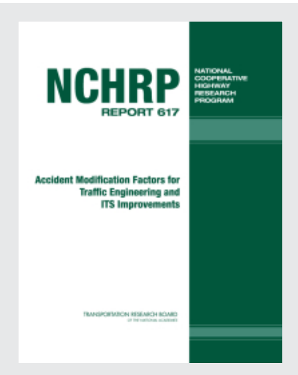

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Accident Modification Factors for Traffic Engineering and ITS Improvements

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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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FOREWORD

By Charles W. Niessner
Staff Officer
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This report presents the findings of a research project to develop accident modification factors (AMFs) for traffic engineering and ITS improvements. AMFs 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.

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

Currently, AMFs 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. AMFs 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). AMFs are also key components of the latest safety-estimation tools and procedures, including the Interactive Highway Safety Design Model and the procedures now being developed for the Highway Safety Manual.

Even though accurate AMFs are critically important to states and municipalities in their attempts to achieve the greatest return on investment when choosing among alternative safety treatments, there is no accepted standard set of AMFs. This is because the accuracy and reliability of many published AMFs is questionable, and no AMFs exist for many important safety treatments. The sources of the problem include the lack of AMFs for newer treatments and for common combinations of treatments. AMFs also vary with factors such as traffic volume, and in some evaluations, crash migration and spillover effects that result from some treatments are not accounted for in the AMF. However, the major problems with many existing AMFs result from the poor data and poor evaluation methods used in their development. Often, AMFs are based on simple before-after studies of high-crash locations, and the results can be very biased toward overestimating accident reductions.

Under NCHRP Project 17-25, "Crash Reduction Factors for Traffic Engineering and ITS Improvements," researchers at the University of North Carolina Highway Safety Research Center developed or modified AMFs for a number of high-priority treatments. The research team reviewed the literature and ongoing research related to AMF development and prepared an initial list of treatments deemed to be important in safety decisions. A survey of state DOTs expanded the list to 100 treatments. The determination of which of the many possible AMFs should be developed or improved was based on several factors, including the results of the state survey, the measure of crash-related harm that might be affected by the treatment, and the availability of data needed in AMF development or improvement.

Two approaches were used in developing the AMFs. The first approach was the rigorous statistical evaluation of crash data, with priority given to conducting as many empirical Bayes before-after evaluations of the high-priority treatments as possible. The second approach to AMF development/modification involved two analysis-driven expert panels.

In summary, this project has verified, modified, or developed 35 AMFs that are deemed to be of high or medium-high quality. These have been documented in formats that are usable by both practitioners and researchers. These AMFs are the primary project outputs. However, the project has also documented both a process that can be used with future analysis-driven expert panels and the detailed discussions of the two expert panels that were part of this effort. This material should be helpful in future efforts to develop or improve AMFs. Finally, the project developed and documented a procedure for ranking needed AMF research that incorporates not only state DOT user and researcher opinions and knowledge of the quality of AMFs in the published literature, but also a method for estimating how crash-related harm might be affected by each treatment. An approach combining these procedures could also be used in more global efforts to prioritize roadway safety research needs in general.

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The authors wish to acknowledge the assistance and support of others who made this project a success. Two expert panels were convened to review current knowledge and develop accident modification factors (AMFs) for both urban/suburban arterials and rural multilane roads. These panels included the following individuals, and the authors express their thanks to them for their efforts before, during and after the actual panel meetings.

- Dr. James A. Bonneson, Texas Transportation Institute
- Mr. Doug Harwood, Midwest Research Institute
- Dr. Ezra Hauer, Independent Consultant
- Mr. Loren Hill, Minnesota DOT
- Dr. Dominique Lord, Texas A&M University
- Mr. Brian Mayhew, North Carolina DOT
- Mr. Stan Polanis, City of Winston Salem
- Dr. Simon Washington, Arizona State University
- Mr. Thomas Welch, Iowa DOT

The authors also wish to express additional thanks to Mr. Stan Polanis, Traffic Engineer for the City of Winston-Salem, North Carolina, for his assistance in efforts to improve AMFs for five key urban treatments. Mr. Polanis provided the authors with detailed information on the specifics of treatment implementation in Winston-Salem along with before-treatment and after-treatment crash data that had been manually screened by his staff. His efforts were significant and critical to the success of that project task.

Finally, because the project involved the assessment and improvement of existing AMFs and the development of new ones through multiple approaches that could not all be envisioned at the beginning of the effort, there was considerable interaction with both NCHRP staff and the NCHRP project oversight panel. The authors wish to express sincere thanks to NCHRP Senior Program Officer Charles Niessner for his assistance throughout the project and to the individual members of the project panel, who provided extremely helpful feedback on the many documents they were asked to review.

SUMMARY

Accident Modification Factors for Traffic Engineering and ITS Improvements

Crash reduction factors (CRFs)—related to accident modification factors (AMFs)—provide a quick way of estimating crash reductions associated with highway safety improvements. (The remainder of this report will use the term AMF to be consistent with other ongoing NCHRP research in this area.) AMFs are used by many states and local jurisdictions 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. AMFs are also key components of the latest safety-estimation tools and procedures, including the Interactive Highway Safety Design Model (IHSDM) and the procedures now being developed for the Highway Safety Manual (HSM).

Even though accurate AMFs are critically important to states and municipalities in their attempts to achieve the greatest return on their investment when choosing among safety treatments, there is no accepted standard set of AMFs. This is because the accuracy and reliability of many published AMFs is questionable, and no AMFs exist for many important safety treatments. This lack of reliability, accuracy, and comprehensiveness has been documented in this study, in prior work, and in ongoing HSM development efforts. The sources of the problem include the lack of AMFs for newer ITS treatments and for common combinations of treatments, the fact that AMFs vary with other factors such as traffic volume, a publication bias that results in publishing only positive findings, and crash migration and spillover effects that result from some treatments but are not accounted for in the AMF. However, the major problems with existing AMFs result from the poor data and poor evaluation methods used in their development. Often, AMFs are based on simple before-after studies of high-crash locations, and the results can be very biased toward overestimating accident reductions.

The goals of this study were to (1) produce AMFs for high-priority treatments or treatment combinations where none currently exist, and/or (2) to increase the level of predictive certainty for existing AMFs in other high-priority areas. Due to funding limitations, not all possible treatment strategies could be effectively studied within this single project; therefore, the emphasis was on high-priority treatment strategies that are broadly implemented by states and local agencies and that can affect significant numbers of crash-related deaths and injuries. Reliable AMFs, at a minimum, must meet the following criteria:

- The AMFs are methodologically and statistically valid.
- The applicability of the AMF (i.e., the subset of crashes, crash locations, or crash conditions to which it is applicable) is known and documented.
- The AMFs reflect improvements or combinations of improvements that are of interest to DOTs.
- The AMFs reflect the impact of the improvement on different crash-severity and crash-type categories.

- The AMFs reflect variability by including both the best estimate of the AMF along with some measure of variability (e.g., ranges, confidence intervals, and standard deviation).
- The AMFs reflect the savings in "total harm" provided by the treatments, where "total harm" is a combination of frequency and severity.

The identification and development of AMFs that meet most of the above requirements involved a project effort that included four basic types of analyses:

- **Empirical Bayes (EB) Before-After Evaluation.** Before-treatment and after-treatment crash data were acquired for locations where the treatment of interest had been installed. The latest statistical methodologies (i.e., EB) for conducting before-after studies were applied to produce AMFs.
- **Reanalysis of Existing/Supplemental Data.** Data from prior before-after evaluations were acquired and reanalyzed using the more rigorous EB methodology. In many cases, supplemental data were acquired to enhance the evaluation.
- **Analysis-Driven Expert Panel.** A panel of knowledgeable researchers and practitioners was convened to review critical research studies and reach a consensus on AMFs for a given treatment. In some cases, the AMF was developed through further analysis by one of the NCHRP project teams sponsoring the expert panel meeting.
- **Cross-Section Modeling.** A new analysis was conducted in which a cross-sectional model was produced and used to derive AMFs for a specific treatment.

The project team developed an initial list of 78 treatments deemed to be important in safety decisions. The treatments were divided into four groups: intersection-related, roadway-segment-related, ITS-related, and other. Additional treatments suggested by 34 state DOT users, who responded to the project survey, and further refinements by the project team expanded the list to 100 treatments. A review of the literature discovered no AMFs for 50 of these treatments. Critical literature reviews were then conducted for the remaining 50 treatments. Of that group, 20 were felt to have a high or medium-high level of certainty. Summary information for each of these 20 AMFs along with a knowledge matrix for all 100 treatments was published in *NCHRP Research Results Digest 299* as an interim product of this research study. Each summary includes the AMF(s), the level of predictive certainty, the study methodology, a description of the sites used in the study, and supplemental comments and footnotes to describe the study results and applicability.

The results of this initial effort clearly supported the need for additional research to develop new AMFs and to strengthen those with less than a medium-high level of certainty. The determination of which of the many possible AMFs should be developed or improved was based on the following:

- Results of the survey of state DOT users,
- Judgment of the level of predictive certainty of existing AMFs from the literature review,
- Measure of the crash-related harm that might be affected by the treatment,
- Whether there was existing ongoing research that might develop an AMF, and
- Availability of data needed in AMF development or improvement.

Priority was given to conducting as many EB evaluations of the high-priority treatments as possible. Based on the funding available and on team knowledge of available data, it was decided that EB analyses would be conducted to develop AMFs for the following high-priority treatments:

- Installation of a traffic signal at a rural intersection;
- Conversion of an undivided four-lane road to three lanes including a two-way-left-turn lane (TWLTL)—a "road diet";

- Increasing pavement friction on intersection approaches;
- Increasing pavement friction on roadway segments;
- Modification of left-turn signal phase (three combinations);
- Replacement of 8-in. signal head with 12-in. head;
- Replacement of single red signal head with dual red signal heads; and
- Conversion of nighttime flashing operation to stop-and-go operation.

The second approach to AMF development/modification involved two analysis-driven expert panels. While earlier project discussions had noted the possibility of expert panels for AMFs related to specific focus areas (e.g., roadside crashes and pedestrian treatments), it was decided by the team and the oversight panel that a more critical need was to assist the project teams from NCHRP Projects 17-26 and 17-29 in developing AMFs needed for the Highway Safety Manual safety prediction tools these teams were developing for urban/suburban arterials and rural multilane highways.

Working with the research teams from those two projects, this research team identified and recruited expert panel members; developed a listing of potential treatments for study; compiled and distributed copies of relevant research reports to the panel; and arranged and hosted the panels. Before each meeting, the panels prioritized the potential list of treatments in order to ensure that the most important ones were discussed, and each panel member was assigned one-third of the high-priority issues and asked to be prepared to present their opinions and lead the discussion. Following the meeting, the project team funded and conducted additional limited analyses and documented the findings of each expert panel in a report. The AMFs developed through consensus from a review of prior research studies or from further analysis recommended by the panels include the following:

- Add exclusive left-turn lane,
- Add exclusive right-turn lane,
- Prohibit right turn on red,
- Modify left-turn signal phase,
- Add intersection lighting,
- Add two-way left-turn lane,
- Change roadside slope,
- Add/remove on-street parking,
- Add segment lighting, and
- Reduce mean travel speed (not treatment-specific).

In summary, this project has verified, modified, or developed 35 AMFs that are felt to be of high or medium-high quality. These have been documented in formats that are usable by both practitioners and researchers. These AMFs are the primary project outputs. However, the project has also documented a process that can be used with future analysis-driven expert panels and the detailed discussions of the two expert panels that were part of this effort. This material should be helpful in future efforts to develop or improve AMFs for treatments for which no AMF could be developed here. Finally, the project developed and documented a procedure for ranking needed AMF research, a procedure incorporating not only state DOT user and researcher opinions and knowledge of the quality of AMFs in the published literature, but also a method for estimating the crash-related harm that might be affected by each treatment. An approach combining these factors could also be used in more global efforts to prioritize roadway safety research needs in general.

CHAPTER 1

Introduction

The Problem

In order to achieve the greatest return on the investment of their often limited safety budgets, state and local highway safety engineers must continually make program planning decisions concerning whether to implement a specific safety treatment and/or to determine the costs and benefits of alternative treatments. Making these program planning decisions requires an accurate measure of safety treatment effectiveness. This measure of effectiveness is referred to as a crash reduction factor (CRF) or accident modification factor (AMF). Both of these terms reflect the percentage reduction (or increase) in crashes that can be expected after implementing a treatment or program, as derived through research studies and program evaluations. The *level of effectiveness* of a treatment is referred to in much of the current safety literature as a CRF or an AMF. The two terms are simply different ways of expressing treatment effectiveness levels. An AMF provides the expected proportional reduction in crash frequency and is developed by dividing the CRF by 100 and subtracting the result from 1.00. Thus, a treatment shown to reduce crashes by 15 percent (CRF = 15%) would have an AMF of 0.85 (1.00 − 15/100). An AMF of 1.00 represents no effect on safety, while AMFs above 1.00 indicate that the treatment can be expected to result in an *increase* in crashes. The term AMF will be used in this report for consistency with other NCHRP efforts.

The importance of AMFs to state department of transportation (DOT) safety engineers was documented by a survey conducted as part of this study. The survey was sent to the identified state safety engineer (usually in the traffic engineering office) and to a state staff person involved with the intelligent transportation systems (ITS) program. All states were surveyed, and 34 provided responses. Of the 34 states responding, all but two indicated that they use AMFs, and most states use them for multiple purposes. AMFs are used for the following, listed from most frequent use to least frequent use:

- Economic analysis of safety treatments,
- Treatment selection for short-term programming of safety improvements,
- Project development to address safety aspects of large projects,
- Design policy development,
- The design exception process, and
- Public awareness campaigns.

In addition to their long-term use by state and local safety engineers, AMFs are key components of the current generation of safety tools and resources being developed for the safety field. They are used in FHWA's *Interactive Highway Safety Design Model (IHSDM)* to predict future safety for different alternative roadway designs or rehabilitation designs (*1*). AMFs are being incorporated into FHWA's *SafetyAnalyst*, where they are applied to estimate the safety effectiveness measures within the economic appraisal tool (*2*). AMFs will be a key component of the Highway Safety Manual (HSM), which is now being produced by a TRB task force and NCHRP (*3*). Finally, better AMFs will allow AASHTO and NCHRP to update guides already developed or guides to be developed in the future for assisting states and local users with the implementation of AASHTO's *Strategic Highway Safety Plan* (*4*).

Even though accurate AMFs are critically important to states and municipalities and to the safety tools previously mentioned, there is no accepted standard set of AMFs. This situation is due to the fact that the accuracy and reliability of many published AMFs is questionable and that no AMFs exist for many important safety treatments. The lack of AMF reliability, accuracy, and comprehensiveness has been documented in this study, in prior work, and in ongoing HSM development efforts. The sources of the problem include the following:

- **Origins/Transferability.** The origins of AMFs are not always clear to the end user. Some states have developed AMFs using their own crash data. Other states have simply adopted AMFs that were developed in other states. The extent to which AMFs are valid when transferred to places beyond the development domain (e.g., from one state to another) that have different roadway, traffic, weather, driver and other relevant characteristics, as well as different accident investigation practices, is unknown.

- **Methodological Issues.** Many existing AMFs are derived from before-after analysis of actual countermeasure implementation. Indeed, such before-after analysis, as opposed to cross-sectional/regression-type analysis, produces the best AMF estimates, but only if conducted properly. Unfortunately, many current studies reflect changes in crash experience resulting from improvements at sites that experienced an unusually high number of crashes in the before-treatment period. The selection bias that results from this approach can yield significantly exaggerated AMF estimates due to the phenomenon of regression to the mean. Other methodological problems that are often found include the following:
  – Failure to properly separate out the safety effects of other changes (e.g., traffic volumes, the impacts of other treatments implemented at the same time, crash reporting differences between jurisdictions or across time, and underlying crash 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 and the subsequent type of crash reduction expected, hundreds or thousands of locations may be necessary, along with many years of crash data. (Pedestrian treatments and crashes are a good example of this problem.)
  – Use of comparison groups that are unsuitable for a variety of reasons.
  – Incorrect interpretation of accuracy of estimates or presentation of results without statements of accuracy.
- **Variability.** The value of an AMF may depend on a variety of factors, such as traffic volumes, crash experience, and site characteristics. Thus, research that results in a single AMF value may be of limited applicability. Accident modification *functions* rather than *factors* may be more appropriate. Several of the AMFs presented in this report are indeed functions.
- **Crash Migration and Spillover Effects.** It is possible that countermeasures implemented in a particular location may be followed by migration of crashes to adjacent locations. For example, the conversion of two-way stop control to all-way stop control at an intersection may lead to an increase in crashes at surrounding intersections that continue to operate as two-way stop control due to driver confusion. Likewise, the prohibition of left turns at an intersection may lead to an increase in left-turn crashes at upstream and downstream intersections. Existing AMFs rarely account for this phenomenon. For AMFs to be useful, they have to account for these effects or, at a minimum, recognize their existence.
- **Lack of Effectiveness Information.** AMFs have not been developed for many ITS improvements and other operational strategies. For example, on many freeways, safety service patrols have become more common as a way of reducing the impact of incidents and reducing secondary accidents. However, no AMFs exist for this countermeasure. Other ITS countermeasures of high interest for which no reliable AMFs exist include dynamic or changeable message signs (including those related to variable speed limits), real-time warning systems (e.g., severe alignment or adverse weather), and pedestrian safety treatments (e.g., in-pavement crosswalk lighting and countdown signals).
- **Combinations of Improvements.** Most AMFs are designed for individual improvements. However, multiple improvements are typically made when a facility is being rebuilt. States use different formulas for combining individual AMFs when considering multiple treatments. However, there is very little sound research on the multitude of actual combinations of treatments that exist in practice. Thus, it is unknown whether current predictions based on combining individual AMFs accurately capture the true combined effect.
- **Publication/Citation Issues.** A less-cited issue that is prevalent in much of the research is related to the quality of the material that is available and often used in the development of AMFs. Specific problems include the following:
  – Publication bias—the tendency to only publish studies that produced favorable results for the treatment being evaluated.
  – Selective citing of results—the tendency to ignore the negative aspects of results such as declining effects over time or unintended consequences that would lead to increases in some crash types. In some cases, a sponsoring organization may not want negative results published because it invested significant funds in a countermeasure/intervention program.

In summary, although several AMFs already exist, there are a number of issues related to the quality of those factors now being used in many states and local jurisdictions. There is a need to improve the quality of existing AMFs and to develop additional AMFs where there are currently voids.

Project Objective and Overview

The objective of this project was to develop reliable AMFs for traffic engineering and ITS improvements. Reliable AMFs, at a minimum, must meet the following criteria:

- **The AMFs are methodologically and statistically valid.** Separate values for AMFs are defined for various influencing factors such as the highway facility, operating condition, weather, time of day, percentage of truck traffic, and pre-existing crash history as appropriate. (Alternatively, a method could be developed for adjusting the AMFs for these influencing factors.) Should expert judgment be used in developing AMFs, it must be *analysis-driven*.

- **The applicability of the AMF is known and documented.** For example, some AMFs may denote an impact on crashes only at a specific location whereas other AMFs may affect crashes for an entire stretch of roadway. Some AMFs may apply only to specific accident types or to specific pre-existing conditions (e.g., high percentages of wet weather crashes). Some may be applicable only to the state or area where the AMF is developed, and thus adjustment factors must be developed to allow application of the AMF to other regions.
- **The AMFs reflect improvements or combinations of improvements that are of interest to DOTs.** The survey conducted as part of this study requested respondents to indicate which treatments were considered priorities for AMF development.
- **The AMFs reflect the impact of the improvement on different crash categories.** Crash categories might include total crashes, severe-injury crashes, property-damage-only crashes, and specific crash types (such as rear-end and angle).
- **The AMFs reflect variability.** The best estimate of the AMFs, along with some technique that reflects their variability (such as ranges, confidence intervals, standard deviation, or some other technique) should be presented.
- **The AMFs reflect the savings in "total harm" provided by the treatments.** Many treatments affect both crash frequency and crash severity, some affect just crash severity, and some decrease crashes at one level of severity and increase crashes at another level of severity (e.g., traffic signalization can decrease more-severe angle crashes but increase less-severe rear-end crashes). AMFs must capture changes in crash severity as well as changes in crash frequency in order to measure "harm savings."

The identification and development of AMFs that meet most of the above requirements involved a project effort with the following eight tasks divided among two phases. Phase I included the following tasks:

- Task 1—Review of completed and ongoing studies to document existing AMFs,
- Task 2—Survey of states to determine AMF use and priorities and availability of data concerning treatment installation for use in new AMF development,
- Task 3—Follow-up interviews with states having potentially usable treatments and data,
- Task 4—Determination of whether available data from states or other sources could be used in AMF development,
- Task 5—Development of interim report and work plan, and
- Task 6—Project briefing for oversight committee.

Phase II included the following tasks:

- Task 7—Execution of work plan to collect necessary data and develop/improve AMFs and
- Task 8—Preparation of final report.

Thus, Phase I of the effort was focused first on the extraction of information on existing AMFs through a critical review of research literature. The documentation included detailed descriptors of the AMFs, the conditions (e.g., roadway types and locations) for which each AMF was applicable, and a judgment of the level of predictive certainty (i.e., the quality) associated with a given AMF. The remainder of Phase I focused on a series of steps to determine high-priority AMF needs—which existing AMFs should be improved and which new AMFs should be developed within the project budget. This prioritization was based on inputs concerning "most important safety treatments" from a survey of state DOTs combined with other factors concerning the quality of the existing AMF, the size of the crash problem affected by the treatment, and the availability of data needed to develop or improve an AMF. All this information was then used to develop a work plan for the AMF development/upgrade effort.

After approval by the oversight panel, the plan was executed in Phase II of the effort. This execution involved four basic types of analyses:

- **Empirical Bayes (EB) Before-After Evaluation.** Original data were acquired to conduct an analysis and determine the crash-harm effects of a specific high-priority treatment that had been implemented within a state or states (usually at multiple sites) in the late 1990s or early 2000s in order to have a sufficient after-treatment period. The analysis made use of the latest statistical methodologies for before-after studies and produced AMFs with the highest feasible level of confidence. This analysis required not only detailed descriptions of the historic treated sites (e.g., treatment specifics, locations, and dates of installation) and good before-treatment and after-treatment crash, inventory, and traffic data on the treated sites, but also comparable data on a large reference group of somewhat similar sites. Thus, the analysis required either that the project team had easy access to both current and historical crash, inventory, and traffic data, or that the implementing state was willing and able to provide the linkable data files necessary. Since FHWA's Highway Safety Information System (HSIS) includes historic crash, inventory, and traffic data from nine states, and since most non-HSIS states do not store historic roadway inventory data, attempts were made to find treatments implemented in these HSIS states.

- **Reanalysis of Existing/Supplemental Data.** An existing AMF was improved by applying a more rigorous evaluation methodology to existing data from a prior study. The preferred methodology was again the EB before-after approach. Again, this required adequate data for both treatment and non-treatment sites. In many cases, supplemental data (e.g., data for the development of a reference group) were acquired to meet this requirement and enhance the analysis.
- **Analysis-Driven Expert Panel.** An expert panel was convened to review the existing studies concerning a specific AMF and then define a consensus AMF based on the studies reviewed. The expert panel included expert researchers (knowledgeable about the AMFs of interest and the strengths and weaknesses of study methods) and a group of expert state and local AMF users (i.e., safety engineers) with knowledge of the specifics of the AMFs needed and the real-world conditions under which those evaluated treatments were probably implemented. At times, limited additional analyses were conducted. The use of an expert panel required that the body of literature be robust enough to be subject to assimilation/meta-analysis by team members and then presented to an expert panel to develop a reliable AMF with at least a medium-high level of confidence.
- **Cross-Section Modeling.** A cross-sectional model was developed and used for the derivation of an AMF for a specific treatment. Some treatments of interest are not installed or changed in a manner that allows for a before-after evaluation. For example, it is unlikely that changes would be made to roadside slopes without making other changes, such as addition of a shoulder, at the same time. For these types of treatments, the development of road safety models is still an alternative to determine safety effectiveness.

It is important to note that other AMF projects were going on at the same time as NCHRP Project 17-25. At approximately the same time that NCHRP Project 17-25 was initiated, NCHRP and a TRB task force also began a series of projects aimed at the planned 2008 publication of the first edition of the Highway Safety Manual (HSM) (see www.highwaysafetymanual.org/) (*3*). The HSM will be a repository of (1) current knowledge related to roadway safety treatments, (2) tools for use in predicting the safety effects of different roadway design alternatives for various classes of roadways, and (3) tools for identifying sites needing safety improvements and the best treatments for them. NCHRP has funded the following projects in support of the HSM:

- NCHRP Project 17-18(04), Highway Safety Manual, was a scoping study that included the development of the initial concept, outline, and prototype procedure chapter.
- NCHRP Project 17-27, Parts I and II of the Highway Safety Manual, included documentation of the state of current safety knowledge and preparation of chapters that included AMFs.
- NCHRP Project 17-26, Methodology to Predict the Safety Performance of Urban and Suburban Arterials, included the development of predictive tools and an HSM chapter for urban and suburban arterials.
- NCHRP Project 17-29, Methodology to Predict the Safety Performance of Rural Multilane Highways, included the development of predictive tools and an HSM chapter for rural multilane highways.
- NCHRP Project 17-34, Prepare Parts IV and V of the Highway Safety Manual, included the development of chapters for roadway safety management and safety evaluations.
- NCHRP Project 17-36, Production of the First Edition of the Highway Safety Manual, was preparation of the first edition of the HSM for publication.

The safety knowledge documented in the HSM is being stated in terms of AMFs, and the HSM safety prediction tools include AMFs as a key component. Because the AMFs developed in NCHRP Project 17-25 are so closely related to the AMFs developed for and documented in the HSM and because the safety predictive tools for urban and suburban arterials and for rural multilane roads both require AMFs, this project and NCHRP Projects 17-26 and 17-29 were closely coordinated by the different teams, with information being shared on a regular basis. The criteria developed in NCHRP Project 17-25 for assessing AMF quality served as the basis for criteria used in NCHRP Project 17-27. However, there were differences in how the final decisions on what constituted "acceptable AMFs" were made. There are also differences in AMFs chosen for publication here and those AMFs that will be in the HSM. While the AMFs published here are only those judged to have high or medium-high levels of predictive certainty, the HSM will be more inclusive, publishing AMFs with lower levels of predictive certainty accompanied by a rating and warnings concerning use. The research team for NCHRP Project 17-25 conducted a detailed comparative review of the AMFs developed for this project and the AMFs developed for the HSM under NCHRP Project 17-27. This review led to some changes in the final procedures used in NCHRP Project 17-27 and to a high level of consistency between the AMF-related results of the two projects for the higher-certainty AMFs. In addition, to develop AMFs for treatments on urban/suburban arterials (NCHRP Project 17-26) and on rural multilane highways (NCHRP Project 17-29), researchers for NCHRP Project 17-25 organized two analysis-driven expert panels jointly with the two project teams, again ensuring both coordination of the efforts and consistency in the results.

Organization of Report

This report provides a description of the processes followed to document existing AMFs and to determine the focus of additional AMF development efforts. The results of new AMF-related research conducted in this study are included along with recommendations for future research. The components of this report are as follows:

- Chapter 2: Status of Existing AMFs and Identification of AMF Needs includes a description of the processes used to develop an initial list of important traffic engineering and ITS treatments, the process and criteria used to rate the quality of AMFs discovered for these treatments, details of the AMFs that were judged to be of high or medium-high quality and thus included in *NCHRP Research Results Digest 299* (*5*), and the processes used to prioritize and select other treatments for additional analyses and AMF development.
- Chapter 3: Development of New AMFs through Analysis or Reanalysis of Crash Data includes a description of the treatments studied, the data used in the evaluations, the statistical methodology used, and the results of each evaluation.
- Chapter 4: Development of New AMFs through Expert Panels includes a listing of the participants in each of the two panels, a description of the overall process followed for the two panels with respect to identifying and prioritizing the treatments to be explored, and the results of the panel discussions.
- Chapter 5: Compilation of Recommended AMFs includes a listing of all AMFs verified, modified, or developed in this research effort along with a summary page for each AMF.
- Chapter 6: Conclusions includes a summary of the study objectives, project findings, and recommendations for future AMF research.

CHAPTER 2

Status of Existing AMFs and Identification of AMF Needs

This chapter includes a description of the processes used to develop an initial list of important traffic engineering and ITS treatments, the process and criteria used to rate the quality of the AMFs discovered for these treatments, details of the AMFs that were judged to be of high or medium-high quality and thus included in *NCHRP Research Results Digest 299* (*5*), and the processes used to prioritize and select other treatments for additional analyses and AMF development.

Extracting Information on Existing AMFs and Determining AMF Quality

Determining the Treatments to Be Considered

Numerous treatments are used by state and local safety agencies in their efforts to reduce the number and severity of crashes at intersection and non-intersection (i.e., segment) locations. The NCHRP Project 17-25 team developed an initial list of 78 such treatments, categorized as intersection-related, segment-related, ITS-related, other, and combined treatments. This list was based on treatments proposed in past safety guidance documents such as the *NCHRP Report 500* guides for implementation of the *AASHTO Strategic Highway Safety Plan* (*6*, *4*) and on project team knowledge of state practices and knowledge of past treatment evaluations. As part of this project, an AMF state-of-the-practice survey was sent to each of the 50 state DOTs. Working with FHWA, the project team identified the safety engineer and an ITS engineer in each DOT and attempted to reach them with the survey. Responses were ultimately received from 34 states. Respondents were asked to list additional treatments for which an AMF is needed, which expanded the list of treatments to be reviewed to 113. After some further screening based on the literature review process and collapsing of redundant treatments, the final list included 100 treatments.

Literature Review Process

The project team then searched for evaluation reports for each of these treatments in a variety of sources. These included the reference lists of the *NCHRP Report 500* guides (*6*), documents identified through the Transportation Research Information Service (TRIS) and other resource search engines, and references being reviewed in developmental work for the HSM. Given the broad scope of this project effort—traffic engineering and ITS improvements—the challenge was to quickly identify the most relevant studies for each treatment that required a more thorough review. Given that the focus of this effort is on AMFs, the initial screening criterion applied to each study was that the results must be founded on a crash-based analysis. Studies based on traffic behavior, survey results, or other outcomes were eliminated from consideration.

The studies for each treatment were further screened to determine which ones included the development of AMFs or a methodology that could be used to develop AMFs. 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:

- Evaluate the research approach and statistical methodology, including an examination of possible pitfalls such as regression to the mean or site-selection bias.
- Document the magnitude and assess the quality of any AMFs produced.
- Determine whether and how each particular study could be used in Phase II of the research effort, in which additional research on critical treatments was to be conducted. The three possible uses were the following:
  - Source data for the study could be available for further analysis using a more rigorous methodology.
  - Study results (and/or source data) could be used as part of a meta-analysis.
  - Study results could be provided to an analysis-driven expert panel.

Levels of AMF Quality

As noted in the second point above, the output of this effort was to be not only the documentation of the AMF, the level of effectiveness of the treatment, but also the development of a measure of the quality of the AMF—a measure of its *level of predictive certainty* (LOPC). This estimate of the LOPC is a reflection of the study methodology used to define the AMF. The LOPCs used in this review and the criteria for each are as follows:

- **High.** The AMF was developed in a rigorous before-after study that incorporated the current best study design and statistical analysis methods. At this time, the empirical Bayes (EB) methodology described by Hauer represents the best available approach (*7*). The study must also have included a sufficiently large number of treatment sites, a large reference group composed of comparable sites, and enough crashes for statistical validity.
- **Medium-High.** The AMF was developed in an EB before-after study with limited numbers of treatment sites and/or crashes or a before-after study that incorporated sound (but not EB) statistical methods and/or may have been reviewed and "vetted" by an expert panel of researchers. This level may include AMFs that were produced by an expert research panel from the combination of findings from different (less-controlled) before-after and cross-sectional studies. The panel's judgment concerning the quality of the AMF is reflected in the LOPC and did not always merit a medium-high rating. This level also includes AMFs that were developed in a rigorous meta-analysis by a recognized meta-analysis expert. (Meta-analysis is the combination of the results of various studies using statistical techniques that allow the expert to overcome some of the shortcomings of the original research.) Not all meta-analysis results warranted a medium-high LOPC (see discussion below).
- **Medium-Low.** The AMF was developed from a cross-sectional analysis (controlling for other factors statistically) or from less-than-rigorous before-after studies, but is still judged to be of value. An example would be a before-after study in which regression to the mean was not viewed as a major potential bias because the population of treated sites included more than just "high-accident locations."
- **Low.** The AMF was developed in a simple before-after study without control for biases or from cross-sectional studies in which modeling techniques are questionable.
- **Non-existent.** No studies were found that included AMFs for this treatment.

It is also important to understand that within each LOPC, there can be a wide range of accuracy or confidence. For example, some AMFs have been developed in cases where the expert panel was able to utilize the results of at least one key study that was considered critical and very well done. However, in other cases, the expert panel may not have been able to identify any studies without flaws and may have been forced to rely on their collective knowledge, experience, and judgment in combining the results of these less-valid studies. It is obvious that the AMFs developed without the results from any critically valid studies have a lower level of predictive certainty than the ones developed with at least one such study.

The criteria listed above indicate that an AMF produced from a rigorous meta-analysis may be considered to have a LOPC of medium-high. Many of the meta-analyses that have been conducted include studies from multiple countries as well as studies that are several decades old. There are enough differences among the applications of treatments in North America, Europe, and Australia to warrant caution in combining the results of these studies. There have also been enough changes in drivers and vehicles to warrant caution in the inclusion of studies that are more than 25 years old. Thus, the following criteria were used in assessing whether an AMF from a meta-analysis was deemed to be of medium-high quality:

- A minimum of three North American studies (post-1980) had to be included in the analysis, and the percentage of North American studies had to be at least 20 percent. There was an exception to this threshold if the treatment was believed to produce operational characteristics in the United States that were different than the operational characteristics produced in other countries. For example, road shoulders in many European countries are designed and used for passing maneuvers, which is completely different from the function of road shoulders in the United States. In cases in which the treatment was believed to produce operational characteristics in the United States that were different than the operational characteristics produced in other countries, the percentage of studies from the United States needed to be substantially greater than 20 percent.
- The treatment in the meta-analysis had to be clearly defined to be sure the results were applicable to the "treatment of interest," including specifics on applicability to various classes of roadways. For example, if the treatment of interest was speed limit reduction on two-lane rural roads, then a meta-analysis in which the only U.S. studies were related to Interstates was not considered.
- The results had to be statistically significant (i.e., the 95-percent confidence interval could not include 0). The intent here was to avoid including any AMF for which the sign may change (i.e., the lower end of the confidence interval results in a crash decrease while the upper end results in a crash increase).

Results of the Literature Review

Of the 100 treatments examined, the existing research literature allowed the team to conduct detailed critical reviews on 50 treatments. The information derived from these critical reviews was used to summarize existing knowledge and prioritize research for Phase II of this study. First, the information was included in an "AMF Knowledge Matrix" that provides a status report on the quality of AMFs for these 100 treatments, as indicated by checkmarks within the cells in Table 1. In addition to the measure of AMF quality, the matrix also provides information on the user priority level for the 25 highest rated treatments and information on other ongoing or planned research that would potentially increase the quality of the AMF. The cells that are shaded within the matrix represent the top 25 treatments as rated by the state DOT respondents. The rank-order of these top 25 treatments is shown in the column labeled "User Priority Level." (Note that Table 1 reflects AMF knowledge through 2004. Additional AMFs have since been developed in this and other projects and are included in the final AMF listing in Chapter 5 of this report.)

Of the 50 treatments critically reviewed (and the 100 treatments considered), 20 were judged to have a high or medium-high LOPC. These treatments are summarized in Table 2. The asterisks in Table 2 denote the treatments in the top quartile of the user ratings. Thus, 11 of the 20 treatments deemed to have AMFs of acceptable quality were in the users' top 25. Summary information for each of these 20 AMFs along with the knowledge matrix were published in *NCHRP Research Results Digest 299* (*5*) as an interim product of this research study. Each summary includes the AMF(s), the LOPC, the study methodology, a description of the sites used in the study, and supplemental comments and footnotes to describe the study results and applicability. These same resulting AMFs are presented in Chapter 5 of this report along with new AMFs produced by the Phase II efforts of this research.

Prioritizing Phase II Efforts to Develop Additional AMFs

The results of the literature review and the input from DOT practitioners clearly supported the need for additional research to develop new AMFs and to strengthen those with less than a medium-high LOPC. Only 20 of the 100 treatments being studied had AMFs of high or medium-high quality, meaning that 80 had lower quality AMFs (or didn't have them at all), including 14 of the DOT users' top-25 treatments. Given project funding limitations, a decision was made concerning which treatments should be further researched in the Phase II efforts. This decision was based on the following factors:

- **User Priority Level.** The state DOT survey respondents rated each treatment in terms of how important it was to have an AMF. These ratings were combined to provide the user priority ranking. Particular attention was given to the top quartile of these ranked treatments.
- **Level of Predictive Certainty.** As described above, for each treatment where a critical literature review was possible, an LOPC was assigned—high, medium-high, medium-low, or low. Any treatment for which no prior research study was discovered was categorized under "non-existent." Phase II efforts concentrated on the lower three levels.
- **Ongoing/Future Research.** Determination of whether there was ongoing or planned research that might improve the AMF 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). The studies referenced in Table 1 are those that have the greatest potential for producing AMFs for specific treatments. Results from these studies should be reviewed in the future to determine if the LOPC for an AMF has been improved.
- **Estimate of Crash-Related Harm Possibly Affected by the Treatment.** The importance of a treatment, and thus its AMF, is a function of the size of the safety problem that the treatment affects and the probability that the treatment will be implemented. For those treatments ranked high in terms of user priorities, it was assumed that implementation would be widespread given a sound AMF. Each of these high-priority treatments was assigned a high, medium-high, medium-low, or low *crash-harm* rating. This was done by assigning a target crash type to the treatment—the crash type or types that would be most affected—and defining the appropriate rating based on the economic level of national "crash harm" associated with that crash type. The economic estimates for each of 31 crash types were based on work by Miller (*71*). A more detailed discussion of this methodology is presented in Appendix A.
- **Availability of Needed Research Data.** For each treatment being considered, detailed historic data concerning treatment descriptions and treatment dates from the implementing agencies were necessary, as well as linkable historic crash, roadway inventory, and traffic flow data for both treated sites and for comparison/reference sites. The data either had to be available from the implementing jurisdictions or from FHWA's Highway Safety Information System (HSIS), which includes such historic data for nine states.

The first four of these factors were then captured for a subset of the treatments shown in the AMF knowledge matrix—those that were in the users' top 25 rankings and additional treatments of interest to the project oversight panel (see Table 3).

Table 1. AMF knowledge matrix showing AMF quality, user priority, and ongoing or future research for 100 intersection, roadway segment, and miscellaneous treatments.

Treatment	User Priority Level	Level of Predictive Certainty					Ongoing/ Future Work
		High	Medium-High	Medium-Low	Low	Non-Existent	
Intersection Treatments							
Install a roundabout	19	✓ (8)[1]					
Reduce or eliminate intersection skew				✓ (9)			
Correct sight distance				✓ (9)			
Install offset T's						✓	
Install turn lane or bypass lane at T-intersection				✓ (10, 11)			
Add exclusive left-turn lane	1	✓ (12)					
Install double left-turn lane (change from single)						✓	
Create positive offset for opposing left-turn lanes					✓ (13)		✓ (14)
Add exclusive right-turn lane	4	✓ (12)					
Add channelization for right-turns	11					✓	✓ (15, 16)
Install median acceleration lane						✓	
Add raised/painted median islands				✓ (12,17)			
Install a traffic signal	2	✓ (18)[2]					
Remove a traffic signal		✓ (19)[3]					
Add a left-turn phase (protected or protected/permissive)	8			✓ (20, 21)			
Modify signal change interval			✓ (22)				
Add all-red phase						✓	
Change cycle length						✓	
Change from incandescent to LED signals						✓	
Add signal heads				✓ (23)			
Increase signal head size				✓ (24)			
Add backplates						✓	
Install red-light cameras		✓ (25,26)					
Install red-light hold systems							✓ (27)[4]
Install dynamic advance warning flashers "Red Signal Ahead"	17				✓ (28)		
Install overhead flashing beacon						✓	(29)
Convert to all-way stop			✓ (30)				
Remove all-way stop						✓	
Convert stop-control to yield-control			✓ (31)				
Prohibit left turns						✓	
Install rumble strips on approach to intersection						✓	✓ (32,33)
Install intersection lighting	13				✓ (34,35,36)		✓ (37)
Close driveways near intersections	22					✓	
Install marked crosswalk				✓ (38)[5]			
Add pedestrian signals or pedestrian phase						✓ (39,40)	
Install curb extensions (bulbouts)						✓	
Install raised crosswalks						✓	
Install raised/tabled intersection						✓	
Reduce turn radius (shorten pedestrian crossing)						✓	
Remove parking near intersection						✓ (41)	
Roadway Segment Treatments							
Add a travel lane	8				✓ (42)		
Convert two-lane road to multilane road							
Reduce number of lanes (road diet)				✓ (43,44)[6]			
Narrow lane widths to add lanes			✓ (45)[7]				
Narrow urban lanes to install turn lane						✓	
Add two-way left-turn lane (TWLTL)			✓ (9)[8]				✓ (46)
Replace a TWLTL with median/left-turn bays						✓	
Add passing lanes (two-lane roads)			✓ (9)				✓ (47)
Widen median					✓ (48,49)		
Install raised median	20					✓	✓ (8,9,45)
Increase lane width	21		✓ (9,51)[9]				
Change shoulder width and/or type	15		✓ (9)[9]				
Flatten horizontal curve	12		✓ (9,52)[10]				
Improve curve superelevation	18		✓ (9)				
Reduce grade					✓(9)		
Flatten vertical curve						✓	
Add static curve warning signs and/or pavement markings						✓	
Add dynamic curve warning sign						✓	

Table 1. (Continued).

Treatment	User Priority Level	Level of Predictive Certainty					Ongoing/ Future Work
		High	Medium-High	Medium-Low	Low	Non-Existent	
Add shoulder rumble strips	5		✓ *(53)*[11]				✓ *(54,55)*
Add edgeline rumble strips	14					✓*(56)*[12]	✓ *(14)*
Add centerline rumble strips (two-lane roads)	10		✓ *(57)*				✓ *(54,14)*
Remove roadside obstacle	3			✓ *(9)*			✓ *(58)*
Flatten sideslope	22			✓ *(59)*			✓ *(52)*
Install/upgrade guardrail	22		✓ *(60)*				
Install median barriers	6			✓ *(60)*			✓ *(61)*[13]
Relocate utility poles				✓ *(62)*			
Use shoulder on freeways/expressways for bus lane						✓	
Remove parking						✓	
Eliminate left-turns at driveways	16					✓	
Add delineation						✓	
Install roadway segment lighting	23			✓ *(63)*			
Use dynamic message sign						✓	
Use variable speed limit							✓ *(64)*
Use automated speed enforcement						✓	
Install reversible roadways/lane control						✓	
Reduce speed limit				✓ *(60)*			✓ *(65,66)*
Use differential speed limit						✓	
Add sidewalk/walkway						✓	
Stripe bicycle lane						✓	
Add midblock pedestrian signal						✓	
Install raised crosswalks (non-intersection)						✓	
Install mid-block pedestrian crossing						✓	
Miscellaneous Treatments							
Lengthen acceleration lane						✓	
Consolidate driveways				✓ *(9)*[14]			
Traffic calming						✓	
Provide signal coordination	7					✓ *(67)*	
Increase pavement friction					✓ *(68)*		
Provide pedestrian refuge				✓ *(69,70)*			
Install raised medians at crosswalk			✓*(39)*				
Install pedestrian countdown signals							
Install crosswalk in-pavement lighting						✓	
Install automatic pedestrian detectors						✓	
Fog/wind/weather detection and warning systems						✓	
Install ramp metering						✓	
Use safety service patrols						✓	
Implement 511/traveler information						✓	
Implement integrated public safety/transportation communications						✓	
Use drone radars						✓	
Install truck rollover warning system						✓	
Install truck height warning						✓	

[1] Numbers in parentheses refer to the references for the best available AMF(s) or the ongoing/planned research effort(s).
[2] AMF was developed from urban intersection dataset; no AMF exists for rural intersections.
[3] AMF is for one-way streets in an urban environment.
[4] Yellow-light-hold study.
[5] For unsignalized intersections only; no AMF for signalized intersections.
[6] There have been two studies recently conducted using different methodologies that have arrived at different conclusions regarding the magnitude of the safety effect. Both were reanalyzed as part of this research study; see results in Chapter 3.
[7] Freeways only, no AMFs for other road types.
[8] Information available for two-lane roads only.
[9] AMFs available for rural two-lane and multilane roads; no AMF available for urban/suburban arterials.
[10] AMF available for rural two-lane roads; no AMF available for rural multilane or urban/suburban arterials.
[11] AMF available for freeways only; no AMF available for other road classes.
[12] There has been some work on profiled pavement markings that have some similarities to edge-line rumble strips (*71*).
[13] The project team is aware of a TRB paper under review which should increase the knowledge level significantly.
[14] AMF available for rural two-lane roads only; no AMF available for rural multilane roads or urban/suburban arterials.

Table 2. Treatments with AMFs that have a high or medium-high level of predictive certainty.

Treatment	Level of Predictive Certainty
Intersection Treatments	
*Install a roundabout	High
*Add exclusive left-turn lane	High
*Add exclusive right-turn lane	High
*Install an urban traffic signal	High
Remove an urban traffic signal	High
Modify signal change interval	Medium-High
Convert to all-way stop control	Medium-High
Convert stop-control to yield-control	Medium-High
Install red-light cameras	High
Roadway Segment Treatments	
Narrow lane widths to add lanes	Medium-High
Add passing lanes (two-lane roads)	Medium-High
Add two-way left-turn lane (TWLTL)	Medium-High
*Increase lane width	Medium-High
*Change shoulder width and/or type	Medium-High
*Flatten horizontal curve	Medium-High
*Improve curve superelevation	Medium-High
*Add shoulder rumble strips on freeways	Medium-High
*Add centerline rumble strips	Medium-High
*Install/upgrade guardrail	Medium-High
Miscellaneous Treatments	
Install raised medians at crosswalks	Medium-High
*Treatments in top quartile of the DOT users' priority listing.	

These four factors were combined by the project team into an overall ranking (high, medium-high, medium-low, or low) for possible additional research as shown in the last column of Table 3. It is noted that even though only a limited number of these higher-ranked treatments could be further researched in Phase II of this project effort, the rankings in this table could also be used in future decisions concerning funding for treatment evaluations.

For those treatments with a high or medium-high ranking for possible additional research, the project team then completed their exploration of possible available data (the final factor in the above list of decision factors). As noted above, data requirements for a sound evaluation (such as an EB before-after analysis) included both treatment information (i.e., treatment details, date of installation, and location) and historic crash, roadway inventory, and traffic data before and after the treatment installation date for both the treatment sites and for comparable reference sites. The latter requirement is most difficult to meet. State DOTs often have details of treatments and sometimes have conducted a simple before-after study, which means that before-treatment and after-treatment crash counts were documented. State DOTs are less likely to have retained information on traffic volume changes during the before-treatment and after-treatment periods for the treatment site. While some states do retain historic traffic volume, average annual daily traffic (AADT) data, virtually no state retains historic files of roadway inventories. The latter is necessary to identify segments of roadways or intersections that were similar to the treated locations, but were untreated during the before-treatment and after-treatment periods. Such historical data are available in HSIS for nine states. Use of those data would require that the treatment being considered was implemented in one of those nine states and that treatment details can be found. As part of the user survey, the project team also asked states to provide a listing of treatment evaluations they had conducted in the past. If a state had evaluated one of the higher-ranked treatments of interest, follow-up conversations were held to determine if historic crash, inventory, and traffic data were available for both treatment sites and possible comparison/reference sites. Based on information about available data from both sources, the project team then developed a listing of proposed AMF development strategies for each treatment in Table 3 for which the overall priority for future work was high or medium-high. Table 4 shows the AMFs proposed for development or improvement and presents suggested study methodologies for each—an EB evaluation based on new data, an analysis-driven expert panel, or a reanalysis of prior study data.

Based on their review of these suggestions and on a series of follow-up discussions with the project team, the oversight panel recommended that priority should be given to conducting as many EB evaluations of these high-priority treatments as possible, that expert panels were acceptable as long as they were analysis-driven (i.e., based on review of past research findings with limited additional analyses where needed), and that the project efforts should continue to be closely coordinated with ongoing work to develop safety prediction tools for urban/suburban arterials (NCHRP Project 17-26) and rural multilane highways (NCHRP Project 17-29) for use in the HSM. Based on the funding available and on team knowledge of available data, it was decided that EB analyses would be conducted to develop AMFs for the following high-priority treatments:

- Installation of a traffic signal at a rural intersection (new EB before-after evaluation);
- Conversion of an undivided four-lane road to three lanes including a two-way left-turn lane (TWLTL)—a "road diet" (reanalysis of data from two previous studies);
- Increasing pavement friction on intersection approaches (reanalysis of previous study data); and
- Increasing pavement friction on roadway segments (reanalysis of previous study data).

In addition, in order to maximize the number of AMFs produced through EB evaluations, project staff conducted a detailed analysis of data provided by Winston-Salem, North Carolina. There, the Director of Transportation had documented installation records for over 70 treatment types implemented since the 1980s. There were multiple sites for

Table 3. Factors used and final rankings for additional research on intersection, segment, and miscellaneous treatments.

Treatments	User Priority Ranking	Level of Predictive Certainty	Ongoing/ Future Work[1]	Crash Harm Rating[2, 3]	Overall Priority for Future Work[2]
Intersection Treatments					
Install a roundabout	19	Medium High	✓	H (4,5)	L
Reduce or eliminate intersection skew		Medium Low		ML* (4)	ML
Install offset T's		Non-Existent		ML* (5)	ML
Add exclusive left-turn lane	1	High	✓	MH (10)	L
Create positive offset for opposing left-turn lanes		Non-Existent	✓	H (5)	ML
Add exclusive right-turn lane	4	High	✓	L* (27)	L
Add channelization for right-turns	11	Non-Existent		L (27)	MH
Install a traffic signal	2	High (urban) None (rural)		H (4)	L (urban) H (rural)
Add a left-turn phase (protected or protected/permissive)	8	Medium Low		H (5)	MH
Install dynamic advance warning flashers "Red Signal Ahead"	17	Low		MH (10)	MH
Install overhead flashing beacon		Non-Existent	✓	H (4)	ML
Convert to all-way stop		Medium High		H (4)	ML
Prohibit left turns		Non-Existent		MH* (5)	MH
Install intersection lighting	13	Low	✓	MH* (4,9)	ML
Close driveways near intersections	22	Non-Existent		ML (16)	ML
Install marked crosswalk		Medium Low	✓	L* (7)	L
Road Segment Treatments					
Add a travel lane	8	Low	✓	MH (11)	MH
Reduce number of lanes (road diet)		Medium Low		MH* (1)	MH
Add passing lanes (two-lane roads)		Medium High	✓	H (6)	L
Widen median		Low		ML* (11,6)	MH
Install raised median	20	Non-Existent	✓	L* (6)	L
Increase lane width (two-lane)	21	Medium High	✓	H (6)	L
Increase lane width (multilane)	21	Non-Existent	✓	L (6)	L
Change shoulder width and/or type (two-lane)	15	Medium High	✓	H (2,3)	L
Change shoulder width and/or type (multilane)	15	Non-Existent	✓	L* (2,3)	ML
Flatten horizontal curve (two lane)	12	Medium High		H (2,3)	L
Flatten horizontal curve (multilane)	12	Non-Existent	✓	L* (2,3)	ML
Improve curve superelevation	18	Medium High		H (2,3)	ML
Add static curve warning signs and/or pavement markings		Non-Existent	✓	H (2,3)	H
Add shoulder rumble strips (freeways)	5	Medium High	✓	H[1] (2,3)[2]	L
Add shoulder rumble strips (multi-lane divided)	5	Medium Low	✓	L* (2,3)	ML
Add shoulder rumble strips (two lane)	5	Non-Existent	✓	H (2,3)	MH
Add edgeline rumble strips	14	Non-Existent	✓	H (2,3)	MH
Add centerline rumble strips (two-lane roads)	10	Medium High	✓	H (6)	L
Remove roadside obstacle	3	Medium Low	✓	H (2)	MH
Flatten sideslope	22	Low	✓	H (3)	MH
Install/upgrade guardrail	22	Medium High		H (2,3)	ML
Install median barriers	6	Medium Low	✓	L* (6)	L
Eliminate left turns at driveways	16	Non-Existent		ML (16)	MH
Install roadway segment lighting	23	Medium Low		MH	MH
Add sidewalk/walkway		Non-Existent		ML* (1)	ML
Add midblock pedestrian signal		Non-Existent		MH* (1)	MH
Install raised crosswalks (non-intersection)		Non-Existent		MH* (1)	MH
Install mid-block pedestrian crossing		Non-Existent	✓	MH* (1)	ML
Miscellaneous Treatments					
Consolidate driveways		Medium Low		MH (10,20)	ML
Provide signal coordination	7	Non-Existent		MH (10,12)	MH
Increase pavement friction		Low		MH* (2,3)	MH
Install crosswalk in-pavement lighting		Non-Existent	✓	H (1)	ML

[1]Checkmarks reflect treatments for which there is ongoing or planned future work to develop AMFs.
[2]H = High, MH = Medium-High, ML = Medium-Low, L = Low.
[3]Primary crash types are shown in parentheses with the crash harm rating. See Appendix A for discussion of the crash types. Those ratings that were adjusted are designated with an asterisk.

Table 4. Possible study methodologies for high-priority AMFs.

High Priority Treatments (Grey shading indicates high ranking in user survey)	Overall Priority for Future Work	Possible Study Methodologies		
		EB Evaluation	Expert Panel	Reanalysis of Prior Study Data
Intersection AMFs				
Install or remove a signal	H (Rural)	✓		
Add a left-turn phase (permissive/protected or protected-only)	MH	✓		
Channelize right turns	MH	✓		✓
Install dynamic advance warning flashers "Red Signal Ahead"	MH		✓	
Provide signal coordination	MH	✓	✓	✓
Prohibit left turns	MH	✓		
Increase pavement friction on approaches	H			✓
Segment AMFs				
Add a travel lane	MH		✓	
Remove roadside obstacles (including urban)	MH	✓	✓	
Add shoulder rumble strips (two-lane/others)	MH	✓		✓
Add edgeline rumble strips	MH	✓		
Eliminate left turns at driveways	MH	✓		
Flatten sideslopes	MH	✓	✓	✓
Install roadway segment lighting	MH	✓	✓	
Add advance curve warning signs/on-pavement markings	H	✓		
Increase pavement friction	MH			✓
Add midblock pedestrian signal	MH		✓	
Raise crosswalks (non-intersection)	MH		✓	
Reduce number of lanes (road diet)	MH	✓		
Widen median	MH		✓	✓
*H = High, MH = Medium-High, ML = Medium-Low, L = Low.				

most of the treatment types. He had consistently conducted simple before-after studies of the effects of these treatments on both total crashes and "target" crashes (e.g., angle crashes for stop-to-signal conversions). These studies usually contained 3 to 5 years of both before-treatment and after-treatment crash data. The documented data did not contain AADT data across the study years, and there were no computerized data files that would allow the development of a reference group for use in EB analyses. However, if these data could be obtained from other sources, then, if carefully chosen, multiple treatments could be analyzed using the same reference group. The project team then examined the data to identify treatment types evaluated in recent years that had sufficient sample sizes in the before-treatment and after-treatment periods to allow statistical significance tests. The team also identified "clean" treatment sites with each treatment type, where no additional treatments had been applied during the before-treatment and after-treatment periods (a major undertaking since many of the sites had undergone more than one treatment).

Based on these preliminary analyses, a decision was made to evaluate the following treatments at signalized intersections:

- Modification of a left-turn signal phase (three combinations),
- Replacement of an 8-in. signal head with 12-in. head,
- Replacement of a single red signal head with dual red signal heads, and
- Conversion of nighttime flashing operation to steady operation.

The first of these, the left-turn phase treatment, is included in Table 4. While the latter three treatments are not included as high-priority treatments in that table, examination of earlier studies in the Phase I literature review indicated that the AMFs existing for the second and third treatments (replacing 8-in. signal head with 12-in. head and replacing single red signal head with dual red signal heads) were rated as medium-low in predictive certainty. The final one (converting nighttime flashing operation to steady operation) had no AMF. In addition, this work allowed the researchers to develop AMFs for treatments of high interest to local (urban) traffic engineers. Finally, as noted above, the use of a single reference group greatly lowered the evaluation cost per treatment.

The other approach to AMF development/modification involved two analysis-driven expert panels. While earlier project discussions and information in Table 4 suggested the possibility of expert panels for AMFs related to specific focus areas (e.g., roadside crashes and pedestrian treatments), it was decided by the team and the oversight panel that a more critical need was to assist the research teams for NCHRP

Projects 17-26 and 17-29 in developing AMFs for the safety prediction tools they were developing for urban/suburban arterials and rural multilane highways. Because of the large number of serious and fatal crashes that occur on two-lane rural roads, much of the past AMF development work had focused on treatments for that roadway class. Literature on AMFs for other roadway classes is limited. It was hoped that expert panels might be able to combine the limited past evaluations specific to these two roadway classes with modified versions of two-lane AMFs to develop the needed estimates. It was also hoped that this option might produce multiple AMFs at a cost lower than the cost of new analyses. The results of these efforts are presented in Chapter 4.

Summary

The Phase I efforts of this research study identified 100 treatments that are used by state and local DOTs, ranked these treatments based on inputs from a state DOT user survey, and produced documentation of 20 AMFs that were judged to be of high or medium-high quality from a critical review of existing research literature. This effort was closely coordinated with other ongoing NCHRP efforts to document AMFs for the upcoming publication of the HSM. Indeed, the criteria used to make this judgment of AMF quality were the basis for similar AMF reviews in the HSM project. The project team then developed a unique process for identifying high-priority AMF research needs that incorporates the priorities of DOT practitioners, the current level of AMF quality, knowledge of other ongoing or future research that might enhance certain treatment AMFs, and a measure of the effect on crash harm that a specific treatment might have if implemented widely. For those treatments that were ranked highest in terms of need by this procedure, the team explored available state and national databases and proposed a research strategy to develop or improve the AMF for each treatment. Working with the project oversight panel, a final list of research tasks for the Phase II effort was developed. The research conducted is described in the next two chapters of this report.

CHAPTER 3

Development of New AMFs through Analysis or Reanalysis of Crash Data

This chapter provides a summary of each of the data analysis efforts to produce or enhance AMFs. The narrative includes a description of the treatment studied, the data used, the statistical methodology, and the results of each evaluation. More detailed descriptions of these efforts are included in appendices to this report.

Introduction

Much of the Phase II effort involved new analysis or reanalysis of crash and other safety data for the treatments identified by the oversight panel and project team. Individual summaries are presented for the following four treatments:

- Installation of a traffic signal at a rural intersection (new EB evaluation);
- Conversion of undivided four-lane road to three lanes including a two-way left-turn lane—a "road diet" (reanalysis of data from two previous studies);
- Increasing pavement friction on intersection approaches (reanalysis of previous study data); and
- Increasing pavement friction on roadway segments (reanalysis of previous study data).

The EB analyses of the following four urban signalized-intersection treatments will be described in one section, since the same reference group was used for all four:

- Modification of left-turn signal phase (3 combinations),
- Replacement of 8-in. signal head with 12-in. head,
- Replacement of single red signal head with two signal heads, and
- Replacement of nighttime flashing operation with regular signal phasing.

Also, as noted in the Chapter 4 discussion, the analysis-driven expert panels recommended additional analysis for several AMFs. Many of the recommendations were based on a consensus that prior research was valid and applicable to the roadway class in question and thus that the AMFs from the research were appropriate. Other recommendations required additional analysis to be conducted by one or more of the NCHRP project teams. Two of those analysis efforts were undertaken in this project.

The first analysis effort focused on travel speed. While travel speed is known to be a critical factor in both crash frequency and crash severity, limited effort has been focused on producing a relationship that would allow prediction of the crash-related effects of reducing average speeds by a given amount. If such a relationship could be developed, it could be used as an AMF for a wide spectrum of treatments with known effects on average speeds. For example, if the effects on travel speed of changing a speed limit or installing a neighborhood traffic calming device could be estimated, these effects could be converted into expected changes in crashes. Based on the panel recommendation, a reanalysis of data from a prior research study was conducted to confirm or modify the results and to determine if the findings, which were based on the many non-U.S. studies, were applicable to U.S. roadways. A summary of this analysis is provided in this chapter.

The second analysis effort was conducted by the suburban/urban panel and involved examining existing studies of the effects of median width on crashes. The panel was unable to come to a consensus on an AMF. At the panel's recommendation, the project team conducted additional analysis of this issue using HSIS data from California. Note that because median widths are not normally changed without changes in other critical roadway components (e.g., changes in number of lanes and/or shoulder width), a traditional EB before-after analysis was not possible. Instead, as described later in this chapter, cross-sectional regression analyses were conducted.

Each of the summaries will provide information on the treatment, the methodology, the data used, and the results of the analyses. Because all but two of the analyses conducted in this project utilized EB analyses, the following section provides a brief description of that general methodology. A more comprehensive description is provided in Appendix B.

Overview of the Empirical Bayes (EB) Methodology

The general analysis methodology used in many of the following evaluations was the empirical Bayes (EB) before-after analysis as described by Hauer (*7*), which has become the standard of practice in recent years. This methodology does the following:

- Properly accounts for regression to the mean,
- Overcomes the difficulties of using crash rates in normalizing for volume differences between the before-treatment and after-treatment periods,
- Reduces the level of uncertainty in the estimates of safety effect,
- Provides a foundation for developing guidelines for estimating the likely safety consequences of the contemplated implementation of the evaluated treatment, and
- Properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

To accomplish this, the EB analysis requires before-treatment and after-treatment crash and AADT data on the treatment sites and on a reference group of similar untreated sites. The similarity of untreated sites is determined on the basis of the geometrics of the sites (e.g., rural, four-leg, stop-controlled intersections and non-intersection locations on urban, undivided, four-lane, non-freeways), on similar AADT ranges, and on crash history in the before-treatment period. Using the reference group, a safety performance function (SPF) is developed—a regression equation that predicts an outcome variable (e.g., total crashes per year or injury right-angle crashes per year) based on either AADT only or on AADT plus other site descriptors (e.g., lane width or presence of a left-turn lane). (In the studies conducted for this project, generalized linear modeling was used to estimate model coefficients in the regression equations using the SAS software package and assuming a negative binomial error distribution, practices consistent with the state of research in developing these models.) A “time trend factor” based on the reference group data was also developed for each year in the before-treatment and after-treatment periods and is typically reflected as an SPF multiplier. This multiplier is used to account for annual effects due to variations in weather, demography, crash reporting, and so forth, across the study period. The SPF outputs are combined with the observed crashes in the before-treatment period to produce an estimate of before-treatment crash frequency that is adjusted for regression to the mean. Using the SPF to control for AADT growth and the time trend factor, this adjusted before-treatment-period estimate is then projected to predict what would happen in each year of the after-treatment period *if the treatment had not been implemented*. The sum of these predictions (i.e., what would happen without treatment in the entire after-treatment period) is compared to the observed crashes during that period (with the treatment implemented) to produce an estimate of the effect of the treatment. The procedure also calculates the standard deviation of this effect estimate, which makes it possible to determine if the measured effect is statistically significant or not at a specified level of significance.

Installation of a Rural Traffic Signal

Description of Treatment and Crash Types of Interest

This analysis examined the safety impacts of converting rural intersections from stop-controlled operation to signal-controlled. The basic objective was to estimate the change in crashes. Target crash types considered included the following:

- All crash types,
- Right-angle (side-impact) crashes,
- Left-turn-opposing (one-vehicle-oncoming) crashes, and
- Rear-end crashes.

The change in crash frequency was analyzed as well as the changes in overall economic costs, recognizing that different crash types and severity levels have different economic costs. Appendix B provides the details associated with this evaluation.

Data Used

Geometric, traffic-volume, and accident data for treatment and reference sites were acquired from HSIS for the states of California (1993–2002) and Minnesota (1991–2002) to facilitate the analysis. In addition, the Iowa DOT provided a dataset of high-speed rural intersections in Iowa that were converted from stop-controlled to signal-controlled. The Iowa DOT also provided a reference group of similar sites. Because these data were limited, the time trend necessary to conduct an EB analysis could not be developed, but the results from a cursory analysis of the Iowa data were used to reaffirm the results from the analysis of California and Minnesota data.

Methodology

The general analysis methodology used was the EB before-after analysis, as previously described. The evaluation not only included analysis of the effects of the treatment on crash frequencies for different accident types and severities individually; it also included analysis of the effects on the overall economic cost (or "crash harm") of crashes before and after the treatment. Since different crash types are characterized by different severities (e.g., rear-end crashes are often less severe than angle crashes), the economic cost of a crash can be assigned based on crash type and severity using type/severity economic costs from a recent FHWA study (*72*). Then, using an EB method that parallels the method described above for crash frequencies, the overall estimate of treatment effect when all crash types and severities are combined can be calculated. A much more detailed statistical description of the EB method for both crash frequency and economic costs is found in Appendix B.

The analyses attempted to develop AMFs for two crash-severity levels (i.e., injury versus no-injury) within each of the four crash types (i.e., total, right-angle, left-turn-opposing, and rear-end) within three types of stop-controlled (before-treatment) intersections. This was not possible in both states. The intersection types and the treatment and reference group sample sizes are noted in Table 5. Iowa data included a total of 19 treatment sites and 59 reference sites (three- and four-leg combined).

In addition to providing data on these stop-controlled sites, California and Minnesota provided data on other intersections that were signalized throughout the entire before-treatment and after-treatment period (63 four-legged sites from California, 21 four-leg sites from Minnesota). These data were used in two ways. First, the signalized intersection datasets were used to verify that the treated intersections in the after-treatment period performed similarly to intersections that were already signalized during the after-treatment period. In general, the treated intersections did perform similarly, indicating that the treated sites were not an unusual group of intersections. This similar performance helps validate the calculated crash-related AMF. Second, the data on intersections that were signalized throughout the entire before-treatment and after-treatment period were used to develop a more detailed procedure for assessing whether a contemplated signal installation is warranted at a given location. In one sense, the initial EB analysis produces an AMF for each target crash type, but the AMF does not vary with AADT. The procedure provides a type of "AMF function," allowing the engineer to input specific before- and after-conversion AADTs to estimate the expected effects. This procedure is documented in Appendix B.

Table 5. Number of sites for treatment and reference groups.

Intersection Type	State	
	California	Minnesota
Three leg	--	2 treatment 522 reference
Three leg, two lanes on major road	4 treatment 1,405 reference	--
Four leg	--	15 treatment 736 reference
Four leg, two lanes on major road	14 treatment 742 reference	--
Four leg, four lanes on major road	10 treatment 183 reference	--
-- = no sites.		

Results

The initial EB evaluation of crash frequency by crash types indicated a significant effect of signal installation on angle, left-turn and rear-end crashes. Table 6 shows the individual and combined results of the California and Minnesota analyses—the AMFs and their standard deviation.

As shown in Table 6, the Iowa results are similar to those from the other two states, providing some validation for those results. The best overall estimate of effect is shown in the bottom row where the California and Minnesota results are combined. There, for all intersection types combined, signal installation is expected to reduce total crashes by 44 percent, right-angle crashes by 77 percent, left-turn crashes by 60 percent, and increase rear-end crashes by 58 percent. The analyses conducted indicated that while there were slight differences in effects for the different intersection types and crash severities, these differences were not statistically significant. Thus, the overall AMFs shown above are appropriate for all rural site types.

However, the significant increase in rear-end crashes raises questions concerning how much of the angle and left-turn savings are negated by this rear-end increase. An examination of the economic costs of the changes based on an aggregation

Table 6. Crash frequency AMFs (and standard deviations) by crash type for rural signalization.

State	Total Crashes	Right-Angle (RA)	Left-Turn (LT)	Rear-End (RE)
California	0.778 (0.061)	0.221 (0.036)	0.433 (0.065)	2.474 (0.373)
Minnesota	0.488 (0.027)	0.228 (0.019)	0.374 (0.063)	1.300 (0.141)
Iowa	0.950 (0.085)	0.265 (0.053)	n/a	2.075 (0.323)
California + Minnesota	0.559 (0.025)	0.227 (0.017)	0.401 (0.047)	1.579 (0.142)

Table 7. Economic cost of AMFs (and standard deviations) for different before-treatment-period conditions, based on combined results from California and Minnesota.

Characteristic	Cost AMF
Total crashes	0.265 (0.001)
California	0.315 (0.002)
Minnesota	0.247 (0.001)
Three leg	0.286 (0.004)
Four leg	0.264 (0.001)
Two lanes on major	0.265 (0.002)
Four lanes on major	0.265 (0.001)
AADT < 20,000	0.314 (0.003)
AADT > 20,000	0.253 (0.001)
Expected RA/Expected RE ≤ 4.5*	0.324 (0.002)
Expected RA/Expected RE >4.5*	0.215 (0.001)

* EB estimates for right-angle and rear-end when under stop-controlled conditions

of rear-end, right-angle, and "other" crash costs for various severity levels, which is intended to cast light on this issue, is the subject of the economic analysis. Table 7 shows the results of that analysis.

The results indicated that when crash types are combined using the costs of the different crash types, the rear-end increase does not negate the effect on angle and left-turn crashes. There are significant reductions in crash costs, with the top row in the table indicating that total costs are reduced by 73 percent (100[1-0.265]). The results also provide guidance on the intersection conditions under which signal installation would be most beneficial. While there is little difference in the effects on three-leg sites versus four-leg sites and on sites with two lanes versus sites with four lanes on the major road, the results indicate that the benefits are greater on higher volume intersections and are greater where the ratio of expected right-angle crashes to rear-end crashes is higher.

Conversion of an Undivided Four-Lane Road to Three Lanes and a Two-Way Left-Turn Lane—a "Road Diet"

Description of Treatment and Crash Types of Interest

This analysis examined the safety impacts of converting four-lane roadways to three-lane roadways where the center lane is now a two-way left-turn lane. The site locations are in urbanized areas.

The basic objective was to estimate the change in total crashes. A secondary objective was to use EB methodology to compare the results with results from a previous study that used full Bayes modeling and time series data for a group of treated and comparison sites matched on a one-to-one basis (*44*). Appendix C provides the details associated with this evaluation.

Data Used

Data were acquired from two sources. Geometric, traffic-volume, and accident data for 15 Iowa treatment sites used in a previous full Bayes study and data for an additional 296 reference sites were provided by the Iowa DOT (*44*). The same types of data for 30 treatment sites and 51 reference sites in the cities of Bellevue and Seattle in Washington state and Mountain View, Oakland, Sacramento, San Francisco, San Leandro, and Sunnyvale in California were acquired from HSIS, whose staff had conducted the original evaluation of these installations (*43*). In the HSIS study, comparison sites were matched with treatment sites that were similar in terms of functional class, type of development, speed limit, intersection spacing, and access control. Although the sites were located in different states, all sites were four-lane to three-lane conversions.

Methodology

The general analysis methodology used was the EB before-after analysis, as previously described. Separate AMF estimates were produced for the Iowa and the HSIS data, and the results were then aggregated to develop a combined AMF. While the Iowa data allowed the development of the annual factors to account for the time trend in the EB analysis, the HSIS data did not. The HSIS reference group was much smaller than the Iowa group (51 reference sites versus 296 sites), but that HSIS reference group had been chosen by local traffic engineers to be similar to the treated sites.

Results

The EB evaluation of total crash frequency indicated that the road-diet treatment had a significant effect in both datasets and when the results were combined. Table 8 shows the results from each of the two studies and the combined results—the AMFs and their standard error.

As can be seen, the measured effects from the two databases differ markedly. The Iowa data indicate a 47-percent reduction in total crashes while the HSIS (California and Washington) data indicate a 19-percent decrease. The aggregated estimate is a 29-percent decrease in total crashes. The difference may be a function of traffic volumes and characteristics of the urban

Table 8. Crash frequency AMFs (and standard errors) for road diets.

Dataset	AMF	Standard error
Iowa	0.534	0.020
HSIS	0.811	0.025
All	0.707	0.016

environments where the road diets were implemented. The sites in Iowa ranged in AADT from 3,718 to 13,908 and were predominately on U.S. or state routes in small urban towns with an average population of 17,000. The sites in Washington and California ranged in AADT from 6,194 to 26,376 and were predominately on corridors in suburban environments that surrounded larger cities, with an average population of 269,000. In addition, in Iowa there appeared to be a calming effect as evidenced in a study (*44*) of one site that revealed a 4 to 5 mph reduction in 85th-percentile free flow speed and a 30-percent reduction in percentage of vehicles traveling more than 5 mph over the speed limit (i.e., vehicles traveling 35 mph or higher). The researchers' speculation is that this calming effect would be less likely in the larger cities in the HSIS study, where the approaching speed limits (and traffic speeds) might have been lower to start with.

The "new" Iowa results also seem to be incompatible with those in the earlier Iowa analysis of the same treatment site data (*44*). However, the 25-percent reduction reported in that study was based on average effects per mile derived by comparing average crashes per mile after treatment with expected average crashes per mile without treatment. These results are not comparable to the "new" results since sites of different lengths were weighted equally. (The "new" results are overall effects that provide more weight to sites of longer length.) In addition, the "new" results use a much larger comparison group than the previous study, which used an equal number of treatment and comparison sites.

Increasing Pavement Friction on Roadway Segments and at Intersection Approaches

Description of Treatment and Crash Types of Interest

This analysis examined the safety impacts of improving pavement skid resistance using data from the state of New York. The New York State DOT has implemented a skid accident reduction program (SKARP), which identifies sections of pavement with a high proportion of wet-road accidents, performs friction tests on these locations, and treats those with both a high proportion of wet-road accidents and low friction numbers (below the Programmatic Design Target Friction Number, FN40R, of 32). The treatment generally involves a 1.5-in. resurfacing or a 0.5-in. microsurfacing using non-carbonate aggregates. This treatment is applied principally on the major road approaches at intersections, but is often extended some distance away from the intersection as well.

The goal of this analysis was to develop separate AMFs for different crash types occurring at seven different intersection types (i.e., all intersections combined; three-leg signalized, stop-controlled and yield-controlled; and four-leg signalized, stop-controlled and yield-controlled) and on five types of roadway segments (i.e., all segments combined, rural two-lane segments, rural multilane segments; urban two-lane segments, and urban multilane segments). Appendix D provides the details associated with this evaluation. The target crash types of interest in the intersection analyses included the following:

- Total,
- Wet road,
- Dry road,
- Rear end,
- Rear end wet,
- Right angle, and
- Right-angle wet-road.

The target crash types considered for segments included:

- Total,
- Wet road,
- Dry road,
- Rear end,
- Rear-end wet-road,
- Rear-end dry-road,
- Single vehicle, and
- Single-vehicle wet-road.

Data Used

The data for this study were provided by the New York State DOT and included crash, geometric, and AADT data for treated and untreated intersections and segments during the period of 1994 to 2003. Data were included for 256 treated intersections and 3,993 untreated reference intersections, as well as for 36.3 miles (118 segments) of treated non-intersection locations and 1,242.4 miles (2,108 segments) of untreated reference locations.

Methodology

The general analysis methodology used was the EB before-after analysis, as previously described. SPFs and annual correction factors were successfully developed for each of the site type/crash type combinations noted above.

Results

Intersection Treatments

Estimates of the AMFs for the crash frequency analyses for intersection skid-reduction treatments are given in Table 9. Results that are statistically significant at the 95-percent level are in shown in boldface type.

Table 9. Crash frequency AMFs (and standard error) by crash type for intersection skid-reduction treatments.

Intersection Type	Total crashes (s.e.)	Wet-road (s.e.)	Rear-end (s.e.)	Dry (s.e.)	Rear-end wet (s.e.)	Right-angle (s.e.)	Right-angle wet (s.e.)
All	**0.799 (0.028)**	**0.426 (0.030)**	**0.582 (0.034)**	**1.149 (0.051)**	**0.322 (0.041)**	1.045 (0.078)	0.799 (0.123)
Three-leg signalized	**0.667 (0.050)**	**0.372 (0.053)**	**0.554 (0.065)**	0.959 (0.093)	**0.261 (0.066)**	0.787 (0.125)	**0.470 (0.161)**
Three-leg stop-controlled	**0.819 (0.048)**	**0.355 (0.046)**	**0.586 (0.057)**	**1.302 (0.095)**	**0.335 (0.075)**	0.828 (0.218)	0.828 (0.218)
Three-leg yield-controlled	**0.590 (0.114)**	**0.217 (0.103)**	**0.304 (0.086)**	1.392 (0.321)	**0.221 (0.161)**	n/a	n/a
Four-leg signalized	**0.797 (0.052)**	**0.546 (0.070)**	**0.585 (0.068)**	0.992 (0.081)	**0.361 (0.084)**	0.898 (0.117)	1.105 (0.294)
Four-leg stop-controlled	1.271 (0.143)	**0.597 (0.137)**	0.943 (0.188)	1.754 (0.242)	**0.482 (0.215)**	**1.687 (0.323)**	0.829 (0.351)
Four-leg yield-controlled	0.589 (0.216)	0.361 (0.371)	**0.504 (0.248)**	0.651 (0.273)	n/a	n/a	n/a

The results show statistically significant reductions at almost all types of intersections in total crashes; wet-road; rear-end; and rear-end, wet-road crashes. As expected, the largest effects were on total wet-road crashes (i.e., 40-percent to 78-percent reductions) and rear-end, wet-road crashes (i.e., 52-percent to 78-percent reductions). There was very little effect on wet-road, right-angle crashes. Overall, dry road crashes showed a statistically significant 14-percent increase. However, this did not negate the effects on wet-road crashes, as shown by the statistically significant 20-percent decrease in total crashes when all intersection and crash types were combined. To see if the principal benefits of improved skid resistance on wet-road crashes declined over time, the effect on wet-road accidents was analyzed by year after treatment. The analysis indicated no discernable decreasing trend over the 6 years of after-treatment-period data.

Segment Treatments

Estimates of the AMFs for the crash frequency analyses for segment-based skid-resistance treatments are given in Table 10. Results that are statistically significant at the 95-percent level are in bold.

In general, the results show statistically significant reductions in total crashes and in wet-road; rear-end; rear-end, wet-road; single-vehicle; and single-vehicle, wet-road crashes for most roadway categories. The only exception was for two-lane rural roads, where no significant decreases or increases in frequency were found. As expected, the largest statistically significant effects were on total wet-road crashes (i.e., 46-percent to 74-percent reductions), on wet-road, rear-end crashes (i.e., 36-percent to 66-percent reductions) and on wet-road, single-vehicle crashes (i.e., 38-percent to 71-percent reductions). The only statistically significant increase found was for dry-road crashes on urban multilane roads (i.e., a 13-percent increase). However, that increase did not negate the overall treatment effect in that there was a 14-percent reduction in total crashes (i.e., dry plus wet) on these roads.

A final analysis examined changes in the overall proportions of wet-road crashes before and after the treatments. It found a statistically significant reduction in the proportion of wet-road accidents at intersection locations (i.e., 40 percent

Table 10. Crash frequency AMFs (and standard errors) by crash type for segment skid-reduction treatments.

Segment Type	Total Crashes (s.e.)	Wet-road (s.e.)	Rear-end (s.e.)	Dry (s.e.)	Rear-end wet-road (s.e.)	Rear-end dry-road (s.e.)	Single-vehicle (s.e.)	Single-vehicle wet-road (s.e.)
All	**0.764 (0.023)**	**0.434 (0.024)**	**0.828 (0.043)**	1.003 (0.043)	**0.575 (0.055)**	0.977 (0.068))	**0.698 (0.040)**	**0.399 (0.039)**
Rural 2 lanes	0.964 (0.073)	0.852 (0.126)	1.047 (0.149)	1.167 (0.114)	0.971 (0.256)	1.235 (0.219)	1.078 (0.141)	1.125 (0.287)
Rural >2 lanes	**0.684 (0.032)**	**0.346 (0.028)**	**0.776 (0.068)**	**0.875 (0.061)**	**0.474 (0.079)**	0.838 (0.098)	**0.588 (0.046)**	**0.292 (0.038)**
Urban 2 lanes	**0.599 (0.082)**	**0.260 (0.066)**	**0.612 (0.142)**	0.992 (0.195)	**0.344 (0.145)**	0.695 (0.216)	0.921 (0.232)	0.523 (0.247)
Urban > 2 lanes	**0.862 (0.038)**	**0.538 (0.045)**	**0.866 (0.059)**	**1.132 (0.065)**	**0.640 (0.084)**	1.120 (0.099)	**0.800 (0.083)**	**0.615 (0.115)**

before treatment versus 16 percent after treatment) and segment locations (i.e., 38 percent before treatment versus 16 percent after treatment).

Signalized Intersection Treatments in Urban Areas

Description of Treatment and Crash Types of Interest

This analysis examined the safety impacts of four urban safety treatments implemented at signalized intersections in Winston-Salem, North Carolina. The treatments were the following:

- Modification of left-turn signal phase (three combinations),
- Conversion of nighttime flashing operation to steady operation,
- Replacement of 8-in. signal heads with 12-in. heads, and
- Replacement of single red signal head with dual red signal heads.

The basic objective was to estimate the change in target crashes for each of the treatments. Target crashes, which differed depending on the treatment, included left-turn crashes, nighttime angle crashes, and right-angle crashes. However, since the treatment might increase other types of crashes (e.g., the conversion back to regular nighttime phasing could increase rear-end crashes on the major road), additional crash types and total crashes were examined. The specific crash types for each treatment are presented below. Appendix E provides the details associated with this evaluation.

Data Used

Unlike many other jurisdictions, the City of Winston-Salem has documented the installation records for a large number of urban safety treatments implemented at intersection and non-intersection locations and has systematically conducted simple before-after studies of those treatments. Documentation exists for over 70 individual treatments or combinations of treatments installed since the 1980s, along with target and total crash counts for before-treatment and after-treatment periods of 3 to 5 years. The City of Winston-Salem provided these files to the research team. The team then chose the four treatments for evaluation based on the following:

- A statistical analysis of available crash sample size to ensure the possibility of statistically significant results;
- The timeliness of the treatments to ensure a reasonable current driver and vehicle population (i.e., treatments in 1994 and later);
- The quality of the existing AMF, based on the information described in Chapter 2 of this report; and
- The availability of a group of similar but untreated intersections to be used as a reference group.

The original Winston-Salem documentation did not include information on before-treatment-period and after-treatment-period AADTs. Research team members traveled to Winston-Salem and extracted the AADTs for each treatment intersection approach for each before-treatment and after-treatment year from AADT books available at the City of Winston-Salem DOT.

Winston-Salem does not have a computerized intersection inventory that is linkable to crash records. Thus, they could not provide the research team with data to be used in the development of a reference group of similar untreated sites. After consideration of other alternatives, a reference group was manually developed. The Winston-Salem Traffic Engineer and his staff identified 75 untreated signalized intersections that were similar to the treated sites in terms of traffic volume, number of legs, number of approach lanes, and other characteristics during the study period (1990 to 2004). Crash data for all crashes in Winston-Salem for the full study period were extracted from the North Carolina DOT crash files, which contain data on all crashes statewide, and these data were manually matched to the reference intersections based on street names found on the crash reports. AADT data for each year in the full period were then extracted for each reference intersection from the Winston-Salem AADT books noted above. After eliminating intersections lacking in AADT or other data, 60 untreated intersections were available for developing the required SPFs.

Methodology

The general analysis methodology used was the EB before-after analysis previously described. SPFs and annual correction factors were successfully developed for total crashes. Efforts at estimating SPFs for specific crash types were not successful. Hence, the proportion of crashes for each crash type and a recalibrated over-dispersion parameter were used in the EB analysis.

Results

Table 11 presents the results of the EB analyses for each of the four treatment types. For each treatment, results are presented for both the primary target crashes and for other important crash types. Statistically significant results are indicated by asterisks.

Modification of Left-Turn Phase

Three types of left-turn phasing treatments were identified. In all cases, the target crashes for these treatments were

Table 11. Crash frequency AMFs for urban signalized intersection treatments by treatment type.

Treatment Type	No. of Treatment Sites	Crash Type	AMF (standard error)
Replace permissive left-turn phasing with permissive/protected (1)	3	Left-Turn All	0.978 (0.277) 1.045 (0.135)
Replace permissive left-turn phasing with protected (2)	8	Left-Turn All	0.021 (0.021)** 0.975 (0.085)
Replace permissive/protected left-turn phasing with protected (3)	4	Left-Turn All	0.000 (0.006)** 1.020 (0.123)
Replace permissive or permissive/protected with protected (combination of 2 and 3)	12	Left-Turn All	0.014 (0.014)** 0.992 (0.070)
Convert nighttime flash to normal phasing (4)	12	Nighttime Angle All Nighttime	0.659 (0.180)* 0.651 (0.145)**
Replace 8-in. signal heads with 12-in. heads (5)	26	Right-Angle All	0.580 (0.070)** 0.970 (0.060)
Add second signal head (6)	8	Right-Angle All	1.050 (0.130) 1.180 (0.110)

** Statistically significant at the 0.05 significance level
* Statistically significant at the 0.10 significance level

identified as those involving at least one left-turning vehicle on the treated roadway. The first treatment involved replacing a permissive left-turn phase with a permissive/protected phase at three sites. There was little change in either the target or total crashes, but the small sample size suggests caution in concluding "no effect."

The second treatment involved replacing a permissive left-turn phase with a fully protected phase at eight sites. Here, the target left-turn crashes were reduced by approximately 98 percent, a statistically significant reduction, and total crashes changed very little.

The third treatment type involved replacing a permissive/protected phase with a fully protected phase at four sites. Here, the left turn crashes were eliminated while the total crashes changed little.

Since the results of the second and third treatments refer to conversions to a fully protected phase and since the results were similar, they were combined into one group to increase the sample of sites to 12. As shown, the combined AMF was 0.014 for the left-turn crashes (a statistically significant result), and the total crashes again were virtually unchanged. Since the left-turn crashes decreased substantially and total crashes did not, it is evident that there must have been an increase in non-left-turn crashes of the same order as the decrease in left-turn crashes. Unfortunately, these data did not allow the research team to examine changes in other specific crash types. Further research is necessary to determine the specific reasons for the effect on non-left-turn crashes. However, it seems reasonable to speculate that introducing a protected left-turn phase tended to increase rear-end crashes more than others because of the increased number of phases (and therefore dilemma zone opportunities) and the increase in queues that can result from the reduced green time available for all traffic not protected by the introduced phase. If this is the case, the implication is that this is still a very safety-effective measure from a total-harm perspective since left-turn crashes tend to be of the side-impact variety and therefore are more severe than rear-end crashes. The results also imply that the treatment would be most effective overall where there is a relatively high frequency of left-turn crashes.

Conversion of Nighttime Flashing Operation to Steady Operation

There were 12 intersections where nighttime (9 p.m. to 6 a.m.) flashing operation was replaced with regular phasing. The EB analysis indicated that nighttime angle crashes (the ones most likely to be positively affected) were reduced by approximately 34 percent, a statistically significant reduction at the 0.10 level of significance. Total nighttime crashes also saw a significant reduction of approximately 35 percent

Replacement of 8-in. Signal Heads with 12-in. Heads

There were 26 intersections where 8-in. signal heads were changed to 12-in. heads. The EB analysis indicates that right-angle crashes experienced a statistically significant decrease of approximately 42 percent. Total crashes experienced virtually no change. This implies an increase in non-angle crashes of approximately the same size as the decrease in angle crashes. While it is not possible to determine the specific crash types for the non-angle crashes, one could hypothesize that they are predominately rear-end crashes, which might be increased by more drivers stopping rather than proceeding through the signal—the same effect seen for red-light cameras at intersections. Since a "tradeoff" occurred and since the severities of angle and non-angle crashes can differ, an economic analysis was conducted in order to accurately estimate the effect of this treatment on overall "crash harm." Based on a recent report from FHWA (*72*), the comprehensive cost per crash is $47,333 for angle crashes and $26,735 for rear-end crashes. Assuming that the overall severity of non-angle crashes is quite similar to that of rear-end crashes, the economic analysis revealed a reduction of about $11,800 per intersection-year in the overall crash harm due to this treatment.

Replace Single Red Signal Head with Dual Red Signal Heads

A second red signal head was added to the existing head at eight intersections in Winston-Salem. The EB analysis indicates a slight, but not statistically significant, increase in both right-angle and total crashes after installation. Given the limited sample of sites that were evaluated, these results suggest that the installation of double red signal heads does not appear to be an effective strategy for reducing total or angle crashes.

Speed Change and Crashes

Description of Treatment and Crash Types of Interest

The objective of this analysis was to develop an AMF that would relate speed change caused by a treatment to a change in crash frequency for a certain level of crash severity (i.e., fatal, injury, no-injury). Thus, if one could estimate the effect of a treatment on mean speed, the AMF would then translate this change in mean speed to an estimated change in crash frequency. With this speed change AMF, if the change in mean speed can be anticipated so can the potential safety effect. If the change in mean speed can be measured, the future safety effect can be estimated without waiting for crashes to materialize. The treatments could theoretically include "passive" treatments such as changes in speed limits or increased speed enforcement (i.e., "passive" in the sense that the driver can choose to react or not react to the treatment) and "active" treatments that could include changes to the roadway such as residential traffic-calming speed tables (i.e., "active" in the sense that the driver is "forced" to reduce speed by the treatment).

A study by Nilsson (*73*) hypothesized a "power model" relating the ratio of before-treatment and after-treatment crash frequency to the ratio of before-treatment and after-treatment mean speed raised to some power, with the power changing for different crash severities. Elvik et al. (*74*) further developed this power model using a large set of data extracted from published research reports. The objective of the reanalysis of the Elvik et al. data done in this research was to determine if such a relationship exists, and if so, whether the power model or some alternative model form best describes the relationship between speed changes and crash frequency.

Thus, this AMF (or series of AMFs) is related to any treatment that is associated with a changed mean speed. Appendix F provides the details associated with this evaluation.

Data Used

The data used in this reanalysis were supplied by Elvik from his earlier study (*74*). His research team had extracted data on mean speed change and the related crash-frequency change from 97 published international studies containing 460 results. Each result contained information on mean speed and crash frequency before treatment and mean speed and crash frequency after treatment. Some studies included information on mean speed and crash frequency for a set of comparison locations where no treatment was installed. Each result also included study details such as the type of study (e.g., simple before/after or time series), the country where the study was conducted, the type of location (urban/rural) and the road system. The country data were important since a secondary objective of this reanalysis was to determine if the results from non-U.S. studies could be applied to U.S. roads.

The research team then reexamined each of the study results and clarified possible errors through a series of conversations with Elvik. The research team also calculated revised estimates of standard errors of the crash and speed changes based on the study types, using procedures that will be used in the upcoming Highway Safety Manual.

Methodology

The final dataset was then used to examine the power model results and to develop alternative model forms. One alternative model form was based on the "maneuver time needed to avoid a crash," which is a function of initial speed and the distance to an obstacle or vehicle. The other alternative model form was based on the underlying physics of speed versus crash frequency and crash injury. The two alternative model forms were then compared and used to develop a final set of proposed AMFs.

Results

Like the results of the earlier study (*74*), both alternative models indicated that the data supported the existence of a relatively strong relationship between speed change and change in fatal and non-fatal injury crash frequency. The relationship with property-damage-only (PDO) crashes was not distinct. Both of the alternative model forms indicated that the speed-versus-crash relationship in the foreign studies was similar to that in the U.S. studies. Quality of fit statistics indicated that both model forms were slightly more accurate than the power model. As expected, the two alternative models produced slightly different values for the injury-crash AMF and the fatal-crash AMF. The decision was then made to combine the AMF values from the two models to produce the recommended AMFs. Table 12 provides these combined AMFs.

To illustrate the use of these AMFs, consider a road on which the mean speed is 60.0 mph. If some measure is expected to increase the mean speed by 2.0 mph, injury accidents are expected to increase by a factor of 1.10 and fatal accidents by a factor of 1.18. Thus, what may appear to be a small change in mean speed has a large impact on accidents.

It is expected that these AMFs would be usable for treatments associated with change in mean speed on freeways and rural highways. Their usefulness for urban-street treatments is less certain. There were some indications in the data that speed change related to passive treatments on urban streets had less effect on crash frequency than is shown in Table 12 (i.e., an AMF closer to 1.0) and that the effect of active speed control on these streets (i.e., road humps, traffic circles, chicanes, and so forth) may not be fully captured here. However, neither of these indications was found to be fully confirmed in the statistical analysis. In the absence of other knowledge, it is concluded that the tabulated AMFs can be applied to both active and passive treatments on urban streets. However, the user should understand that there is less certainty about the AMFs when they are used for urban streets than when they are used for freeways and rural highways.

Effect of Median Width

Description of Treatment and Crash Types of Interest

Studies on the effect of median width have shown that increasing width reduces cross-median crashes, but the amount of reduction varies across studies. The effect of median width on median-related or all crashes is even less clear. The basic objective of the research was to develop AMFs for median width for different types of roads.

Methodology

The preferred method for developing an AMF is to conduct a before-after study in which the treatment installation/removal/change date is known, and thus the safety before and after this date can be tracked. The current state-of-the-art methodology for conducting such studies makes use of an EB approach, which helps to account for issues such as regression to the mean, changes in traffic volumes, and changes in crashes over time that are due to other factors (e.g., weather). However, there are a number of treatments in the roadway environment that are not "installed" or changed in a manner that allows for a before-after study. Median width is one such treatment. It is very unlikely that the median width on a highway will ever be changed without making other significant changes to the geometric cross-section. For example, the most common change in median width would occur when additional travel lanes are being added to the left-hand side of a roadway, thus narrowing the median. In this case, the fact that there is a significant change other than the change in median width makes it more difficult to isolate the effects of the change in width in an EB before-after evaluation. In this case, a cross-section model that predicts safety on the basis of varying median widths, traffic volumes, and other factors is still the most feasible option for determining the expected safety benefits as median width changes. In this evaluation, negative binomial (NB) regression models were developed with crash frequency as the dependent variable and site characteristics such as traffic volume, shoulder width, and median width as independent variables. The parameter estimates from the NB models were used to develop AMFs. The analysis focused on total crashes and cross-median

Table 12. Crash-frequency AMFs for injury and fatal crashes based on initial speed and speed change.

Non-fatal Injury Crashes						
$\Delta\bar{v}$ (mph)	$\bar{v}_0$ (mph)					
	30	40	50	60	70	80
−5	0.57	0.66	0.71	0.75	0.78	0.81
−4	0.64	0.72	0.77	0.80	0.83	0.85
−3	0.73	0.79	0.83	0.85	0.87	0.88
−2	0.81	0.86	0.88	0.90	0.91	0.92
−1	0.90	0.93	0.94	0.95	0.96	0.96
0	1.00	1.00	1.00	1.00	1.00	1.00
1	1.10	1.07	1.06	1.05	1.04	1.04
2	1.20	1.15	1.12	1.10	1.09	1.08
3	1.31	1.22	1.18	1.15	1.13	1.12
4	1.43	1.30	1.24	1.20	1.18	1.16
5	1.54	1.38	1.30	1.26	1.22	1.20

$\bar{v}_0$ = initial mean travel speed
$\Delta\bar{v}$ = change in mean travel speed

Fatal Injury Crashes						
$\Delta\bar{v}$ (mph)	$\bar{v}_0$ (mph)					
	30	40	50	60	70	80
−5	0.22	0.36	0.48	0.58	0.67	0.75
−4	0.36	0.48	0.58	0.66	0.73	0.80
−3	0.51	0.61	0.68	0.74	0.80	0.85
−2	0.66	0.73	0.79	0.83	0.86	0.90
−1	0.83	0.86	0.89	0.91	0.93	0.95
0	1.00	1.00	1.00	1.00	1.00	1.00
1	1.18	1.14	1.11	1.09	1.07	1.05
2	1.38	1.28	1.22	1.18	1.14	1.10
3	1.59	1.43	1.34	1.27	1.21	1.16
4	1.81	1.59	1.46	1.36	1.28	1.21
5	2.04	1.75	1.58	1.46	1.36	1.27

$\bar{v}_0$ = initial mean travel speed
$\Delta\bar{v}$ = change in mean travel speed

crashes (definitive and probable). Whether a crash was cross-median was deduced based on the location of the crash and the movement preceding the crash.

Data Used

Ten years of data (1993 to 2002) on divided roadway sections in California were obtained from HSIS. HSIS has a crash file providing detailed information about individual crashes, a roadway file that has data on traffic volume and other site characteristics, and an intersection/ramp file that shows the location of intersections and ramps. Data for about 27,131 mile-years of divided roadway sections without median barriers were extracted from HSIS. Sites where the two sides of the roadway were on separate grades were eliminated. To the extent possible, only "traversable" median locations were included in the dataset. A preliminary analysis of the dataset revealed that median widths of 100 ft or larger were coded as 99 ft in the dataset. Hence, all sections with median width coded as 99 ft or larger were removed. Sections with "variable median width" were also removed. In addition, whenever the type of access control changed for a particular year, data were eliminated for that section for that year. Eliminating these sections resulted in 19,933 mile-years. Table 13 shows the number of mile-years by access control, number of lanes, and type of area (i.e., rural or urban).

For roads with partial or no access control and more than four lanes, the number of mile-years was minimal, and hence, this group was not considered for the analysis. Table 14 shows the total number of crashes and cross-median crashes for the different roadway types. Cross-median crashes represent between 3 percent and 6 percent of total crashes on roads with full access control and about 12 percent of total crashes on roads with partial or no access control. Roads with full access control experience relatively fewer cross-median crashes probably because these roads generally have larger median widths. In the sample for this research, the average median width for roads with full access control ranged from 55 to 60 ft, whereas the average median width for roads with partial or no access control ranged from 29 to 40 ft.

Full access control roads in rural areas with more than four lanes had relatively few cross-median crashes (i.e., 548), and thus it was not possible to develop satisfactory models for this group. Hence, AMFs were not developed for this group.

Table 13. Mile-years by roadway type.

Access Control	Number of Lanes	Area Type	
		Rural	Urban
Partial or No Access Control	4	3,258	1,549
	5+	70	107
Full Access Control	4	8,331	3,037
	5+	1,604	1,970

Results

Tables 15 and 16 show the AMFs for median width derived from the NB models for all crashes and cross-median crashes. The AMFs were calculated by using a 10-ft median width as the base case. It is clear that increasing median width is associated with a reduction in total crashes as well as with cross-median crashes. Here are the findings regarding the AMFs:

- As expected, median width has a larger effect on cross-median crashes than on total crashes;
- The AMFs for cross-median crashes are very similar for the two urban roadway types with full access control (i.e., with four lanes and five or more lanes);
- The AMFs for cross-median crashes are very similar for the two rural roadway types; and
- The AMFs for total crashes are very similar for the two four-lane urban roadway types (with full access control and partial or no access control).

Overall, the AMFs are quite similar to those obtained from previous studies that were also based on cross-sectional models (*48, 49, 75, 76, 77*). However, this study used a much larger sample of mile-years and crashes in arriving at the AMFs. Separate AMFs were also developed on the basis of area type (rural or urban), level of access control (full or partial/none), and type of collision (total or cross-median). Hence, the AMFs produced in this effort are those recommended in Chapter 5.

Table 14. Number of crashes (total and cross-median) by roadway type.

Level of Access Control	No. of lanes	Area Type					
		Rural			Urban		
		Total	Cross-Median	% Cross-Median	Total	Cross-Median	% Cross-Median
Partial or No Access Control	4	13,255	1,593	12.0	28,185	3,438	12.2
Full Access Control	4	33,009	1,961	5.9	35,690	1,554	4.4
	5+	12,624	548	4.3	43,385	1,507	3.5

Table 15. AMFs for median width for roads with full access control.

Median Width (ft)	Rural, 4 Lanes, Full Access Control		Urban, 4 Lanes, Full Access Control		Urban, 5+ Lanes, Full Access Control	
	Total Crashes	Cross-median Crashes	Total Crashes	Cross-median Crashes	Total Crashes	Cross-median Crashes
10	1.00	1.00	1.00	1.00	1.00	1.00
20	0.96	0.86	0.95	0.89	0.93	0.89
30	0.93	0.74	0.90	0.80	0.86	0.79
40	0.90	0.63	0.85	0.71	0.80	0.71
50	0.87	0.54	0.80	0.64	0.74	0.63
60	0.84	0.46	0.76	0.57	0.69	0.56
70	0.81	0.40	0.72	0.51	0.64	0.50
80	0.78	0.34	0.68	0.46	0.59	0.45
90	0.75	0.29	0.65	0.41	0.55	0.40
100	0.73	0.25	0.61	0.36	0.51	0.35

Table 16. AMFs for median width for roads with partial or no access control.

Median Width (ft)	Rural, 4 Lanes, Partial or No Access Control		Urban, 4 Lanes, Partial or No Access Control	
	Total Crashes	Cross-median Crashes	Total Crashes	Cross-median Crashes
10	1.00	1.00	1.00	1.00
20	0.95	0.84	0.95	0.87
30	0.91	0.71	0.90	0.76
40	0.87	0.60	0.85	0.67
50	0.83	0.51	0.81	0.59
60	0.79	0.43	0.77	0.51
70	0.76	0.36	0.73	0.45
80	0.72	0.31	0.69	0.39
90	0.69	0.26	0.65	0.34
100	0.66	0.22	0.62	0.30

CHAPTER 4

Development of New AMFs through Expert Panels

This chapter includes a discussion of the second methodology used in this study to develop AMFs—analysis-driven expert panels. The chapter includes a listing of the participants in each of the two panels convened, a description of the overall process followed for the two panels with respect to identifying and prioritizing the treatments to be explored, and the results of the panel discussions.

Introduction

As noted in Chapter 2, one approach to AMF development/modification involved two analysis-driven expert panels. While other alternative expert panels were discussed during the project planning effort, it was decided by the team and the oversight panel that a more critical need was to assist the research teams from NCHRP Projects 17-26 and 17-29 in developing AMFs needed for the safety prediction tools they were developing for urban/suburban arterials and rural multilane highways. Because of the large number of serious and fatal crashes that occur on two-lane rural roads, much of the past AMF development work has focused on treatments for that roadway class. Literature on AMFs for other roadway classes is limited. It was hoped that expert panels might be able to combine the limited past evaluations specific to these two roadway classes (urban/suburban arterials and rural multilane highways) with modified versions of rural two-lane AMFs to develop the needed estimates. It was also hoped that this option might produce multiple AMFs at a lower cost than the cost of new analyses.

Members of the Panels

A critical requirement was that the expert panels be *analysis-driven*. The AMFs derived by the panels were to be based on critical reviews of the existing research literature and on a consensus decision that the results from the research literature were robust enough to allow development of an AMF with at least a medium-high level of predictive certainty. Given this orientation, expert panel membership needed to include expert researchers knowledgeable about the AMFs of interest and the strengths and weaknesses of study methods and a group of expert state and local AMF users (i.e., safety engineers) with knowledge of both the specifics of the AMFs needed and of the real-world conditions under which evaluated treatments were probably implemented. The decisions on expert panel membership were made jointly by the Principal Investigators of the three involved NCHRP projects (NCHRP Projects 17-25, 17-26, and 17-29). Members of the expert panels for each project are shown in Figure 1.

Procedures Followed

The same procedures were followed for both expert panels. Both expert panels met for a 3-day period. Because the number of potential AMFs was greater than could be studied and discussed in this time frame, the AMFs were prioritized before each meeting. For each meeting, The NCHRP Project 17-25 research team and the Principal Investigator for each companion NCHRP project (17-26 and 17-29) developed two lists of candidate treatments to consider for AMF development—one for roadway segments and one for intersections. These lists were based on the results of the earlier-described AMF knowledge matrix and on the specific AMF needs of the companion NCHRP projects. The two lists were sent to each member of the expert panel before the meeting. The expert panel members reviewed each list separately (intersection and segment treatments) and ranked each variable with respect to level of importance as either primary (P) or secondary (S). Primary variables were those believed to be the most important predictors of safety on the road type in question and in definite need of discussion at the meeting. Secondary variables were those believed to be of less importance with respect to predicting safety, which should only be considered for discussion at the meeting if

Suburban and Urban Arterials

- Doug Harwood, Midwest Research Institute (Principal Investigator, NCHRP 17-26)
- David Harkey, UNC Highway Safety Research Center (Principal Investigator, NCHRP 17-25)
- Dr. James A. Bonneson, Texas Transportation Institute
- Dr. Forrest Council, VHB
- Kim Eccles, VHB
- Dr. Ezra Hauer, University of Toronto (Retired)
- Dr. Bhagwant Persaud, Ryerson University
- Stan Polanis, City Traffic Engineer, City of Winston Salem, NC
- Dr. Raghavan Srinivasan, UNC Highway Safety Research Center
- Tom Welch, State Transportation Safety Engineer, Iowa DOT

Rural Multilane Arterials

- Dr. Dominique Lord, Texas A&M University (Principal Investigator, NCHRP 17-29)
- David Harkey, UNC Highway Safety Research Center (Principal Investigator, NCHRP 17-25)
- Dr. James A. Bonneson, Texas Transportation Institute
- Dr. Forrest Council, VHB
- Kim Eccles, VHB
- Dr. Ezra Hauer, University of Toronto (Retired)
- Loren Hill, State Highway Safety Engineer, Minnesota DOT
- Brian Mayhew, North Carolina DOT
- Dr. Bhagwant Persaud, Ryerson University (representing NCHRP 17-29)
- Dr. Raghavan Srinivasan, UNC Highway Safety Research Center
- Dr. Simon Washington, Arizona State University
- Tom Welch, State Transportation Safety Engineer, Iowa DOT

UNC = University of North Carolina. VHB = Vanasse Hangen Brustlin, Inc.

Figure 1. Members of the analysis-driven expert panels.

time permitted. The primary variables were also ranked from most important (first) to least important (last). These rankings were based on each member's assessment of (1) the perceived magnitude of the effect of the variable on safety and (2) the quality and extent of reliable information in the literature on which an AMF could be based. The expert panel inputs were then compiled by the NCHRP Project 17-25 team to develop a final list for discussion.

The research team then developed and distributed to each expert panel member a resource notebook. This notebook included the results of the prioritization task, contact information for all expert panel members, resource materials for each variable/treatment, and pre-meeting assignments for the expert panel members. The resource materials included the following for each AMF under consideration:

- **The AMF summary material developed in NCHRP Project 17-25 and described in Chapter 2 of this report.** This material included the draft research results digest for those AMFs considered to have high or medium-high levels of predictive certainty and summary pages from the interim report for those of lower quality.
- **The AMF summary from NCHRP Project 17-27 (Parts I and II of the Highway Safety Manual).** This draft summary was completed in 2005 and included assessments of AMFs; a discussion of the studies from which the AMFs were taken or derived; and a discussion of materials reviewed without the recommendation of an AMF or a listing of possible resources that could be reviewed for future AMF development consideration.
- **Copies of five cross-sectional studies.** These studies included a number of the high-priority elements. A description of the models developed and the variables included were provided for each study. The models could possibly provide additional insight into the direction and magnitude of the effect of the variables found to be significant.
- **A draft procedure for adjusting AMF estimates and standard errors.** This procedure was developed and applied under NCHRP Project 17-27.

In order to ensure that all treatments or variables were adequately addressed, the expert panel members were given pre-meeting assignments. The expert panel was divided into three groups, and each group was assigned a subset of the variables to review prior to the meeting and asked to help lead the discussion on those topics. The expert panel was asked to focus on three questions:

(1) **Do the materials presented include enough quantitative information to potentially develop an AMF for urban and suburban arterials (or rural multilane highways)?** The materials provided to the panel included a wide spectrum of study types (e.g., rigorous before-after studies, simple before-after studies, cross-sectional studies, or less

Table 17. Treatments reviewed and AMFs developed by expert panels.

Treatment	Review Panel[A]	AMF Developed[B]	Comments[C]
Intersection Treatments			
Intersection Skew Angle	U/S Arterials	No	
Left-Turn Lanes	U/S Arterials RML Highways	Yes No	
Right-Turn Lanes	U/S Arterials RML Highways	Yes No	
Intersection Medians	U/S Arterials	No	
Signal Installation	RML Highways	No	Developed by separate 17-25 analysis
Left-Turn Phasing	U/S Arterials RML Highways	Yes No	Combined findings from two studies; further developed by separate 17-25 analysis
Signal Change Interval	U/S Arterials	No	
Signal All-Red Interval	U/S Arterials	No	
Signal Cycle Length	U/S Arterials	No	
Right-Turn-On-Red (effects on vehicle crashes)	U/S Arterials	Yes	Further developed by additional 17-26 analysis
Right-Turn-On-Red (effects on pedestrian crashes)	U/S Arterials	No	Possible development in 17-26
Driveways Near Intersection	U/S Arterials	No	
Intersection Sight Distance	U/S Arterials	No	
Curb Parking Near Intersection	U/S Arterials	No	
Intersection Lighting	U/S Arterials RML Highways	Yes Yes	Further developed by additional 17-25 and 17-26 analysis
Red-Light Cameras	U/S Arterials	Not needed	Available from prior study (*26*)
Left-Turn Channelization	U/S Arterials RML Highways	Not needed No	
Right-Turn Channelization	U/S Arterials RML Highways	No No	
Approach Speeds	U/S Arterials	No	
Roundabouts	U/S Arterials	Not needed	Available from prior study (*8*)
Roadway Segment Treatments			
Number of Lanes	U/S Arterials	No	
Lane Width	U/S Arterials	No	
Shoulder Type	U/S Arterials RML Highways	No Yes	
Shoulder Width	U/S Arterials RML Highways	No No	
Add a Median	U/S Arterials	No	
Median Width	U/S Arterials RML Highways	No No	Developed by separate 17-25 analysis
Two-Way Left-Turn Lane (TWLTL)	U/S Arterials	Yes	
Horizontal Curvature	U/S Arterials	No	Possible development in 17-29
	RML Highways	No	
Sideslope	RML Highways	Yes	
Clearzone Width	RML Highways	No	
Roadside Fixed Objects	U/S Arterials RML Highways	No No	Developed by additional 17-26 analysis
Driveways/Access Points	U/S Arterials RML Highways	No No	17-26 analysis produced separate models for driveway accidents
Speed Limits/Zoning	U/S Arterials RML Highways	No No	Developed by separate 17-25 analysis
On-Street Parking	U/S Arterials	Yes	
Segment Lighting	U/S Arterials	Yes	Further developed by additional 17-25 and 17-26 analysis
Rumble Strips	U/S Arterials RML Highways	Not Needed No	
Miscellaneous Treatments			
Pedestrian/Bicycle Treatments	U/S Arterials	No	Some being developed in 17-26
Far-Side vs. Near-Side Bus Stops	U/S Arterials	No	

[A] Indicates which panel considered the treatment to be a priority, reviewed the relevant research, and discussed the potential for AMF development; U/S Arterials = urban/suburban arterials and RML Highways = rural multilane highways.
[B] "Yes" indicates that consensus was reached at the expert panel meeting on an acceptable AMF from the critical review and discussion of prior research.
[C] Numbers in "Comments" refer to NCHRP projects. Note that the 17-26 and 17-29 teams were involved in their respective panels.

vigorous data assessments). In many cases, the materials and existing AMFs were related to rural two-lane roads. Expert panel members were asked to assess whether or not the material was sufficient for the specification of an AMF for an urban/suburban arterial or rural multilane highway.

(2) **If an AMF can be developed from the material provided, what is the magnitude of the effect and to what types and severities of crashes does it apply?**

(3) **Are there other studies that are not included in the existing set of materials that should be discussed at the meeting?**

The project team completed all logistics for the meeting, the expert panel members prepared for the meeting, and the meeting was held at the University of North Carolina (UNC) Highway Safety Research Center facilities. The project team recorded detailed notes of the ensuing discussions and continually displayed both the notes and possible findings. Final decisions were then made by expert panel consensus.

Results

The suburban/urban arterial expert panel reviewed research materials on 14 segment treatments, 19 intersection treatments, and 2 miscellaneous treatments. They reached consensus on acceptable AMFs for eight of these and, after discussion, found three to be unnecessary for this class of roadways (see Table 17). There were four additional AMFs that were developed by the NCHRP project research teams through further analysis after the meeting. The rural multilane arterials expert panel reviewed material on 10 segment treatments and 7 intersection treatments and developed AMFs for 3 of these. In addition, both expert panels recommended reanalysis of the data from the Elvik et al. study (*74*) to validate or modify the AMF for speed change versus crash frequency change. Since neither expert panel could reach consensus regarding an AMF for median width, they also recommended an additional analysis for this treatment. Both of these efforts were described in Chapter 3 of this report. The details on all AMFs resulting from these expert panels are presented in Chapter 5 of this report.

CHAPTER 5

Compilation of Recommended AMFs

Introduction

This chapter includes a detailed description of each AMF verified, modified, or developed in this research effort. Table 18 includes the listing of AMFs and the source of each AMF. The possible sources include the following:

- **Literature Review.** Completed research was discovered and critically reviewed. The assessment revealed that AMFs existed for the given treatment with an LOPC of either high or medium high.
- **EB Before-After Evaluation.** Before-treatment and after-treatment crash data were acquired for locations where the treatment of interest had been installed. The latest statistical methodologies (i.e., EB) for conducting before-after studies were applied to produce AMFs.
- **Reanalysis of Existing/Supplemental Data.** Data from prior before-after evaluations were acquired and reanalyzed using the more rigorous EB methodology. In many cases, supplemental data were acquired to enhance the evaluation.
- **Analysis-Driven Expert Panel.** A panel of knowledgeable researchers and practitioners was convened to review critical research studies and reach a consensus on AMFs for a given treatment. In some cases, the AMF was developed through further analysis by one of the NCHRP project research teams sponsoring the expert panel meeting.
- **Cross-Sectional Model.** A new analysis was conducted in which a cross-sectional model was produced and used to derive AMFs for a specific treatment.

AMF Summaries

For each AMF listed in Table 18, a summary of the research from which the AMF was developed is given below. Each summary includes the AMF mean estimate(s) with standard errors shown in parentheses, the LOPC, the study methodology, a description of the sites used in the study, and supplemental comments and footnotes to describe the study results and applicability. Table 19 presents a glossary of acronyms used in the AMF summaries.

Table 18. List of AMFs developed or modified in NCHRP Project 17-25.*

Treatment	Source of AMF
Intersection Treatments	
Install Roundabout	Literature Review
Add Exclusive Left-Turn Lane	Literature Review/Expert Panel
Add Exclusive Right-Turn Lane	Literature Review/Expert Panel
Install Traffic Signal at Urban Intersection	Literature Review
Install Traffic Signal at Rural Intersection	EB Before-After Evaluation
Remove Traffic Signal (Urban Environment)	Literature Review
Modify Signal Change Interval	Literature Review
Prohibit Right Turn on Red	Expert Panel/Further Analysis
Modify Left-Turn Phase	Expert Panel/Reanalysis of Existing/Supplemental Data
Replace 8-in. Signal Heads with 12-in. Signal Heads	Reanalysis of Existing/Supplemental Data
Replace Single Red Signal Head with Dual Red Signal Heads	Reanalysis of Existing/Supplemental Data
Convert Nighttime Flash Operation to Steady Operation	Reanalysis of Existing/Supplemental Data
Convert to All-Way Stop Control	Literature Review
Convert Stop Control to Yield Control	Literature Review
Install Red-Light Cameras	Literature Review
Add Intersection Lighting	Expert Panel
Increase Pavement Friction on Intersection Approach	Reanalysis of Existing Data
Roadway Segment Treatments	
Narrow Lane Widths to Add Lanes	Literature Review
Add Passing Lanes (Two-Lane Roads)	Literature Review
Add Two-Way Left-Turn Lane (TWLTL)	Literature Review/Expert Panel
Change Lane Width	Literature Review
Change Shoulder Width and/or Type	Literature Review
Flatten Horizontal Curve	Literature Review
Improve Curve Superelevation	Literature Review
Add Shoulder Rumble Strips	Literature Review
Add Centerline Rumble Strips	Literature Review
Install/Upgrade Guardrail	Literature Review
Convert Undivided Four-Lane Road to Three-Lane and TWLTL (Road Diet)	Reanalysis of Existing Data
Increase Pavement Friction on Roadway Segment	Reanalysis of Existing Data
Change Median Width	Cross-Sectional Model
Change Roadside Sideslope	Expert Panel
Add/Remove On-Street Parking	Expert Panel
Add Roadway Segment Lighting	Expert Panel
Miscellaneous	
Install Raised Medians at Crosswalks	Literature Review
Reduce Mean Travel Speed	Reanalysis of Existing Data

*AMFs are listed in order of their presentation in this report.

Table 19. Glossary of acronyms for AMF summaries.

AADT	Average annual daily traffic
ADT	Average daily traffic
AMF	Accident modification factor
B/A	Before/after
EB	Empirical Bayes
HOV	High-occupancy vehicle
HSIS	Highway Safety Information System
LTL	Left-turn lane
LOPC	Level of predictive certainty
MH	Medium high
PDO	Property damage only
RTL	Right-turn lane
RTOR	Right turn on red
SD	Superelevation deficiency
SPF	Safety performance function
TWLTL	Two-way left-turn lane
vpd	Vehicles per day

TREATMENT: Install Roundabout	**AMF Level of Predictive Certainty: High**	
METHODOLOGY: Empirical Bayes Before-After	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**	
REFERENCE: Rodegerdts et al. - 2007 (*8*).		

STUDY SITES:

- Treatment sites included 55 intersections that were converted to roundabouts (36 were previously two-way stop-controlled, 10 were all-way stop-controlled, and 9 were controlled by signals).
- The roundabouts were in rural, suburban, and urban environments.
- Single-lane and multilane roundabouts were included; traffic volumes at the treatment sites in the after condition ranged from 2,668 vpd to 58,800 vpd.

COMMENTS:

- A non-significant increase of 3% was found for 10 sites which were all-way stop-controlled prior to conversion to a roundabout.
- The authors were not able to determine the safety effects for pedestrians and bicyclists, but refer the reader to the positive results that have been found in Scandinavian evaluations.[A]
- No evidence was found to indicate roundabouts result in more difficulties for older drivers.

Single Lane - Urban/Suburban (prior control - two-way stop-controlled)	**No. of Improved Sites**	**AMF**
All Crashes	16	0.44 (0.06)
Injury Crashes		0.22 (0.07)
Single Lane - Rural (prior control - two-way stop-controlled)		
All Crashes	9	0.29 (0.04)
Injury Crashes		0.13 (0.03)
Multilane - Urban/Suburban (prior control - stop sign)		
All Crashes	11	0.82 (0.08)
Injury Crashes		0.28 (0.09)
Single/Multilane - Urban/Suburban (prior control - signal)		
All Crashes	9	0.52 (0.05)
Injury Crashes		0.22 (0.06)
All Sites		
All Crashes	55	0.65 (0.03)
Injury Crashes		0.24 (0.03)

FOOTNOTES:

[A] Ulf and Jörgen - 1999 (*78*).

TREATMENT: Add Exclusive Left-Turn Lane

AMF Level of Predictive Certainty: High*

METHODOLOGY: Empirical Bayes Before-After/Analysis-Driven Expert Panels

REFERENCE: Harwood et al. - 2002 (*12*); NCHRP Project 17-25 research results

STUDY SITES:

- Included rural and urban sites located in eight states – Illinois, Iowa, Louisiana, Minnesota, Nebraska, North Carolina, Oregon, and Virginia
- 199 treatment sites where a left-turn lane (LTL) was added, as well as 300 similar intersections that were not improved during the study period and used for comparison and reference sites.
- All improvements were made during the years 1989 through 1998. Mean duration of before and after periods were 6.7 years and 3.9 years, respectively.

COMMENTS:

- The study applied two alternative evaluation approaches (B/A with yoked comparisons and B/A with a comparison group) and recommended that the EB evaluation results be used if statistically significant. If not, it was recommended that statistically significant comparison group results be used, followed by statistically significant yoked comparison results. The authors note that results from either comparison method may be "overly optimistic."
- Stop-controlled locations had stop signs on the minor road approaches.
- Mean total entering ADT for rural stop-controlled, rural signalized, urban stop-controlled, and urban signalized improved sites were 9,700 vpd, 17,800 vpd, 15,500 vpd, and 26,800 vpd, respectively.
- All tests of statistical significance in this report were performed at the 5% significance level (95% confidence level). Only statistically significant results are shown.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Total Intersection Accidents (all severity levels, all accident types)	**No. of Improved Sites**	**AMF**	
		One Approach	**Both[A] Approaches**
Rural Stop-Controlled Intersection (four legs)	25	0.72 (0.03)	0.52 (0.03)
Rural Stop-Controlled Intersection (three legs)	36	0.56 (0.06)	—
Rural Signalized Intersection (four legs)		0.82[D]	0.67[D]
Rural Signalized Intersection (three legs)		0.85[D]	—
Urban Stop-Controlled Intersection (four legs)	9	0.73[C] (0.03)	0.53[C] (0.04)
Urban Stop-Controlled Intersection (three legs)	8	0.67 (0.12)	—
Urban Signalized Intersection (four legs)	39	0.90 (0.01)	0.81 (0.13)
Urban Signalized Intersection (three legs)		0.93[D]	—
Fatal and Injury Intersection Accidents (all accident types)			
Rural Stop-Controlled Intersection (four legs)	24	0.65 (0.03)	0.42 (0.04)
Rural Stop-Controlled Intersection (three legs)	11	0.45[C] (0.08)	—
Urban Stop-Controlled Intersection (four legs)	9	0.71[C] (0.04)	0.50[C] (0.06)
Urban Stop-Controlled Intersection (three legs)		0.65[F]	—
Urban Signalized Intersection (four legs)	39	0.91 (0.01)	0.83 (0.02)
Urban Signalized Intersection (three legs)		0.94[F]	—
Project-Related Accidents (all severity levels)[B]			
Rural Stop-Controlled Intersection (four legs)	23	0.63 (0.07)	0.40
Rural Stop-Controlled Intersection (three legs)	35	0.38[C] (0.15)	—
Urban Stop-Controlled Intersection (four legs)	7	0.74 (0.07)	0.55
Urban Signalized Intersection (four legs)	35	0.87[E] (0.03)	0.76[E]

*LOPC considered to be MH for AMFs derived by analysis-driven expert panels.

FOOTNOTES:

[A] AMF (both approaches) = AMF (one approach) x AMF (one approach).

[B] Project-Related Accidents - All accidents involving one or more vehicles that had made, were making, or intended to make the specific left-turn maneuver(s) for which the left-turn lane(s) being evaluated were installed.

[C] AMF based on comparison group evaluation.

[D] Recommended AMF based on analysis-driven expert panel results (rural two-lane roads) from Harwood et al. - 2000 (*9*).

[E] AMF based on yoked comparison evaluation.

[F] Recommended AMF based on analysis-driven expert panel results from NCHRP 17-25/17-26 expert panel on urban/suburban arterials.

TREATMENT: Add Exclusive Right-Turn Lane	**AMF Level of Predictive Certainty: High***
METHODOLOGY: Empirical Bayes Before-After/Analysis-Driven Expert Panel	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**
REFERENCE: Harwood et al. - 2002 (*12*); NCHRP Project 17-25 research results	
STUDY SITES: • Included rural and urban sites located in eight states – Illinois, Iowa, Louisiana, Minnesota, Nebraska, North Carolina, Oregon, and Virginia. • 108 treatment sites where a right-turn lane (RTL) was added, as well as 300 similar intersections that were not improved during the study period and used for comparison and reference sites. • All improvements were made during the years 1989 through 1998. Mean duration of before and after periods were 6.7 years and 3.9 years, respectively.	

Total Intersection Accidents (all severity levels, all accident types)	**No. of Improved Sites**	**AMF One Approach**	**AMF Both[A] Approaches**
Rural Stop-Controlled Intersection (four legs)	28	0.86 (0.05)	0.74
Rural Signalized Intersection (four legs)		0.96[B] (0.02)	0.92[B]
Urban Signalized Intersection (four legs)	18	0.96 (0.02)	0.92
Urban Signalized Intersection (three legs)		0.96[C]	—
Urban Stop-Controlled Intersection (four legs)		0.86[C]	0.74[C]
Fatal and Injury Intersection Accidents (all accident types)			
Rural Stop-Controlled Intersection (four legs)	29	0.77[D] (0.07)	0.59[D]
Rural Signalized Intersection (four legs)		0.91[B] (0.03)	0.83[B]
Urban Signalized Intersection (four legs)	17	0.91 (0.03)	0.83
Urban Signalized Intersection (three legs)		0.91[C]	—
Urban Stop-Controlled Intersection (four legs)		0.77[C]	0.59[C]

*LOPC considered to be MH for AMFs derived by analysis-driven expert panels.

COMMENTS:

• The study applied two alternative evaluation approaches (B/A with yoked comparisons and B/A with a comparison group) and recommended that the EB evaluation results be used if statistically significant. If not, it was recommended that statistically significant comparison group results be used, followed by statistically significant yoked comparison results. The authors note that results from either comparison method may be "overly optimistic."

• Stop-controlled locations had stop signs on the minor road approaches.

• Mean total entering ADT for rural stop-controlled, rural signalized, urban stop-controlled, and urban signalized improved sites were 9,700 vpd, 17,800 vpd, 15,500 vpd, and 26,800 vpd, respectively.

• All tests of statistical significance in this report were performed at the 5% significance level (95% confidence level). Only statistically significant results are shown.

FOOTNOTES:

[A] AMF (both approaches) = AMF (one approach) x AMF (one approach).

[B] Authors recommend that the AMFs for urban signalized intersections be applied to rural signalized intersections.

[C] Recommended AMF based on analysis-driven expert panel results from NCHRP 17-25/17-26 panel on urban/suburban arterials.

[D] AMF based on comparison group evaluation.

TREATMENT: Install Traffic Signal at Urban Intersection	**AMF Level of Predictive Certainty: High**		
METHODOLOGY: Empirical Bayes Before-After	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: McGee, Taori, and Persaud - 2003 (*18*)	**Three-Leg Intersections**	**No. of Improved Sites**	**AMF**
STUDY SITES: • Included sites located in five states – California, Florida, Maryland, Virginia, Wisconsin – and Toronto. • Three-leg intersection data included 22 treatment sites (converted from stop to signal control) and 118 reference group sites (99 stop-controlled and 19 signalized intersections). • Four-leg intersection data included 100 treatment sites (converted from stop to signal control) and 295 reference group sites (96 stop-controlled and 199 signalized intersections). • An additional reference group was developed from the HSIS California urban data and included 1,418 stop-controlled and 799 signalized intersections.[A] • Minor street traffic volumes for the treatment sites ranged from 911 to 3,952 vpd; major street volumes ranged from 11,739 to 24,584 vpd.	All Crashes	22	0.86 (0.32)
	Right-Angle Crashes		0.66 (0.45)
	Rear-End Crashes		1.5 (0.51)
	Four-Leg Intersections		
	All Crashes	100	0.77 (0.22)
	Right-Angle Crashes		0.33 (0.20)
	Rear-End Crashes		1.38 (0.39)

COMMENTS:

• AMFs are for crashes involving fatalities and injuries only; property-damage-only (PDO) crashes were excluded from the analysis.
• AMFs were developed using data from **urban** intersections. The authors do not recommend that these results be applied to rural intersections.
• The study notes that the results could be adapted (i.e., reversed) to assess the safety of removing a traffic signal. The authors of the study do not have as much confidence in using the results in this way.

FOOTNOTES:

[A] The Highway Safety Information System (HSIS) is a multistate safety database that contains accident, roadway inventory, and traffic volume data for a select group of states and is sponsored by the FHWA.

TREATMENT: Install Traffic Signal at Rural Intersection

AMF Level of Predictive Certainty: High

METHODOLOGY: Empirical Bayes Before-After

REFERENCE: NCHRP Project 17-25 research results

STUDY SITES:

• Included sites located in Minnesota and California. Data were acquired from the Highway Safety Information System.[A]
• Three-leg intersection data included six treatment sites (converted from stop to signal control) and 1,927 stop-controlled reference group sites.
• Four-leg intersection data included 39 treatment sites (converted from stop to signal control) and 1,661 stop-controlled reference group sites.
• An additional reference group was developed using 84 signalized intersections to develop a more sophisticated procedure for evaluating the potential safety effects of a contemplated signal conversion.
• Minor street traffic volumes for the treatment sites ranged from 101 to 10,300 vpd; major street volumes ranged from 3,261 to 29,926 vpd

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Three-Leg and Four-Leg Intersections Combined	No. of Improved Sites	AMF
All Crashes	45	0.56 (0.03)
Right-Angle Crashes		0.23 (0.02)
Rear-End Crashes		1.58 (0.14)
Left-Turn Crashes		0.4 (0.05)

ECONOMIC ANALYSIS

Three-Leg and Four-Leg Intersections Combined	AMF
All Crashes	0.27 (0.001)

COMMENTS:

• The authors of the study do not recommend that the results be adapted (i.e., reversed) to assess the safety of removing a traffic signal.
• The treatment benefits are greater on higher volume intersections and are greater where the ratio of expected right-angle crashes to rear-end crashes is higher. There is little difference between the effects on three-leg vs. four-leg sites or on sites with two lanes on the major vs. four lanes. Thus, the overall crash frequency AMFs can be assumed to apply to all rural site types.
• Economic analysis was conducted to determine if the increase in rear-end crashes negated the decrease in other, generally more severe, collision types. The economic analysis may be used to develop AMFs for total crashes, which account for the differences in injury severity that occur with different collision types. The AMF for all crash severities would be 0.27.

FOOTNOTES:

[A] The Highway Safety Information System (HSIS) is a multistate safety database that contains accident, roadway inventory, and traffic volume data for a select group of states and is sponsored by the FHWA.

TREATMENT: Remove Traffic Signal (Urban Environment)	AMF Level of Predictive Certainty: High		
METHODOLOGY: Empirical Bayes Before-After	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: Persaud et al. - 1997 (*19*)	**Type of Collision (all severities)**	**No. of Improved Sites**	**AMF**
STUDY SITES: • 199 treatment sites and 71comparison sites in Philadelphia. • Treatment sites were unwarranted signals and mostly changed from signal control to all-way stop control between 1979 and 1988. • All intersections were at one-way streets in non-arterial streets in an urban environment. • Crash data were acquired for the years 1978 through 1992. • Traffic volumes were often estimated from upstream and downstream AADTs due to the sparse volume data available.	All Crashes	199	0.76 (0.38)
	Right-Angle and Turning Crashes		0.76 (0.35)
	Rear-End Crashes		0.71 (0.06)
	Pedestrian Crashes		0.82 (0.12)
	Fixed-Object Crashes		0.69[A]
	Light Condition (all severities)		
	Day	199	0.78
	Night		0.70
	Injury Severity (all collision types)		
	Severe	199	0.47 (0.10)
	Minor		0.76 (0.18)

COMMENTS:

• The authors note the inability to account for year-to-year variation in traffic volumes, but nonetheless express confidence in the results.
• It is important to note that this study was for one-way streets in an urban environment. There are no comparable studies for two-way streets or for intersections in rural environments.

FOOTNOTES:

[A] The AMF for fixed object crashes was based on the classical estimate (i.e., expected number of crashes in the after period is based on count of crashes in the before period as opposed to the EB estimate of before-period crashes).

TREATMENT: Modify Signal Change Interval

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Before-After with Control Group

REFERENCE: Retting, Chapline, and Williams - 2002 (*22*)

STUDY SITES:

• Included crash data from 40 treatment intersections and 56 control intersections in Nassau County and Suffolk County, New York.

• All intersections were standard four-leg junctions.

• The treatment sites were randomly selected for the signal timing change, eliminating the site-selection bias.

• Six years of crash data were used in the analysis (October 1991 through October 1997), with 3 years each in the before and after periods.

• Analysis included only "reportable" crashes, which require an injury or a minimum of $1,000 in property damage in New York.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Accident Type (all severities)	**No. of Treated Sites**	**AMF**
All Crashes	40	0.92 (0.09)
Multiple-Vehicle Crashes		0.95[A]
Rear-End Crashes		1.12[A] (0.16)
Right-Angle Crashes		0.96[A] (0.18)
Pedestrian/Bicyclist Crashes		0.63
Accident Type (injury crashes only)		
All Crashes	40	0.88 (0.09)
Multiple-Vehicle Crashes		0.91
Rear-End Crashes		1.08[A] (0.17)
Right-Angle Crashes		1.06[A] (0.22)
Pedestrian/Bicyclist Crashes		0.63

COMMENTS:

• IMPORTANT NOTE - Both the yellow change interval and the red clearance interval were adjusted at the treatment sites to conform to the Institute of Transportation Engineers *Determining Vehicle Change Intervals: A Proposed Recommended Practice* (*95*). In some cases, this meant an increase in the interval, while in others, the interval was decreased. Thus the AMFs do not reflect the effects of increasing only the change and clearance intervals.
• AMFs are based on the odds ratios.
• Yellow change intervals at the treatment sites ranged from 3 to 4 seconds in the before period and 2.6 to 5.4 seconds in the after period. Red clearance intervals ranged from 2 to 3 seconds in the before period and 1.1 to 6.5 seconds in the after period.
•Authors acknowledge that the results do not account for variables such as geometry, traffic volume, and other signal parameters such as cycle length and number of phases

FOOTNOTES:

[A] Results were not significant at a 90% confidence level (P > 0.10). AMF of 1.0 recommended for these accident types.

TREATMENT: Prohibit Right Turn on Red	**AMF Level of Predictive Certainty: Medium-High**
METHODOLOGY: Analysis-Driven Expert Panel	**ACCIDENT MODIFICATION FUNCTION**
REFERENCE: NCHRP Projects 17-25 and 17-26 research results	**AMF = $(0.984)^n$** where: n = number of signalized intersection approaches where RTOR is prohibited Note: AMF applies to total intersection crashes.
COMMENTS: • Expert panel on urban/suburban arterials considered this AMF function to be the best estimate for the prohibition of right turn on red (RTOR). • The AMF was derived from a simple before-after analysis of intersections in Alabama and South Carolina after the passage of laws in both states that permitted RTOR.[A] The results were presented in terms of the effect on total crashes at an intersection if RTOR was permitted (AMF = 1.067). Making an assumption that most of the intersections were four-leg locations, the AMF for each approach becomes 1.016. • The inverse of the Clark AMF was derived to reflect the prohibition of RTOR (1/1.016 = 0.984).	**FOOTNOTES:** [A] Clark, Maghsoodloo, and Brown - 1983 (*79*)

TREATMENT: Modify Left-Turn Phase	**AMF Level of Predictive Certainty: Medium-High**
METHODOLOGY: Empirical Bayes Before-After/Analysis-Driven Expert Panel	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**
REFERENCE: NCHRP Project 17-25 research results	
STUDY SITES: • The treatment sites included 12 signalized intersections in Winston-Salem, NC. Among those 12 sites, the left-turn phase was changed from permissive to protected-only at eight sites and from permissive/protected to protected-only at four sites.	

Accident Type	No. of Sites	AMF
Change from Permissive or Permissive/Protected to Protected-Only Phasing		
Left-Turn Crashes	12	0.01 (0.01)**
Total Crashes		0.99[A] (0.07)
Change from Permissive to Permissive/Protected Phasing		
Left-Turn Crashes	35	0.84[B] (0.02)
Total Crashes		1.00[B]

FOOTNOTES:

** statistically significant at the 95% confidence level.

[A] AMF of 0.99 was not statistically significant; AMF of 1.00 recommended.

[B] Recommended AMF based on analysis-driven expert panel results from NCHRP Projects 17-25/17-26 panel on urban/suburban arterials. Primary source of information was the study by Lyon et al. - 2005 (*21*), which included 35 four-leg intersections in Toronto.

COMMENTS:

• There was evidence that non-left-turn crashes increased following the change to protected-only left-turn phasing. Further research is necessary to determine the specific reasons for the effect on non-left-turn crashes. However, it seems reasonable to speculate that introducing a protected left-turn phase will tend to increase mostly rear-end crashes (which are in general less severe compared to left-turn crashes) because of the increased number of phases (and therefore dilemma zone opportunities) and the increase in queues that results from reduced green time available for all traffic not protected by the introduced phase. This also implies that the measure would be most effective overall where there is a relatively high frequency of left-turn crashes.

TREATMENT: Replace 8-in. Signal Heads with 12-in. Signal Heads

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Empirical Bayes Before-After

REFERENCE: NCHRP Project 17-25 research results

STUDY SITES:

• Treatment sites included 26 signalized intersections from Winston-Salem, NC.

• Safety performance functions were developed with data from 60 signalized intersections in Winston-Salem using data from 1991 to 2004.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Accident Type	No. of Sites	AMF
Right-Angle	26	0.58[A] (0.07)
All		0.97[B] (0.06)

FOOTNOTES:

[A] Statistically significant at the 95% confidence level.

[B] AMF for all crashes was 0.97 but was not statistically significant; AMF of 1.00 is recommended.

COMMENTS:

• There is evidence of an increase in non-right-angle crashes that almost offsets the decrease in right-angle crashes. It is possible that the increased signal head size encouraged more drivers to stop at the red light and probably led to an increase in rear-end crashes. Rear-end crashes are generally less severe compared to right-angle crashes. An economic analysis in which the decreased angle collision costs are combined with the increased rear-end collision costs revealed a reduction of about $11,800 per intersection-year in the overall crash harm due to this treatment. Collision costs developed in FHWA Study by Council et al. in 2005 (*72*).

TREATMENT: Replace Single Red Signal Head with Dual Red Signal Heads	**AMF Level of Predictive Certainty: Medium-High**		
METHODOLOGY: Empirical Bayes Before-After	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: NCHRP Project 17-25 research results	**Accident Type**	**No. of Sites**	**AMF**
STUDY SITES: • Treatment sites included eight signalized intersections from Winston-Salem, NC. • Safety performance functions were developed with data from 60 signalized intersections in Winston-Salem using data from 1991 to 2004.	Right-Angle	8	1.05 (0.13)[A]
	All		1.18 (0.11)[A]
	FOOTNOTES: [A] AMF was not statistically significant; AMF of 1.00 is recommended.		
COMMENTS: • Adding additional signal heads does not seem to be effective in reducing right-angle or total crashes. With only eight sites, the sample size is small. Thus, the results have to be treated with caution.			

TREATMENT: Convert Nighttime Flash Operation to Steady Operation	**AMF Level of Predictive Certainty: Medium-High**		
METHODOLOGY: Empirical Bayes Before-After	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: NCHRP Project 17-25 research results	**Accident Type**	**No. of Sites**	**AMF**
STUDY SITES: • The treatment sites included 12 signalized intersections from Winston-Salem, NC. • Data were available for 518 intersection-months before the change and 516 intersection-months after the change. • Safety performance functions were developed with data from 60 signalized intersections in Winston-Salem using data from 1991 to 2004.	Nighttime Angle	12	0.66[A] (0.18)
	All Nighttime		0.65[B] (0.15)
	FOOTNOTES: [A] Statistically significant at the 95% confidence level. [B] Statistically significant at the 90% confidence level.		
COMMENTS: • Number of sites is low and hence results should be treated with caution. • The reduction in nighttime angle and nighttime crashes (about 35%) is lower than the reductions shown in other simple before-after studies indicating that bias due to regression to the mean was probably significant in those studies.			

TREATMENT: Convert to All-Way Stop Control

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Before-After Analysis w/Likelihood Functions

REFERENCE: Lovell and Hauer - 1986 (*30*)

STUDY SITES:

• Included data from three urban regions (San Francisco, Philadelphia, and Toronto) and one rural region (Michigan).
• The number of treatment sites in which an intersection was converted to all-way stop control in each region is as follows:
- San Francisco: 49 sites (from two-way stop control).
- Philadelphia: 222 sites (one-way streets, prior traffic control not stated).
- Michigan: 10 sites (from two-way stop control).
- Toronto: 79 sites (from two-way stop control).

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Type of Collision (all severities)	No. of Improved Sites	AMF
All Crashes	360[A]	0.53
Right-Angle Crashes		0.28 (0.03)
Rear-End Crashes		0.87 (0.13)
Left-Turn Crashes		0.80 (0.52)
Pedestrian Crashes		0.61 (0.08)
Crash Severity (all collision types)		
All Crashes	360[A]	0.53
Injury Crashes		0.29 (0.06)

COMMENTS:

• Analysis included the reanalysis of datasets from San Francisco, Philadelphia, and Michigan to correct for regression to the mean bias and a new analysis of data from Toronto. Likelihood functions were used to combine the results from the various cities.

• The AMF for All Crashes (all collision types and all severities) was vetted by an expert panel on rural two-lane roads and included as the recommended AMF for this treatment within FHWA's Interactive Highway Safety Design Model — IHSDM (Harwood et al. - 2000 [9]).

FOOTNOTES:

[A] Includes all sites from the four regions.

TREATMENT: Convert Stop Control to Yield Control	**AMF Level of Predictive Certainty: Medium-High**		
METHODOLOGY: Before-After with Control Group	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: McGee and Blankenship - 1989 (*31*)	**Total Accidents (all severities)**	**No. of Treated Sites**	**AMF**
	All Crashes	141[A]	2.37

STUDY SITES:

• Treatment sites were converted from stop control to yield control; comparison sites were stop-control intersections. The numbers of each type in each city were as follows:
- Saginaw, MI (53 treatment sites, 42 control sites).
- Pueblo, CO (69 treatment sites, 15 control sites).
- Rapid City, SD (19 treatment sites, 8 control sites).

• The conversions took place between 1982 and 1987.

• The number of years of crash data included in each before and after period ranged from 1 to 2 years, depending on the city and year of conversion.

COMMENTS:

• AMF computed from the cross product ratio (odds ratio) of the before and after crash frequencies at the treatment and control sites.

• No additional AMFs were provided. The authors do indicate that the proportion of fatal or injury accidents does not appear to increase with the conversion, nor is there a change in the distribution of collision types.

• The authors note that the probability of an increase in crashes is greater with higher volumes, either major street volume, minor street volume, and/or the combination of the two volumes.

FOOTNOTES:

[A] Includes all sites from the three cities.

TREATMENT: Install Red-Light Cameras

AMF Level of Predictive Certainty: High

METHODOLOGY: Empirical Bayes Before-After

REFERENCES: Persaud et al. - 2005 (*25*) and Council, Persaud et al. - 2005 (*26*)

STUDY SITES:

- Included data from seven jurisdictions across the U.S. for 132 treatment intersections where red-light cameras had been installed.
- The reference group included similar signalized intersections in each jurisdiction that were not equipped with red-light cameras, which were used to develop SPFs and to investigate possible spillover effects.
- A second reference group of unsignalized intersections was used to account for time trends and to calibrate the SPFs.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

All Crash Severities	**No. of Treated Sites**	**AMF**
Rear-End Crashes	132	1.15 (0.03)
Right-Angle Crashes		0.75 (0.03)
Injury Crashes Only		
Rear-End Crashes	132	1.24 (0.12)
Right-Angle Crashes		0.84 (0.06)

ECONOMIC ANALYSIS

All Crash Severities	**Economic AMF**
Total Crashes	0.91 (0.004)
Rear-End Crashes	1.09 (0.007)
Right-Angle Crashes	0.72 (0.006)
Injury Crashes Only	
Total Crashes	0.86 (0.005)
Rear-End Crashes	1.02 (0.008)
Right-Angle Crashes	0.711 (0.006)

COMMENTS:

- Economic analysis was conducted to determine if the increase in rear-end crashes negated the decrease in right-angle collisions. Results showed there was a net economic benefit that ranged from $39,000 to $50,000 per year per site where red-light camera systems were installed.
- The economic analysis may be used to develop AMFs for total crashes, which account for the differences in injury severity that occur with different collision types. The AMF for all crash severities would be 0.91, while the AMF for injury crashes only would be 0.86.

TREATMENT: Add Intersection Lighting	**AMF Level of Predictive Certainty: Medium-High**	
METHODOLOGY: Meta-Analysis/Analysis-Driven Expert Panel	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**	
REFERENCE: Elvik and Vaa - 2004 (*60*); NCHRP 17-25 Final Report; NCHRP 17-26 Final Report	**Nighttime Crashes**	**AMF**
STUDY SITES: • 38 studies were evaluated as part of the meta-analysis, including 14 U.S. studies.[A] • Distributions of crashes by injury severity and time of day were obtained from the HSIS data for the states of North Carolina and Minnesota.	Total Crashes	0.79
	All Injury Crashes	0.71
	All Crashes	**AMF**
	Total Crashes	0.96
	All Injury Crashes	0.94

COMMENTS:

• The meta-analysis results produced AMF estimates for reductions in fatal, injury and property-damage-only accidents of 0.36, 0.72, and 0.83, respectively.[A]
• The NCHRP 17-25/17-26 expert panel on urban/suburban arterials recommended that the meta-analysis results be applied to intersections and that the fatal and injury results be combined into a single AMF for all levels of injury.
• The NCHRP 17-26 Final Report includes a distribution of crashes by time of day and injury severity for different types of intersections.

FOOTNOTES:
[A] Elvik and Vaa (*60*)

TREATMENT: Increase Pavement Friction on Intersection Approach	**AMF Level of Predictive Certainty: High**		
METHODOLOGY: Empirical Bayes Before-After	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: NCHRP Project 17-25 research results	**Accident Type**	**No. of Treated Sites**	**AMF**
	All Crashes	256	0.8 (0.03)
STUDY SITES:	Wet-Road Crashes		0.43 (0.03)
	Rear-End Crashes		0.58 (0.03)
	Dry-Road Crashes		1.15 (0.05)
	Rear-End Wet-Road Crashes		0.32 (0.04)
• The treatment data for this analysis were from the Skid Accident Reduction Program (SKARP) developed by NY State DOT in 1995.[A] • Data were collected for 256 treated intersections and 3,993 reference intersections. Intersections were in both urban and rural locations. • For the treated sites, 73 were signal-controlled, 176 were stop-controlled, and 7 were yield-controlled. Fifty-seven were four-leg and 199 were three-leg intersections. • Sites are selected for treatment based on both a high proportion of wet-road accidents and low friction numbers.	**COMMENTS:** • The treatment generally involved a 1.5-in. resurfacing or a 0.5-in. microsurfacing using non-carbonate aggregates. • Table 9 in Chapter 3 of this report provides additional AMFs by categories for traffic control and number of legs.		

FOOTNOTES:

[A] Bray - 2001 (*80*).

TREATMENT: Narrow Lane Widths to Add Lanes

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Empirical Bayes Before-After

REFERENCE: Bauer et al. - 2004 (*45*)

STUDY SITES:

• All treatment and reference sites were located on four freeways in Los Angeles and San Diego Counties, California.
• The treatments included two project types: (1) four to five lanes and (2) five to six lanes. The first type included 79 sites and 36.4 miles, while the second included 45 sites and 12.5 miles. All conversions were made in 1993.
• Crash data were acquired from the FHWA HSIS and included 2 years of before data and 7 years of after data.[A]
• Traffic volumes at the treatment sites ranged from 77,000 vpd to 128,000 vpd.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Four-to-Five-Lane Conversions	**No. of Treated Sites**	**AMF**
All Crashes	79	1.11 (0.03)
Fatal, Injury, and PDO-Tow-Away Crashes		1.10 (0.04)
Fatal and Injury Crashes		1.11 (0.05)
Five-to-Six-Lane Conversions		
All Crashes	45	1.03* (0.05)
Fatal, Injury, and PDO-Tow-Away Crashes		1.04* (0.06)
Fatal and Injury Crashes		1.07* (0.07)

* Results for the five-to-six-lane conversions were not statistically significant. Recommended AMF of 1.0 recommended for five-to-six-lane conversions.

COMMENTS:

• The treatment described here is the addition of a travel lane to an urban freeway by decreasing existing lane widths through restriping, converting all or part of the shoulder to a travel lane, or by using both in combination. In most cases, the shoulder conversion was done to add an HOV lane. **Results are not applicable to other roadway types.**
• Other EB analyses conducted found:
- Increase in sideswipe collisions at four-to-five-lane conversions and a decrease in such collisions at five-to-six-lane conversions.
- Increase in crashes adjacent to on- or off-ramps for both types of conversions. Increase in crashes away from ramps for four-to-five-lane conversions, but a decrease in crashes away from ramps for five-to-six-lane conversions.
• The authors also examined accident migration patterns upstream and downstream of the conversions. The findings suggest that the conversion projects may result in fewer crashes upstream and an increased number of crashes downstream, which may reflect the fact that the operational bottleneck has been shifted.

FOOTNOTES:

[A] The Highway Safety Information System (HSIS) is a multistate safety database that contains accident, roadway inventory, and traffic volume data for a select group of states and is sponsored by the FHWA.

TREATMENT: Add Passing Lanes (Two-Lane Roads)

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Analysis-Driven Expert Panel

REFERENCE: Harwood et al. - 2000 (*9*)

COMMENTS:

• Expert panel considered these AMFs to be the best estimates for the installation of passing lanes on rural two-lane roadways. **Results are not applicable to other roadway types.**

• Expert panel notes that these AMFs are based on the assumption that the passing lanes are operationally warranted, and the length is appropriate for conditions.

• The AMFs apply to total accidents within the passing-lane section of the roadway and do not include upstream or downstream accidents.

• The AMF for short, four-lane sections does not apply to extended lengths of four-lane highways.

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Type of Passing Lane	AMF[A]
One-way (single direction of travel)	0.75
Two-way (short four-lane sections)	0.65

FOOTNOTES:

[A] Estimates are based on work by Harwood and St. John - 1984 (*81*) and Nettelbad - 1979 (*82*).

<table>
<tr><td>TREATMENT: Add Two-Way Left-Turn Lane (TWLTL)</td><td>AMF Level of Predictive Certainty: Medium-High</td></tr>
<tr><td>METHODOLOGY: Analysis-Driven Expert Panels</td><td>ACCIDENT MODIFICATION FUNCTION</td></tr>
<tr><td>REFERENCE: Harwood et al. - 2000 (9)

COMMENTS:

• Expert panel considered this AMF function to be the best estimate for the installation of a TWLTL without data on left-turn volumes within the TWLTL.

• Expert recommends a minimum driveway density of 5 driveways/mile for the AMF to be applied; the AMF for any lesser density would be equal to 1.0.

• Estimate function for driveway-related accidents is based on work by Hauer, which included a critical review of 14 studies conducted between 1964 and 1997.[A] The AMF function shown here is more conservative than the Hauer AMF.

• Most of the studies reviewed by Hauer analyzed TWLTLs in urban and suburban areas. Hauer noted that the safety effects on rural roads should be at least as large as those on urban and suburban roads. Thus, the AMF shown here is applicable to rural and urban two-lane and multilane roads.

• NCHRP Project 17-25 urban/suburban expert panel confirmed the adoption of this AMF for the road classes noted above.</td><td>$$AMF = 1 - 0.7P_D P_{LT/D}$$
where:
P_D = driveway-related accidents as a proportion of total accidents
P_D estimated as:
$$\frac{0.0047DD + 0.0024DD^2}{1.199 + 0.0047DD + 0.0024DD^2}$$
where: DD = driveway density (driveways per mile)

$P_{LT/D}$ = left-turn accident susceptible to correction by TWLTL as a proportion of driveway-related accidents

$P_{LT/D}$ = 0.5 (estimated by expert panel on the basis of work by Hauer)[A]

FOOTNOTES:
[A] Hauer - 2000 (83).</td></tr>
</table>

TREATMENT: Change Lane Width

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Analysis-Driven Expert Panel

REFERENCES: Harwood et al. - 2000 (*9*) and Harwood et al. - 2003 (*51*)

COMMENTS:

- The AMFs for ADTs greater than 2,000 are largely based on work by Zegeer et al.; AMFs for ADTs less than 400 are based on work by Griffin and Mak. AMFs for ADTs between 400 and 2,000 were based on expert panel judgment and an extensive critique of the literature by Hauer.[A]
- If lane widths differ for the two directions of travel, the AMF should be determined for each direction and then averaged to obtain an AMF for the roadway.
- The factors for rural multilane roads were developed by an expert panel. There is less confidence in the rural multilane AMF.

- **The AMFs developed do not apply to urban roadways.**

FOOTNOTES:

[A] Zegeer et al. - 1988 (*84*); Griffin and Mak - 1987 (*85*); Hauer - 2000 (*86*).

[B] Related accidents include single-vehicle run-off-road, multiple-vehicle head-on, and opposing- and same-direction sideswipe accidents.

[C] Table developed in Harwood et al. - 2003 (*51*).

ACCIDENT MODIFICATION FUNCTION

Rural Two-Lane Roads

$$AMF = (AMF_{RA} - 1.0)P_{RA} + 1.0$$

where:

AMF = accident modification factor for total accidents

AMF_{RA} = accident modification factor for related accidents[B]

AMF_{RA} is calculated by dividing the AMF for the after-improvement condition by the AMF for the before condition - each can be selected from the following table:[C]

Lane Width	Average Daily Traffic (ADT)		
	≤ 400	400 to 2000	≥ 2000
9 ft	1.05	$1.05+2.81\times10^{-4}$ (ADT-400)	1.50
10 ft	1.02	$1.02+1.75\times10^{-4}$ (ADT-400)	1.30
11 ft	1.01	$1.01+2.5\times10^{-5}$ (ADT-400)	1.05
12 ft	1.00	1.00	1.00

P_{RA} = proportion of total accidents constituted by related accidents

P_{RA} = 0.35 (estimated from distribution of accident types)

Rural Multilane Roads

$$AMF = f\,(AMF_{RA} - 1.0)P_{RA} + 1.0$$

where:

f = factor for roadway type

f = 0.75 for multilane undivided and 0.50 for divided

TREATMENT: Change Shoulder Width and/or Type	**AMF Level of Predictive Certainty: Medium-High**

METHODOLOGY: Analysis-Driven Expert Panel

REFERENCES: Harwood et al. - 2000 (*9*) and Harwood et al. - 2003 (*51*)

COMMENTS:

• Shoulder width AMFs for ADTs greater than 2,000 are largely based on work by Zegeer et al. (1988); AMFs for ADTs less than 400 are based on low-volume roads work by Zegeer et al. (1981). AMFs for ADTs between 400 and 2,000 were based on expert panel judgement and an extensive critique of the literature by Hauer.[A]

• Shoulder Type AMFs are based on work by Miaou for differences in gravel and paved shoulders and Zegeer et al (1988) for differences in turf and paved shoulders. Composite shoulders are 50% paved and 50% turf; the AMFs are averages for the two types.[A]

• If shoulder widths/types differ for the two directions of travel, the AMF should be determined for each direction and then averaged to obtain an AMF for the roadway.

• **The AMFs developed do not apply to urban roadways**

FOOTNOTES:

[A] Zegeer et al. - 1988 (*84*); Zegeer, Dean, and Mayes - 1981 (*87*); Miaou - 1996 (*88*); Hauer - 2000 (*89*).

[B] Related accidents include single-vehicle run-off-road, multiple-vehicle opposing- and same-direction sideswipe accidents.

[C] Table developed in Harwood et al. - 2003 (*51*).

ACCIDENT MODIFICATION FUNCTION

Rural Two-Lane and Multilane Roads

$$AMF = (AMF_{WRA}\ AMF_{TRA} - 1.0)P_{RA} + 1.0$$

where:

AMF = accident modification factor for total accidents

AMF_{WRA} = accident modification factor for related accidents based on shoulder width[B]

AMF_{WRA} is calculated by dividing the AMF for the after-improvement condition by the AMF for the before condition - each can be selected from the following table:[C]

Shoulder Width	Average Daily Traffic (ADT)		
	≤ 400	400 to 2000	≥ 2000
0 ft	1.10	$1.1+2.5\times10^{-4}(ADT-400)$	1.50
2 ft	1.07	$1.07+1.43\times10^{-4}(ADT-400)$	1.30
4 ft	1.02	$1.02+8.125\times10^{-5}(ADT-400)$	1.15
6 ft	1.00	1.00	1.00
8 ft	0.98	$0.98+6.875\times10^{-5}(ADT-400)$	0.87

AMF_{TRA} = accident modification factor for related accidents based on shoulder type[B]

AMF_{TRA} is calculated by dividing the AMF for the after-improvement condition by the AMF for the before condition - each can be selected from the following table:

Shoulder Type	Shoulder Width (ft)							
	0	1	2	3	4	6	8	10
Paved	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Gravel	1.00	1.00	1.01	1.01	1.01	1.02	1.02	1.03
Composite	1.00	1.01	1.02	1.02	1.03	1.04	1.06	1.07
Turf	1.00	1.01	1.03	1.04	1.05	1.08	1.11	1.14

P_{RA} = proportion of total accidents constituted by related accidents

P_{RA} = 0.35 (estimated from distribution of accident types)

TREATMENT: Flatten Horizontal Curve	**AMF Level of Predictive Certainty: Medium-High**
METHODOLOGY: Analysis-Driven Expert Panel	**ACCIDENT MODIFICATION FUNCTION**
REFERENCE: Harwood et al. - 2000 (*9*)	$$AMF = \frac{1.55L_C + \frac{80.2}{R} - 0.012S}{1.55L_C}$$ where: L_C = length of horizontal curve (miles); does not include spiral curve length; R = radius of curvature (ft); S = 1 if spiral transition curve is present and 0 if no such transition exists
COMMENTS: • AMF applies to total accidents on the curved roadway segment. • AMF was derived from the regression model developed by Zegeer et al.[A] • **The AMF is applicable to rural two-lane roads only.**	**FOOTNOTES:** [A] Zegeer et al. - 1992 (*90*).

TREATMENT: Improve Curve Superelevation	**AMF Level of Predictive Certainty: Medium-High**	
METHODOLOGY: Analysis-Driven Expert Panel	**Superelevation Deficiency (SD)**	**AMF**
REFERENCE: Harwood et al. - 2000 (*9*)	< 0.01	1.00
	0.01 ≤ SD < 0.02	1.00 + 6(SD - 0.01)
COMMENTS:	≥ 0.02	1.06 + 3(SD - 0.02)
• AMF applies to total accidents occurring on curved roadway segments. • Expert panel noted there was no safety effect until the superelevation reached 0.01. • AMF was derived from the results of Zegeer et al.[A] • **The AMF is applicable to rural two-lane roads only.**	**FOOTNOTES:** [A] Zegeer et al. - 1992 (*90*).	

TREATMENT: Add Shoulder Rumble Strips	**AMF Level of Predictive Certainty: Medium-High**		
METHODOLOGY: Before-After with Comparison Sites	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: Griffith - 1999 (*53*)	**All Freeways (Rural and Urban)**	**No. of Improved Sites**	**AMF**
STUDY SITES: • Included 55 treatment sites and 55 matched comparison sites from rural and urban freeways in Illinois. • The treatment sites covered 196 miles of rural freeway and 67 miles of urban freeway. • The treatment sites were not selected on the basis of accident history; thus, there was no selection bias.	All Single-Vehicle Run-Off-Road Crashes	55	0.82 (0.07)
	Injury Single-Vehicle Run-Off-Road Crashes		0.87 (0.12)
	Rural Freeways		
	All Single-Vehicle Run-Off-Road Crashes	29	0.79 (0.10)
	Injury Single-Vehicle Run-Off-Road Crashes		0.93 (0.16)
	COMMENTS: • Results for all freeways based on yoked comparison analysis; results for rural freeways based on comparison group method using 29 of the treatment sites. Results could not be developed for urban sites separately. • An analysis of multi-vehicle accidents showed the rumble strips to have no effect on such accidents. **• The AMF is not applicable to other road classes (two-lane or multilane).**		

TREATMENT: Add Centerline Rumble Strips

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Empirical Bayes Before-After

REFERENCE: Persaud, Retting, and Lyon - 2003 (*57*)

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Accident Type (all severities)	No. of Improved Sites	AMF
All Crashes	98	0.86 (0.05)
Frontal/Opposing-Direction Sideswipe Crashes		0.79 (0.12)
Accident Type (injury crashes)		
All Crashes	98	0.85 (0.08)
Frontal/Opposing-Direction Sideswipe Crashes		0.75 (0.15)

STUDY SITES:

• Crash and traffic volume data were collected for 98 treatment sites, consisting of 210 miles, where centerline rumble strips had been installed on rural two-lane roads in the states of California, Colorado, Delaware, Maryland, Minnesota, Oregon, and Washington.

• The average length of the treatment sites was 2 miles, and the traffic volumes ranged from 5,000 to 22,000 vpd.

• The reference group of sites was developed from HSIS data for the states of California, Washington, and Minnesota.[A] Additional data were acquired from Colorado for SPF calibration for the Colorado sites.

COMMENTS:

• The authors note that the results cover a wide range of geometric conditions, including curved and tangent sections and sections with and without grades.

• The results include all rumble strip designs (milled-in, rolled-in, formed, and raised thermo-plastic) and placements (continuous versus intermittent) that were present.

• **The AMF is not applicable to other road classes (multilane).**

FOOTNOTES:

[A] The Highway Safety Information System (HSIS) is a multistate safety database that contains accident, roadway inventory, and traffic volume data for a select group of states and is sponsored by the FHWA.

TREATMENT: Install/Upgrade Guardrail	**AMF Level of Predictive Certainty: Medium-High**	
METHODOLOGY: Meta-Analysis	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**	
REFERENCE: Elvik and Vaa - 2004 (*60*)	**Run-Off-Road Accidents**	**AMF**
STUDY SITES: • 20 studies were evaluated, including 12 U.S. studies (6 of which were conducted in 1982 or later).	Fatal Injury Crashes	0.56 (0.10)
	All Injury Crashes	0.53 (0.05)
COMMENTS: • The results apply to the installation of guardrail along an embankment. The studies were not differentiated by roadway class. • The analysis also included an estimate for the change in accident rate, but the results were not significant. • Results were also included for changing to softer guardrails. However, specifics on the type of change in hardware were not indicated, and not all results were significant. Therefore, they are not included here.		

TREATMENT: Convert Undivided Four-Lane Road to Three-Lane and TWLTL (Road Diet)

AMF Level of Predictive Certainty: High

METHODOLOGY: Empirical Bayes Before-After

REFERENCE: NCHRP Project 17-25 research results

STUDY SITES:

• 15 urban locations in Iowa with a mean length of 1.02 miles, a minimum and maximum length of 0.24 and 1.72 miles. AADT after conversion ranged from 3,718 to 13,908.

• 30 urban locations from Washington and California studied previously with a mean length of 0.84 miles, a minimum and maximum length of 0.08 and 2.54 miles. AADT after conversion ranged from 6,194 to 26,376.

CRASH TYPE STUDIED AND ESTIMATED EFFECT

State/Site Characteristics	Accident Type	No. of Treated Sites	AMF
Iowa Predominately U.S. and state routes within small urban areas (average population of 17,000)	Total Crashes	15 15 miles	0.53 (0.02)
California/Washington Predominately corridors within suburban areas surrounding larger cities (average population of 269,000)	Total Crashes	30 30 mi	0.81 (0.03)
All Sites	Total Crashes	45 40 mi	0.71 (0.02)

FOOTNOTES:

[A] Huang, Stewart, and Zegeer - 2002 (*43*).

[B] Pawlovich et al. - 2006 (*44*).

COMMENTS:

• The study conducted was a reanalysis of data from two prior studies. [A,B]

• The reanalysis of the Washington/California data indicated a 19% decrease in total crashes. The reanalysis of the Iowa data showed a reduction of 47% in total crashes. If the characteristics of the treated site can be defined on the basis of road and area type (as shown above), the AMFs of 0.53 and 0.81 should be used. Otherwise, it is recommended that the aggregate AMF of 0.71 be applied.

TREATMENT: Increase Pavement Friction on Roadway Segment

AMF Level of Predictive Certainty: High

METHODOLOGY: Empirical Bayes Before-After

REFERENCE: NCHRP Project 17-25 research results

CRASH TYPE STUDIED AND ESTIMATED EFFECTS

Accident Type	No. of Treated Sites	AMF
All Crashes	36 miles	0.76 (0.02)
Wet-Road Crashes		0.43 (0.02)
Rear-End Crashes		0.83 (0.04)
Rear-End Wet-Road Crashes		0.58 (0.06)
Single Vehicle Crashes		0.7 (0.04)

STUDY SITES:

• The treatment data for this analysis were from the Skid Accident Reduction Program (SKARP) developed by NY State DOT in 1995.[A]
• Data were collected from New York State for 36.3 miles of treated segments and 1,242.4 miles of reference segments. Locations were in both urban and rural locations.
• The segments are in close proximity to treated intersections, which are the primary targets of the treatment.
• Sites are selected for treatment based on both a high proportion of wet-road accidents and low friction numbers.

COMMENTS:
• The treatment generally involved a 1.5-in. resurfacing or a 0.5-in. microsurfacing using non-carbonate aggregates.

• Table 10 in Chapter 3 of this report provides additional AMFs by categories for number of lanes and urban versus rural locations, although not all are statistically significant.

FOOTNOTES:
[A] Bray - 2001 (*80*).

TREATMENT: Change Median Width	**AMF Level of Predictive Certainty: Medium-High**
METHODOLOGY: Cross-Sectional Model	**ACCIDENT MODIFICATION FACTORS**
REFERENCES: NCHRP Project 17-25 research results	**Full Access Control**

STUDY SITES:

• Ten years of data from 1993 to 2002 on divided roadway sections in California were obtained from the Highway Safety Information System (HSIS).

• The dataset included 500 miles of rural and urban roadways with parital or no access control and 1,400 miles with full access control. There were no median barriers on any of these roadway segments, meaning the barriers were traversable. Median widths for the segments included in the analysis ranged from 4 ft to 100 ft.

• Over the 10-year period, the partial/no-access control sections experienced approximately 41,000 total crashes and 5,000 cross-median crashes. The full-access control sections experienced approximately 125,000 total crashes and 5,000 cross-median crashes.

Full Access Control

Median Width (ft)	Rural 4 Lanes		Urban 4 Lanes		Urban 5+ Lanes	
	All	CM	All	CM	All	CM
10	1.00	1.00	1.00	1.00	1.00	1.00
20	0.96	0.86	0.95	0.89	0.93	0.89
30	0.93	0.74	0.90	0.80	0.86	0.79
40	0.90	0.63	0.85	0.71	0.80	0.71
50	0.87	0.54	0.80	0.64	0.74	0.63
60	0.84	0.46	0.76	0.57	0.69	0.56
70	0.81	0.40	0.72	0.51	0.64	0.50
80	0.78	0.34	0.68	0.46	0.59	0.45
90	0.75	0.29	0.65	0.41	0.55	0.40
100	0.73	0.25	0.61	0.36	0.51	0.35

All = total crashes, all severities
CM = cross-median crashes, all severities

Partial or No Access Control

Median Width (ft)	Rural 4 Lanes		Urban 4 Lanes	
	All	CM	All	CM
10	1.00	1.00	1.00	1.00
20	0.95	0.84	0.95	0.87
30	0.91	0.71	0.90	0.76
40	0.87	0.60	0.85	0.67
50	0.83	0.51	0.81	0.59
60	0.79	0.43	0.77	0.51
70	0.76	0.36	0.73	0.45
80	0.72	0.31	0.69	0.39
90	0.69	0.26	0.65	0.34
100	0.66	0.22	0.62	0.30

All = total crashes, all severities
CM = cross-median crashes, all severities

COMMENTS:

• NCHRP Projects 17-25/17-26 expert panel reviewed several studies of the effects of median width on crashes and reached a recommendation to either reanalyze data from one of those efforts or conduct a more robust analysis.

TREATMENT: Change Roadside Sideslope

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Expert Panel

REFERENCES: NCHRP Project 17-25 research results

COMMENTS:

• Original study conducted by Zegeer et al.[A] used log linear regression models to develop estimates of the effects of sideslope on single-vehicle crashes and total crashes on rural two-lane roads. The AMFs shown were derived from these models.

• The NCHRP Projects17-25/17-29 expert panel on rural multilane highways concluded that the AMFs derived were valid and the best available for both rural two-lane roads and rural multilane highways.

FOOTNOTES:

[A] Zegeer et al. - 1988 (*84*).

ACCIDENT MODIFICATION FACTORS

Single Vehicle Crashes				
Sideslope in Before Condition	Sideslope in After Condition			
	1:4	1:5	1:6	1:7
1:2	0.90	0.85	0.79	0.73
1:3	0.92	0.86	0.81	0.74
1:4	~	0.94	0.88	0.81
1:5	~	~	0.94	0.86
1:6	~	~	~	0.92

Total Crashes				
Sideslope in Before Condition	Sideslope in After Condition			
	1:4	1:5	1:6	1:7
1:2	0.94	0.91	0.88	0.85
1:3	0.95	0.92	0.89	0.85
1:4	~	0.97	0.93	0.89
1:5	~	~	0.97	0.92
1:6	~	~	~	0.95

TREATMENT: Add/Remove On-Street Parking	**AMF Level of Predictive Certainty: Medium-High**
METHODOLOGY: Analysis-Driven Expert Panel	**ACCIDENT MODIFICATION FUNCTION**
REFERENCE: Bonneson, Zimmerman, and Fitzpatrick - 2005 (*91*)	$$AMF = 1 + P_{pk} (B_{pk} - 1)$$ where: P_{pk} = proportion of curb length with on-street parking (= $0.5L_{pk}/L$) L_{pk} = curb length with on-street parking (mi) L = roadway segment length (mi) $B_{pk} = (1.10 + 0.365I_{u2} + 0.609P_{b/o})[(f_{ap/pp} - 1.0)P_{ap} + 1.0]$ where: I_{u2} = cross-section indicator variable (two-lane street = 1; otherwise = 0) $P_{b/o}$ = proportion of street with parking that has business or office as adjacent land use $f_{ap/pp}$ = ratio of crashes on streets with angle parking to crashes on streets with parallel parking (= 2.34; see comment) P_{ap} = for that part of the street with parking, the proportion of the street with angle parking
COMMENTS: • Expert panel on urban/suburban arterials considered this AMF function to be the best estimate for the addition or removal of on-street parking. • AMF was derived from a negative binomial regression model (Bonneson and McCoy)[A] and from other prior study data (McCoy et al.).[B] • Value for the ratio of crashes on streets with angle parking to crashes on streets with parallel parking ($f_{ap/pp}$) derived by Bonneson et al.[C] to be 2.34 on the basis of data from McCoy et al.[B] and Box.[D]	**FOOTNOTES:** [A] Bonneson and McCoy - 1997 (*92*). [B] McCoy et al. - 1990 (*93*). [C] Bonneson, Zimmerman, and Fitzpatrick - 2005 (*91*). [D] Box - 2002 (*94*).

TREATMENT: Add Roadway Segment Lighting	**AMF Level of Predictive Certainty: Medium-High**	
METHODOLOGY: Meta-analysis/Expert Panel	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**	
REFERENCE: Elvik and Vaa - 2004 (*60*); NCHRP 17-25 Final Report; NCHRP 17-26 Final Report	**Nighttime Crashes**	**AMF**
STUDY SITES: • 38 studies were evaluated as part of the meta-analysis, including 14 U.S. studies.[A] • Distributions of crashes by injury severity and time of day were obtained from the HSIS data for the states of Minnesota and Michigan.	Total Crashes	0.80
	All Injury Crashes	0.71
	All Crashes	**AMF**
	Total Crashes	0.94
	All Injury Crashes	0.92

COMMENTS:

• The meta-analysis results produced AMF estimates for reductions in fatal, injury and property-damage-only accidents of 0.36, 0.72, and 0.83, respectively.[A]
• The NCHRP 17-25/17-26 expert panel on urban/suburban arterials recommended that the meta-analysis results be applied to roadway segments and that the fatal and injury results be combined into a single AMF for all levels of injury.
• The NCHRP 17-26 Final Report includes a distribution of crashes by time of day and injury severity for several roadway classes.
• AMFs shown represent the mean estimates for all roadway classes and were derived on the basis of these distributions and the meta-analysis AMFs.

FOOTNOTES:
[A] Elvik and Vaa (*60*)

TREATMENT: Install Raised Medians at Crosswalks	**AMF Level of Predictive Certainty: Medium-High**		
METHODOLOGY: Matched Comparison	**CRASH TYPE STUDIED AND ESTIMATED EFFECTS**		
REFERENCE: Zegeer et al. - 2001 (*38*)	**Total Pedestrian Accidents (all severities)**	**No. of Median Sites**	**AMF**
STUDY SITES: • 2,000 sites were included in the study to evaluate the effect of marked vs. unmarked crosswalks (1,000 matched pairs of each type), • 260 of these sites were on multilane roads and had raised medians. • On average, 5 years of crash data were collected for each site, as well as traffic data and pedestrian volume estimates.	Marked Crosswalks*	173	0.54
	Unmarked Crosswalks*		0.61
	* Applicable to urban and suburban multilane roads (up to eight lanes) with traffic volumes greater than 15,000 vpd.		
	COMMENTS: • The AMFs were computed from the pedestrian crash rates (pedestrian crashes per million crossings) for sites with medians versus the sites without medians.		

TREATMENT: Reduce Mean Travel Speed

AMF Level of Predictive Certainty: Medium-High

METHODOLOGY: Reanalysis of Existing Data

REFERENCES: NCHRP Project 17-25 research results

COMMENTS:

• Original study conducted by Elvik and colleagues used the Power Model to develop estimates of the effectiveness of changes in mean travel speeds. Data included mean speed change and the related crash-frequency change from 97 published international studies containing 460 results. Each result contained information on mean speed and crash frequency before treatment and mean speed and crash frequency after treatment. [A]

• The NCHRP Projects 17-25/17-26 expert panel reviewed the original study and requested supplemental analysis to explore the validity of the results and to develop AMFs.

NOTE: This series of AMFs is related to any treatment that is associated with a changed mean speed (e.g., changes in enforcement or installation of traffic calming measures).

FOOTNOTES:

[A] Elvik, Christensen, and Amundsen - 2004 (*74*).

ACCIDENT MODIFICATION FACTORS

Non-fatal Injury Crashes

	$\bar{v}_0$ [mph]					
$\Delta\bar{v}$ [mph]	30	40	50	60	70	80
-5	0.57	0.66	0.71	0.75	0.78	0.81
-4	0.64	0.72	0.77	0.80	0.83	0.85
-3	0.73	0.79	0.83	0.85	0.87	0.88
-2	0.81	0.86	0.88	0.90	0.91	0.92
-1	0.90	0.93	0.94	0.95	0.96	0.96
0	1.00	1.00	1.00	1.00	1.00	1.00
1	1.10	1.07	1.06	1.05	1.04	1.04
2	1.20	1.15	1.12	1.10	1.09	1.08
3	1.31	1.22	1.18	1.15	1.13	1.12
4	1.43	1.30	1.24	1.20	1.18	1.16
5	1.54	1.38	1.30	1.26	1.22	1.20

$\bar{v}_0$ = initial mean travel speed

$\Delta\bar{v}$ = change in mean travel speed

Fatal Injury Crashes

	$\bar{v}_0$ [mph]					
$\Delta\bar{v}$ [mph]	30	40	50	60	70	80
-5	0.22	0.36	0.48	0.58	0.67	0.75
-4	0.36	0.48	0.58	0.66	0.73	0.80
-3	0.51	0.61	0.68	0.74	0.80	0.85
-2	0.66	0.73	0.79	0.83	0.86	0.90
-1	0.83	0.86	0.89	0.91	0.93	0.95
0	1.00	1.00	1.00	1.00	1.00	1.00
1	1.18	1.14	1.11	1.09	1.07	1.05
2	1.38	1.28	1.22	1.18	1.14	1.10
3	1.59	1.43	1.34	1.27	1.21	1.16
4	1.81	1.59	1.46	1.36	1.28	1.21
5	2.04	1.75	1.58	1.46	1.36	1.27

$\bar{v}_0$ = initial mean travel speed

$\Delta\bar{v}$ = change in mean travel speed

CHAPTER 6

Conclusions

AMFs are a key component of existing procedures used by state and local transportation agencies to choose and target safety treatments and of a series of new safety analysis tools being developed to make these safety decision processes even more effective and efficient. AMFs can be developed from an analysis of crash data, usually in a before-after evaluation, and from combinations of information from prior research studies. While there have been decades of effort aimed at developing credible AMFs, there have been surprisingly few developed that are of a quality that withstands critical scrutiny.

However, in the past 10 years, there has been greatly increased emphasis on the development of credible AMFs. With this emphasis has come greatly increased funding, both in the NCHRP program funded by AASHTO and in FHWA's research program. NCHRP funded the development of the *NCHRP Report 500* guides, which have captured information on safety program effects from existing research literature in 20 different roadway, driver, and vehicle emphasis areas, in support of the implementation of the AASHTO Strategic Highway Safety Plan. In response to knowledge needs cited in a group of the *NCHRP Report 500* guides, FHWA is funding a continuing series of scientifically sound evaluations of low-cost treatments for roadways. NCHRP is also funding a series of projects aimed at development and publication of the Highway Safety Manual, including a detailed "current knowledge" section that captures AMFs from published literature, the aforementioned project to develop crash prediction tools and AMFs for rural multilane highways, and the aforementioned project to develop similar tools and AMFs for suburban/urban arterials.

The project effort described in this report is the final major AMF development effort recently funded by NCHRP. As shown in Table 18 (see Chapter 5) AMFs have been verified, modified, or developed here. When published this year, the Highway Safety Manual will provide a larger list of AMFs.

However, even with this amount of concentrated effort, there remain a number of critical safety treatments, including many ITS treatments, for which credible AMFs do not exist. As described in Chapter 2, the research team developed and used a detailed procedure for ranking AMFs needing development. The procedure included not only an assessment of the current status of AMF knowledge (the level of predictive certainty) but also priority ratings by state DOT users, an estimate of crash-related harm possibly affected by the treatment, knowledge of ongoing or future research that might develop AMFs, and the current availability of needed evaluation data. Table 20 provides a listing of treatments that are considered to be high-priority targets for future development based on this ranking methodology. Clearly, others would be added if another ranking method was used.

In summary, this project has verified, modified, or developed 35 AMFs that are perceived to be of high or medium-high quality. These have been documented in formats that are usable by both practitioners and researchers. These AMFs are the primary project outputs. The project has also documented a process that can be used with future analysis-driven expert panels, and notes from the detailed discussions of the two expert panels that were part of this effort can be provided to others. This material should be helpful in future efforts to develop or improve AMFs for treatments for which no AMF could be developed in this research. Finally, a procedure for ranking needed AMF research was developed and documented—a procedure incorporating not only state DOT user and researcher opinions and knowledge of the quality of AMFs in the published literature, but also a method for estimating the crash-related harm that might be affected by each treatment. An approach combining these factors could be used in more global efforts to prioritize roadway safety research needs in general.

Table 20. High priority treatments needing AMF development in future research.

High Priority Treatments (Gray shading indicates high ranking in user survey)	Overall Ranking for Future Research*
Intersection Treatments	
Channelize right turns	MH
Install dynamic advance warning flashers "Red Signal Ahead"	MH
Provide signal coordination	MH
Prohibit left turns	MH
Segment Treatments	
Add a travel lane	MH
Add shoulder rumble strips (two-lane/others)	MH
Add edgeline rumble strips	MH
Eliminate left turns at driveways	MH
Remove roadside obstacles (including urban)	MH
Flatten sideslopes	MH
Add advance curve warning signs/on pavement markings	H
Add midblock pedestrian signal	MH
Install raised crosswalk (non-intersection)	MH
* H = High, MH = medium high	

References

1. Krammes, R. A. and C. Hayden. Making Two-Lane Roads Safer. *Public Roads Magazine*, Vol. 66, No. 4, January/February 2003, pp. 38–40.
2. SafetyAnalyst Homepage. Federal Highway Administration. www.safetyanalyst.org. Accessed August 10, 2007.
3. Highway Safety Manual Home Page. Transportation Research Board. Hosted by Washington State DOT. www.highwaysafety-manual.org. Accessed August 10, 2007.
4. American Association of State Highway and Transportation Officials. *AASHTO Strategic Highway Safety Plan—A Comprehensive Plan to Substantially Reduce Vehicle-Related Fatalities and Injuries on the Nation's Highways*. American Association of State Highway and Transportation Officials, Washington, D.C., 2005.
5. Harkey, D. L., R. Srinivasan, C. Zegeer, B. Persaud, C. Lyon, K. Eccles, F. Council, and H. McGee. *NCHRP Research Results Digest 299: Crash Reduction Factors for Traffic Engineering and Intelligent Transportation System (IFS) Improvements: State-Of-Knowledge Report*. Transportation Research Board of the National Academies, Washington, D.C., November 2005.
6. Various authors. *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan*, Volumes 1–17 and 19. Transportation Research Board of the National Academies, 2003–2007.
7. Hauer, E. *Observational Before—After Studies in Road Safety: Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety*. Pergamon Press, Elsevier Science, Ltd., Oxford, UK, 1997.
8. Rodegerdts, L., M. Blogg, E. Wemple, E. Myers, M. Kyte, M. Dixon, G. List, A. Flannery, R. Troutbeck, W. Brilon, N. Wu, B. Persaud, C. Lyon, D. Harkey, and D. Carter. *NCHRP Report 572: Roundabouts in the United States*. Transportation Research Board of the National Academies, Washington, D.C., 2007.
9. Harwood, D. W., F. M. Council, E. Hauer, W. E. Hughes, and A. Vogt. *Prediction of the Expected Safety Performance of Rural Two-Lane Highways*. Publication FHWA-RD-99-207. FHWA, U.S. DOT, December 2000.
10. Preston, H. and T. Schoenecker. *Bypass Lane Safety, Operations, and Study Design*. Publication MN/RC-2000-22, Minnesota DOT, July 1999.
11. Sebastian, O. L. and R. S. Pusey. *Paved-Shoulder Left-Turn Bypass Lanes: A Report on the Delaware Experience*. Delaware DOT, October 1982.
12. Harwood, D. W., K. M. Bauer, I. B. Potts, D. J. Torbic, K. R. Richard, E. R. Kohlman Rabbani, E. Hauer, and L. Elefteriadou. *Safety Effectiveness of Intersection Left- and Right-Turn Lanes*. Publication FHWA-RD-02-089, FHWA, U.S. DOT, July 2002.
13. Khattak, A. J., B. Naik, and V. Kannan. *Safety Evaluation of Left-Turn Lane Line Width at Intersections with Opposing Left-Turn Lanes*. Final Report, Nebraska Department of Roads, Lincoln, NE, December 2004.
14. Evaluation of Low-Cost Safety Improvements, Phase II/Phase III. FHWA, U.S. DOT. Expected completion date unknown.
15. Hughes R. (Principal Investigator). NCHRP Project 3-78, "Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities." Transportation Research Board of the National Academies, Washington, D.C., Expected completion—November 2008.
16. NCHRP Project 3-89, "Design Guidance for Channelized Right-Turn Lanes." Transportation Research Board of the National Academies, Washington, D.C., Expected completion date unknown.
17. Bowman, B. L. and R. L. Vecellio. Effects of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety. In *Transportation Research Record 1445*, Transportation Research Board, National Research Council, Washington, D.C., 1994, pp. 169–179.
18. McGee, H., S. Taori, and B. Persaud. *NCHRP Report 491: Crash Experience Warrant for Traffic Signals*. Transportation Research Board of the National Academies, Washington, D.C., 2003.
19. 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, No. 6, Pergamon Press, Oxford, NY, 1997, pp. 803–810.
20. Hauer, E. *Left-Turn Protection, Safety, Delay and Guidelines: A Literature Review*. Prepared for FHWA, U.S. DOT, October 2004. www.roadsafetyresearch.com. Accessed August 11, 2005.
21. Lyon, C., A. Haq, B. Persaud, and S. Kodama. Safety Performance Functions for Signalized Intersections in Large Urban Areas: Development and Application to Evaluation of Left-Turn Priority Treatment. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1908*, Transportation Research Board, National Research Council, Washington, D.C., 2005, pp. 165–171.
22. 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, No. 2, Pergamon Press, Oxford, NY, 2002, pp. 215–220.
23. Hamilton Associates. The Safety Benefits of Additional Primary Signal Heads. Insurance Corporation of British Columbia, 1998.
24. Sayed, T., W. Abdelwahab, and J. Nepomuceno. Safety Evaluation of Alternative Signal Head Design. In *Transportation Research*

Record 1635, Transportation Research Board, National Research Council, Washington, D.C., 1998, pp. 140–146.

25. Persaud, B., F. Council, C. Lyon, K. Eccles, and M. Griffith. A Multi-Jurisdictional Safety Evaluation of Red Light Cameras. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1922*, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 29–37.
26. Council, F. M., B. Persaud, C. Lyon, K. Eccles, M. Griffith, E. Zaloshnja, and T. Miller. Implementing Red Light Camera Programs: Guidance for Economic Analysis of Safety Benefits. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1922*, Transportation Research Board of the National Academies, Washington, D.C., 2005, pp. 38–43.
27. Evaluation of Yellow-Light Hold System to Reduce Rear-End Collisions. Insurance Institute for Highway Safety, Arlington, VA. Expected completion is unknown.
28. Sayed, T., H. Vahidi, and F. Rodriguez. Advance Warning Flashers: Do They Improve Safety. In *Transportation Research Record: Journal of the Transportation Research Board*, *No.1692*, Transportation Research Board, National Research Council, Washington, D.C., 1999, pp. 30–38.
29. Srinivasan, R., D. Carter, B. Persaud, K. Eccles, N. Lefler, C. Lyon, and R. Amjadi. *Safety Evaluation of Flashing Beacons at Stop-Controlled Intersections*. Publication FHWA-HRT-08-048. FHWA, U.S. DOT, August 2007.
30. Lovell, J. and E. Hauer. The Safety Effect of Conversion to All-Way Stop Control. In *Transportation Research Record 1068*, Transportation Research Board, National Research Council, Washington, D.C., 1986, pp. 103–107.
31. McGee, H. W. and M. R. Blankenship. *NCHRP Report 320: Guidelines for Converting Stop to Yield Control at Intersections.* Transportation Research Board, National Research Council, Washington, D.C., 1989.
32. Ray, B. (Principal Investigator, Kittelson & Associates). NCHRP Project 3-74, "Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections." Transportation Research Board of the National Academies, Washington, D.C. Expected publication of final report—June 2008.
33. Transverse Rumble Strips at Stop-Controlled Intersections in Iowa. Highway Safety Information System, FHWA, U.S. Department of Transportation. Expected completion date—2008.
34. Walker, F. W. and S. E. Roberts. Influence of Lighting on Accident Frequency at Highway Intersections. In *Transportation Research Record 562*, Transportation Research Board, National Research Council, Washington, D.C., 1976, pp. 73–78.
35. Lipinski, M. E., and R. H. Wortman. Effect of Illumination on Rural At-Grade Intersection Accidents. In *Transportation Research Record 611*, Transportation Research Board, National Research Council, Washington, D.C., 1976, pp. 25–27.
36. Preston, H. and T. Schoenecker. Safety Impacts of Street Lighting at Isolated Rural Intersections. Publication MN/RC-1999-17. Minnesota DOT, April 1999.
37. Rea, M. S. (Principal Investigator at Rensselaer Polytechnic Institute). NCHRP Project 5-19, "Guidelines for Roadway Lighting Based on Safety Benefits and Costs." Transportation Research Board of the National Academies, Washington, D.C. Expected completion—July 2008.
38. Zegeer, C. V., J. R. Stewart, H. Huang, and P. Lagerway. Safety Effects of Marked Versus Unmarked Crosswalks at Uncontrolled Locations: Analysis of Pedestrian Crashes in 30 Cities (with Discussion and Closure). In *Transportation Research Record: Journal of the Transportation Research Board*, *No.1773*, Transportation Research Board, National Research Council, Washington, D.C., 2001, pp. 56–68.
39. Zaidel, D. M. and I. Hocherman. Safety of Pedestrian Crossings at Signalized Intersections. In *Transportation Research Record 1141*, Transportation Research Board, National Research Council, Washington, D.C., 1987, pp. 1–6.
40. Zegeer, C. V., K. S. Opiela, and M. J. Cynecki. Effect of Pedestrian Signals and Signal Timing on Pedestrian Accidents. In *Transportation Research Record 847*, Transportation Research Board, National Research Council, Washington, D.C., 1982, pp. 62–72.
41. Andreassen, D. The Treatment/Crash Reduction Matrix. www.dotars.gov.au/transprog/downloads/road_bs_matrix.pdf. Accessed August 11, 2005.
42. Council, F. M. and J. R. Stewart. Safety Effects of the Conversion of Rural Two-Lane to Four-Lane Roadways Based on Cross-Sectional Models. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1665*, Transportation Research Board, National Research Council, Washington, D.C., 1999, pp. 35–43.
43. Huang, H. F., J. R. Stewart, and C. V. Zegeer. Evaluation of Lane Reduction "Road Diet" Measures on Crashes and Injuries. In *Transportation Research Record: Journal of the Transportation Research Board*, *No.1784*, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 80–90.
44. Pawlovich, M., L. Wen, A. Carriquiry, and T. Welch. Iowa's Experience with Road Diet Measures: Use of Bayesian Approach to Assess Impacts on Crash Frequencies and Crash Rates. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1953*, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 163–171.
45. Bauer, K. M., D. W. Harwood, W. E. Hughes, and K. R. Richard. Safety Effects of Using Narrow Lanes and Shoulder-Use Lanes to Increase the Capacity of Urban Freeways. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1897*, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 71–80.
46. Persaud, B., C. Lyon, K. Eccles, N. Lefler, D. Carter, and R. Amjadi. *Safety Evaluation of Installing Center Two-Way Left-Turn Lanes on Two-Lane Roads*. Publication FHWA-HRT-08-042. FHWA, U.S. DOT, March 2008.
47. Harwood, D. W., D. K. Gilmore, K. R. Richard, and J. M. Dunn. *NCHRP Report 605: Passing Sight Distance Criteria*. Transportation Research Board of the National Academies, Washington, D.C., 2008.
48. Hadi, M. A., J. Aruldhas, L. Chow, and J. Wattleworth. Estimating Safety Effects of Cross-Section Design for Various Highway Types Using Negative Binomial Regression. In *Transportation Research Record 1500*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 169–177.
49. Knuiman, M. W., F. M. Council, and D.W. Reinfurt. Association of Median Width and Highway Accident Rates. In *Transportation Research Record 1401*, Transportation Research Board, National Research Council, Washington, D.C., 1993, pp. 70–82.
50. Maze, T. (Principal Investigator at Iowa State University). NCHRP Project 15-30, "Median Intersection Design for Rural High-Speed Divided Highways."
51. Harwood, D. W., E. R. K. Rabbani, K. R. Richard, H. W. McGee, and G. L. Gittings. *NCHRP Report 486: Systemwide Impact of Safety and Traffic Operations Design Decisions for 3R Projects.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
52. Hauer E. *Safety of Horizontal Curves: Review of Literature for the Interactive Highway Safety Design Model*. March 2000. www.roadsafetyresearch.com. Accessed August 11, 2005.

53. Griffith, M. S. Safety Evaluation of Rolled-in Continuous Shoulder Rumble Strips Installed on Freeways. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1665*, Transportation Research Board, National Research Council, Washington, D.C., 1999, pp. 28–34.
54. Torbic, D.J. (Principal Investigator, Midwest Research Institute). NCHRP Project 17-32, "Guidance for the Design and Application of Shoulder and Centerline Rumble Strips." Transportation Research Board of the National Academies, Washington, D.C. Expected completion—August 2008.
55. Patel, R. B., F. M. Council, and M. S. Griffith. Estimating Safety Benefits of Shoulder Rumble Strips on Two-Lane Rural Highways in Minnesota: Empirical Bayes Observational Before-and-After Study. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 2019*, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 205–211.
56. Lindly, J. K. and R. K. Wijesundera. Evaluation of Profiled Pavement Markings. Publication UTCA 01465. University Transportation Center for Alabama, Tuscaloosa, AL, November 2003.
57. Persaud, B. N., R. A. Retting, and C. Lyon. *Crash Reduction Following Installation of Centerline Rumble Strips on Rural Two-Lane Roads*. Insurance Institute for Highway Safety, Arlington, VA, September 2003.
58. Dixon, K. (Principal Investigator, Georgia Tech Research Corporation). NCHRP Project 16-04, "Design Guidelines for Safe and Aesthetic Roadside Treatments in Urban Areas." Transportation Research Board of the National Academies, Washington, D.C., 2003–2007.
59. Zegeer, C. V., J. Hummer, D. Reinfurt, L. Herf, and W. Hunter. *Safety Effects of Cross-Section Design for Two-Lane Roads—Volumes I and II*. Publication FHWA-RD-87-008, FHWA, U.S. DOT, 1987.
60. Elvik, R. and T. Vaa. *The Handbook of Road Safety Measures*, Elsevier Science, Oxford, UK, 2004.
61. Miaou, S., R. P. Bligh and D. Lord. Developing Guidelines for Median Barrier Installation: Benefit-Cost Analysis with Texas Data. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1904*, Transportation Research Board of the National Academies, D.C., 2005, pp. 3–19.
62. Zegeer, C. V. and M. J. Cynecki. Determination of Cost-Effective Roadway Treatments for Utility Pole Accidents. In *Transportation Research Record 970*, Transportation Research Board, National Research Council, Washington, D.C., 1984, pp. 52–64.
63. Elvik, R. Meta-Analysis of Evaluations of Public Lighting as Accident Countermeasure. In *Transportation Research Record 1485*, Transportation Research Board, National Research Council, Washington, D.C., 1995, pp. 112–123.
64. Weiss, A. (Principal Investigator, Northwestern University). NCHRP Project 3-59, "Assessment of Variable Speed Limit Implementation Issues." Transportation Research Board of the National Academies, Washington, D.C., 2000–2005.
65. Results of Field Tests on Impacts of Setting and Enforcing Rational Speed Limits. Cooperative Agreement Projects. FHWA, U.S. DOT. Expected completion date is unknown.
66. Kockelman, K. *NCHRP Research Results Digest 303: Safety Impacts and Other Implications of Raised Speed Limits on High-Speed Roads*. Transportation Research Board of the National Academies, Washington, D.C., April 2006.
67. Rakha, H., A. Medina, F. Sin, M. Dion, M. Van Aerde, and J Jenq. Traffic Signal Coordination Across Jurisdictional Boundaries: Field Evaluation of Efficiency, Energy, Environmental, and Safety Impacts. In *Transportation Research Record: Journal of the Transportation Research Board*, *No. 1727*, Transportation Research Board, National Research Council, Washington, D.C., 2000.
68. Bray, J. S. Skid Accident Reduction Program (SKARP): Targeted Crash Reductions. In 2003 ITE Technical Conference and Exhibit. CD-ROM. Institute of Transportation Engineers, Washington, D.C., March 2003.
69. Bowman, B. L., and R. L. Vecellio. Effects of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety. In *Transportation Research Record 1445*, Transportation Research Board, National Research Council, Washington, D.C., 1994, pp. 169–179.
70. Gårder, P. Pedestrian Safety at Traffic Signals. In *Accident Analysis and Prevention*, Vol. 21, No.5, 1989, pp. 435–444.
71. Miller, T., T. Schlax, D. Lestina, M. Galbraith, P. Mabery, R. Deering, K. L. Campbell, and D. L. Massie. Understanding the Harm from U.S. Motor Vehicle Crashes. In *Proceedings of the 39th Annual Meeting of the Association for the Advancement of Automotive Medicine*. Association for the Advancement of Automotive Medicine, Barrington, IL, 1995, pp. 327–342.
72. Council, F., E. Zaloshnja, T. Miller, and B. Persaud. *Crash Cost Estimates by Maximum Police-Reported Injury Severity within Selected Crash Geometries*. Publication FHWA-HRT-05-051, FHWA, U.S. DOT, October 2005.
73. Nilsson, G. *Traffic Safety Dimensions and the Power Model to Describe the Effect of Speed on Safety*. Lund Institute of Technology, Department of Technology and Society, Traffic Engineering, Lund, Sweden, 2004. www.lub.lu.se/luft/diss/tec_733/tec_733.pdf.
74. Elvik, R., P. Christensen, and A. Amundsen. *Speed and Road Accidents: An Evaluation of the Power Model*. TOI Report 740, Institute of Transport Economics (TOI), Oslo, Norway, 2004.
75. Lee, J. and F. Mannering. *Analysis of Roadside Accident Frequency and Severity and Roadside Safety Management, Final Research Report*. Publication No. WA-RD 475.1, Washington State DOT, 1999.
76. Donnell, E. T., D. W. Harwood, K. M. Bauer, J. M. Mason, and M. T. Pietrucha. Cross-Median Collisions on Pennsylvania Interstates and Expressways. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1784*, Transportation Research Board of the National Academies, Washington, D.C., 2002, pp. 91–99.
77. Bligh, R., S. Miaou, D. Lord, and S. Cooner. *Median Barrier Guidelines for Texas*. Publication No. FHWA/TX-06/0-4254-1. Texas Department of Transportation, August 2006.
78. Ulf, B. and L. Jörgen. *Traffic Safety of Roundabouts for Cyclists and Pedestrians*. Swedish National Road and Transport Research Institute (VTI), Linköping, Sweden, 1999.
79. Clark, J. E., S. Maghsoodloo, and D. Brown. Public Good Relative to Right-Turn-On-Red in South Carolina and Alabama. In *Transportation Research Record 926*, Transportation Research Board, National Research Council, Washington, D.C., 1983, pp. 24–31.
80. Bray, J. S. Memo on Skid Accident Reduction Program (SKARP). 2001
81. Harwood, D. W. and A. D. St. John. *Passing Lanes and Other Operational Improvements on Two-Lane Highways*. Publication FHWA/RD-85/028. FHWA, U.S. DOT, July 1984.
82. Nettelbad, P. *Traffic Safety Effects of Passing (Climbing) Lanes: An Accident Analysis Based on Data for 1972–1977*. Meddelande TU 1979-5. Swedish National Road Administration, 1979.
83. Hauer E. *The Median and Safety: Review of Literature for the Interactive Highway Safety Design Model*. March 2000. www.roadsafetyresearch.com. Accessed August 11, 2005.
84. Zegeer, C. V., D. W. Reinfurt, J. Hummer, L. Herf, and W. Hunter. Safety Effects of Cross-Section Design for Two-Lane Roads. In

Transportation Research Record 1195, Transportation Research Board, National Research Council, Washington, D.C., 1988, pp. 20–32.

85. Griffin, L. I. and K. K. Mak. *The Benefits to Be Achieved from Widening Rural, Two-Lane Farm-to-Market Roads in Texas*. Publication IAC (86-87)-1039. Texas Transportation Institute, College Station, TX, April 1987.
86. Hauer E. *Lane Width and Safety: Review of Literature for the Interactive Highway Safety Design Model*. March 2000. www.roadsafetyresearch.com. Accessed August 11, 2005.
87. Zegeer, C. V., R. C. Dean and J. G. Mayes. Effect of Lane and Shoulder Widths on Accident Reduction on Rural, Two-Lane Roads. In *Transportation Research Record 806*, Transportation Research Board, National Research Council, Washington, D.C., 1981, pp. 33–43.
88. Miaou, S. *Measuring the Goodness-of-Fit of Accident Prediction Models*. Publication FHWA-RD-96-040. FHWA, U.S. DOT, December 1996.
89. Hauer E. *Shoulder Width, Shoulder Paving and Safety: Review of Literature for the Interactive Highway Safety Design Model*. March 2000. www.roadsafetyresearch.com. Accessed August 11, 2005.
90. Zegeer, C. V., J. R. Stewart, F. M. Council, D. W. Reinfurt, and E. Hamilton. Safety Effects of Geometric Improvements on Horizontal Curves. In *Transportation Research Record 1356*, Transportation Research Board, National Research Council, Washington, D.C., 1992, pp. 11–19.
91. Bonneson, J. A., K. Zimmerman, and K. Fitzpatrick. *Roadway Safety Design Synthesis*. Publication No. FHWA/TX-05/0-4703-P1. Texas DOT, November 2005.
92. Bonneson, J. A. and P. T. McCoy. *NCHRP Report 395: Capacity and Operational Effects of Midblock Left-Turn Lanes*. Transportation Research Board, National Research Council, Washington, D.C., 1997.
93. McCoy, P. T., M. Ramanujam, M. Moussavi, and J. L. Ballard. Safety Comparison of Types of Parking on Urban Streets in Nebraska. In *Transportation Research Record 1270*, Transportation Research Board, National Research Council, Washington, D.C., 1990, pp. 28–41.
94. Box, P. C. Angle Parking Issues Revisited. *ITE Journal*, Institute of Transportation Engineers, Washington, D.C., March 2002, pp. 36–47.
95. Institute for Transportation Engineers. Determining Vehicle Change Intervals: A Proposed Recommended Practice. *ITE Journal*, Vol. 59, No. 7, Institute of Transportation Engineers, Washington, D.C., 1989, pp. 27–32.

APPENDICES

The following appendices are available in on the TRB website at http://trb.org/news/blurb_detail.asp?id=8965:

- Appendix A: Methodology for Determining Crash-Harm Rating for Treatments,
- Appendix B: Effects of Converting Rural Intersections from Stop to Signal Control,
- Appendix C: Safety Effects of Four-Lane to Three-Lane Conversions,
- Appendix D: Safety Effects of Improving Pavement Skid Resistance,
- Appendix E: Evaluation of the Safety Effectiveness of Urban Signal Treatments,
- Appendix F: An Empirical Examination of the Relationship Between Speed and Road Accidents, and
- Appendix G: Accident Modification Factors for Median Width.

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
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
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