obtained for the two jurisdictions. At both intersection and approach levels the results indicate substantial and highly significant benefits for the target crash type, involving a left-turn vehicle and a through vehicle from the opposing approach. As expected, the benefit at the intersection level is greater at intersections where more than one approach is treated.

One of the fundamental questions the study was expected to answer was the extent to which the decrease in target crashes may be offset by a compensating increase in a non-target crash type such as rear-end. At both the intersection and approach levels, there were small percentage increases in rear-end crashes, which was statistically significant at the 0.05 level, when the results of the two jurisdictions are combined.

To evaluate the safety of implementing flashing yellow arrow for permissive left turns, data from urban areas in Oregon, Washington, and North Carolina were used. For Oregon and Washington, data on reference sites were limited in most of the jurisdictions and hence the EB methodology could not be applied with the required rigor: the methodology applied combined some aspects of the empirical Bayes and Comparison Group approaches. For North Carolina, data on reference sites were available and hence the EB methodology could be applied.

For Oregon and Washington, CMFs could be developed for total intersection crashes, intersection left-turn crashes, and left-turn crashes on the treated approaches. For North Carolina, CMFs could be developed for total intersection crashes, intersection injury and fatal crashes, intersection left-turn crashes, and intersection left-turn opposing through crashes. For the combined data from Oregon, Washington, and North Carolina, CMFs could be developed for total intersection crashes and intersection left-turn crashes for the following three scenarios based on the phasing in the converted legs in the before period:

- Permissive or combination of permissive and protected-permissive (i.e., at least 1 converted leg was permissive in the before period) to flashing yellow Arrow (FYA) protected-permissive (9 sites).
- Protected-permissive (all converted legs had protected-permissive in the before period) to FYA protected-permissive (13 sites).
- Protected (i.e., all converted legs had protected in the before period) to FYA protected-permissive (29 sites).

It was clear from the results that converting from protected phasing to FYA operation (third scenario) leads to a dramatic increase in left-turn crashes. However, there appears to be a benefit for both left-turn and total intersection crashes if there was permissive left-turn operation in at least one of the legs in the before period (i.e., first scenario). The sites where the converted legs were protected-permissive (second scenario) seem to have experienced a smaller reduction in left-turn and total intersection crashes (compared to the sites in the first scenario), but this reduction was not statistically significant at the 0.05 level. It is important to note that the number of sites in each of the first two scenarios was limited and hence those individual results should be treated with due caution.

CHAPTER 1

Introduction

Background

In 1997, the American Association of State and Highway Transportation Officials (AASHTO) Standing Committee for Highway Safety along with Federal Highway Administration (FHWA), National Highway Traffic Safety Administration (NHTSA), and the Transportation Research Board (TRB) Committee on Transportation Safety Management convened a meeting of national experts in the highway safety area to develop a Strategic Highway Safety Plan. This plan focuses on 22 highway safety challenges or emphasis areas that have an impact on highway safety. To advance the implementation of countermeasures to reduce accidents and injuries, NCHRP Project 17-18(3) began the development of a series of implementation guides which were subsequently published in the form of several volumes of *NCHRP Report 500.* Each guide addresses one of the 22 emphasis areas, and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. Each strategy is designated as: proven, tried, or experimental.

Many of the strategies discussed in these guides have not been rigorously evaluated. FHWA has initiated a Low Cost Safety Improvements Pooled Funds study to evaluate some of these strategies. The first two phases have been completed and included the evaluation of the following strategies: (1) center TWLTLs for two-lane roads, (2) higher retro-reflectivity sheeting for STOP signs, (3) pavement markings noting 'stop ahead,' (4) flashing beacons at stop controlled intersections, (5) the trade-off between lane and shoulder width given a pavement width, (6) advance street name signs, (7) curve delineation, and (8) offset left-turn lanes at signalized intersections. These evaluations were conducted using before-after data from locations where the safety improvements have been made and a reference group of untreated locations.

As a follow-up to these FHWA evaluations, NCHRP initiated NCHRP Project 17-35. The focus of this project is to select and evaluate strategies from *NCHRP Report 500, Volume 12: A Guide for Reducing Collisions at Signalized Intersections* (Antonucci et al., 2004). The desired result would be a set of Crash Modification Factors (CMFs) that specify the ratio of the expected crash frequency after and before the implementation of a treatment. It is expected that the CMFs developed would augment the CMFs currently in the Highway Safety Manual.

Study Objectives and Overview

The objective of this project was to evaluate the safety effectiveness for selected strategies identified in *NCHRP Report 500, Volume 12.* The intent is to develop reliable CMFs. At a minimum, for CMFs to be *reliable* they must meet the following criteria:

1. **CMFs should be methodologically and statistically valid.** Many existing CMFs are derived from before-after analysis of actual countermeasure implementation. Indeed, such before-after studies, as opposed to cross-sectional/regression-type analysis, will produce the best CMF estimates, but only if conducted properly to account for the regression to the mean effects at sites selected for treatment because of unusually high accident frequencies. Unfortunately, much of the available knowledge on CMFs may be tainted by this problem because this selection bias is quite prevalent. Other methodological problems that have affected the reliability of currently available CMFs include:
   - Failure to properly separate out the safety effects of other changes (e.g., traffic volumes, the impacts of other measures, crash reporting, underlying trends across time).
   - Sample sizes that are too small—large numbers of sites with the same combination of applied countermeasures are needed for a valid analysis. For some treatments that are expected to affect a low proportion of the total crashes at a site (e.g., pedestrian treatments), hundreds of locations may be necessary along with many years of crash data.

  - Use of comparison groups that are unsuitable for a variety of reasons, including the fact that sites may have been affected by the treatment.
  - Incorrect interpretation of accuracy of estimates or presenting results without statements of accuracy.
  - For many treatments, there may be different effects at different sites, so a single CMF that is typically estimated is often not applicable.
2. **The CMFs should represent the different crash categories that reflect the impact of the improvement.** Crash categories might include total crashes, severe injury crashes, property damage only crashes, and specific crash types (such as rear end and angle).
3. **The variability in CMFs should be stated.** The best estimate of the CMFs, along with some technique that reflects their variability (such as ranges, confidence intervals, standard deviation, or some other technique) should be presented. This will facilitate not only the application of the CMF but also the amalgamation with CMF results from other evaluation studies.
4. **The CMF should reflect the savings in "total harm" that the treatment provides.** Many treatments affect both crash frequency and crash severity, some just severity, and some tradeoff crashes of different severities (e.g., traffic signalization can decrease more-severe angle crashes but increase less-severe rear-end crashes). CMFs must capture changes in severity as well as frequency in order to measure "harm savings."

The identification and development of CMFs that meet most of these requirements involved a study effort with the following tasks:

- Task 1—Literature Review
- Task 2—Conduct a Survey of State and Local Agencies
- Task 3—Develop a Work Plan
- Task 4—Meet with the Panel
- Task 5—Collect Data and Conduct Evaluation
- Task 6—Develop a Final Report

In Task 1, based on a critical review of published studies for each treatment/strategy, the research team assigned a *level of predictive certainty* for each available CMF. Four levels of predictive certainty were defined: High, Medium-High, Low-Medium, and Low. The literature review also covered knowledge about ongoing or planned research, which was based on a review of several research-in-progress databases, discussions with other highway safety researchers, and conversations with research sponsors such as FHWA and the Insurance Institute for Highway Safety (IIHS). Details about the literature review are presented in Chapter 2.

In Task 2, web-based surveys were conducted using a tool called Zoomerang. The survey was sent to two listservs, contacts in all 50 States, and several local agencies. The respondents were asked to indicate if they had implemented a particular strategy/treatment and the approximate number of installations for each strategy/treatment. In addition, they were also asked to rate the importance of knowing the CMF for each treatment. These ratings along with the information about the installations were used to develop a short list of treatments for further consideration. To get further information about the availability and suitability of the data for the short-listed strategies, selected agencies that responded to the original web-based survey were contacted by telephone. Further description of Task 2 can be found in Chapter 3.

In Task 3, the research team developed a recommended and prioritized list of strategies to be evaluated to provide the best use of available funds, and a work plan for evaluating these strategies. Task 4 involved a meeting with the NCHRP panel to discuss the work plan and develop the list of strategies to be evaluated in Task 5. Further description about Tasks 3 and 4 can be found in Chapter 4.

Task 5 involved an evaluation of the strategies. The results from this evaluation are provided in Chapter 5. Chapter 6 provides a summary page showing the recommended CMFs for each treatment that was evaluated in this study. Chapter 7 provides some general conclusions and directions for further research.

CHAPTER 2

Literature Review

Provided in this chapter is a summary of the literature review and the identification of future and ongoing research. Given that the focus of this effort was on developing CMFs, the initial screening criterion applied to each study was that the results must be founded on a crash-based analysis (as opposed to analyses of driver behaviors, citations, or other "surrogate" measures). Hence, the focus of this review was on studies that evaluated treatments at signalized intersections using crash-based analysis. The studies for each treatment were further screened to determine which ones included the development of CMFs or a methodology that may be used to develop CMFs. The studies meeting this criterion and believed to be the most credible were then subjected to a more critical review. Each critical review was undertaken with the following objectives:

1. Evaluate the research approach and statistical methodology, including an investigation of the potential for pitfalls such as regression-to-the-mean (RTM) or site-selection bias. A thorough discussion of these possible pitfalls is presented in *NCHRP Synthesis 295: Statistical Methods in Highway Safety Analysis* (Persaud, 2001).
2. Document the magnitude and assess the confidence level of any CMFs produced.

The results of the critical reviews are organized by strategies listed from *NCHRP Report 500, Volume 12.* One of the outcomes from the critical reviews was the confidence level of the CMFs of each treatment. This qualitative measure reflects the *level of predictive certainty* in the CMF derived and is a reflection of the study methodology. The confidence levels and the levels of predictive certainty can be qualified as follows:

- **High**—The CMF was developed in a rigorous observational before-after study that incorporates what are currently considered the *best* study design and statistical analysis methods, namely the empirical Bayes (EB) method described by Hauer (1997) or the full Bayes (FB) method.
- **Med-High**—The CMF was developed in a before-after study that incorporated sound (but not the current state-of-the-art) statistical methods and/or may not have been reviewed and "vetted" by an expert panel of researchers (as were the CMFs in the Highway Safety Manual). This level would also include CMFs that result from the combination of findings from different (i.e., less controlled) before-after and cross-sectional studies by an expert research panel. The panel's judgment concerning the *certainty level* of the CMF would be reflected in our rating. This level would also include CMFs that have been developed in a rigorous meta-analysis by a recognized meta-analysis expert. (Meta-analysis is the combination of the results of various studies using techniques that allow the expert to accommodate some of the shortcomings of the original research.)
- **Low-Med**—The CMF was developed from cross-sectional analysis (controlling for other factors statistically), or less-than-rigorous before-after studies still judged to be of value (e.g., a before-after study in which regression-to-the-mean was not viewed as a major potential bias due to the fact that "high-crash locations" were not selected for the treatment of the evaluation).
- **Low**—The CMF was developed in a simple before-after study without control for regression to the mean and other confounders, or from cross-sectional studies where modeling techniques and assumptions are questionable.

Table 2.1 shows the predictive certainty for each treatment, along with the key reference.

Table 2.1. Key references for strategies/treatments from *NCHRP Report 500*, *Volume 12*, along with level of predictive certainty.

Strategy Name	P, T, or E[1]	Predictive Certainty	Key References
17.2 A1: Employ multiphase signal operation – protected left-turn signal phase	P	Medium-High	• Harkey et al., 2008.
17.2 A1: Employ multiphase signal operation – permissive-protected or protected-permissive left-turn signal phase	P?	Medium-High	• Lyon et al., 2005.
17.2 A1: Employ multiphase signal operation – split phases	T	Non-Existent	No key studies
17.2 A2: Optimize clearance intervals	P	Medium-High	• Retting et al., 2002
17.2 A2: All red clearance interval	P	Low-Medium	• Souleyrette et al., 2004 • Polanis, 2002
17.2 A3: Restrict or eliminate turning maneuvers using channelization or signing	T	Non-Existent	No key studies
17.2 A3: Introduce/Prohibit RTOR	T	Medium-High	• Harkey et al., 2008
17.2 A4: Employ signal coordination	P	Non-Existent	The following studies use surrogate measures (which are not yet proven) to try to deduce the effect on safety. • Rakha et al., 2000 • Berg et al., 1986
17.2 A5: Employ emergency vehicle preemption	P	Non-Existent	No key studies
17.2 A6: Improve operation of pedestrian and bicycle facilities at signalized intersections: • Pedestrian signs, signals, and markings • Crossing guards for school children • Lights in crosswalks in school zones • Pedestrian-only phase or pedestrian-lead phase during signal operation	Combination of P and T	Low for Pedestrian Signals	• Zegeer et al., 1982 • Elvik and Vaa, 2004
17.2 A6: Improve operation of pedestrian and bicycle facilities at signalized intersections: Prohibition of RTOR	Combination of P and T	Low-Medium	• Preusser et al., 1982.
17.2 A7: Remove unwarranted signals	P	High	• Persaud et al., 1997.

[1] P (proven), T (Tried), and E (Experimental); From *NCHRP Report 500, Volume 12.*

Strategy Name	P, T, or E[1]	Predictive Certainty	Key References
17.2 B1: Provide or improve left-turn channelization: Providing left-turn lanes	Combination of P and T	High	• Harwood et al., 2002.
17.2 B1: Provide or improve left-turn channelization: Lengthening left-turn lanes	Combination of P and T	Low	• Harwood et al., 2002.
17.2 B1: Provide or improve left-turn channelization: Providing left-turn lanes: Providing positive offset for left-turn lanes	Combination of P and T	High	• Khattak et al., 2004. • Persaud et al., 2009.
17.2 B1: Provide or improve left-turn channelization: Providing positive guidance with channelization	Combination of P and T	Non-Existent	No Key Studies
17.2 B1: Provide or improve left-turn channelization: Delineating turn path	Combination of P and T	Non-Existent	No Key Studies
17.2 B2: Provide or improve right-turn channelization: add exclusive right-turn lane	P	High	• Harwood et al., 2002.
17.2 B2: Provide or improve right-turn channelization: provide channelization that includes raised or painted islands	P	Non-Existent	The following two studies may evaluate the safety aspects of different types of channelization treatments: • NCHRP Project 3-78 (ongoing) • NCHRP Project 3-89 (ongoing)
17.2 B2: Lengthen right-turn lanes	P	Non-Existent	No Key Studies
17.2 B3: Improve geometry of pedestrian and bicycle facilities: • Continuous sidewalks • Signed and marked crosswalks • Sidewalk set-backs • Median refuge areas • Pedestrian overpasses • Intersection lighting • Physical barriers to restrict pedestrian crossing maneuvers • Relocation of transit stops • Other traffic calming applications	Combination of P and T	Non-Existent	The following studies the safety effects of marked versus unmarked crosswalks at unsignalized locations. It is not clear if the results are transferable to signalized locations: • Zegeer et al., 2001
17.2 B4: Revise geometry of complex intersections – convert a four-leg intersection to two T intersections	T	Non-Existent	The following study did a meta-analysis based on 9 studies that had looked at the effects of

(continued on next page)

[1] P (proven), T (Tried), and E (Experimental); From *NCHRP Report 500, Volume 12.*

Table 2.1. (Continued).

Strategy Name	P, T, or E[1]	Predictive Certainty	Key References
			converting four-leg to two T intersections. However, the study does not report whether these intersections are signalized or not. • Elvik and Vaa, 2004.
17.2 B4: Revise geometry of complex intersections – convert two T intersections to one four-leg intersection	T	Non-Existent	No key studies
17.2 B4: Revise geometry of complex intersections – improve intersection skew angle	P	Non-Existent	No key studies
17.2 B4: Revise geometry of complex intersections – Remove deflection in through-vehicle travel path	T	Non-Existent	No key studies
17.2 B4: Revise geometry of complex intersections – Close intersection leg	T	Non-Existent	No key studies
17.2 B5: Construct special solutions: provide indirect left turn	T	Non-Existent	No key studies
17.2 B5: Construct special solutions: Convert to roundabout	T	Medium High	• Persaud et al., 2001. • Rodegerdts et al., 2007.
17.2 B5: Construct special solutions: Convert two-way streets to a one-way pair	T	Non-Existent	The following studies report reduction in pedestrian crashes, but no information is available about the methodology that was used: • Wiley, 1959 • Karagheuzoff, 1972
17.2 B5: Construct special solutions: Construct interchange or grade separation	T	Non-Existent	The following study did a meta-analysis based on 4 studies. However, none of these studies were from the USA: • Elvik and Vaa, 2004
17.2 C1: Clear sight triangles	T	Non-Existent	No key studies
17.2 C2: Redesign intersection approaches	P	Non-Existent	No key studies
17.2 D1: Improve visibility of intersections on approach(es) • Improve signing and delineation • Install larger signs	T	Non-Existent	No key studies
17.2 D1: Improve visibility of intersections on approach(es): Provide intersection lighting	T	Low-Medium	• Lipinski and Wortman, 1976 • Preston and Schoenecker, 1999. • Walker and Roberts, 1976. • Donnell et al., 2009. • Harkey et al., 2008.

[1] P (proven), T (Tried), and E (Experimental); From *NCHRP Report 500, Volume 12.*

Strategy Name	P, T, or E[1]	Predictive Certainty	Key References
17.2 D1: Improve visibility of intersections on approach(es) • Install rumble strips on approaches • Install queue detection systems • Install red-light hold systems	T	Non-Existent	No key studies
17.2 D1: Improve visibility of intersections on approach(es): Install dynamic advance-warnings flashers 'Red Signal Ahead'	T	Low	• Sayed et al., 1999.
17.2 D2: Improve visibility of signals and signs at intersections: Install additional signal heads	T	Medium High	• Harkey et al., 2008.
17.2 D2: Improve visibility of signals and signs at intersections: • Provide visors to shade signal heads • Provide louvers, visors, or special lenses so drivers are able to view signals only for their approach • Install backplates	T	Medium High for Signal Lens Upgrade	The following study conducted a before-after EB evaluation using a combination of different treatments to improve visibility. Different groups of intersections had a slightly different set of treatments. However, results were not disaggregated by type of treatment: • Sayed et al., 2007.
17.2 D2: Improve visibility of signals and signs at intersections: Install larger (12 inch) signal lenses	T	High	• Sayed et al., 1998. • Harkey et al., 2008.
17.2 D2: Improve visibility of signals and signs at intersections: • Remove or relocate unnecessary signs • Provide far-side left-turn signal	T	Non-Existent	No key studies
17.2 E1: Provide public information and education	T	Non-Existent	No key studies
17.2 E2: Provide targeted conventional enforcement of traffic laws	T	Non-Existent	No key studies
17.2 E3: Implement automated enforcement of red-light running	P	High	• Council et al., 2005. • Shin and Washington, 2006 • Miller et al., 2006.
17.2 E4: Implement automated enforcement of approach speeds	T	Non-Existent	The following studies looked at the effect of automated enforcement on safety at different corridors, but did not report on crashes at signalized intersections: • Cunningham et al., 2005. • Chen et al., 2002. • Mountain et al., 2004.

(continued on next page)

[1] P (proven), T (Tried), and E (Experimental); From *NCHRP Report 500, Volume 12.*

Table 2.1. (Continued).

Strategy Name	P, T, or E[1]	Predictive Certainty	Key References
17.2 E5: Control speed on approaches: • Construct a horizontal curve to reduce speeds • Speeding vehicle activated traffic signals • Traffic calming treatments	E	Non-Existent	No key studies
17.2 F1: Restrict access to properties using driveway closures or turn restrictions	T	Low	• Xu, 2001
17.2 F2: Restrict cross-median access near intersections	T	Non-Existent	No key studies
17.2 G1: Improve drainage in intersection and on approaches	T	Non-Existent	No key studies
17.2 G2: Provide skid resistance in intersection and on approaches	T	High	• Harkey et al., 2008.
17.2 G3: Coordinate closely spaced signals near at-grade railroad crossings	T	Non-Existent	No key studies
17.2 G4: Relocate signal hardware out of clear zone	T	Non-Existent	No key studies
17.2 G5: Restrict or eliminate parking on intersection approaches	P	Non-Existent	The following study did a meta-analysis based on 13 studies that had looked at the effects of changes in parking. However, it is not clear how many of the locations were close to signalized intersections: • Elvik and Vaa, 2004.

[1] P (proven), T (Tried), and E (Experimental); From *NCHRP Report 500, Volume 12.*

CHAPTER 3

Survey of Agencies

This chapter provides a summary of several surveys that were conducted of state and local agencies as part of this project. The intent of this task was to obtain information on the installation of treatments by different agencies, determine their priorities for different treatments, and assess the quality of the available data.

Web-Based Surveys

The web-based surveys were developed using a tool called Zoomerang. The intent of the web-based survey was to determine if a particular agency had installed a particular treatment, the approximate number of installations, and the agency's assessment of the importance of knowing the CMF of a particular treatment. Based on the research team's past experience in conducting surveys of this nature, the research team felt that the shorter the survey, more agencies will respond. Hence, to improve the response rate, the list of treatments was divided into two parts (Part 1 and Part 2) based on an assessment of how often specific treatments are installed in the field and the quality of CMFs that are available from previous research. Part 1 requested information for 23 treatments and Part 2 requested information for 36 treatments.

A draft version of the web-based survey was submitted to the NCHRP panel in March 2007. Changes were made to the survey after receiving comments from the NCHRP panel. The surveys were launched in June 2007.

The surveys were posted online and an e-mail notification was sent to State DOTs, selected local agencies, and listservs including the Traffic Control Device listserv and the State Safety Engineer listserv. Individual requests were also sent to 130 local agencies. Forty-three agencies responded to Part 1 of the survey, and 33 agencies responded to Part 2 of the survey.

Assessment of User Priorities and Development of Short List

The results of the survey were summarized and disseminated to the project team. In order to select a recommended and prioritized list of strategies, the research team felt that it was necessary to contact select agencies by telephone to get further information regarding their roadway, traffic, crash data, and installation records. In order to be able to do this efficiently, it was necessary to develop a shorter list of treatments for further consideration. As discussed in Chapter 1, the research team considered the likelihood and importance of evaluating each strategy based on the following:

- Extent of the coverage in previous/ongoing work. Chapter 2 provides a summary of the CMFs developed in previous research.
- Importance to the user (as identified in the survey response). This is assumed to be a good measure of how often a treatment would be implemented if a sound CMF were developed (i.e., high interest would imply higher future implementation).
- Ability to identify crash effects. Strategies that may lead to diversion of traffic and/or have a system-wide effect will require more extensive data collection efforts and hence may not be cost effective. Similarly, treatments that may have a small effect on total crashes may require a significantly large sample of sites to conduct an evaluation and hence may not be cost effective.
- Data assessment. This was done based on the responses to the web survey and the research team's knowledge based on working with HSIS and the FHWA Low Cost Pooled Fund Study.

The research team also attempted to examine a measure of "crash harm"—the size of the national crash problem potentially affected by each treatment. The first step in this analysis was to assign a primary crash type to each treatment that was being studied (e.g., left-turn crashes for left-turn phasing). The next step was to use the General Estimate System (GES) to calculate the number of crashes per year for each primary crash type that was identified earlier. By multiplying the number of crashes of a particular type with the average cost for that type of crash (based on Council et al., 2005), we can get the crash harm associated with that particular crash type. However, in attempting to do this, we realized that in order for this crash harm analysis to be useful, we would need to include measures of both the expected size of the effect (before the evaluation) and either the proportion of signalized intersections or the proportion of signalized-intersection crashes that might be affected by each treatment to be assessed. For example, while left-turn phasing and split phasing can both be targeted to reducing crashes involving left-turning vehicles, they might affect a different proportion of the left-turn crashes, and more importantly, they might be only suitable for use at a different proportion of signalized intersections. Since there is no national inventory of signalized intersections, it was not possible to develop the needed estimates. Thus, we assumed that the inputs from users concerning treatment priorities give some indication of the size of the remaining signalized-intersection problem to be solved in their jurisdiction—the "problem size" for them.

Based on the project team's review and assessment of the first three of these four aspects (i.e., the data assessment required follow-up phone interviews with the states), the list of potential treatments was narrowed down to the following:

- 17.2 A1: Split phasing
- 17.2 A1: Adding protected left-turn phasing*
- 17.2 A2: Modifying the change interval*
- 17.2 A3: Restricting or eliminating turns at the intersection
- 17.2 A7: Remove unwarranted signals
- 17.2 B1: Adding left-turn lanes*
- 17.2 B1: Lengthening left-turn lanes
- 17.2 B2: Improving right-turn channelization
- 17.2 B4: Modify intersection skew
- 17.2 C2: Improve sight distance
- 17.2 D1: Advance Warning Signs for Red Signal
- Improvements in signal visibility and conspicuity including
  - 17.2 D2: Backplates
  - 17.2 D2: Adding reflective sheeting to backplates
  - 17.2 D2: Increase signal head size to 12 inches*
  - 17.2 D2: Installing louvers and visors
  - 17.2 D2: Installing additional signal heads*
  - 17.2 D2: Installing far side left-turn signals

Note that the treatments designated with asterisks in the previous list have existing CMFs which have been judged to be of at least "medium high" predictive certainty. However, they continued to be included on the potential treatment listing since (1) they are rated highly in the survey, and (2) the research team feels that the existing CMFs could be further improved depending on the availability of data, e.g., to provide variable CMFs for different implementation circumstances.

Following is a list of treatments that were rated by the survey respondents among the top 15 in terms of importance, but were **not selected** in the short list:

- **Coordinate signals along routes or corridors.** The research team felt that this treatment is mainly used to improve traffic flow and reduce delays and not specifically implemented to improve safety. For this reason, it was felt that the development of an improved safety-based CMF would not significantly affect use of this treatment, and that a true evaluation would need to trade-off safety findings and delay findings, something beyond the scope of this project. In addition, the evaluation of this treatment is expected to be difficult since (1) finding coordinated systems that had no coordination before might be difficult, and (2) the coordinated system might change over time, making it difficult to clearly specify a treatment corridor.
- **Delineate turn path inside an intersection.** The research team felt that the effects of this treatment on safety are small and hence would require a substantial number of sites to statistically detect this expected change in safety, and hence, research would not be cost-effective.
- **Utilizing crossing guards for school children.** The exposure to this treatment is limited (i.e., during school openings, closings, and during lunch), reducing the number of potential crashes for study. Thankfully, pedestrian crashes are rare events. Hence, hundreds if not thousands of sites would be needed in order to do an effective study. In addition, conducting an evaluation will require data on pedestrian crossing volumes that the research team found very difficult to find based on previous studies that have been conducted. Hence, the research team felt that allocating resources to evaluate this treatment will not be an efficient use of the project budget.

Phone Calls to Selected Agencies

Based on survey information on available data, the following agencies were initially contacted for follow-up telephone interviews:

- **City of Grand Junction, CO;**
- City of Memphis, TN;
- **City of Overland Park, KS;**
- **City of San Diego, CA;**
- City of Scottsdale, AZ;
- **City of Sparks, NV;**
- **City of Tempe, AZ;**
- **Broward County DOT, FL;**
- **Lee County DOT, FL;**
- **Lexington-Fayette Urban County Government, KY;**
- Washtenaw County Road Commission, MI;

- Arkansas State Highway and Transportation Dept;
- **Hawaii DOT;**
- **Kansas DOT;**
- **Minnesota DOT;**
- **Missouri DOT;** and
- South Carolina DOT.

These agencies were selected because they indicated they had a sizeable amount of installations of one or more of the treatments of interest and they did not indicate any problems with their crash data in their survey response. The project team interviewed representatives from each of the agencies that responded to the follow-up contact (indicated in bold in the previous list). A series of questions were asked regarding the installation data, crash data, traffic data, roadway data, and individual treatments. Examples of the questions asked included:

- Do you keep records of installation for these treatments? If yes, what is the format?
- Who maintains the crash data?
- What years of crash data are available?
- How are the locations of crashes referenced in the data?
- In what format are the traffic data maintained?
- In what format are the traffic counts presented? Raw data? ADT? AADT?
- Are turning movement counts available?
- What source of information is available on roadway/intersection geometry?
- Are there any known problems with any of the data?
- Was the protected left-turn phasing used when the intersection was built or was it added after the intersection was already operational?
- Are the advanced warning signs dynamic or static?

CHAPTER 4

Prioritization of Strategies

The follow-up interviews discussed in the previous chapter revealed many problems with using data from many of the agencies. Some of the difficulties uncovered during the follow-up interviews included:

- Lack of resources to participate in an evaluation.
- Unable or unwilling to participate in this study.
- Inadequacies in crash data.
  - No electronic crash data (i.e., crash reports are only available in paper copies).
  - Recent historical data (i.e., older than 3 years) are not available.
  - Crash data cannot be linked to intersections.
- Installation records for the strategy were not available.
- The strategy was installed at the same time the road was built (therefore, there is no before data for a before-after evaluation).
- Lack of data for reference group intersections.
- Inadequacies in supporting data.
  - No volume data.
  - No historical volume data.
  - No inventory data.
- Other improvements were made at the same time.
- Changes have been made since installation.

Based on the outcomes of the interviews, a prioritized list of strategies for evaluation along with a work plan was submitted to the NCHRP Panel as part of the Interim Report. In developing the list of prioritized strategies, tried, experimental, and proven strategies (based on *NCHRP Report 500*, *Volume 12*) were considered. The original solicitation had indicated that the focus should be on tried and experimental strategies. However, comments from the panel members on the quarterly progress reports indicated that proven strategies should be considered as well.

The prioritized list of strategies was developed after considering the following:

- **Extent of the coverage in previous/ongoing work.** Task 1 (literature review) indicated if a particular strategy has been rigorously evaluated by previous work or is being evaluated in another ongoing study, and the quality and predictive certainty of the CMFs developed so far.
- **Importance to the user.** In order for the results of this study to be successfully implemented, it needs to focus on strategies that are important to the end user. Results of Task 2 (i.e., the importance as identified by the survey respondents) were used to determine the importance of the strategies to the end user.
- **Data assessment.** The objective was to identify databases and determine the quality and quantity of data available for the development of high-quality CMFs using a rigorous before/after study. Phone interviews were conducted of respondents who potentially had data as part of Task 2 in order to make a preliminary assessment of this factor. The intent was to identify agencies that can provide data for multiple treatments and thereby reduce data collection costs.
- **Ability to identify crash effects.** Strategies that may lead to diversion of traffic and/or have a system-wide effect would require more extensive and cost-prohibitive data collection efforts. Similarly, treatments that may have a small effect on total crashes may require a relatively large sample of sites to conduct a cost-effective evaluation.

Based on these criteria and on the available budget, three treatments were identified for evaluation:

- Adding protection for left-turning vehicles which includes the following treatments:
  - Introduce protected left-turn phasing.
  - Introduce permissive-protected or protected-permissive left-turn phasing.
  - Modify left-turn phasing and add left-turn lane at the same time.
  - Lengthen left-turn lanes.

- Optimize clearance intervals.
- Install dynamic advance warning flashers.

Work plans were developed for each of these. Note that this in effect includes six different treatments, since the first group includes four treatments.

In addition to these six treatments, the following five treatments were identified as backups in case it was not possible to evaluate any of the six high priority ones:

- Implement Split phasing.
- Add left-turn lanes.
- Provide or improve right-turn channelization.
- Add signal heads.
- Converting signalized intersections to roundabouts.

The work plan consisted of a plan for the following four activities:

- Collecting in-depth installation data.
- Developing an experimental design for the treatments.
- Collecting crash, roadway inventory, site characteristics.
- Conducting a rigorous evaluation of the strategies.

Interim Meeting with NCHRP Panel

The prioritized list of strategies and the work plan were discussed at the Interim Meeting in Washington, D.C., in November 2007. At the meeting, the project team and the NCHRP Panel agreed on a set of Tier I treatments (higher priority) and a set of Tier II treatments (lower priority) for the evaluation. At the meeting, it was agreed that funds would probably not be available to address all the treatments in Tier I. In addition, if data were not available to evaluate one or more of the treatments in Tier I, treatments in Tier II could be included. The following is a list of treatments in Tier I and Tier II.

Tier I (higher priority):

- Change to Protected phasing,
- Change to Protected-permissive phasing,
- Modify phasing and add left-turn lane,
- Add left turn only,
- Lengthen left-turn lane,
- Dynamic advance warning flashers,
- Optimize clearance intervals, and
- Flashing yellow arrow.

Tier II (lower priority):

- Convert signalized intersections to roundabouts,
- Right-turn channelization,
- Add signal heads,
- Improving friction at approaches to intersections,
- Changing fonts, and
- Change to Split phasing.

After the interim meeting, the project team started compiling the necessary data for evaluating the treatments in Tier I. The project team could not find sufficient data for some of the treatments in Tier I, and after discussing this issue with the panel, it was decided to include one of the treatments from Tier II (convert signalized intersections to roundabouts) for which there appeared to be a research need coupled with the availability of data for a substantial number of treatment sites. The following is the final list of treatments that were evaluated in this study:

- Install Dynamic Advanced Warning Flashers,
- Convert Signalized Intersections to Roundabouts,
- Change Clearance Intervals,
- Change Left-Turn Phasing, and
- Introduction of Flashing Yellow Arrow.

CHAPTER 5

Safety Evaluation

This Chapter provides a summary of the results of the evaluation of the five treatments mentioned in Chapter 4. The first part of this Chapter gives an overview of the different evaluation methods that were used to develop the CMFs. Following that is a summary of each evaluation that provides the description of the treatment, data used, methodology, and results. (Full details of each evaluation study are provided in a series of appendices which can be found online at http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=461.)

Three evaluation methods were used in this study. The primary, and preferred one, is the EB before-after method, which is considered to be one of the best methods for conducting before-after studies in that it properly accounts for regression to the mean. The second method utilized is the comparison group before-after method. This method does not effectively address the bias due to regression to the mean, but is effective in accounting for other non-treatment effects such as those due to trends in crash reporting and changes in traffic volume. The third method is based on cross-sectional multiple regression models where the CMFs are derived based on the coefficients of variables in these models that pertain to the CMF. The cross-sectional regression models were used if the sample size for the EB evaluation was limited. A secondary objective of using cross-section models for some evaluations was to examine the comparability of before-after and cross-sectional studies, a subject of topical interest in CMF development, for which there is little research. An overview of these methods follows. More details can be found in a recent FHWA Guide entitled *A Guide to Developing Quality Crash Modification Factors* (Gross et al., 2010).

Overview of Methods

Before-After Analysis Using the Empirical Bayes Method

The EB method properly accounts for regression to the mean bias in before-after studies. It also overcomes the difficulties of using crash rates in normalizing for volume differences between the before and after periods and properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions. The EB method estimates the expected crashes that would have occurred in the after period (λ) and compares that with the number of reported crashes in the after period (π).

The following steps are used to estimate λ:

1. Identify a reference group of untreated sites that is otherwise similar to the treatment group.
2. Use the reference group data to estimate safety performance functions (SPFs) (mathematical equations) that predict the number of crashes of different types as a function of traffic volumes and other site characteristics. Typically, SPFs are negative binomial regression models that are estimated using generalized linear modeling.
3. In estimating SPFs, calibrate annual SPF multipliers (time trend factors) to account for the temporal effects (e.g., variation in weather, demography, and crash reporting) on safety.
4. Use the SPFs, the annual SPF multipliers, and data on traffic volumes and site characteristics for each year in the before period for each treatment site to estimate the number of crashes that would be predicted in each year of the before period for each treatment site.
5. Use the predicted number of crashes in the before period (from the SPFs) and the observed crashes in the before period at each treatment site to estimate the EB-expected number of crashes in the before period in each site. The EB-expected crash frequency is then estimated to adjust for possible bias due to regression to the mean.
6. Estimate λ (expected crashes in the after period if the treatment had not been implemented) as the product of the EB-expected number of crashes in the before period and the sum of the annual SPF predictions for the after period divided by the sum of these predictions for the

before period (for each treatment site). The EB procedure also produces an estimate of the variance of λ.

7. The estimate of λ is then summed over all sites in a treatment group of interest and compared with the count of crashes during the after period in that group. The variance of λ is also summed over all sites in the strategy group.
8. These parameters (the summation of λ and its variance) are then used, along with the summation of crash counts after treatment, to estimate an effect of the treatment (CMF). The standard deviation of the CMF is also estimated, which makes it possible to determine if the CMF is statistically different from 1.0 for a specific level of significance.

Before-After Analysis Using the Comparison Group Method

This method does not account for regression to the mean but can be effective in accounting for other non-treatment effects such as those due to trends in crash reporting and changes in traffic volume. This method can make use of an untreated comparison group of sites that are similar to the treatment sites used to estimate an SPF to account for changes in traffic volume and temporal trends in crash occurrence. Steps 1 through 3 that were discussed for the EB method could potentially be the same for the comparison group method as well. The departure from the EB method is that, instead of using steps 4 and 5 to estimate the expected number of crashes in the before period, the observed crashes in the before period is used for this estimate. This estimate could be biased if crashes are selected for treatment because of a randomly high observed crash count.

Cross-Sectional Regression Models

Cross-sectional studies derive CMFs by comparing the crash statistics from sites with and without the treatment. If it is possible to find sites that are similar to each other (apart from having or not having the treatment), then the CMF could be defined as the ratio of the average number of crashes in sites with the treatment to the average number of crashes in the sites without the treatment. In practice, it is very difficult to find sites that are similar to each other, and so regression models are typically used. The state of the art is to use negative binomial regression models where crash frequency is the dependent variable and the independent variables may include site characteristics including major and minor road AADT. The model coefficients are used to derive the CMFs. One problem with using cross-sectional models is that the differences in crashes between the sites with treatment and without treatment may be due to factors that were measured and could not be included in the model, factors which could not be measured, or even factors that are unknown. Hence, at this time, the CMFs from cross-sectional models are not considered as reliable as CMFs derived from well-designed before-after studies, unless they can be corroborated with results from rigorous before-after studies.

Further discussion of these methods is provided in the appendices that discuss the results of each evaluation in detail which can be found online at http://apps.trb.org/TRBNetProjectDisplay.asp?ProjectID=461. Another resource is a recent publication from the Federal Highway Administration entitled *A Guide to Developing Quality Crash Modification Factors* (Gross, Persaud, and Lyon, 2010) that includes more information concerning different methods for developing CMFs. The rest of this chapter provides a summary of the results obtained from each evaluation.

Evaluation Summaries

Installation of Dynamic Signal Warning Flashers

Description of Treatment and Crash Types of Interest

This analysis examines the safety impacts of installing dynamic signal warning flashers (DSWF) in advance of signalized intersections. DSWF provides drivers with advance notice of the phase change. Specifically, the DSWF is linked to the signal, and flashers are actuated when the signal is about to change from green to yellow. The flashers are located in advance of the intersection and are actuated at a time when the driver would not be able to clear the intersection before the onset of the red phase.

The basic objective was to estimate the change in crashes. Target crash types considered included the following:

- All crash types (all severities);
- Rear-end crashes (all severities);
- Angle crashes (all severities);
- Fatal and injury crashes (all crash types); and
- Truck-related crashes (all severities).

The change in crash frequency was analyzed by employing multiple methods using data gathered from three states. Appendix A provides the details associated with this evaluation along with example photographs.

Data Used

Departments of transportation in Nevada, Virginia, and North Carolina helped identify treatment sites (i.e., intersections where DSWF had been installed). They also provided geometric, traffic volume, and crash data. For Nevada, data from 1994 to 2008 were available, but only a subset of that data was used in order to avoid any major construction activity. For Virginia, data from 1998 to 2008 were available, and again only a subset was used to avoid construction activity. For North Carolina, data from 1993 to 2009 were used.

Methodology

With respect to all the treatment sites in Nevada and most of the treatment sites in Virginia, it was discovered that the traffic signals and DSWF were installed at the same time. This observation had an important implication on the selection of an analytical method for this analysis. Since it would be difficult to separate the effects of the signal installation from the effects of the DSWF installation, using before-after methods (e.g., comparison group method or EB method) for those sites would be problematic. In contrast, all of the treatment sites in North Carolina were already signalized when the DSWF were installed. Therefore, a before-after method could be employed with the North Carolina data without difficulty. Because of the issue with the timeframe for signal installations, a single method could not be employed for all three states. Instead, three methods were used: cross-sectional analysis, before-after with comparison group, and EB before-after.

With respect to the Nevada data, a cross-sectional method was employed using two groups of sites: one group consisting of signalized intersections where DSWF were present and another group consisting of signalized intersections where DSWF were not present. In all, 261 site-years and 3,224 total crashes were included in this analysis.

With respect to the Virginia data, two analytical methods were employed. A cross-sectional analysis was conducted with the Virginia data using two groups of sites: one group of sites consisting of signalized intersections where DSWF were present and another group consisting of signalized intersections where DSWF were not present. The Virginia cross-sectional analysis included 452 site-years and 1,201 total crashes. A before-after with comparison group method was also employed with the Virginia data with the goal of validating the results of the cross-sectional analysis. This analysis was possible because, for a subset of the treatment sites in Virginia, the DSWF installations occurred after the traffic signal installations.

Another cross-sectional analysis was performed using a dataset which combined the Nevada and Virginia data. As with the individual state analyses, two groups were defined. One group consisted of sites in Nevada or Virginia where DSWF had been installed, and another group consisted of sites in Nevada or Virginia where DSWF had not been installed.

With the North Carolina data, the DSWF were installed at intersections which were already signalized. Consequently, the problem of separating the effects of signal installation and DSWF installation was not present, and the state-of-the-art EB before-after method was used. The treatment group contained 14 sites, 1,000 total crashes in the before period, and 256 total crashes in the after period. The reference group consisted of 63 signalized intersections in North Carolina with 5,948 total crashes.

Results

The evaluation of DSWF utilized three analysis methods: cross-sectional, before-after with comparison group, and before-after with EB. The cross-sectional analyses for Nevada, Virginia, and the two states combined, show a consistent reduction in total crashes at intersections that had DSWF. The results from the before-after analyses validated these findings. The results also suggest that DSWF may help to reduce angle, injury, and heavy vehicle crashes, although the sample size was limited for many of the individual crash types. It was possible to investigate both angle and injury crashes using all three methods and the results consistently indicated a reduction in expected crashes with the presence of DSWF.

The results were less consistent for rear-end crashes. The cross-sectional and comparison group analyses were similar, indicating a reduction in expected rear-end crashes with the presence of DSWF. However, the EB analysis indicated an increase in rear-end crashes. Note again that the cross-sectional and comparison group analyses were based on data from Nevada and Virginia, while the EB analysis was based on data from North Carolina.

Multiple methods were used in this analysis of DSWF, resulting in multiple sets of CMFs. Of the various sets of CMFs produced in this analysis, the results of the combined cross-sectional analysis were ultimately deemed to be the most reliable. Table 5.1 presents the CMFs from the combined cross-sectional analysis, with the respective standard errors. It is important to note that the standard errors shown are 'ideal' standard errors, and the Highway Safety Manual recommends that these standard errors be increased by a factor of 2.0 for

Table 5.1. Crash frequency CMFs (and standard errors) by crash type for installation of DSWF.

	Total Crashes	Rear-end	Angle	Injury & Fatal	Heavy Vehicle
CMF	0.814#	0.792#	0.745#	0.820#	0.956
Standard Error	0.062	0.079	0.086	0.083	0.177

Note: #Statistically significant at the 0.05 level (based on the ideal standard errors reported in this table)

CMFs from cross-sectional regression models to account for the fact that results from cross-sectional models are not as reliable as those from well-designed before-after studies for estimating CMFs.

The results seem to indicate that the dynamic signal warning flashers do provide a benefit with the largest percent reduction in angle crashes. The relatively large reduction in fatal and injury crashes is likely the greatest benefit of the dynamic signal warning flashers in terms of overall safety. Future research could investigate the safety effects of the many variations of DSWF including roadside and overhead signs.

Conversion of Signalized Intersections to Roundabouts

Description of Treatment and Crash Types of Interest

This analysis examined the safety impacts of converting signalized intersections to roundabouts. Roundabouts have the potential to reduce both the frequency and severity of crashes compared to a similar signalized intersection. The basic objective was to estimate the change in crashes. Target crash types considered included:

- All crashes (all types and severities);
- Property damage only crashes (all crash types); and
- Fatal and injury crashes (all crash types).

The change in total crash frequency was analyzed as well as the changes in different crash severities, recognizing that the treatment may have a different level of effect on the various severities. Appendix B provides the details associated with this evaluation.

Data Used

Geometric, traffic volume, and crash data for treatment sites were acquired from the States of Indiana (2003–2008); New York (3 years before and after treatment); Washington (2001–March 2009); Michigan (2000–2009); and North Carolina (1999–2009) to facilitate the analysis. Data were also obtained from NCHRP Project 3-65 which was published as *NCHRP Report 572: Roundabouts in the United States* (Rodegerdts et al., 2007) where signalized intersections were replaced with roundabouts. NCHRP Project 3-65 provided data for 1 site in Florida, 3 sites in Colorado, 1 site in South Carolina, 2 sites in Maryland, and 1 site in Vermont for this analysis. A total of 28 sites were used in the evaluation (see Table 5.2).

Table 5.2. Number of sites for treatment group.

Location	Treatment Sites
Colorado	3
Florida	1
Indiana	3
Maryland	2
Michigan	2
New York	11
North Carolina	2
South Carolina	1
Vermont	1
Washington	2
Total	28

Data for reference sites (i.e., signalized intersections similar to those converted to roundabouts) were sought for use in developing the SPFs required for the EB methodology. Unfortunately, such data were difficult to obtain for all states in which treatment sites were identified. Reference sites were identified in Indiana, North Carolina, and New York. Crash, traffic volume, and geometric data were collected for the reference group. The data from Indiana and North Carolina were used to directly calibrate SPFs for the two states. For all other locations, the SPFs previously used in NCHRP Project 3-65 were applied.

In order to investigate the effect of approach speed on safety at the roundabouts, the research team attempted to obtain data from the different States regarding approach speed and/or speed limits. Data on approach speeds or speed limits were not available before the construction of the roundabouts. Speed limit and/or advisory speed data were obtained for the 'after' condition along the major road for each of the study sites. This was called "associated speed" and was based on the approach advisory speed when posted, and when it was not posted, based on the nearest upstream posted speed limit.

Methodology

The primary analysis methodology used was the EB before-after analysis as previously described. The evaluation analyzed the effects of the treatment on crash frequencies for different crash severities before and after the treatment.

The EB analysis attempted to develop CMFs by severity (i.e., PDO vs. fatal/injury vs. total crashes). The reference sites from Indiana and North Carolina were used to develop SPFs for use in the EB before-after analysis. SPFs developed under a previous effort (NCHRP Project 3-65) were used for the other locations.

In addition to treatment and reference sites, Indiana provided data on additional intersections that were newly constructed as roundabouts. It was not possible to include these sites in the before-after analysis because there was no before period. Instead, these data were used as part of a cross-sectional analysis employed to compare the safety performance of similar signalized intersections and roundabouts.

The EB analysis was used to investigate the safety effects of converting signals to roundabouts, but the study was based on a relatively small sample size. To further investigate the treatment, a cross-sectional study was employed, using negative binomial regression models to analyze a larger sample of signalized intersections and roundabouts in Indiana and New York. The cross-sectional analysis was based on a total of 321 site-years, including 42 signalized intersections and 26 roundabouts. Several potential confounding factors were included in the cross-sectional analysis, including traffic volume, area type, number of approaches, and number of approach/roundabout lanes.

Results

The data collected and analyzed for this study show a general safety benefit for converting signalized intersections to roundabouts. The EB before-after analysis indicated a significant reduction in both total and injury crashes. A disaggregate analysis was also conducted to identify differential effects based on specific site characteristics (traffic volume, area type, number of approaches, number of lanes, and associated speed). Regarding the effect on total crashes, the safety benefit of roundabouts appears to decrease as traffic volumes increase. The analysis also suggested that the safety benefit is larger for suburban than for urban conversions and for intersections with four approaches compared to those with three. There was no clear pattern regarding the effectiveness of the roundabout with regard to 'associated speed' (as mentioned earlier, associated speed is the posted advisory speed or the nearest upstream posted speed limit on the major road during the 'after' period). Perhaps the most apparent and telling result of the disaggregate analysis is that the reduction in fatal and injury crashes is substantial and highly significant in all scenarios. This is a result of the basic configuration of a roundabout, where crossing-path and left-turn crashes are physically eliminated.

While the study team employed the EB method to estimate the safety effects of converting signals to roundabouts, the study was based on a relatively small sample size. A cross-sectional analysis, employing negative binomial regression, was conducted to provide support for the EB analysis. Interaction terms were explored during the cross-sectional analysis to further investigate the relationship between traffic volume and the effect of installing roundabouts at signalized intersections. Interaction terms were significant in several of the cross-sectional models for total crashes, indicating differential effects for different volumes. The interaction term was insignificant in the injury-related models, confirming the sustained benefit across the range of traffic volumes.

The results of the cross-sectional analysis are relatively consistent with, and corroborate, the results of the EB analysis. In particular, both the EB and cross-sectional analyses indicated that the effects of the treatment on total crashes may change as AADT changes. Specifically, with respect to total crashes, the safety benefit of roundabouts appears to decrease as traffic volumes increase. The two analysis methods also show a substantial and sustained reduction in fatal and injury crashes for roundabouts across the range of traffic volumes.

Table 5.3. Crash frequency CMFs (and standard deviations) by crash severity for converting signalized intersections to roundabouts.

Condition	Severity	CMF / CMFunction
All	All	0.792 (0.050)#
	All	0.00004*AADT + 0.303
	Injury and Fatal	0.342 (0.058)#
2-lane	All	0.809 (0.061)#
	Injury and Fatal	0.288 (0.065)#
1-lane	All	0.735 (0.086)#
	Injury and Fatal	0.451 (0.115)#
Suburban	All	0.576 (0.053)#
	Injury and Fatal	0.259 (0.066)#
Urban	All	1.150 (0.093)
	Injury and Fatal	0.445 (0.100)#
3 approaches	All	1.066 (0.163)
	Injury and Fatal	0.370 (0.172)#
4 approaches	All	0.759 (0.052)#
	Injury and Fatal	0.338 (0.061)#

Note: #Statistically significant at the 0.05 level
AADT is total intersection AADT
*represents a product, i.e., 0.0004*AADT is the product of 0.0004 and AADT

Based on the relative rigor of the EB method and the reasonableness of the results, the recommended CMFs were taken from the EB analysis. Table 5.3 shows the CMFs and CMFunctions as applicable. For total crashes, the overall CMF was 0.792, but the CMF was found to increase (i.e., approach 1.0) with increasing AADT, and a CMFunction (0.00004*AADT + 0.303) was found to be appropriate. The CMFunction is applicable between a total intersection AADT of 5,300 and 43,000.

Increasing the Change Interval

Description of Treatment and Crash Types of Interest

This analysis examined the safety impacts of modifying the change interval at signalized intersections. The change interval is the time allocated for the yellow and all red phases for a given approach. The basic objective was to estimate the change in crashes. Target crash types considered included:

- All crashes (all types and severities);
- Fatal and injury crashes (all crash types);
- Angle crashes (all severities); and
- Rear-end crashes (all severities).

The change in total crash frequency was analyzed as well as the changes in different crash types and severities, recognizing that the treatment may have a different level of effect on the various types and severities. Appendix C provides the details associated with this evaluation.

Data Used

Geometric, traffic volume, signal timing, and crash data for both treatment and reference sites were acquired from the States of California (1992–2002) and Maryland (1992–2002) to facilitate the analysis. Specifically, data were obtained in California from the cities of San Diego and San Francisco and in Maryland from the counties of Howard and Montgomery. The sites include data for two types of signalized intersections: (1) signalized intersections where the change interval *was* modified during the study period, and (2) signalized intersections where the change interval *was not* modified during the study period. If there were major changes to the geometry or operations during the study period, the sites were excluded.

Methodology

The primary analysis methodology used was the EB before-after analysis as previously described. The evaluation analyzed the effects of the treatment on crash frequencies for different crash types and severities before and after the treatment.

Specifically, the EB analysis was employed to investigate five specific scenarios. Three scenarios were related to various combinations of increasing the yellow and all red time:

- Increasing *both* the yellow and all red phases,
- Increasing the all red phase only, and
- Increasing the yellow phase only.

Two other scenarios were investigated, comparing the total change interval to the ITE recommended practice (see Appendix C for a description of the ITE recommended practice). In both cases, the before condition was represented by signalized intersections where the total change interval was less than the ITE recommended practice. The after period was represented by signalized intersections with the following characteristics:

- Total change interval remains less than the ITE recommended practice and
- Total change interval is greater than the ITE recommended practice.

The analyses attempted to develop CMFs by severity (i.e., fatal/injury vs. total crashes) and by crash types (i.e., total, angle, and rear-end) for both States. The before-after analysis was based on a total of 31 treatment sites as noted in Table 5.4. Reference sites were identified in each jurisdiction to develop SPFs for use in the EB before-after analysis.

In addition to treatment and reference sites, California and Maryland provided data on additional intersections that were signalized throughout the entire study period, but signal timing data were only available for a portion of the study period. These data were combined with the reference sites and data from the treatment sites in a cross-sectional analysis to investigate the individual yellow and all red phases with respect to the ITE recommended practice.

Table 5.4. Number of sites for treatment and reference groups.

Location	Treatment Sites	Reference Sites
Howard County, MD	2	29
Montgomery County, MD	6	38
San Diego, CA	16	36
San Francisco, CA	7	32
Total	31	135

The EB analysis was used to investigate the safety effects of modifications to the *total* change interval with respect to the ITE recommended practice. Due to a relatively small sample size, it was not possible to investigate the individual yellow and all red phases with respect to the ITE recommended practice, using the EB method. Instead, a cross-sectional study was employed, using negative binomial regression models to analyze a larger sample of signalized intersections with various combinations of yellow and all red phases. The cross-sectional analysis was based on a total of 916 site-years where the specific yellow and all red time were known for each year.

Results

In discussing the results, it should be noted that the modifications to the yellow and all red time were not equivalent for all sites. This applies to both the existing conditions and the increase in the yellow and/or all red intervals. For example, several of the intersections did not include an all red phase in the before condition. For sites where both the yellow and all red time were increased, the average increases in the yellow and all red times were 0.8 seconds (minimum of 0.5 seconds and maximum of 1.6 seconds) and 1.2 seconds (minimum of 1.0 second and maximum of 2.0 seconds), respectively. For sites where only the yellow interval was increased, the increase in yellow time was 1.0 second in all the sites. For sites where only the all red interval was increased, the average increase in the all red time was 1.1 seconds (minimum of 1.0 second and maximum of 2.0 seconds). For sites where the total change interval was increased, but still less than the ITE recommended practice, the average increase was 0.9 seconds (minimum was 0 seconds and the maximum was 1.5 seconds). For sites where the total change interval was increased and exceeded the ITE recommended practice, the average increase was 1.6 seconds (minimum was 1.0 second and maximum was 3.0 seconds).

Based on the rigor of the EB method, and the generally insignificant results of the cross-sectional analysis, the recommended CMFs were taken from the EB analysis.

Table 5.5. Crash frequency CMFs (and standard errors) by crash type for increasing the yellow and/or all red interval.

Treatment (Number of sites)	Crash Type	Severity	CMF (S.E. of CMF)	Average Increase in Yellow Interval (min, max)	Average Increase in All Red Interval (min, max)	Number of All Red Intervals = 0 Before Treatment
Increase Yellow and All Red (11 sites)	All	All	0.991 (0.146)	0.8 (0.5, 1.6)	1.2 (1.0, 2.0)	11
	All	Injury & Fatal	1.020 (0.156)			
	Rear-end	All	1.117 (0.288)			
	Angle	All	0.961 (0.217)			
Increase Yellow Only (5 sites)	All	All	1.141 (0.177)	1.0 (1.0, 1.0)	--	1
	All	Injury & Fatal	1.073 (0.216)			
	Rear-end	All	0.934 (0.237)			
	Angle	All	1.076 (0.297)			
Increase All Red Only (14 sites)	All	All	0.798 (0.074)#	--	1.1 (1.0, 2.0)	10
	All	Injury & Fatal	0.863 (0.114)			
	Rear-end	All	0.804 (0.135)			
	Angle	All	0.966 (0.164)			

Note: #Statistically significant at the 0.05 level

The EB before-after analyses indicated a significant reduction in total, injury, and rear-end crashes under various scenarios. Specifically, the EB analysis indicated a statistically significant reduction (at the 0.05 level) in total crashes as a result of (1) increasing the all red phase only, and (2) increasing the total change interval to be less than the ITE recommended practice. Injury crashes were significantly reduced as a result of increasing the total change interval to be less than the ITE recommended practice. Rear-end crashes were significantly reduced as a result of increasing the total change interval to be greater than the ITE recommended practice. The change in angle crashes was statistically insignificant under all scenarios investigated.

Table 5.5 shows the CMFs and standard errors for total, injury, rear-end, and angle crashes as they relate to increasing the yellow and/or all red intervals. Table 5.6 shows similar results for increasing the total change interval. Each table also indicates the average increase in the respective interval, the applicable range of values, and the number of sites without an all red phase in the before period. It is important to note that the number of sites in this evaluation was limited, and hence the results should be treated with due caution.

Change Left-Turn Phasing (From Permissive to Protected-Permissive)

Description of Treatment and Crash Types of Interest

The objective was to estimate the general safety effects of changing from permissive to protected-permissive phasing at signalized intersection approaches. Additionally, a particular goal was to investigate the effects on non-left-turn related crash types and look at the effects of traffic volume, left-turn volume, and number of opposing lanes on the estimated change in crashes.

Table 5.6. Crash frequency CMFs (and standard errors) by crash type for increasing the change interval.

Treatment	Crash Type	Severity	CMF (S.E. of CMF)	Average Increase in Total Change Interval (min, max)	Number of All Red Intervals = 0 Before Treatment
Increase Change Interval (< ITE) (12 sites)	All	All	0.728 (0.077)#	0.9 (0, 1.5)	11
	All	Injury & Fatal	0.662 (0.099)#		
	Rear-end	All	0.848 (0.142)		
	Angle	All	0.840 (0.195)		
Increase Change Interval (> ITE) (15 sites)	All	All	0.922 (0.089)	1.6 (1.0, 3.0)	10
	All	Injury & Fatal	0.937 (0.114)		
	Rear-end	All	0.643 (0.130)#		
	Angle	All	1.068 (0.156)		

Note: #Statistically significant at the 0.05 level

The site types of interest were signalized intersections with left-turn lanes in either urban or rural environments, which have been converted to protected-permissive for at least part of the daily operation.

The following crash types were of interest:

- Total crashes;
- Injury crashes;
- Left-turn crashes;
- Left-turn opposing through crashes (crashes involving a left-turn vehicle and a through vehicle from the opposing approach); and
- Rear-end crashes.

Appendix D provides the details of this evaluation.

Data were acquired from the City of Toronto, Canada, and urban areas in North Carolina, for both treated and untreated signalized intersections.

Data from Toronto

The City maintains a database of signalized intersections including many variables related to geometry (e.g., number of lanes by type by approach), traffic volumes, and crash data. Volume and crash data from 1999 to 2007 were collected.

This database was augmented by querying the crash data for specific crash types and adding left-turn AADTs. A separate database of intersection approaches was also created as it was desired to evaluate left-turn protection improvements at both the intersection-level and approach-level. Intersections at which only one approach had an improvement in left-turn protection were used for the approach-level analysis.

Treated sites were identified in a two-step process. First, an electronic file of work orders for signalized intersections was scanned to identify sites where a change in left-turn phasing was made. Using this list, a subsequent search of hard copy signal timing reports for these sites identified those where the left-turn phasing on at least one approach was changed to either protected-permissive or fully protected at any time of day.

The group of 59 intersection level and 46 approach level treatment sites represented a range of before and after conditions with regard to left-turn phasing options. Hence, sites were categorized based on the predominant phasing system.

A reference group of untreated signalized intersections was identified to match the treatment sites based on site characteristics, including number of approaches, presence of left-turn lanes, and traffic volumes.

Data from North Carolina

In North Carolina, data were available for 19 four-leg intersections that experienced a change in left-turn phasing on at least one leg of the intersection. All these 19 sites were in urban areas. The change in phasing was one of the following three categories:

- From Permissive to Protected-Permissive (12 intersections);
- From Permissive or Protected-Permissive to Protected (5 intersections); and
- From Protected to Permissive or Protected-Permissive on at least 2 legs (2 intersections).

Since the number of intersections in the last two categories is very limited, results are provided here only for the first category of sites, i.e., for intersections where the phasing was changed from permissive to protected-permissive phasing in at least one leg of the intersection. All the treatment locations had a left-turn lane on the major legs of the intersection.

Unlike Toronto, crash data by approach were not available in North Carolina without a manual review of crash reports. So, in North Carolina the analysis was focused at the intersection level.

Methodology

The methodology applied was the empirical Bayes (EB) before-after study, which was described at the beginning of this chapter. Further details about the methodology are provided in Appendix D.

A number of SPFs were calibrated as follows:

- SPFs were calibrated separately for Total, Injury, Left-turn, Left-turn-opposing through, and Rear-end crashes.
- SPFs at the intersection-level and approach-level were separately developed for Toronto. For North Carolina, SPFs were estimated at the intersection-level.
- For the City of Toronto, separate models were also developed for intersections without and with one-way roads.

Results

The results are shown in Tables 5.7 and 5.8. Approach level results are based on data from Toronto. Intersection level results are based on data from both Toronto and North

Table 5.7. Approach level results (Toronto).

Crash Type	CMF (s.e.)
All	1.077 (0.037) #
Injury and Fatal	1.150 (0.056) #
LTOPP	0.776 (0.098) #
Rear end	1.103 (0.118)

Note: #Statistically significant at the 0.05 level

Table 5.8. Intersection level results (Toronto and North Carolina combined).

Crash Type	Grouping	No. Sites	CMF (s.e.)
All	All sites	71	1.033 (0.023)
	1 treated approach	50	1.085 (0.028) #
	>1 treated approach	21	0.945 (0.040)
Injury and Fatal	All sites	71	0.958 (0.037)
	1 treated approach	50	1.005 (0.045)
	>1 treated approach	21	0.878 (0.062) #
LTOPP	All sites	71	0.858 (0.056) #
	1 treated approach	50	0.919 (0.069)
	>1 treated approach	21	0.762 (0.088) #
Rear end	All sites	71	1.063 (0.038)
	1 treated approach	50	1.091 (0.046) #
	>1 treated approach	21	1.021 (0.062)

Note: #Statistically significant at the 0.05 level

Carolina (all intersections were four-leg). Intersection level results are provided for two categories of intersections: intersections where only 1 approach was treated and intersections where more than 1 approach was treated. Among the 21 intersections where more than 1 approach was treated, 17 of them had 2 approaches treated, 2 of them had 3 approaches treated, and 2 of them had 4 approaches treated.

At both intersection and approach levels, the results indicate substantial benefits for the target crash type, left-turn opposing involving a left-turn vehicle and a through vehicle from the opposing approach (LTOPP). As expected, the benefit at the intersection level is greater at intersections where more than one approach is treated.

One of the fundamental questions the study was expected to answer was the extent to which the decrease in target crashes may be offset by a compensating increase in a non-target crash type such as rear-end. At both the intersection and approach levels, there were small percentage increases in rear-end crashes. The actual (rather than percentage) increase in rear-end crashes was of the order of 60–75% of the decrease in left-turn opposing crashes. Disaggregation of the effects by AADT, either total entering or left turn, did not reveal any trend. This may be because the intersections did not have a wide enough distribution of these variables.

In summary, it may be concluded that in estimating the net safety benefit of left-turn protection, consideration must be given to the increase in non-target crashes as well as the decrease in target crashes. It is recommended that the intersection level results for Toronto and North Carolina be used to refine the current CMF for changing from permissive to protected-permissive in the Highway Safety Manual. Further research could investigate the specific safety effects of changing left-turn phasing during particular times of day (e.g., peak versus off-peak) and days of the week (e.g., weekday versus weekend). Another area of research is to investigate the effect of combined left-turn treatments: adding a left-turn lane and changing the left-turn phase at the same time. There were a few sites in North Carolina where such combined treatments were implemented, but they were not sufficient to conduct an evaluation.

Installation of Flashing Yellow Arrow for Permissive Left Turns

Description of Treatment and Crash Types of Interest

The objective was to evaluate the safety impacts due to the installation of flashing yellow arrow (FYA) for permissive left-turn movements. The intent of the flashing yellow arrow is to avoid the confusion for drivers turning left on a permissive circular green signal indication who may assume that the left turn has the right of way over opposing traffic, especially under some geometric conditions. The following primary target crash types were considered:

- Total intersection crashes;
- Total left-turn crashes; and
- Total left-turn crashes from the FYA treated approach (this crash type was examined in Washington and Oregon, but not in North Carolina).

Appendix E provides the details of this evaluation.

Data Used

The data included 5 locations in Kennewick, Washington, 34 locations from cities in Oregon, and 16 locations from urban areas in North Carolina. In Kennewick, FYA was introduced in these five locations between 2004 and 2006. Four of these locations had protected-permissive phasing before FYA was introduced and one location had permissive phasing before FYA was introduced. The City of Kennewick provided many variables related to geometry (e.g., number of lanes by type and approach), traffic volumes in the form of major and minor road AADTs, peak hour left-turn movements, and crash data.

In Oregon, the city of Beaverton provide data for 15 sites, the city of Gresham provided data for 6 sites, the city of Oregon City provided data for 3 sites, and the city of Portland provided data for 10 sites with FYA. Twenty-four of these locations had protected phasing before the FYA was introduced, 3 of them had permissive phasing, 3 of them had protected-permissive phasing, and 4 had prohibited left turns. The four cities in Oregon were able to provide many variables related to geometry (e.g., number of lanes by type by approach) and crash data. Left-turn volumes were not available for the Oregon locations.

In North Carolina, in all 16 intersections that were evaluated, flashing yellow arrow (FYA) was introduced in two out of the four legs. The changes were divided into the following three categories:

- Change from protected phasing to FYA protected-permissive in 2 legs of the intersection (5 intersections);
- Change from doghouse (conventional protected-permissive) to FYA protected-permissive in 1 leg and from permissive to FYA protected-permissive in another leg (5 intersections); and
- Change from doghouse (conventional protected-permissive) to FYA protected-permissive in 2 legs of the intersection (6 intersections).

In North Carolina, turning volumes were not available at the treatment or reference sites. However, data on major and minor road AADT were available for the treatment and reference sites.

Methodology

For the cities in Washington and Oregon, data on reference sites was limited in most of the jurisdictions, and hence the EB methodology could not be applied with the required rigor. The cities did indicate that the sites were not selected based on crash history, but some evidence of an absence of regression-to-the-mean was still desired. The investigation of potential regression-to-the-mean involved aggregating the crash data over all treatment sites and plotting the totals for each year before treatment (e.g., 1 year before treatment, 2 years before treatment, 3 years before treatment, etc.). This test was conducted for each city separately, and for each, it was concluded that there was no evidence for regression-to-the-mean notwithstanding the natural randomness of crash counts. The methodology applied combined some aspects of the EB and Comparison Group approaches. Adjustments for changes in AADT were done by using an SPF calibrated for Kennewich, WA, which had sufficient sites for this purpose, and then dividing the SPF estimate using the after period AADT by the SPF estimate using the before period AADT. The adjustment for time trends was determined using a group of comparison sites by dividing the sum of SPF predictions per year for the after periods by the sum of SPF predictions per year in the before period for the comparison group.

In North Carolina, the state of the art EB method could be applied. Safety performance functions were estimated using a reference group of 49 intersections in North Carolina. Further detail about the methodology is provided in Appendix E.

Results

Crash Modification Factors are provided in Table 5.9 for total intersection crashes and total intersection left-turn crashes (the common crash type investigated in the 3 states). Results are provided for three categories of changes depending on the left-turn phasing of the converted legs before FYA was introduced:

- Intersections where the converted legs had either permissive or protected-permissive phasing in the before period, and at least one of the legs had permissive phasing. This group includes 9 four-leg intersections (total of 36 legs). A total of 20 legs were treated with FYA: 15 of the treated legs had permissive phasing in the before period while 5 of the treated legs had protective-permissive phasing in the before period.
- Intersections where the converted legs only had protected-permissive phasing in the before period. This group included 1 3-leg and 12 4-leg intersections (total of 51 legs). A total of 27 legs were treated with FYA; all of them had protected-permissive phasing in the before period.

Table 5.9. CMFs and standard errors for flashing yellow arrow installation.

Left-Turn Phasing Before (sites) (legs treated)	Crash Type	CMF (S.E.)
Permissive or combination of permissive and protected-permissive (at least 1 converted leg was permissive in the before period) (9 sites) (20 legs treated)	Total Intersection Crashes	0.753 (0.094) #
	Total Intersection Left-Turn Crashes	0.635 (0.126) #
Protected-Permissive (all converted legs had protected-permissive in the before period) (13 sites) (27 legs treated)	Total Intersection Crashes	0.922 (0.104)
	Total Intersection Left-Turn Crashes	0.806 (0.146)
Protected (all converted legs had protected in the before period) (29 sites) (56 legs treated)	Total Intersection Crashes	1.338 (0.097) #
	Total Intersection Left-Turn Crashes	2.242 (0.276) #

Note: #Statistically significant at the 0.05 level

- Intersections where the converted legs only had protected only phasing in the before period. This group included 5 3-leg intersections and 24 4-leg intersections (total of 111 legs). A total of 56 legs were treated with FYA; all of them had protected only phasing in the before period.

Intersections in the first group experienced reductions in total intersection crashes and total intersection left-turn crashes that were statistically significant at the 0.05 level. Intersections in the second group experienced a smaller reduction that was not statistically significant at the 0.05 level. As expected, on the basis of individual results and those in Noyce et al. (2007), intersections in the third group (with protected only phasing in the before period) experienced significant increases in total and left-turn crashes. As Noyce et al. commented, the change in signal phasing may have had a more significant impact on safety than the change to FYA permissive indication. Collectively, these results indicate that the largest benefit can be found at sites where at least one of the converted legs had permissive only operation before the FYA was implemented with protected-permissive operation. It is important to note that the number of sites in the first two groups was limited, and hence the individual results should be treated with due caution.

Most of the sites had 2 legs that were converted (except for the few 3-leg intersections in the sample). So, it was not possible to specifically investigate the relationship between the number of legs that are treated and the associated safety benefits for left-turn crashes. This could be an area for future research. Another area of future research is an investigation into the effect of left-turn volume and opposing through volume.

CHAPTER 6

Compilation of CMFs

This Chapter includes Tables 6.1 through 6.5 which show the CMFs that were developed for each treatment that was evaluated in this study. For each treatment, the study methodology and a description of the sites used in the study (along with the range of AADT values) are provided along with the CMFs and the standard error of the CMFs.

Table 6.1. Evaluation of installing dynamic signal warning flashers.

TREATMENT: Install Dynamic Signal Warning Flashers

METHODOLOGY: Cross-Sectional Regression Model

REFERENCE: NCHRP 17-35 Final Report

STUDY SITES:

- Data from Virginia and Nevada were used to develop the recommended CMFs for Dynamic Signal Warning Flashers (DSWF).
- 15 intersections with DSWF in Virginia and 15 intersections with DSWF in Nevada were used in the cross-sectional models (along with intersections without DSWF).
- For intersections with DSWF in Virginia, the average major road AADT was 18,729 (minimum major road AADT was 7,500 and maximum major road AADT was 33,000) and the average minor road AADT was 2,408 (minimum minor road AADT was 40 and the maximum minor road AADT was 5,000).
- For intersections with DSWF in Nevada, the average major road AADT was 36,329 (minimum major road AADT was 9,765 and maximum major road AADT was 99,000) and the average minor road AADT was 7,263 (minimum minor road AADT was 1,300 and the maximum minor road AADT was 20,100).

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Crash Type and Severity	Sites with DSWF	CMF (S.E. of CMF)
All Crashes	30	0.814 (0.062)#
Rear-End Crashes		0.792 (0.079)#
Angle Crashes		0.745 (0.086)#
Injury and Fatal Crashes		0.820 (0.083)#
Heavy Vehicle Crashes		0.956 (0.177)

Statistically significant at the 0.05 level (based on ideal standard errors)

COMMENTS:

- The analysis included different methods: cross-sectional models, before-after with comparison group, and before-after EB methods.
- The results from the cross-sectional models were found to be the most reliable.

Table 6.2. Evaluation of converting a signalized intersection to a roundabout.

Treatment: Convert Signalized Intersection to Roundabout

METHODOLOGY: Before-After EB

REFERENCE: NCHRP Project 17-35

STUDY SITES:

• Among the 28 sites, 3 were from Colorado, 1 from Florida, 3 from Indiana, 2 from Maryland, 2 from Michigan, 2 from North Carolina, 11 from New York, 1 from South Carolina, 1 from Vermont, and 2 from Washington.

• 16 roundabouts were 2 lane and the remaining 12 roundabouts were single lane. 15 roundabouts were from suburban areas and the remaining 13 were from urban areas. 6 of the roundabouts were 3 leg and the remaining 22 were 4 leg.

• In the before period, the average total intersection AADT was 18,529 (minimum AADT was 5,322 and maximum AADT was 43,123).

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Condition, Crash Type, and Severity	No. of Improved Sites	CMF (S.E. of CMF)
All Crashes	28	0.792 (0.050)#
All Crashes (CMFunction)		0.00004*AADT+0.303
Injury and Fatal Crashes		0.342 (0.058)#
2 lane roundabouts (all crashes)	16	0.809 (0.061)#
2 lane roundabouts (Injury and Fatal Crashes)		0.288 (0.065)#
1 lane roundabouts (all crashes)	12	0.735 (0.086)#
1 lane roundabouts (Injury and Fatal Crashes)		0.451 (0.115)#
Suburban (all crashes)	15	0.576 (0.053)#
Suburban (Injury and Fatal Crashes)		0.259 (0.066)#
Urban (all crashes)	13	1.150 (0.093)
Urban (Injury and Fatal Crashes)		0.445 (0.100)#
3 leg roundabouts (all crashes)	6	1.066 (0.163)
3 leg roundabouts (Injury and Fatal Crashes)		0.370 (0.172)#
4 leg roundabouts (all crashes)	22	0.759 (0.052)#
4 leg roundabouts (Injury and Fatal Crashes)		0.338 (0.061)#

COMMENTS:
• # Statistically significant at the 0.05 level.
• For total crashes, the average CMF was 0.792. However, this CMF was found to be a function of AADT and so a CMFunction was estimated. The CMFunction is valid between total intersection AADT of about 5,300 to about 43,000.
• For injury crashes, the CMF was not found to be a function of AADT.
• * represents a product, i.e., 0.00004*AADT is the product of 0.00004 and AADT.

Table 6.3. Evaluation of increasing signal change interval.

TREATMENT: Increase Signal Change Interval

METHODOLOGY: Before-After EB

REFERENCE: NCHRP Project 17-35 final report

STUDY SIDES:

• The sample included 2 sites from Howard County, Maryland, 6 sites from Montgomery County, Maryland, 16 sites from San Diego, California, and 7 sites from San Francisco, California.

• In the before period, the average major road AADT was 17,417 (minimum major road AADT was 5,950 and maximum major road AADT was 31,600) and the average minor road AADT was 8,484 (minimum minor road AADT was 2,650 and the maximum minor road AADT was 20,225).

• Modifications to the yellow and all red time were not equivalent for all sites. For sites where both the yellow and all red time were increased, the average increases in the yellow and all red times were 0.8 seconds and 1.0 seconds, respectively. For sites where only the yellow interval was increased, the average increase in the yellow interval was 1.0 seconds. For sites where only the all red interval was increased, the average increase in the all red time was 1.1 seconds. For sites where the total change interval was increased, but still less than the ITE recommended practice, the average increase was 0.9 seconds. For sites where the total change interval was increased and exceeded the ITE recommended practice, the average increase was 1.6 seconds.

• The sample of sites used in this evaluation is limited. So these results should be used with due caution.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Treatment, Crash Type, and Severity	No. of Treated Sites	CMF (S.E. of CMF)
Increase Yellow and All Red (All)	11	0.991 (0.146)
Increase Yellow and All Red (Injury & Fatal)		1.020 (0.156)
Increase Yellow and All Red (Rear end)		1.117 (0.288)
Increase Yellow and All Red (Angle)		0.961 (0.217)
Increase Yellow Only (All)	5	1.141 (0.177)
Increase Yellow Only (Injury & Fatal)		1.073 (0.216)
Increase Yellow Only (Rear end)		0.934 (0.237)
Increase Yellow Only (Angle)		1.076 (0.297)
Increase All Red Only (All)	14	0.798 (0.074)#
Increase All Red Only (Injury & Fatal)		0.863 (0.114)
Increase All Red Only (Rear end)		0.804 (0.135)
Increase All Red Only (Angle)		0.966 (0.164)
Increase Change Interval (< ITE) (All)	12	0.728 (0.077)#
Increase Change Interval (< ITE) (Injury & Fatal)		0.662 (0.099)#
Increase Change Interval (< ITE) (Rear end)		0.848 (0.142)
Increase Change Interval (< ITE) (Angle)		0.840 (0.195)
Increase Change Interval (> ITE) (All)	15	0.922 (0.089)
Increase Change Interval (> ITE) (Injury & Fatal)		0.937 (0.114)
Increase Change Interval (> ITE) (Rear end)		0.643 (0.130)#
Increase Change Interval (> ITE) (Angle)		1.068 (0.156)

Statistically significant at the 0.05 level.

Table 6.4. Evaluation of changing left-turn phase from permissive to protected-permissive.

TREATMENT: Change Left-Turn Phase (from Permissive to Protected-Permissive)

METHODOLOGY: Before-After EB

REFERENCE: NCHRP 17-35 Final Report

STUDY SITES:

• 59 intersections from Toronto and 12 from North Carolina. All of them were four leg intersections from urban areas.

• In Toronto, in the before period, the average major road AADT was 35,267 (minimum was 14,489 and maximum was 74,990) and the average minor road AADT was 18,096 (minimum was 1,466 and maximum was 42,723).

• In North Carolina, in the before period, the average major road AADT was 12,302 (minimum was 4,857 and maximum was 18,766) and the average minor road AADT was 5,124 (minimum was 1,715 and maximum was 9,300).

COMMENTS:

• It is important to note that left-turn phasing was not constant throughout the day for most of the sites (especially in Toronto), and hence, the sites were categorized based on the predominant phasing system.
• Among the 21 sites where more than 1 approach was treated, 17 of them had 2 approaches treated, 2 of them had 3 approaches treated, and 2 of them had 4 approaches treated.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Number of Treated Approaches and Crash Type at Intersection Level	No. of Sites	CMF (S.E. of CMF)
Change from Permissive or Permissive/Protected		
All sites (all crashes)	71	1.031 (0.022)
1 treated approach (all crashes)	50	1.081 (0.027)#
>1 treated approach (all crashes)	21	0.958 (0.036)
All sites (injury and fatal crashes)	71	0.962 (0.035)
1 treated approach (injury and fatal crashes)	50	0.995 (0.043)
>1 treated approach (injury and fatal crashes)	21	0.914 (0.055)
All sites (left-turn opposing through crashes)	71	0.862 (0.050)#
1 treated approach (left-turn opposing through crashes)	50	0.925 (0.067)
>1 treated approach (left-turn opposing through crashes)	21	0.787 (0.072)#
All sites (rear-end crashes)	71	1.075 (0.036)#
1 treated approach (rear-end crashes)	50	1.094 (0.045)#
>1 treated approach (rear-end crashes)	21	1.050 (0.059)

• # Statistically significant at the 0.05 level.

Table 6.5. Evaluation of implementing protected-permissive phasing with flashing yellow arrow for the permissive phase.

TREATMENT: Implement Protected-Permissive Phasing with Flashing Yellow Arrow for the Permissive Phase

METHODOLOGY: Combination of EB before-after and Comparison Group

REFERENCE: NCHRP 17-35 Final Report

STUDY SITES:

- Five locations from Kennewich, WA, and 34 locations from Oregon were included in this evaluation. In Oregon, City of Beaverton provide data for 15 sites, City of Gresham provided data for 6 sites, City of Oregon City provided data for 3 sites, and City of Portland provided data for 10 sites with FYA. Data were obtained from 16 sites in urban areas from North Carolina.

- For the sites from Kennewich, WA, the average major road AADT in the before period was 18,568 (minimum was 11,443 and maximum was 22,756) and the average minor road AADT was 6,729 (minimum was 3,020 and maximum was 11,765).

- For the sites from Oregon, the average major road AADT in the before period was 22,490 (minimum was 8,260 and maximum was 32,350) and the average minor road AADT in the before period was 3,455 (minimum was 780 and maximum was 10,620).

- For the sites from North Carolina, the average major road AADT in the before period was 24,206 (minimum was 9,100 and maximum was 43,000), and the average minor road AADT in the before period was 5,048 (minimum was 660 and maximum was 11,350).

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Before Period and Crash Type	No. of Sites	CMF (S.E. of CMF)
Permissive or combination of permissive and protected-permissive (at least 1 converted leg was permissive in the before period)		
Total intersection crashes	9	0.753 (0.094)#
Intersection left-turn crashes		0.635 (0.291)#
Protected-Permissive (all converted legs had protected-permissive in the before period)		
Total intersection crashes	13	0.922 (0.104)
Intersection left-turn crashes		0.806 (0.146)
Protected (all converted legs had protected in the before period)		
Total intersection crashes	29	1.338 (0.097)#
Intersection left-turn crashes		2.242 (0.276)#

Statistically significant at the 0.05 level.

COMMENTS:

- The sample for the conversion from permissive or permissive/protected to FYA is limited. So these results should be used with due caution.

CHAPTER 7

Conclusions

The importance of reliable estimates of the effectiveness of safety improvements has become more apparent as safety decisions have become more data-driven and safety analysis has become more sophisticated. Specifically, SAFETEA-LU was signed into law in 2005, creating a positive agenda for increased safety on our highways by nearly doubling the available funds for infrastructure safety. With the increased funding, SAFETEA-LU also required strategic highway safety planning (i.e., data-driven decision-making), which increased the need for information to quantify the effects of safety strategies.

The CMF is one important piece of information to support a data-driven decision-making process. CMFs indicate the expected effectiveness of a given strategy and allow agencies to compare the relative benefits of multiple treatments. Programs such as the Highway Safety Improvement Program (HSIP) necessitate the use of CMFs in the prioritization of funding for safety improvements. Additionally, several new safety tools such as the Highway Safety Manual and SafetyAnalyst incorporate CMFs in their safety analysis process.

Several large separate efforts have been undertaken to develop *reliable* estimates of the safety effectiveness of improvements. As a result of NCHRP Project 17-18(3), a series of implementation guides was developed and subsequently published as part of the *NCHRP Report 500* series. Each volume of the series addresses one of the 22 emphasis areas from the National AASHTO Strategic Highway Safety Plan, and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. Expected effectiveness (i.e., a CMF) was provided for some of the strategies, but many strategies did not have (and still do not have) an associated CMF. In some cases, the existing information related to the effectiveness was not based on a rigorous evaluation.

The objective of this project was to evaluate the safety impact of selected strategies from *NCHRP Report 500, Volume 12: A Guide for Reducing Crashes at Signalized Intersections* and develop reliable CMFs. CMFs were developed for the following five treatments at signalized intersections:

- Installation of Dynamic Signal Warning Flashers,
- Convert Signalized Intersection to Roundabout,
- Increase Clearance Interval,
- Change Left-Turn Phasing from Permissive to Protected-Permissive, and
- Install Flashing Yellow Arrow.

Based on the evaluations, CMFs and measures of uncertainty are provided in this report. Each strategy and evaluation is also described with respect to methodology, sample size, and general applicability. While CMFs for five strategies were developed as part of this effort, there still remain several strategies in the *NCHRP Report 500* series without quality CMFs. To help identify priority strategies for future research, the research team also conducted a survey of practitioners to determine the CMFs that are of greatest need to them. Based on the priority ratings from practitioners and an assessment of the current status of CMF knowledge of specific treatments, the following list identifies treatments at signalized intersections that may be considered as high priority for future research. The critical component for future evaluations is the agencies who are currently installing these strategies and the related data. Rigorous evaluations are only possible when accurate and reliable data are available for the strategy of interest.

- Install left-turn lane along with changes to left-turn phasing;
- Coordinate signals along corridors;
- Provide split phasing;

- Lengthen existing left-turn lanes;
- Delineate turn path inside an intersection;
- Utilize crossing guards for school children;
- Replace standard signal heads with 12″ signal heads;
- Restrict turning movements;
- Install pedestrian countdown signals; and
- Install additional signal heads.

In addition to the development of quality CMFs, it is necessary for the practitioner to apply the CMFs appropriately. Users are encouraged to consider the quality and applicability of CMFs when selecting a CMF for use in the decision-making process. Users are also encouraged to consider the measures of uncertainty (e.g., standard error or standard deviation) associated with a given CMF.

References

Antonucci, N. D., Hardy, K. K., Slack, K. L., Pfefer, R., and Neuman, T. R. (2004), *NCHRP Report 500, Volume 12: A Guide for Reducing Collisions at Signalized Intersections.* Transportation Research Board of the National Academies, Washington, DC.

Berg, W. D., Kaub, A. R., and Belscamper, B. W. (1986), "Case Study Evaluation of the Safety and Operational Benefits of Traffic Signal Installation," *Transportation Research Record* 1057, pp. 58–64. National Research Council, Washington DC.

Chen, G., W. Meckle, and J. Wilson, "Speed and safety effect of photo radar enforcement on a highway corridor in British Columbia," *Accident Analysis and Prevention,* Vol. 34, 2002, pp. 129–138.

Council, F. M., Persaud, B., Eccles, K., Lyon, C., and Griffith, M. (2005), "Safety Evaluation of Red Light Cameras," FHWA Report NO. FHWA-HRT-05-048, Federal Highway Administration, April 2005.

Cunningham, C. M., J. E. Hummer, and J. P. Moon, "An evaluation of the safety effects of speed enforcement cameras in Charlotte, NC," Institute of Transportation Research and Education, NC State University, Raleigh, NC, Final Report, October 2005.

Donnell, E., Shankar, V., and Porter, R. J., (2009), "Analysis of the Safety Effect for Presence of Roadway Lighting," Unpublished report prepared for the Transportation Research Board on NCHRP Project 5-19.

Elvik, R. and Vaa, T. (2004), *The Handbook of Road Safety Measures,* Elsevier Science, Oxford, UK.

Gross, F., Persaud, B., and Lyon, C. (2010), *A Guide to Developing Quality Crash Modification Factors,* Report FHWA-SA-10-032, Federal Highway Administration.

Harkey, D., et al. (2008), *NCHRP Report 617: Crash Reduction Factors for Traffic Engineering and ITS Improvements,* Transportation Research Board of the National Academies. Washington, DC.

Harwood, D. W., Council, F. M., Hauer, E., Hughes, W. E., and Vogt, A. (2000), "*Prediction of the Expected Safety Performance of Rural Two-Lane Highways,*" FHWA-RD-99-207, Federal Highway Administration.

Harwood, D. W., Bauer, K. M., Potts, I. B., Torbic, D. J., Richard, K. R., Kohlman Rabbani, E. R., Hauer, E., and Elefteriadou, L. (2002), *Safety Effectiveness of Intersection Left- and Right-Turn Lanes,* FHWA-RD-02-089, Federal Highway Administration.

Hauer, E. (1997), *Observational Before-After Studies in Road Safety,* Elsevier Science.

Hauer, E. (2004), Statistical Road Safety Modeling, *Transportation Research Record* 1897, pp. 81–87. Transportation Research Board of the National Academies. Washington, DC.

Karagheuzoff, T. (1972), Traffic Engineering Succeeds in New York City, *ITE Traffic Engineering,* September 1972, pp. 18–27.

Khattak, A., Naik, B., and Kannan, V. (2004), *Safety Evaluation of Left-Turn Lane Width at Intersections with Opposing Left-Turn Lanes,* Contract Number SPR-P1(03)P554, Nebraska Department of Roads.

Lipinski, M. E. and Wortman, R. H. (1976), "Effect of Illumination on Rural At-Grade Intersection Accidents," *Transportation Research Record 611,* 25–27. National Research Council. Washington, DC.

Lyon, C., Haq, A., Persaud, B., and Kodama, S. T. (2005), Safety Performance Functions for Signalized Intersections in Large Urban Areas: Development and Application to Evaluation of Left-Turn Priority Treatment, *Transportation Research Record* 1908, pp. 165–171, 2005. Transportation Research Board of the National Academies. Washington, DC.

Miller, J. S., Khandelwal, R., and Garber, N. J. (2006), Safety Impacts of Photo-Red Enforcement at Suburban Signalized Intersections: An Empirical Bayes Approach, *Transportation Research Record* 1969, pp. 27–34. Transportation Research Board of the National Academies. Washington, DC.

Mountain, L., W. Hirst, and M. Maher, "A Detailed Evaluation of the Impact of Speed Cameras on Safety," *Traffic Engineering and Control,* September 2004, pp. 280–287.

Noyce, N. A., C. R. Bergh, J. R. Chapman (2007), *NCHRP Web-Only Document 123: Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation, NCHRP Project* 20-7/Task 222. Transportation Research Board of the National Academies. Washington, DC.

Persaud, B., E. Hauer, R. A. Retting, R. Vallurupalli, and K. Mucsi. Crash Reductions Related to Traffic Signal Removal in Philadelphia. In *Accident Analysis and Prevention,* Vol. 29(6), 1997, pp. 803–810.

Persaud, B. N. (2001), *NCHRP Synthesis 295: Statistical Methods in Highway Safety Analysis,* Transportation Research Board of the National Academies. Washington, D.C.

Persaud, B. N., Retting, R., Garder, P. and Lord, D. (2001), "Safety Effect of Roundabout Conversions in the U.S.: Empirical Bayes Observational Before-After Study," *Transportation Research Record 1757.* Transportation Research Board of the National Academies. Washington, DC.

Persaud, B., F. M. Council, C. Lyon, K. Eccles, and M. Griffith (2005), Multijurisdictional Safety Evaluation of Red Light Cameras, *Transportation Research Record* 1922, pp. 29–37. Transportation Research Board of the National Academies. Washington, DC.

Persaud, B., Lyon, C., Eccles, K., Lefler, N., and Gross, F. (2009), *Safety Evaluation of Offset Improvements for Left-Turn Lanes,* Report FHWA-HRT-09-035, Federal Highway Administration.

Polanis, S. (2001), "Low Cost Safety Improvements: An Update," presented at the *2001 Annual Meeting of the Institute for Transportation Engineers,* Chicago.

Polanis, S. (2002), "Improving Intersection Safety Through Design and Operations," presented at *2002 Spring Meeting of the Institute for Transportation Engineers,* Palm Harbor, Florida.

Preston, H. and Schoenecker, T. (1999), *Safety Impacts of Street Lighting at Isolated Rural Intersections,* Final Report 1999-17, Minnesota Department of Transportation.

Preusser, D. F., Leaf, W. A., DeBartolo, K. B., Blomberg, R. D., and Levy, M. M. The Effect of Right-Turn-on-Red on Pedestrian and Bicyclist Accidents, *Journal of Safety Research,* Vol. 13, pp. 45–55, 1982.

Rakha, H., Medina, A., Sin, H., Dion, F., Van Aerde, M., and Jenq, J. (2000), "Traffic Signal Coordination Across Jurisdictional Boundaries: Field Evaluation of Efficiency, Energy, Environmental, and Safety Impacts," *Transportation Research Record* 1727, pp. 42–51. Transportation Research Board of the National Academies. Washington, DC.

Retting, R. and Kyrychenko, S. (2001), *Crash Reductions Associated with Red Light Enforcement in Oxnard, California,* Insurance Institute for Highway Safety, April 2001.

Retting, R. A., J. F. Chapline, and A. F. Williams. Changes in Crash Risk Following Re-timing of Traffic Signal Change Intervals. In *Accident Analysis and Prevention,* Vol. 34, 2002, pp. 215–220.

Rodegerdts, L., et al. (2007), *NCHRP Report* 572: *Roundabouts in the United States,* Transportation Research Board of the National Academies, Washington, D.C.

SafeLight. Charlotte. Reviewed from data and reports on its website, http://www.ci.charlotte.nc.us/citransportation/programs/safelight.htm

Sayed, T., Abdelwahab, W. and Nepomuceno, J. (1998), "Safety Evaluation of Alternative Signal Head Design," *Transportation Research Record 1635,* 140–146. Transportation Research Board of the National Academies. Washington, DC.

Sayed, T., Vahidi, H. and Rodriguez, F. (1999), "Advance Warning Flashers: Do They Improve Safety," *Transportation Research Record 1692,* 30–38. Transportation Research Board of the National Academies. Washington, DC.

Sayed, T., El Esawey, L. and J. Pump. (2007), Evaluating the Safety Impacts of Improving Signal Visibility at Urban Signalized Intersections. Transportation Research Board 2007 Annual Meeting CDROM, Paper 07-0135.

Shin, K., and Washington, S. (2006), The Impact of Red Light Cameras on Safety in Arizona, Presented at the 2006 Annual Meeting of the Transportation Research Board, Washington, D.C.

Souleyrette, R. R., O'Brien, M. M., McDonald, T., Preston, H. and Storm, R. (2004), *Effectiveness of All-Red Clearance Interval on Intersection Crashes,* Report MN/RC-2004-26, Minnesota Department of Transportation.

Walker, F. W. and Roberts, S. E. (1976), "Influence of Lighting on Accident Frequency at Highway Intersections," *Transportation Research Record 562,* 73–78.

Wiley, T. T. (1959), Traffic Engineering in The City of New York, *ITE Traffic Engineering,* September 1959, pp. 11–13, 50.

Xu, L., "Right Turns Followed by U-Turns Versus Direct Left Turns: A Comparison of Safety Issues." *ITE Journal,* Vol. 71(11), 2001, pp. 36–43.

Zaidel, D. M. and Hocherman, I. (1987), "Safety of Pedestrian Crossings at Signalized Intersections," *Transportation Research Record 1141.* Transportation Research Board of the National Academies, Washington, DC.

Zegeer, C. V., Opiela, K. S. and Cynecki, M. J. (1982), "Effect of Pedestrian Signals and Signal Timing on Pedestrian Accidents", *Transportation Research Record 847,* 62–72. Transportation Research Board of the National Academies. Washington, DC.

Zegeer, C. V., Stewart, J. R., Huang, H. and Lagerway, P. (2001), "Safety Effects of Marked Versus Unmarked Crosswalks at Uncontrolled Intersections," *Transportation Research Record 1773,* 56–68. Transportation Research Board of the National Academies. Washington, DC.

Abbreviations and acronyms used without definitions in TRB publications:

AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	Air Transport Association
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation