Impact of Shoulder Width and Median Width on Safety

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Impact of Shoulder Width and Median Width on Safety

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Field of Design—Area of General Design

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FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report contains the findings of research performed to quantify the safety and operational impacts of design element trade-offs and their associated risks. The report details the research performed and includes specific recommended crash prediction models and Accident Modification Factors (AMFs) for shoulder width and median width on rural four-lane roads. Thus, the report will be of immediate interest to engineers in state highway agencies responsible for geometric design and traffic operations and safety.

Design standards provide a benchmark for the development of elements that compose a highway design. Ideally, every highway design meets the appropriate standards. Realistically, designers are sometimes faced with situations where adherence to standards may not be practical from an engineering, environmental, community, or benefit-cost perspective. In such cases, designers must make decisions regarding the impacts and risks associated with meeting or exceeding the design standards or allowing exceptions to them, for example, in context-sensitive situations. A comprehensive assessment of the safety and operational impacts of trade-offs in design elements is needed to guide designers in weighing appropriate trade-offs in design elements against safety and operational concerns for the full range of highway designs, from low volume to high volume, locals to arterials, and 3-R to new construction.

This research had two objectives. The first was to quantify the safety and operational impacts of design element trade-offs and their associated risks. The second objective was to develop guidelines to assist designers in making reasonable choices among possible design element trade-offs. The research was carried out in two phases. In Phase I, a literature review and the development of methodology for data collection and analysis were conducted for use in the second phase. In Phase II, extensive data were collected from the literature and individual state databases in the FHWA Highway Safety Information System and analyzed to develop prediction models and AMFs used to understand the safety and operational impacts of the studied design element trade-offs.

The original scope of the project encompassed evaluation of design element trade-offs encompassing the full range of highway designs, including context-sensitive solutions and common design exceptions. However, this scope was modified by the NCHRP project panel at the conclusion of Phase I, in order to concentrate on design elements and trade-offs for which there were sufficient data of adequate quality from which to develop well-founded guidance. Specifically, the project panel recommended investigation of the safety impact of design flexibility on rural multi-lane highways of the following: (1) lane width, (2) shoulder width, and (3) median type and width. Final recommended AMFs are presented in the report for shoulder width and median width for four-lane roads with 12-ft lanes.

Alternate methods are provided for estimating the relative safety of design element choices using either AMFs or prediction models.

The research was performed by the University of Kentucky in Lexington, Kentucky. The report fully documents the research leading to the recommended prediction models and AMFs. The recommendations are under consideration for possible inclusion in the future AASHTO Highway Safety Manual.

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SUMMARY

Impact of Shoulder Width and Median Width on Safety

The objectives of this research were to quantify the safety and operational impacts of design element trade-offs and to develop guidelines to assist designers in making reasonable choices when applying context-sensitive solutions and design exceptions. Existing research results were combined with recent practical field experience to provide a guide for planners and designers to understand relationships and quantify the trade-offs for selected design elements. This research provides the highway design community with information resources and decision tools for designing roadways where design flexibility may be appropriate to the roadway context.

The research was completed in two phases. The first phase was a literature review and the development of a methodology for data collection and analysis to be used in the second phase. In the second phase, data were collected and analyzed to develop the resources and tools needed for understanding the safety and operational impacts from design element trade-offs.

This report documents the findings of the research. The literature review determined that a significant amount of research had been undertaken in an attempt to quantify the relationships between safety and roadway design elements, but that these relationships were not available for cross-section elements on multilane rural roads. Therefore, in an investigation to determine the safety impacts of design flexibility on rural multilane highways, the NCHRP project panel recommended that the second phase of the research focus on three geometric elements: lane width, shoulder width, and median type and width. This decision allowed the development of useful models compatible with the current efforts in the development of the *Highway Safety Manual* (*HSM*) (*1*). The *HSM* is planned as a comprehensive compendium of current knowledge related to roadway safety treatments and a collection of tools for predicting the safety effects of different roadway design alternatives for various classes of roadways.

The design elements that were examined in this research have the potential to affect safety. The degrees of influence vary by design element and application and, often, are specific to a set of roadway conditions. Parallel efforts are currently underway to address the quantification of the safety and operational impacts from design element trade-off for two-lane rural highways and, in the near future, for multilane highways.

The key lesson from the literature is that values for design elements can be varied. Most research has been directed to the task of evaluating specific design elements, without considering the effects when multiple elements are varied in combination. An additional issue that has not been discussed extensively is the potential for creating the opposite effect intended by the selected values for design elements. For example, wider shoulders have shown the potential to improve safety. On the other hand, they also have the potential to present conditions that result in increased operating speeds and increased crash severity. A similar counterbalancing potential was noted for the presence and type of barrier in medians.

Therefore, design decisions and countermeasure applications should consider the types of associated crashes for modification and then determine the appropriate design element.

The research was aimed at developing a set of recommendations to be used in evaluating safety implications from design element trade-offs. Data from three states were used to develop prediction models that could be used for this purpose, with an emphasis on developing crash prediction models and Accident Modification Factors (AMFs) for multilane rural roads with respect to lane width, shoulder width, and median width and type. The available data limited these models to four-lane roadways with 12-ft lanes. Separate models were developed for divided and undivided facilities as well as for both total crashes and injury crashes, each including single-vehicle, multi-vehicle, and all crashes. The research employed an expert-panel approach where prior research was reviewed and discussed along with the models developed herein. In this way, the research compared past results with those obtained to recommend a set of AMFs that may be used to determine the safety effects from the change in the values of a design element.

Final recommendations are provided for shoulder width and median width for four-lane roads with 12-ft lanes. The available data did not permit the development of additional recommendations even though the presence of median barrier was also considered. The AMF values recommended are higher than those proposed in the *HSM* mainly because they address all crashes rather than only crashes related to the specific element. This fact explains the larger magnitude of these AMFs because they capture the effect of a larger number of crashes. A short literature review follows, accompanied by the research findings and the rationale for the recommended values for shoulder and median width.

Shoulder Width

Past Research

Shoulders placed adjacent to travel lanes accomplish several functions including emergency stop and pull off, recovery area for driver error, and pavement edge support (*2*). However, the use of shoulders to provide an area for a stopped vehicle poses a hazard since past research has shown that 11% of fatal freeway crashes are related to vehicles stopped on shoulders (*3*). There is also some evidence that wider shoulders may encourage higher operating speeds because they may communicate to the driver the presence of wider space for correcting errors. Finally, number of lanes, lane width, and shoulder width are all somewhat interrelated, and the geometric value choice for any of these elements typically has an effect on the other elements.

Most of the research completed to date has focused on two-lane, two-way rural roads (*4*) or, more recently, on urban or suburban multilane highways (rather than rural roads), further reducing the number of relevant references. Hadi et al. (*5*) examined the effect of shoulder width on crashes on multilane rural highways. They found that for four-lane rural divided roads, a small reduction in crashes (1% to 3%) could be attained if the unpaved shoulder is widened by 1 ft. These authors also found that roads with shoulders between 10 and 12 ft have the lowest crash rates. This relationship is present only for unpaved shoulders, and the reduction factor should be used cautiously.

Harwood et al. (*6*) produced AMFs for multilane highways. An expert panel then considered an adjustment to the AMF for two-lane rural roads. The panel determined that the AMF could remain the same for both situations based on the determination that shoulder width has a similar effect on multilane and two-lane rural roads.

A recent study by Harkey et al. (*7*) also evaluated traffic engineering and ITS improvements to develop AMFs for rural multilane roadways. The study considered undivided roads with greater than 2,000 vehicles per day, and the AMFs developed were for roadways where the shoulder-related crashes were 35% of the total. Additional procedures are available for roadways with lower volumes or different percentages.

For divided highways, the current draft of the *HSM* uses the recommended values from NCHRP Project 17-29 (*8*), which developed AMFs for paved shoulder width for rural multilane segments. NCHRP Project 17-29 research results are published as *NCHRP Web-Only Document 126* (www.trb.org/news/blurb_detail.asp?id=9099).

NCHRP Project 15-27

The models developed in this research demonstrated that there is a relationship between shoulder width and crashes. The predictive models developed in the research support general trends observed in previous studies for two-lane, two-way rural roads. The current study distinguished between divided and undivided highways and between single- and multi-vehicle crashes. This classification allowed for the development of four distinct models to address the particular issues relative to crash types and the influence of the presence of the median. Aggregate models were also developed for all crashes to permit a comprehensive approach for determining overall effects of shoulder width. It should be noted that the shoulder width used is the average total width for the left and right shoulders (i.e., the sum of right and left shoulders divided by two) in the same direction for divided roads and the average width of right shoulders for undivided segments.

For undivided, four-lane highways, the shoulder width was a significant predictive variable for multi-vehicle and all crashes. The coefficient in the model for multi-vehicle crashes is –0.11 and for all crashes is –0.07. The negative sign is indicative of the beneficial influence of the shoulder width. These values are indicative of the relative safety gains from a 1-ft increase in shoulder width. However, the magnitude of these values seems high, and it is likely that such large reductions may not be reachable.

For divided highways, shoulder width was included in all three models. The coefficients were –0.05 for single-vehicle, –0.14 for multi-vehicle, and –0.12 for all crashes. The negative sign again demonstrates the reduction of crashes associated with the increase of the shoulder width. The magnitude of the coefficients for the multi-vehicle and all crashes again seems to be excessive.

The similar analysis for injury-only crashes did not produce significant changes in the coefficients noted here. The variable was significant only for divided highways, and the coefficients were practically the same as those noted for all crashes. The AMFs developed for each condition based on the models developed are summarized in Table S-1. It should be noted that these factors are for the total number of crashes and for all severities (KABCO).

Based on the project team's review of past literature, the recommended values for the *HSM*, and the AMF from NCHRP Project 15-27, the presence of shoulders appears to influence crash occurrence, and the values noted for all crashes for undivided highways seem reasonable

Table S-1. AMFs based on prediction models for average shoulder width.[1]

Category	Average shoulder width (ft)[2]							
	0	3	4	5	6	7	8	10
Undivided, multi-vehicle	1.39	1.00	0.90	0.80	0.72	0.64	0.58	0.46
Undivided, all crashes	1.22	1.00	0.94	0.87	0.82	0.76	0.71	0.63
Divided, single-vehicle	1.17	1.00	0.95	0.90	0.85	0.81	0.77	0.69
Divided, multi-vehicle	1.51	1.00	0.87	0.76	0.66	0.58	0.50	0.38
Divided, all crashes	1.43	1.00	0.89	0.79	0.70	0.62	0.55	0.44

[1] The AMFs are for all crashes and all severities.
[2] The average shoulder width for undivided is the average of the right shoulders; for divided, it is the average of left and right shoulder in the same direction.

Table S-2. Recommend AMFs for average shoulder width (ft).[1]

Category	Average shoulder width (ft)[2]						
	0	3	4	5	6	7	8
Undivided	1.22	1.00	0.94	0.87	0.82	0.76	0.71
Divided	1.17	1.00	0.95	0.90	0.85	0.81	0.77

[1] The AMFs are for all crashes and all severities.
[2] The average shoulder width for undivided is the average of the right shoulders; for divided, it is the average of left and right shoulder in the same direction.

and in accordance with current trends and literature. The AMF for all crashes for undivided highways is recommended for use since shoulder width was not a significant variable in the single-vehicle models.

The project team considered the values provided for all three models for divided highways and recommended using the values from single-vehicle crashes because the values for multi-vehicles and all crashes were high and probably reflect other influences, such as volume. This adjustment is considered justifiable based on previous work by Harwood et al. (*6*) and the recommended values in the *HSM* (*8*). It should be noted that different parts of the *HSM* provide different AMFs for the same changes in design or operation; these differences are currently being reconciled. The recommended values are summarized in Table S-2.

These modification factors are for all crashes and not for specific types of crashes that could relate to shoulder width issues. The recommended values are similar to those proposed in the *HSM,* as noted above, and those of the divided highways are comparable for almost all categories with the exception of the 8-ft shoulder AMF. For undivided highways, the differences between the NCHRP Project 15-27 and *HSM*-recommended AMFs were larger. These differences are attributed to the fact that the AMFs in the *HSM* are developed for shoulder-related crashes while the AMFs from NCHRP Project 15-27 were developed for all crashes. Even though a comparison to the *HSM* values is not strictly appropriate because of the difference in crashes used in each model, the comparison is meaningful in showing similarities in trends and agreement of findings. Another issue that should be addressed in future research is the lack of AMFs for shoulder width greater than 8 ft since the literature indicates that the safety effects for such shoulder widths are unknown.

Median Width

Past Research

The most important objective for the presence of medians is traffic separation. Additional benefits from medians include the provision of recovery area for errant drivers, accommodation of left-turn movements, and the provision for emergency stopping. Median design issues typically address the presence of the median, along with type and width. There is some research on these issues and their implications on safety.

A review by Hauer (*9*) indicated that it was not possible to identify AMFs for median width but rather noted three safety trends: (1) cross-median crashes (i.e., opposing vehicles) are reduced with wider medians; (2) median-related crashes increase as the median width increases with a peak at about 30 ft and then decrease as the median becomes wider than 30 ft; and (3) the effect of median width on total crashes is questionable. The study conducted by Hadi et al. (*5*) using negative binomial models showed that the median width has an influence on multilane roadways, and they produced two models based on the traffic volume range and number of lanes. This is the only study that has examined the effect of median width on safety for rural, multilane roads since the several studies reviewed by Hauer (*9*) and the *NCHRP Project 17-27 Interim Report* (*10*) deal with freeway median width.

Table S-3. AMFs for median width in rural multilane roadways (*7*).

	Median width (ft)								
Barrier	15	20	30	40	50	60	70	80	90
With	1.000	0.997	0.990	0.984	0.977	0.971	0.964	0.958	0.951
Without	1.000	0.994	0.981	0.969	0.957	0.945	0.933	0.922	0.910

The interim report for NCHRP Project 17-27 described development of a set of AMFs for the effect of median width on crashes for four-lane rural roadways (see Table S-3). The *HSM* section on multilane rural roads developed through NCHRP Project 17-29 (*8*) has also proposed AMF values for rural multilane highways. Two sets of values were developed based on whether a median barrier was present from the studies of Miaou et al. (*11*) and Harkey et al. (*7*). These values accounted for the total number of crashes while considering median-related crashes. The recommended values are summarized in Table S-3 and have been adjusted from the normal baseline of 30-ft medians presented in the report. It should be pointed out that these AMFs are used for evaluating changes in median width for an already existing divided facility—they are not used for estimating the safety performance of highways when an undivided highway is converted to a divided facility.

The models developed in this research determined that median width had an effect on multi-vehicle crashes for divided highways and distinguished between divided and undivided highways as well as between single- and multi-vehicle crashes. The effect of median width was only evaluated for the divided highways. This classification allowed for the development of two distinct models to address the particular issues relative to crash types. Aggregate models were also developed for all crashes to allow for a comprehensive approach and determination of potential overall effects of the median barrier presence.

The only model where median width was significant was that for multi-vehicle crashes, and it had a positive effect—crashes reduce with wider medians. This trend is supported by the general observation that roadways with wider medians will exhibit lower crash rates than will roads with more narrow medians. The model coefficient was –0.010. The analysis of the injury-only crashes included this variable again only in multi-vehicle crashes models with a similar coefficient (–0.009).

The project team reviewed past literature, the recommended values for *HSM,* and the AMF from NCHRP Project 15-27 and concluded that median width does have an influence on crash occurrence. The team determined that the values noted for the only model with median width influence are reasonable and in accordance with current trends and literature. The only available AMF based on the models developed in this research is for multi-vehicle crashes; there is a 1% reduction for every additional foot of median width added. The values obtained from the models for multi-vehicle crashes are reasonable and agree with the previous research. The recommended values are summarized in Table S-4.

These AMFs are for all crashes and not for specific types of crashes that could relate to median width issues. The recommended values are greater than those proposed in the *HSM.* The difference could be attributed to the fact that the *HSM* values specifically account for median-related crashes.

Table S-4. Recommended AMFs for median width, divided roadways.

	Median width (ft)							
Category	10	20	30	40	50	60	70	80
Multi-vehicle	1.00	0.91	0.83	0.75	0.68	0.62	0.57	0.51

This means of accounting for median crashes was not possible in the current research, and similar adjustments could affect the values recommended. Another possible relationship that could influence these values is the presence of a median barrier. Roadway segments with a barrier typically have narrower medians; this could influence the AMFs as shown in the *HSM* values. However, the available dataset was not large enough to examine this interaction.

To determine the AMFs for all crashes, it may be assumed that the median width has "no effect" on single-vehicle crashes and, therefore, the AMF for single-vehicle crashes could be considered 1.00. In this case, a weighted AMF can be estimated using the relative percentages of single- and multi-vehicle crashes for the roadway of concern.

The AMF developed herein can be used to estimate the design element value's relative impact for a rural four-lane roadway segment. The process described could be applied to determine the safety implications using different values for a single or combination of design elements. The ratio of AMFs for two different conditions can be used to establish the relative change in crashes anticipated from the change in design element values. The use of this approach was noted as a method for estimating change in crashes by using Equation S-1:

$$\Delta N = \frac{AMF_1}{AMF_2} - 1 \tag{S-1}$$

where ΔN is the change in crashes and AMF_i are the AMFs for the designs to be evaluated. This equation was modified from the form presented by Lord and Bonneson (*12*) since no base models or base estimates are available. A positive value of ΔN denotes an increase in crash frequency.

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CHAPTER 1

Introduction and Research Approach

Problem Statement

Every roadway design starts with the intention to provide a safe facility that addresses mobility concerns, accommodates the physical and social environment, and is financially feasible. To achieve such designs, engineers rely on guidelines and policies, which aim to address these goals. Sometimes, however, it may not be practical to conform to the highest possible values of all these guidelines. For example, adherence to a certain geometric specification may create environmental concerns, affect historical structures, be economically unfeasible, or otherwise affect a community in an undesirable way. To address such issues, the roadway design may need to deviate from the prevailing optimum value expressed in guidelines and policies. An understanding of the impacts of such alternative designs on both the safety and the operational character of the roadway is essential to making an informed choice among possible designs.

The AASHTO publication *A Policy on Geometric Design of Highways and Streets* (commonly referred to as the *Green Book*) provides guidance to the designer by referencing a recommended range of values for critical dimensions of the design of new roadway alignments and those undergoing major reconstruction (*1*). The *Green Book* provides *guidelines*—not *standards*—that permit sufficient flexibility to encourage distinctive independent and appropriate designs for specific situations. However, such flexibility can introduce uncertainty since there may be insufficient data to quantify potential trade-offs when evaluating design variations. Even though the *Green Book* indicates that the referenced guidelines provide for a safe, comfortable, and aesthetically pleasing roadway, designers may have little information regarding the safety and operational consequences that can result if they deviate from the recommended range of values or select one value from over another within the range.

The *Green Book* provides control values for the design of new alignments or those undergoing major reconstruction that allow flexibility. For most control values, the *Green Book* indicates that the recommended ranges provide a safe, comfortable, and aesthetically pleasing roadway; however, there are cases where additional flexibility is necessary and, therefore, the design exception process is available. This process allows the designer to consider other design values for a specific element in order to better fit the design to the situation. In many cases, there is little research that quantifies such decisions and their impact on safety (*2, 3*).

The concept of guidelines was emphasized even more in *Flexibility in Highway Design* (*4*), a recent publication by U.S. DOT, and is further stressed in AASHTO's *Guide for Achieving Flexibility in Highway Design* (*5*). The previously used approach typically deemphasized the design's impact on human and natural environments, increasing the possibility of creating wide swaths of pavement cutting through communities and natural resources. This approach was typically justified by arguing that it results in designs with increased safety, but this result was not always achieved. A critical review of design guidelines by Hauer (*6*) stated that several design guidelines are based on empirical data from decades ago, with some not validated through research. Also, research demonstrated that other design values lower than those suggested in the *Green Book* work well to achieve flexibility in design while balancing the concerns of safety and capacity. While safety must always be considered when selecting design values, the ramifications of cost restrictions and environmental concerns might warrant consideration of a reduced value for a design element. Proper designs should assess competing constraints and create a solution that meets mobility and safety objectives.

Research Objectives and Approach

This research brought together existing research knowledge and project experience to provide a reference guide for planners and designers. This research effort will provide the highway design community with information resources and decision tools for designing roadways where design flexibility may be appropriate to the roadway context.

The research was conducted in two phases. The first phase comprised a literature review and the development of methodology for data collection and analysis in the second phase. In the second phase, data were collected and analyzed to develop an understanding of the safety and operational impacts from design element trade-offs. The two-phase project included seven specific tasks:

- Phase I Tasks
  - Task 1: Review of past and ongoing work relative to rural multilane highway crash prediction models and accident modification factors (AMFs).
  - Task 2: Development of data acquisition plan identifying states with crash databases that could be used in the next phase as well as specific data elements.
  - Task 3: Development of a data analysis plan for manipulating the collected data and developing appropriate prediction models and AMFs.
  - Task 4: Development of an interim report and work plan.
- Phase II Tasks
  - Task 5: Acquisition of the appropriate data and analysis of the data to develop the appropriate models and AMFs.
  - Task 6: Development of guidelines that could be used by designers in evaluating the safety consequences from design element trade-offs for multilane rural highways.
  - Task 7: Preparation of final report.

The first phase of the project identified a plan for data collection analysis that would produce reasonable models and AMFs for future use. The plan was reviewed by the NCHRP project panel, and adjustments were made to the direction of the work. The major adjustment was a departure from the original objective of identifying the safety implications from several design elements and focusing only on several specific cross-section elements: lane width, shoulder width and type, median width and type, and (possibly) clear zone width. This refocused approach allowed for a better coordination with other ongoing NCHRP projects on the development of the *Highway Safety Manual* (*HSM*) (*7*). The *HSM* is envisioned to be a comprehensive document of current knowledge related to roadway safety treatments as well as to contain tools for predicting the safety effects of different roadway design alternatives for various classes of roadways. Several NCHRP projects were initiated in support of *HSM* development at the same time as Project 15-27, and efforts were undertaken to coordinate with some of these projects to produce compatible results. The project team worked very closely with the team of NCHRP Project 17-29, "Methodology to Predict the Safety Performance of Rural Multilane Highways," which aimed to develop predictive tools and the *HSM* chapter for rural multilane highways.

Organization of the Report

This report presents the findings and conclusions of the research to develop crash prediction models and AMFs for specific design elements of multilane rural highways. The research results are included along with recommendations for future research. The remainder of the report is organized in the following chapters:

- Chapter 2: Literature Review—presents the current knowledge on AMFs and identifies potential needs for the work undertaken herein.
- Chapter 3: Data Analysis—documents the methodology followed to analyze the collected data, includes a description of the data used, and presents the results from the analysis.
- Chapter 4: Design Elements Recommendations—presents the proposed guidelines for the various design elements as a result of this research.
- Chapter 5: Conclusions and Suggested Research—includes a summary of the study objectives, project findings, and recommendations for future research work.

An appendix discusses the use of prediction models to determine the relative safety of design element choices.

CHAPTER 2

Literature Review

Roadway projects where design elements trade-offs are considered typically incorporate a full range of geometric and traffic operational problems, coupled with increasingly restrictive environmental constraints. These problems may require variation from the normally used guidance values or traditional solutions. Moreover, every project is unique in terms of the geometric conditions, traffic, safety history, purpose and need, project context, community character, and public priorities. What is reasonable or may work in one location may not be appropriate in another for any number of technical or context-sensitive reasons. The literature review conducted for this research examined safety implications from geometric element trade-offs, and the findings are presented herein. In addition, *NCHRP Synthesis of Highway Practice 299: Recent Geometric Design Research for Improved Safety and Operations* presents an extensive literature review on geometric design elements for improving safety and operations (*8*). The following section presents first an overview of roadway design issues and then the findings on the effects of specific cross-section elements for multilane highways.

Roadway Design Issues

The *Green Book* lacks background information sufficient for understanding the safety and operational implications of combinations of critical geometric features. The recently published *Guide for Achieving Flexibility in Highway Design* provides some information on these areas, but also lacks any quantifiable relationships for the values of various design elements (*5*). There are several geometric features that have a greater effect when combined than when considered alone—for example, Zegeer and Deacon (*9*) showed that the combined lane and shoulder width has a greater impact on the safety level of two-lane rural roadways than does lane or shoulder width alone. At the same time, there are cases where these combinations have little or no impact. The same combination of lane and shoulder width has a small to possibly no impact on four-lane roadways. Thus, these relationships and their areas of application must be further examined.

Another *Green Book* topic requiring additional background information for designers centers on the relative importance of various geometric elements on safety. It is apparent that not all geometric elements have the same impact on safety and operational effectiveness, and the selected design value can affect additional elements. For example, the choice of a design speed of 45 mph or less for a road allows the designer to use a smaller minimum curve radius, a narrower clear zone, a shorter vertical curve, and shorter sight distances than those for a higher design speed. Here, the impact is significantly greater than when selecting a single design element to be adjusted. Moreover, roadway elements can exert varying degrees of influence even through a single element. For example, lane width will exert an impact on a two-lane roadway that will be different from that exerted on a four-lane roadway. Therefore, a prioritized list is needed to identify the relative significance of each geometric element. Given the current definition of design speed, it is probably the most critical design element to be selected since it has the potential to impact the values used for almost all other design elements (*1*, *5*).

Most studies dealing with safety and speed typically considered speed limit and so little is known about the influence of design speeds on safety. It could be assumed that there is some relationship between design speeds and speed limits, but because of the methods used to establish speed limits in many states, it is not feasible to develop a systematic relationship between the two (*10*). Current highway design approaches emphasize speed as a surrogate for quality and efficiency. This approach is probably reasonable for rural areas where high speeds are frequently desirable, but not for roads in urban or suburban areas.

Several studies have examined cross-section elements and attempted to develop models or relationships that could estimate safety implications from varying individual components. The work of Zegeer et al. (*11–13*) identified the relationship of lane and shoulder width to crashes on two-lane rural roads and quantified these by developing models later included in the Interactive Highway Safety Design Model (IHSDM). A significant and potentially useful conclusion from the literature is that the important element in crash reduction is the total available roadway width. The studies on converting two-lane roads to four-lane roads show that, in general, safety gains are achieved with such conversions (*14, 15*). The findings of *NCHRP Report 330: Effective Utilization of Street Width* indicate that there are certain designs for urban arterials where the implementation of strategies that involve the use of narrower lanes has an effect on safety (*16*). Such strategies include the use of center two-way left-turn lanes or removal of curb parking, and most of these strategies involved projects with restricted right of way and arterials with speeds of 45 mph or less. The study also concluded that even though the use of narrower lanes, when considered alone, may increase specific crash types, the presence of other design features, such as the addition of two-way left-turn lanes, may offset these increases. This study also underscores the potential of interactive effects between various design elements and suggests careful evaluation of the use of narrower-than-typical lanes.

A more recent review of safety in geometric design standards by Hauer (*6*) critically examined the belief that adherence to design standards is directly linked to safe roadways. This review indicated that design guidelines have an inherent safety level, but that little is known about the impacts of their flexibility application in roadway design. Another issue identified by Hauer was the notion that there are two different kinds of safety. One could be called nominal safety and is measured "in reference to compliance with standards, warrants, guidelines, and sanctioned design procedures" (*6*). Substantive safety, by comparison, is based on the roadway's actual safety performance—that is, crash frequency and severity. Designing nominally safe roads does not ensure substantive safe roadways since adherence to values of each guideline does not inherently produce a safe design. Several of the studies examined focused on developing models that investigate and quantify the substantive safety changes from altering design dimensions (*17*). Another aspect of safety noted by Fambro et al. (*18*) is the concept that safety is a continuum and not a single yes/no decision. This implies that a change in the value chosen for a particular design element "can be expected to produce an incremental, not absolute change in crash frequency and severity" (*17*). However, there is a need to better understand the effect on the level of safety from these incremental changes, and such efforts are essential in understanding and quantifying the substantive safety of a roadway. This is critical for projects where design flexibility is considered. Stakeholders do not easily accept designs that are considered nominally safe, but require the evaluation of design alternatives that may deviate from the nominal designs.

An additional concept that merits attention is that of the presence of a *tipping point*—the principle that small changes have little or no effect on a system until a crucial point is reached (*19*). This concept, which has been extensively used in epidemiological research, could also be used in roadway design because of the available flexibility in the values of design elements. It could be hypothesized that safety and operational consequences from altering the values of design elements while remaining within the suggested *Green Book* values are minimal and, thus, do not create significant problems. Moreover, small departures from these values may have no significant impact, and thus the safety consequence tipping point for any single design value may not be detectable. Highway design typically requires a multi-level assurance by professional engineers that the approved design will not result in unacceptable levels of safety consequence. Projects requiring a design exception could be considered as those that are the farthest from the most desirable design value. The recently completed NCHRP Project 15-22, "Safety Consequences of Flexibility in Highway Design," found that the small deviations noted in the case studies analyzed indicate that a generally conservative approach is taken when considering values that vary from traditional design (*20*).

Cross-Section Elements

The literature review conducted for this research focused on three cross-section elements: lane width, shoulder type and width, and median type and width. This section discusses the findings for these design elements. Several of the findings have been cross-referenced with the interim report from NCHRP Project 17-27, "Parts I and II of the Highway Safety Manual," (*21*) and *NCHRP Web-Only Document 126: Methodology to Predict the Safety Performance of Rural Multilane Highways* (*22*).

Lanes

Wider lanes are traditionally associated with higher operating speeds and increased safety. The *Highway Capacity Manual* (*HCM*) (*23*) documents that wider lanes for multilane highways result in higher free-flow speeds. On the other hand, very little has been found on the safety implications of wider lanes. It is reasonable to assume that wider lanes may provide additional space to the driver to correct potential mistakes and thus avoid crashes. However, a driver could be expected to adapt to the available space, and the positive safety effects from the wider lanes may be offset by the higher speeds.

Most completed research on this topic has focused on the lane width of two-lane, two-way roads, and very little is known of the effect of lane width of multilane rural highways (*24*).

The review conducted by Hauer (*24*) of studies that attempted to model the effect of lane width on multilane rural highway crashes found no correlation. The same review indicated that there was only one study where lane width was included in the models (*25*), but these were for freeway facilities. An AMF represents the anticipated change in safety when a particular geometric design element value changes in size. An AMF greater than 1.0 represents the situation where the design change is associated with more crashes; an AMF less than 1.0 indicates fewer crashes. Typically, AMFs are estimated directly from the coefficients of models derived using crash data or expert panels that review current literature and determine the magnitude of the AMF. Estimation of AMFs from models assumes that (1) each AMF is independent since the model parameters are assumed independent and (2) the change in crash frequency is exponential. In practice, AMFs may not be completely independent since changes in geometric design characteristics on highways are not done independently (e.g., lane and shoulder width may be changed simultaneously) and the combination of these changes can influence crash risk. Nonetheless, experience in deriving AMFs in this manner indicates that the assumptions are reasonable and, with thoughtful model development, the resulting AMFs can yield useful information about the first-order effect of a given variable on safety.

A study by Harwood et al. (*26*) examined AMFs as part of resurfacing, restoration, and rehabilitation (3R) projects. An expert panel adjusted the AMFs developed for two-lane, two-way rural roads to allow for their use in multilane roads, specifically four-lane roads. The factors show no effect for 11-ft lanes and an 8% to 11% increase for 9-ft lanes. These AMFs are summarized in Table 1.

The section of the *HSM* on multilane rural roads developed as part of NCHRP Project 17-27 (*21*) also proposed AMF values for lane width on rural multilane highways (see Table 2) based on the work of Harwood et al. (*26*) and Harkey et al. (*27*) through the deliberations of the joint NCHRP Projects 17-25/17-29 Expert Panel Meeting. Two sets of values were developed from the studies of Miaou et al. (*28*) and Harkey et al. (*27*), based on whether the roadway was divided in the presence of a median barrier. These values accounted for the total number of crashes while considering median-related crashes. The recommended values were adjusted from the normal baseline of 30-ft median presented in the report.

Table 1. AMFs for lane width for four-lane highways (*21*).

	Lane width (ft)			
	9	10	11	12
Four-lane undivided	1.11	1.06	1.00	0.99
Four lane divided	1.08	1.04	1.00	0.99

Table 2. AMFs for lane width (*22*).

	Lane width (ft)			
Roadway	9	10	11	12
Undivided	1.13	1.08	1.02	1.00
Divided	1.09	1.05	1.01	1.00

Most available research has examined this relationship for urban roadways, and some relationship has been found between the lane width and crashes for these roadways. However, these relationships are not applicable for the roadways considered in this research project (which examines multilane rural roads only) and therefore are not discussed further. In summary, there is limited past research documenting any effects of lane width on crashes for multilane rural roads. The only study with definitive factors is the new *HSM* work that is based on an expert-panel approach.

Shoulders

Shoulders placed adjacent to travel lanes accomplish several functions including emergency stop and pull off, recovery area for driver error, and pavement edge support (*1*). The use of shoulders to provide an area where a vehicle could stop poses an additional hazard since past research has shown that 11% of fatal freeway crashes are related to vehicles stopped on shoulders (*29*). There is also evidence that wider shoulders may encourage higher operating speeds because they may communicate to the driver the presence of wider space for correcting errors. Finally, the number of lanes, lane width, and shoulder width are interrelated, and the choice of geometric value for each of these elements typically affects the other elements.

Most of the research completed to date focuses on two-lane, two-way rural roads (*30*). An additional problem is that most of the recent studies have analyzed urban or suburban multilane highways (rather than rural roads), resulting in an even smaller number of available references for this design element. Hadi et al. (*25*) examined the effect of shoulder width on crashes on multilane rural highways. Their findings indicated that for four-lane rural divided roads, a small reduction in crashes (1% to 3%) can be attained if the unpaved shoulder is widened by 1 ft. The authors also indicate that the roads with shoulder widths between 10 ft and 12 ft have the lowest crash rates. However, this relationship is present only for unpaved shoulders, and the reduction factor should be used cautiously.

Harwood et al. (*26*) also produced AMFs for multilane highways, again using an expert panel to adjust the AMFs of two-lane rural roads. In this instance, the panel determined that the effect of shoulder width is similar for both multi- and

Table 3. AMF for shoulder width for multilane highways with ADT > 2500 vehicles/day (*21*).

Paved shoulder width (ft; one side)					
3	4	5	6	7	8
1.0	0.97	0.95	0.93	0.91	0.90

Table 5. AMFs for paved shoulder width (*27*).

Paved shoulder width (ft)				
0	2	4	6	8
1.18	1.11	1.05	1.00	0.95

two-lane rural roads, so the AMFs could remain the same. The proposed AMFs are presented in Table 3.

Further research interest has been placed on shoulder type, which can impact crashes and therefore roadway safety. Again, the focus of work on this topic has concentrated on the two-lane, two-way roads: almost no research has been directed to multilane roads. Rogness et al. (*31*) used before-and-after crash-rate changes from converting two-lane rural roads with full shoulders to four-lane undivided rural roads without shoulders. The results indicated that for roads with volumes in the 1,000–3,000 vehicles/day range, crashes increased after the conversion. It should be noted here that the study used Texas roadways where, the report indicates, driving on the shoulder on two-lane rural roads is considered acceptable. This fact could impact the findings of their study and therefore not provide any additional understanding of this shoulder-crash relationship.

Harwood et al. (*32*) developed AMFs for the conversion of shoulder types on rural two-lane roads. An expert panel reviewed these factors and determined that they are appropriate for use in both divided and undivided multilane roadways. These estimates, shown in Table 4, were for converting turf or gravel shoulders to paved shoulders and turf shoulders to composite (partially paved) shoulders.

Harkey et al. (*27*) also developed AMFs for rural multilane roadways as part of a study that evaluated traffic engineering and ITS improvements (see Table 5). The study considered undivided roads with more than 2,000 vehicles per day, and the AMFs developed were for roadways where the shoulder related crashes were 35% of the total. Additional procedures are available for roadways with lower volumes or different percentages.

For divided highways, the draft *HSM* uses recommended values from NCHRP Project 17-29 (*22*), which developed AMFs for shoulder width for rural multilane segments. These AMFs are for paved shoulders and also include the Harkey et al. AMFs for undivided highways (see Table 6).

In general, the literature is silent on the relationship between shoulder and safety for multilane rural roads with the exception of the new *HSM* work. As was the case for the lane width, there is no literature that documents the effect of shoulder width and type on the safety of a roadway segment. Moreover, the new AMFs developed for the *HSM* are based mainly on an expert-panel approach and on the Harkey et al. work that is itself derived from Zegeer's work (*12, 13*).

Medians

The most important objective for the presence of medians is traffic separation. Additional benefits from medians include the provision of recovery areas for errant maneuvers, accommodation of left-turn movements, and the provision for emergency stopping. Median design issues typically address the presence of median, along with its type and width. There has been some research completed on these issues and their implications on safety.

Hauer (*33*) conducted a review of studies that investigated the effect of medians on rural multilane highway safety levels. This review, which was based on a few studies, did not provide conclusive results on the effectiveness of the presence of medians on safety but did identify the potential for the median to impact safety. One of these studies (*34*) examined divided and undivided four-lane rural roadways in the context of the safety differences between two-lane and four-lane roadways. The study concluded that the presence of a median had an effect on crashes that was related to the

Table 4. AMFs for shoulder conversion for multilane roadways based on two-lane roads (*21*).

Treatment	Shoulder width (ft; one side)					
	3	4	5	6	7	8
Convert turf to paved	0.99	0.98	0.97	0.97	0.97	0.96
Convert gravel to paved	1.00	1.00	1.00	0.99	0.99	0.99
Convert turf to composite	1.00	0.99	0.98	0.97	0.98	0.98

Table 6. AMFs for paved shoulder width (*22*).

	Paved shoulder width (ft)				
Roadway	0	2	4	6	8
Undivided	1.18	1.11	1.05	1.00	0.95
Divided	1.18	1.13	1.09	1.04	1.00

roadway volume (crashes for roads with medians as compared with roads without medians exhibited the relationship $0.76 \times ADT^{-0.05}$)[1].

Another study examined the effect of the median presence in Oregon and also reported crash reductions from the presence of medians (*35*). The study found that the AMF for median presence is 0.43[1], showing an agreement with the results of Council and Stewart (*34*), but a larger magnitude for its effect. Elvik and Vaa (*36*) also showed a similar finding with separate models for injury and property damage crashes in a meta-analysis of several studies where a median was added. Their AMFs were 0.88[1] for injury and 0.82[1] for property damage crashes. The interim report for NCHRP Project 17-27 recommended an AMF for the presence of median in the range of 0.85 to 0.50 (*21*).

The contribution of width to the median effect has also been examined. Hauer (*33*) found that it was not possible to identify AMFs for median width but rather noted three safety trends: (1) cross-median crashes (i.e., opposing vehicles) are reduced with wider medians; (2) median-related crashes increase as the median width increases, with a peak at about 30 ft, and then decrease as the median becomes wider than 30 ft; and (3) the effect of median width on total crashes is questionable. Hadi et al. (*25*) used negative binomial models to show that the median width has an influence on multilane roadways; these authors produced two models based on the traffic volume range and number of lanes. This is the only study that examined the effect of median width on safety for rural, multilane roads because the several studies reviewed by Hauer (*33*) and the NCHRP Project 17-27 interim report (*21*) deal with freeway median width.

Table 7, which is taken from the interim report for NCHRP Project 17-27, presents a set of AMFs for the effect of median width on crashes for four-lane rural roadways; these values are based on one study.

The *HSM* section on multilane rural roads developed as part of NCHRP Project 17-29 (*22*) also proposes AMF values for rural multilane highways (see Table 5 in *HSM*). Two sets of values were developed based on whether a median barrier was present. These values are based on the studies of Miaou et al. (*28*) and Harkey et al. (*27*), and they account for the total number of crashes while considering median-related crashes. The recommended values are summarized in Table 8.

Median type has also been examined as it relates to roadway safety. A meta-analysis of several studies conducted by Elvik and Vaa (*36*) suggests there is an effect due to the type of median used. Their analysis examined the relative effects of concrete, steel, and cable guardrail installations on multilane divided highways. The results indicate that the AMF for injury crashes for concrete barriers is 1.15, for steel barriers is 0.65, and for cable is 0.71. The resulting AMF for all crashes for median guardrails is 1.24, indicating that the presence of a median guardrail—and especially a concrete guardrail—has the potential to increase crashes. Thus, designers must carefully consider whether the placement of a median barrier will have an overall positive or negative influence on the safety of a particular roadway segment. A barrier will result in a reduction of cross-median type crashes, but it also has the potential to increase median-related crashes since its absence could allow drivers opportunities to stop their vehicles in the median (*37*). As Hauer states: "The net effect of placing a barrier in the median is an increase in total accidents; an increase in injury accidents and its effect on the total number of fatal accidents is at present unclear" (*33*).

Fitzpatrick et al. (*38*) developed AMFs for median barriers on freeways and four- and six-lane rural highways in Texas. For rural highways the influence of the median barrier was examined as a function of the available left shoulder width. The study concluded that for roads with a barrier, increasing the left shoulder width by 1 ft will result in a 1.6% reduction of crashes for both four- and six-lane highways.

Other studies have demonstrated that the addition of a barrier could contribute to crash occurrence. Elvik (*39*) analyzed the results of 32 studies that examined the effect of median barrier presence. His major conclusion was that ". . . the best current estimates of the effects of median barriers are a 30% increase in accident rate, a 20% reduction in the chance of sustaining a fatal injury, given an accident, and a 10% reduction in the chance of sustaining a personal injury, given an accident." These findings indicate that, in general, crashes can increase, but their severity may decrease. Miaou et al. also noted that crash rates are higher on roadways with median barriers when compared with roads without them and that median barriers present a higher likelihood of vehicle impact (*28*).

A median-type treatment that may be used on multilane rural roads is a two-way left-turn lane (TWLTL). This median type is typically found on rural roads where some development may be present or anticipated. Such a median treatment is often associated with specific types of crashes that are access related, that is, left turns in and out of an access point. An issue of concern in estimating safety impacts from

[1]The values presented here are those stated in the NCHRP Project 17-27 interim report (*21*), and they have ***been adjusted*** from the original studies.

Table 7. AMFs for median width in four-lane rural non-freeway roads (*21*).

Median width (ft)								
10	20	30	40	50	60	70	80	90
1.00	0.91	0.85	0.80	0.76	0.73	0.70	0.67	0.65

TWLTLs is the access density since it has the potential to significantly affect the opportunity for crashes. The impact of these treatments has not been extensively evaluated, and their safety gains still require additional verification (*38*). Hauer (*33*) estimated that the AMF for most urban and suburban TWLTLs ranges from 0.70 to 0.90 based on a review of several studies. These AMFs are for total number of crashes and not the types of crashes associated with the installation of the TWLTL.

In summary, the presence of a median has a positive effect on safety, and some AMFs have been developed based on previous studies. The median width has also an impact on roadway safety where wider medians tend to have a larger AMF. Finally, the placement of a barrier is a balancing act because a barrier has the potential to increase median-related crashes but to reduce cross-median crashes. Even though this element has been examined more than the other two elements, several of the reports reviewed indicated that for multilane roadways, additional research is required either to develop new AMFs or to validate existing AMFs.

Rural Two-Lane Conversions to Multilane

A typical project for rural roadways is the conversion of a two-lane road to a four-lane road with or without a median. Using crash data from four Highway Safety Information System (HSIS) states, Council and Stewart (*34*) attempted to estimate the safety effects from such conversions on rural roads. The study indicated that safety gains ranging from 40% to 60% were achieved for divided roadways, while smaller gains—approximately 20%—were achieved for undivided roads. These estimates were developed using typical cross sections for each roadway type. The authors cautioned that these findings were based on a predictive model and should be validated with actual before-and-after crash data to provide sound support for the conclusions.

Agent and Pigman (*40*) compared the safety impacts of either (1) converting two-lane rural roads to four-lane roads or (2) realigning two-lane roads. The study examined 49 conversion locations and 24 locations where the two-lane roadway was upgraded with realignment and widening of lanes and shoulders. The study concluded that both conversions to four lanes and upgrades of two-lane roadways reduced crashes after project completion. There was a 56% reduction for converted roadways and a 51% reduction for upgraded two-lane roadways. A comparison to statewide crash rates for each roadway type revealed that converted four-lane roads exhibited crash rates similar to the statewide average, while crash rates of upgraded two-lane roads dropped to approximately one-half the statewide rate for two-lane rural roads. The influence of volume on both upgraded and converted roads was also cited, and the authors acknowledge that additional work is needed to evaluate volume impact and determine which approach—conversion or upgrade—is more appropriate. The important finding of this study is that both approaches improve safety and should be considered as design alternatives.

Summary

A significant body of research that attempts to quantify the relationships between safety and roadway design elements has been compiled. As previously noted, *NCHRP Synthesis of Highway Practice 299* has reviewed and discussed several of these issues at length, and the reader seeking more detailed information is encouraged to review that publication (*8*). Several studies have focused on two-lane rural roads and have addressed issues relative to lane widths, shoulder widths and types, clear zones, and horizontal and vertical alignments. Even

Table 8. AMFs for median width in rural multilane roadways (*22*).

	Median width (ft)								
Barrier	15	20	30	40	50	60	70	80	90
With	1.019	1.012	1.000	0.988	0.977	0.967	0.953	0.944	0.935
Without	1.010	1.006	1.000	0.994	0.988	0.983	0.978	0.973	0.968

though these are the general areas of interest for this research, there is a lack of information regarding any association between typical and other than typical design values for several design elements.

To some degree, the design elements selected for further examination in this research have the potential to affect safety. The degrees of influence vary by design element and application and often are specific to a set of roadway conditions. There are current parallel efforts under way to address the quantification of the safety and operational impacts from design element trade-off. Specifically, such models exist for two-lane rural highways, and similar models will be developed in the near future for multilane highways.

The most directly applicable lesson from the literature is that values for design elements can be varied. Most research has been directed to the task of evaluating specific design elements, without considering the effects when multiple elements are varied in combination. An additional issue that has not been discussed extensively is the potentially opposite effects that selected values for design elements can impart. For example, wider shoulders have shown the potential to improve safety. On the other hand, they also have the potential to encourage increased operating speeds that, in turn, can lead to increased crash severity. A similar counterbalancing potential was noted for the presence and type of barrier in medians. Therefore, design decisions and countermeasure applications should consider the types of crashes associated with the modification and then determine the appropriate design element.

A summary of the literature reviewed and pertinent findings relative to the objectives of this research project are presented in Table 9.

Table 9. Summary of literature review.

<table>
<tr><th>Reference</th><th>Element</th><th>Results</th><th>Comments</th></tr>
<tr><td>Harwood et al. 2003 (26)</td><td>Lane width</td><td>AMF for lane width
<table><tr><td></td><td colspan="4">Lane width (ft)</td></tr><tr><td></td><td>9</td><td>10</td><td>11</td><td>12</td></tr><tr><td>Four-lane undivided</td><td>1.11</td><td>1.06</td><td>1.00</td><td>0.99</td></tr><tr><td>Four-lane divided</td><td>1.08</td><td>1.04</td><td>1.00</td><td>0.99</td></tr></table></td><td>AMF for lane width is based on rural two-lane roads and from expert panel recommendation</td></tr>
<tr><td>Lord et al. 2008 (22)</td><td>Lane width</td><td>AMF for lane width
<table><tr><td></td><td colspan="4">Lane width (ft)</td></tr><tr><td>Roadway</td><td>9</td><td>10</td><td>11</td><td>12</td></tr><tr><td>Undivided</td><td>1.13</td><td>1.08</td><td>1.02</td><td>1.00</td></tr><tr><td>Divided</td><td>1.09</td><td>1.05</td><td>1.01</td><td>1.00</td></tr></table></td><td>AMF for undivided is expert panel based in the HSM; divided is based on models</td></tr>
<tr><td>Harwood et al. 2003 (26)</td><td>Shoulder width</td><td>AMF for shoulder width
<table><tr><td colspan="6">Paved shoulder width (ft; one side)</td></tr><tr><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr><tr><td>1.0</td><td>0.97</td><td>0.95</td><td>0.93</td><td>0.91</td><td>0.90</td></tr></table></td><td>AMF for shoulder width is based on rural two-lane roads and from expert panel recommendation</td></tr>
<tr><td>Harwood et al. 2000 (32)</td><td>Shoulder type</td><td>AMF for shoulder conversion
<table><tr><td></td><td colspan="6">Shoulder width (ft; one side)</td></tr><tr><td>Treatment</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td></tr><tr><td>Turf to paved</td><td>0.99</td><td>0.98</td><td>0.97</td><td>0.97</td><td>0.97</td><td>0.96</td></tr><tr><td>Gravel to paved</td><td>1.00</td><td>1.00</td><td>1.00</td><td>0.99</td><td>0.99</td><td>0.99</td></tr><tr><td>Turf to composite</td><td>1.00</td><td>0.99</td><td>0.98</td><td>0.97</td><td>0.98</td><td>0.98</td></tr></table></td><td>AMF for shoulder conversion is based on rural two-lane roads and from expert panel recommendation</td></tr>
<tr><td>Harkey et al. 2008 (27)</td><td>Shoulder width</td><td>AMF for paved shoulder width
<table><tr><td colspan="5">Paved shoulder width (ft)</td></tr><tr><td>0</td><td>2</td><td>4</td><td>6</td><td>8</td></tr><tr><td>1.18</td><td>1.11</td><td>1.05</td><td>1.00</td><td>0.95</td></tr></table></td><td>AMF is developed from expert panel evaluating ITS improvements</td></tr>
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</table>

(continued on next page)

Table 9. (Continued).

<table>
<tr><td>Council & Stewart 1999 (34)</td><td>Median presence</td><td>Crashes for roads with medians $0.76xADT^{-0.05}$</td><td>Based on study of converting 2-to 4-lane roads</td></tr>
<tr><td>Strathman et al. 2001 (35)</td><td>Median presence</td><td>AMF for roads with medians 0.46</td><td>Larger than Council and Stewart but consistent trend; all crashes</td></tr>
<tr><td>Elvik and Vaa 2004 (36)</td><td>Median presence</td><td>AMF for all crashes for roads with medians 0.88
AMF for property damage crashes on roads with medians 0.82</td><td>Based on meta-analysis of several prior studies</td></tr>
<tr><td>iTrans 2005 (21)</td><td>Median presence</td><td>AMF range 0.50–0.85</td><td>General statement by review of prior studies; difficult to be precise</td></tr>
<tr><td>iTrans 2005 (21)</td><td>Median width</td><td>AMF for median width
<table>
<tr><td colspan="6">Median width (ft)</td></tr>
<tr><td>10</td><td>20</td><td>30</td><td>050</td><td>70</td><td>90</td></tr>
<tr><td>1.00</td><td>0.91</td><td>0.85</td><td>0.80</td><td>0.70</td><td>0.65</td></tr>
</table></td><td>AMF for shoulder width is based on rural two-lane roads and from expert panel recommendation</td></tr>
<tr><td>Elvik and Vaa 2004 (36)</td><td>Median type</td><td>AMF for median guardrails: 1.24 all crashes
AMF for concrete barriers: 1.15 injury crashes
AMF for steel barriers: 0.65 injury crashes
AMF for cable barriers: 0.71 injury crashes</td><td>Based on meta-analysis of several prior studies</td></tr>
<tr><td>Lord et al., 2008 (22)</td><td>Median width</td><td>AMF for median width
<table>
<tr><td></td><td colspan="5">Median width (ft)</td></tr>
<tr><td>Barrier</td><td>15</td><td>30</td><td>50</td><td>70</td><td>90</td></tr>
<tr><td>With</td><td>1.019</td><td>1.000</td><td>0.877</td><td>0.953</td><td>0.935</td></tr>
<tr><td>Without</td><td>1.010</td><td>1.000</td><td>0.988</td><td>0.978</td><td>0.968</td></tr>
</table></td><td>Based on expert panel and recommended in the HSM</td></tr>
<tr><td>Hauer 2000 (33)</td><td>TWLTL</td><td>AMF range for presence 0.70 to 0.90</td><td>Reviewing previous studies</td></tr>
<tr><td>Elvik 1995 (39)</td><td>Median presence</td><td>Estimated increase 30% for all crashes</td><td>Based on prior studies for roads with barriers</td></tr>
<tr><td>Fitzpatrick et al., 2008 (38)</td><td>Median and left shoulder</td><td>Roads with median, increasing left shoulder by 1 ft will result in 12% reduction in crashes at 4- and 6-lane highways</td><td>AMF developed for roadways in Texas</td></tr>
</table>

CHAPTER 3

Data Analysis

The first section of this chapter presents the methodological approach and related issues. The second section presents the data used in the development of the prediction models and AMFs.

Methodology

Over the past decades, interest has increased in estimating the safety implications from changes in various design elements. To be able to determine these changes, models were developed that could predict the crash-rate frequency or the number of crashes as a function of various traffic conditions and values of geometric elements. A significant part of past research was devoted to developing such models; in the past decade, most researchers have used negative binomial models for modeling crashes. These models assume that unobserved crash variation across roadway segments is gamma-distributed, while crashes within sites are Poisson-distributed (*41*). The Poisson, Poisson-Gamma (negative binomial), and other related models are collectively called "generalized linear models" (GLM). These models have the general form of Equation 1:

$$E[N] = EXPO\ e^{b_0 + b_1 X_1 + b_2 X_2 + \ldots + b_n X_n} \tag{1}$$

where

$E[N]$ = predicted number of crashes per year for a roadway section,

$EXPO$ = exposure to crashes,

$b_0, \ldots, b_n$ = regression coefficients, and

$X_1, \ldots, X_n$ = predictor variables.

Models developed similar to Equation 1 will be capable of identifying the relationship of the number of crashes to the various elements to be considered. The measure of exposure used in these prediction models could be either the traditional vehicle-miles (i.e., length × Average Daily Traffic (ADT) volume), or the length itself while the ADT becomes a predictor variable.

Negative binomial models are typically used in developing Crash Reduction Factors (CRFs) or Accident Modification Factors (AMFs). Even though these two terms are in general similar in concept, there are slight differences. A CRF is a value that represents the reduction of crashes due to a safety improvement at a roadway spot or section. Such values represent the percent improvement on the roadway and most often have a positive connotation—that is, the safety intervention will have a positive result. On the other hand, an AMF is a constant that represents the safety change due to a change in a value of the segment. These factors are typically the ratio of the expected values of crashes with and without the change. AMFs are also used as multipliers for estimating the expected number of crashes, and values less than 1.0 indicate fewer crashes as a result of the change.

The basic concept of the AMF is to capture the change in crash frequency due to the change of a single element. However, this is often not the case, and these factors have been developed using cross-sectional studies where multivariate models were developed and used in the determination of AMFs. The models typically include all contributing factors that could influence safety and then use them to estimate the change in crashes due to a change in one unit of the variable of concern. This approach is typically completed with the assistance of an expert panel that evaluates the use of the prediction models and estimates the potential effect for each variable of concern. These evaluations could be further supported by the existing literature and current knowledge for the specific variable. This approach was used in the two-lane rural roadway models as part of the IHSDM, where the models developed were used as the basis for the creation of the AMFs. AMFs may appear subjective in nature, but they represent a collective "wisdom" based on expert panel knowledge, field observation, and findings in the research literature. The key limitation to this approach for AMF development is that there may not be adequate literature dealing with the identification of the safety impacts from the elements of interest.

Currently, there are two methods that can be used for estimating AMFs using regression models. The first method consists of estimating AMFs directly from the coefficients of statistical models. This method has been used by Lord and Bonneson (*42*) for estimating AMFs for rural frontage roads in Texas. Washington et al. (*41*) used a similar approach in their study. The AMFs are estimated the following way:

$$AMF_j = e^{(\beta_j \times [x_j - y_j])} \tag{2}$$

where

x_j = range of values or a specific value investigated (e.g., lane width, shoulder width, etc.) for AMF *j;*

y_j = baseline conditions or average conditions for the variable x_j (when needed or available); and

β_j = regression coefficient associated for the variable *j.*

This method provides a simple way to estimate the effects of changes in geometric design features. However, although the variables are supposed to be independent, they may be correlated, which could affect the coefficients of the model. The Variance Inflation Factor (VIF) can be used for detecting correlated variables, but this procedure usually flags only extreme cases of correlation among variables (*43*).

The second method consists of estimating the AMF using baseline models and applying them to data that do not meet the nominal conditions (*41*). These models are developed using data that reflect nominal conditions commonly used by design engineers or could also reflect the average values for some input variables. Such models usually include only traffic flow as the input variable. Examples of nominal conditions for rural four-lane undivided highways may include 12-ft lane and 8-ft shoulder widths, straight sections, and so forth. It is anticipated that by controlling the input variables, the models will more accurately estimate the safety performance of the facility for the given input conditions. However, an important drawback to developing baseline models is associated with the smaller sample size. Because the input data only include data meeting the nominal conditions, the sample size can be significantly reduced. This reduction can (1) affect the model stability, especially if the sample mean value is low (*44*); (2) increase the model error (variance); and (3) decrease the statistical power of the model. Baseline models are currently used for the *HSM* (*45*).

The second method was proposed by Washington et al. (*41*), who have re-calibrated models for estimating the safety performance of rural signalized and unsignalized intersections. For this method, the baseline model is first applied to sites not meeting all of the baseline conditions; then, the predicted and observed values per year are compared, and a linear relationship between these two values is estimated via a regression model to determine whether AMFs can be produced from its coefficients. The linear equation is given by the following equation:

$$Y_i - \mu_i = \gamma_1 X_1 + \ldots + \gamma_m X_m \tag{3}$$

where

μ_i = the predicted number of crashes for Site *i* per year estimated by the baseline model;

Y_i = observed number of crashes for Site *i* per year;

X_m = a vector of the baseline variables (each site not meeting one or more of these variables); and

γ_m = a vector of coefficients to be estimated.

The AMFs are estimated using the following relationship when the coefficients are found to be statistically significant (e.g., at the 5% or 10% level):

$$AMF_m = \frac{\sum_{i=1}^{n} Y_i / n}{\sum_{i=1}^{n} Y_i / n - \gamma_m} \tag{4}$$

where

AMF_m = AMF for Coefficient *m,* and

n = the number of observations in the sample.

Data Base

As noted above, the initial approach was to evaluate the safety implications from specific changes to values of design elements though a review and analysis of cases where such flexibility changes were implemented. The meeting with the NCHRP project panel at the end of Phase I resulted in a significant change of the scope of the work and the type of data to be acquired. The discussion during the meeting focused on the potential problems and issues identified from the original approach. That approach was centered on the identification of cases where design flexibility was used and was documented by a comparison of the safety performance of each case to control sites where no flexibility was required. A variety of issues were identified that led to the need for another approach to produce the most beneficial research. This research must be useful in the ongoing *HSM* efforts, and that required this revised approach. The project panel recommended that the research be concentrated on multilane rural roads and that it should be limited to specific design elements: lane width, shoulder width, and median type and width. The possibility of examining the contribution of clear zones was also discussed, but this decision was made contingent on a determination of data availability and potential feasibility.

The first task in Phase II of the research was to identify candidate states with crash data suitable for analysis. The plan was to retrieve crash data from the states participating in the

HSIS database in a manner that would achieve a broad geographic distribution to ensure consideration of terrain, climate, and other key factors.

The states in the FHWA HSIS database include California, Illinois, Maine, Michigan, Minnesota, North Carolina, Utah, and Washington. Data availability varies among these states with respect to time periods (some have fewer years than others) as well as the type of information available (not all include roadway geometry data in the crash records). Therefore, data from these states were evaluated with respect to the availability of the following data types and classes: (1) multilane rural roads; (2) geometric elements including lane and shoulder width and median type and width; (3) crash severity level; and (4) possibly, crash type. In addition, in order to stratify the data and the potential crash models, the number of lanes and functional classification were needed.

A review of the data available through HSIS for each state found that only Ohio and Washington have data available for horizontal and vertical curves. At the end of Phase I in 2005, 2004 data were available from Minnesota and were being processed for the other states. In addition, data were available from Kentucky that had been used satisfactorily by the research team in the past. To achieve the objective of identifying possible geographic differences among the states and, thus, to achieve a national perspective, the databases from California, Kentucky, and Minnesota were selected for the Phase II analysis. This allows for a reasonable geographic distribution that should adequately cover roadways found throughout the nation. A final element discussed at the project panel meeting was the exclusion of intersections to create a database with midblock sections only.

An understanding of the safety consequences for both the total number and specific types of crashes is of interest in evaluating design element trade-offs. The change in the crash rate will provide an understanding of the overall safety risks of the applied trade-off. There are also specific crash types that would be expected to occur due to a trade-off on a specific geometric element—for example, if the decision involved the use of medians, the number of head-on crashes would be of particular interest. The analysis of such specific types of crashes would provide an understanding of the effect of certain types of decisions. Therefore, the number of all crashes and the number of specific crash types for each case would be collected for evaluating the safety trade-offs from varying values of design elements. An additional evaluation would focus on the severity of the crashes. It is possible that trade-offs for a design element may not show significant impacts on roadway safety expressed in total crashes, but might affect the severity of the crashes.

The California and Minnesota data used for this research were provided by NCHRP Project 17-29, which was also working on a similar issue and had already developed and evaluated the databases for these two states. The Kentucky data were also evaluated by the research team to provide compatibility among the three data sets and to see that all variables to be examined provided the same information and values.

An effort was made to augment the Kentucky data with the available clear zone width for all segments included in the database. Site visits were conducted at all 437 rural multilane segments in the database. The intent of these visits was to review the available information included in the state's Highway Information System and to determine its accuracy. Past work with this data indicated occasional inaccuracies regarding the geometric elements used. Kentucky is conducting a similar review, but their results were not available at the time of this research work. For each site, the lane, shoulder, and median widths were measured, the shoulder and median types were recorded, and an estimate was made of the available clear zone. The data were then used to update the geometry file, which was in turn used to develop the crash database for analysis.

The final data base was developed by aggregating the individual state databases into one. For each state, a 12-year period was used with examination of data covering 2,387 miles. A further evaluation of the data to determine presence of all common available variables and values indicated that the majority of the segments (more than 95%) were four-lane facilities and most (more than 90%) had lane widths of 12 ft. These data indicate that there may be some concerns regarding the distribution of certain variables since a significant mileage was at specific values, which may not allow for the development of complete models. For example, it was envisioned to create separate models for four- and six-lane facilities. However, the available data indicate that there are only 35 segments for six-lane facilities accounting for 205.45 miles (8.6%) of the total mileage. Therefore, the decision was made to develop models only for four-lane, 12-ft lane width segments. This approach resulted in a new data set that had a total extent of 1,433.7 miles with 35,694 crashes of which 9,024 were injury crashes. The ADT ranged from 241 to 77,250 vehicles/day, and the total miles for divided highways was 1,241.4. All segments were classified as non-freeway, even though these facilities could qualify as rural multilane roadways and all have a length greater than 0.10 miles. An average of the left and right shoulder widths was used as the shoulder width since this approach resulted in models with more reasonable and intuitive coefficients. The average shoulder width is computed as the mean of the left and shoulder width in the same direction for divided highways and as the mean for the right shoulders in undivided segments. Moreover, the shoulder type was checked to ensure that both shoulders used in the calculation are of the same type. All segments included in the final data set had the same type of left and right shoulders. Finally, all injury levels (ABC injuries) and fatalities (K) are included in the injury crashes.

These state databases exhibited various values for commonly named variables. For example, the California database codes median barrier types differently than do Minnesota and Kentucky. It was important to decipher these differences and to determine the common categories and groups among all three state databases. It became apparent that the commonality of data coding among these databases should be evaluated in order to avoid misinterpretation of the results.

The unit of analysis in the model development process is a highway segment that has homogenous geometry and traffic conditions. The database developed herein used this approach and, thus, allows for the development of models that will have the segment as a unit. Table 10 presents a summary of the variables considered and the number of segments in the final database by each state (as described above). In all cases, the term "injury crash" denotes both injury and fatality crashes.

The data in Table 10 indicate that most segments are divided highways without median barriers, with shoulder widths between 6 and 8 ft, and with traffic volumes between 5,000 and 15,000 vehicles/day. All are four-lane rural highways with 12-ft lanes. There are differences among the states for certain variables—for example, most of the roads with higher ADT are in California, and they account for approximately one-third of the segments within the state. California and Minnesota also had large numbers of segments with wide medians (greater than 60 ft), while most median widths for Kentucky were narrower (more than one-half of the segments were less than

Table 10. Extent of variables in database.

Variable	Categories	Divided			Undivided		
		CA	*KY*	*MN*	*CA*	*KY*	*MN*
Crashes	All	16,951	8,035	5,106	3,495	1,037	1,068
	Injury	4,045	2,765	681	995	405	133
Principal arterial	Yes	571	539	615	164	73	84
	No	183	71	46	125	8	31
Median barrier	Yes	95	3	6	NA	NA	NA
	No	659	607	655	NA	NA	NA
Paved right shoulder	Yes	624	530	595	243	68	47
	No	130	80	66	46	13	68
Average shoulder width (ft)	0	0	1	10	6	2	49
	0–2	49	27	1	20	7	2
	2–4	102	32	14	124	1	9
	4–6	87	218	99	36	19	13
	6–8	412	329	536	75	31	18
	8+	104	3	1	28	21	24
ADT (vehicles/day; 000s)	<5	65	61	91	103	4	34
	5–10	116	172	268	80	31	38
	10–15	181	239	178	53	23	32
	15–20	131	89	92	34	12	10
	20–25	89	30	26	12	8	
	>25	172	19	6	7	3	1
Median width (ft)	<10	55	101	27	NA	NA	NA
	10–20	177	188	12	NA	NA	NA
	20–30	116	159	20	NA	NA	NA
	30–40	59	108	37	NA	NA	NA
	40–50	149	37	142	NA	NA	NA
	50–60	32	14	185	NA	NA	NA
	>60	166	3	238	NA	NA	NA

20 ft). These differences among states can affect the model development because they may influence the presence or absence of a variable as well as the magnitude of its coefficients.

In addition to this evaluation, a preliminary analysis was also made to estimate the crash rates for the variables of concern (see Table 11). The data show that, in general, divided highways have lower crash rates, the segments with a median barrier have higher crash rates than do segments without, and there is a difference between single- and multi-vehicle crashes depending on whether the roadway is divided. The median width has a positive effect (i.e., lower crash rates) up to 40 feet; the crash rates increase above that width. The same could be observed for shoulder width, where the crash rate decreases up to 6 ft and then varies as the shoulder becomes wider. These trends are simple observations, and statistical tests were not conducted to determine their statistical significance.

Data Analysis

As noted above, predictive models were developed to evaluate trade-offs among selected design elements. The unit of analysis is a roadway segment with its associated crash history. The database records are based on roadway segments that have consistent geometric features for their corresponding length. Each record included the total number of crashes and total number of injury crashes. A distinction was made with respect to the number of vehicles involved in the crash, with crashes classified as single-vehicle or multi-vehicle for both total and injury crashes. The goal of the analysis was to isolate the effect of a single parameter. For example, all road segments in four-lane undivided arterials would be used in developing a model to determine the potential effect of the various features on total number of crashes or other crash types (i.e., single-vehicle, multi-vehicle or injury crashes).

Table 11. Crash rates for selected variables.

Variable	Categories	Divided	Undivided
Principal arterial	Yes	48.97	77.15
	No	51.63	77.83
Median barrier	Yes	98.95	NA
	No	46.67	NA
Vehicles	Single	29.21	36.68
	Multi	20.15	39.44
Paved right shoulder	Yes	74.21	128.84
	No	60.40	79.25
Average shoulder width (ft)	0	89.45	155.51
	0–2	82.26	87.04
	2–4	60.15	75.89
	4–6	53.15	64.51
	6–8	45.47	65.08
	8+	38.92	52.56
ADT (vehicles/day; 000s)	<5	72.78	92.90
	5–10	49.88	75.94
	10–15	40.32	68.28
	15–20	45.55	58.10
	20–25	38.86	89.10
	>25	63.32	93.53
Median width (ft)	<10	74.75	NA
	10–20	55.65	NA
	20–30	47.99	NA
	30–40	38.85	NA
	40–50	42.56	NA
	50–60	43.90	NA
	>60	46.98	NA

Data analysis focused on developing models by design element for assessing safety impacts from trade-offs among values of each design element and predicting the potential safety consequences expressed as number of crashes per unit time. Models for predicting crashes by severity level were also developed. However, models for specific crash types were not developed due to lack of available crash data. For the statistical modeling, GLMs were used because they are considered more appropriate for variables that are not normally distributed. Such models use a maximum likelihood function to determine which variables are significant and how well the model fits the data. Crashes are considered random events that follow a Poisson distribution; therefore, the use of GLMs is appropriate. Such models are derived using a relatively recent statistical approach; the literature suggests they have been gaining popularity among researchers (*39–41*).

The SAS statistical software was used to develop the prediction models and to determine their coefficients (*46*). The Generalized Modeling procedure (GENMOD) was implemented, and the model coefficients were estimated through the maximum-likelihood method. This approach is well suited to the development of models that have predictors that are either continuous or categorical[2]. The residual deviance statistics were used to assess the model's goodness-of-fit. Initially, all variables of concern were included in the model, and variables with coefficients that were not statistically significant (at the 5% level) were removed from the model. This process was followed until a model was obtained in which all variables entered were statistically significant. The signs of the coefficients were also evaluated to determine whether they reflected previously observed crash trends.

A desirable outcome from such a model is the determination of the relative safety impact of specific geometric elements. This requires the availability of adequate data to establish such comparisons as well as the isolation of the impact of each element. There are potential problems that should be considered when a model is developed. First, specific elements may not be easily isolated and examined alone since the literature has indicated that there are elements that interact. Second, there is the potential for significant variability among the various roadway segments included in the database such that, even if an element can be isolated, there may be other variables (such as traffic volume, number of lanes, and functional class) that could also require attention and, thus, require an additional data classification, further reducing a model's strength in reaching statistically sound conclusions.

[2]A *categorical predictor variable* is a variable whose categories identify class or group membership, which is used to predict responses on one or more dependent variables (from http://www.statsoft.com/textbook/glosc.html).

The models developed in this research predict the number of crashes for a given condition. This decision was reached during the project panel meeting, during which the appropriateness of crash rates and number of crashes was discussed. The decision was based on the need to develop results that could be eventually used in the *HSM*. The rationale for this decision is that the current trend is to avoid the use of crash rates because of potential problems arising from the implicit assumption of linearity between volume and crashes as well as the possible misuse by unaware users who may assume that a change in traffic volumes could proportionally affect the number of crashes. It was therefore decided to separate the data in divided and undivided segments and to develop separate models for each group.

Models developed in this research were validated to determine their goodness-of-fit. The available data were randomly divided into two sets: one was used in the model development, while the second was used for the evaluation of the strength of the model to predict the number of crashes. This is an accepted approach to determine the goodness-of-fit of a model, even though it reduces the data available for developing the model by one-half.

Prediction Models

Models were developed and evaluated for their applicability and ability to produce predictors with reasonable coefficient signs. Initially, models were developed where the exposure was considered as the product of length and traffic volume. However, these models produced consistently counterintuitive results: the coefficient signs were opposite to a priori expectations based on past research. Therefore, a second round of models was produced that used volume as a predictor with the goal of obtaining more robust models with coefficients more in accordance with past work. These new models had a better fit, and most coefficients were in agreement with past research findings. The general form of these models was as follows:

$$E\left[N\right]_i = L\, e^{b_0 - \ln 12 + b_1 \ln ADT + b_2 X_1 + b_2 X_2 + \ldots + b_n X_n} \qquad (5)$$

where

$E[N]_i$ = expected crash frequency per year for Condition *i;*
L = segment length (mile);
b_i = model coefficients;
ADT = average daily traffic (vehicles/day); and
X_i = predictors (various variables).

The predictor variables varied for each condition—divided and undivided segments and single-vehicle, multi-vehicle, and all crashes—are discussed in the following paragraphs. The term *ln 12* is included in each model to provide the results in units of *crashes per year* (as 12 years of data were used for estimating the model).

Divided Roads, All Crashes

Single-Vehicle Crashes

$$E[N]_{SD} = L\, e^{b_0 - \ln 12 + 0.597 \ln ADT + 0.407 FC + 0.999 MBAR + 0.166 RSP - 0.053 SW - 0.327 LTLN} \quad (6)$$

Multi-Vehicle Crashes

$$E[N]_{MD} = L\, e^{b_0 - \ln 12 + 1.203 \ln ADT - 0.010 MW + 0.523 MBAR - 0.137 SW + 0.452 LTLN} \quad (7)$$

All Crashes

$$E[N]_{AD} = L\, e^{b_0 - \ln 12 + 0.835 \ln ADT + 0.781 MBAR + 0.172 FC + 0.228 RSP - 0.118 SW} \quad (8)$$

Undivided Roads, All Crashes

Single-Vehicle Crashes

$$E[N]_{SU} = L\, e^{b_0 - \ln 12 + 0.795 \ln ADT + 0.379 RSA} \quad (9)$$

Multi-Vehicle Crashes

$$E[N]_{MU} = L\, e^{b_0 - \ln 12 + 1.223 \ln ADT - 0.474 RSP - 0.111 SW} \quad (10)$$

All Crashes

$$E[N]_{AD} = L\, e^{b_0 - \ln 12 + 0.960 \ln ADT - 0.067 SW} \quad (11)$$

Divided Roads, Injury Crashes

Single-Vehicle Crashes

$$E[N]_{SDI} = L\, e^{b_0 - \ln 12 + 0.571 \ln ADT + 0.251 FC + 0.813 MBAR - 0.053 SW - 0.728 LTLN} \quad (12)$$

Multi-Vehicle Crashes

$$E[N]_{MDI} = L\, e^{b_0 - \ln 12 + 0.981 \ln ADT - 0.009 MW - 0.137 SW} \quad (13)$$

All Crashes

$$E[N]_{ADI} = L\, e^{b_0 - \ln 12 + 0.835 \ln ADT + 0.657 MBAR - 0.068 SW} \quad (14)$$

where

$E[N]_i$ = expected crash frequency per year for Condition i;
L = segment length (mi);
b_0 = model intercept;
ADT = average daily traffic (vehicles/day);
RSP = right shoulder paved (no/yes);
SW = average right and left shoulder width (ft);
MW = median width (ft);
FC = functional class principal arterial (no/yes);
$MBAR$ = median barrier (no/yes); and
$LTLN$ = left turn lane present (no/yes).

The following subscripts are used:

S = single-vehicle crashes,
M = multi-vehicle crashes,
A = all crashes,
D = divided,
U = undivided, and
I = injury crashes.

No predictor variables were statistically significant for the injury models for the undivided roads; hence, these models are not reported here. There are three intercepts (b_0) for the models developed because each state was used as an indicator to allow for a more accurate estimation of the variables and their coefficients. The three intercepts are similar for all models and are presented in Table 12. The user can use any of these in the development of estimates since all will produce results of similar magnitude. An approach for predicting crashes with the models is described later in this section.

As described above, the data were divided into two halves for the analysis: the training and validating datasets, respectively. The training datasets contained 1,028 divided and 242 undivided segments. The validation datasets included 997 divided and 243 undivided segments and were used for

Table 12. Model intercepts.

Highway	Crash Type	CA	KY	MN
Divided	Single	–3.087	–3.567	–3.002
	Multi	–7.974	–7.884	–8.100
	All	–4.235	–4.457	–4.317
Undivided	Single	–4.759	–4.976	–5.043
	Multi	–7.970	–7.052	–7.671
	All	–5.105	–4.758	–5.054
Divided	Single, injury	–3.644	–4.141	–4.711
	Multi, injury	–7.217	–6.764	–7.900
	All, injury	–4.614	–4.569	–5.547

validating the models and determining their statistical accuracy. The statistical performance of the models was assessed by the following methods:

1. *Mean Prediction Bias (MPB):* this measure is an estimate of the direction and magnitude of the average bias of the predictions (*47*). MPB considers the differences between predicted and actual values; a positive value indicates that the model overpredicts crashes. Smaller absolute values of MPB indicate a better predictive model.
2. *Mean Absolute Deviation (MAD):* this measure is the average dispersion of the model (*47*); it can be used to estimate the absolute value of the difference between predicted and observed values. An estimate close to zero suggests that the model predicts the actual values well.
3. *Mean Square Prediction Error (MSPE):* this measure is an assessment of the error associated with the validation dataset and is the sum of the squared differences between the predicted and actual values (*47*). MSPE is used in conjunction with the mean squared error (MSE), which is similar in concept: the difference between the two measures is related to the denominator. For the MSPE, the denominator is the sample size used for the validation dataset; for the MSE, it is the sample size used for estimating the model less the number of variables included in the model (i.e., the degrees of freedom). This difference is an indicator of how well the validation dataset fits the data. An MSPE value larger than the MSE value indicates that the model shows signs of overfitting (i.e., that the model incorporates too many parameters) and that some of the relationships observed may be spurious.
4. *Sum of Model Deviance (SMD):* SMD is a measure of the model's goodness-of-fit; a value of 0 indicates a perfect fit (*48*). In practical terms, SMD represents a lower bound limit for the observed values. The model with the lowest SMD is considered the model with the best fit for predicting crashes when several models are compared.
5. *R^2-like Measure of Fit (RMF):* This measure provides an estimate similar to the R^2 commonly used in linear regression, but is not appropriate for GLMs, and is calculated from the residual sum of squares and total sum of squares after the model is applied to the data (*48*).

The measures described above were used to estimate the goodness-of-fit of the models by using them with the validation datasets. The values obtained for these measures are shown in Tables 13 and 14. Overall, the models for single-vehicle crashes fitted the data better than do the models for multi-vehicle and all crashes. Despite these differences, the measures show that the models perform adequately.

Table 13. Measures of goodness-of-fit for all crashes.

Divided Highways					
Crash Type	*MPB*	*MAD*	*MSPE*	*SMD*	*R^2*
Single	0.90	5.20	157.75	4261.49	0.8425
Multi	1.42	5.31	188.03	5196.85	0.6816
All	2.47	9.44	532.68	6548.12	0.8028
Undivided Highways					
Crash Type	*MPB*	*MAD*	*MSPE*	*SMD*	*R^2*
Single	0.69	4.49	93.21	1001.04	0.7837
Multi	1.07	5.66	202.48	1460.82	0.6598
All	1.78	8.51	469.45	1585.85	0.8055

Trade-Offs from Models' AMFs

Two regression model methods can be used to estimate AMFs (or the effects of changes in geometric design features). Both were described above, and the method selected for this research is presented here. The chosen method consists of estimating AMFs directly from the coefficients of statistical models using Equation 2. This method provides a simple way to estimate the effects of changes in geometric design features.

Divided Highways

Single-Vehicle Crashes

Four variables had single value AMFs: functional classification, paved shoulder, median barrier, and left turn lane presence. The AMF for the functional classification was 1.50, indicating a 50% increase for arterial roads in comparison to other roadways. For paved shoulder, it was 1.18, indicating an 18% increase for roads with paved shoulder. For median barrier, it was 2.72, indicating a 172% increase in crashes for roads with a barrier compared to roads without one. For left turn lane presence, it was 0.72, indicating a 28% reduction when a left turn lane was present. AMFs were also computed for shoulder width, yielding a 6% reduction per foot increase of average (left and right) shoulder width.

Table 14. Measures of goodness-of-fit for injury crashes.

Divided Highways					
Crash Type	*MPB*	*MAD*	*MSPE*	*SMD*	*R^2*
Single	0.18	1.70	13.22	1983.99	0.7982
Multi	0.39	1.56	18.19	1774.24	0.7435
All	0.57	2.78	47.76	2684.18	0.8109
Undivided Highways					
Crash Type	*MPB*	*MAD*	*MSPE*	*SMD*	*R^2*
Single	0.28	1.91	16.85	542.65	0.6974
Multi	0.36	1.54	19.47	498.11	0.4094
All	0.70	2.90	64.80	684.69	0.6558

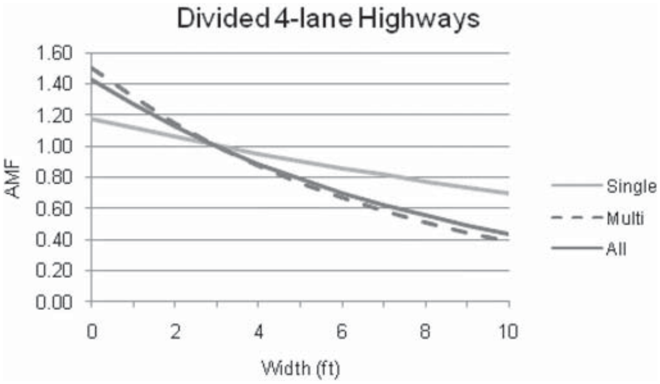

Figure 1. AMFs for average shoulder width.

Multi-Vehicle Crashes

Single value AMFs were obtained for two variables: median barrier and left turn lane. The AMF for median barrier was 1.69, indicating that median barriers increase crash potential by 69% in comparison to roads without barriers. The AMF for left turn lanes was 1.57, indicating that the presence of left turn lanes increases crash potential by 57% in comparison to roads without one. Two additional continuous variables entered the model; the AMFs for these are shown in Figures 1 and 2.

All Crashes

Single value AMFs were obtained for three variables: paved right shoulder, median barrier, and functional classification. The AMF for the paved right shoulder was 1.26 indicating that paved shoulders increase crashes by 26% in comparison to unpaved shoulders. For median barrier, the AMF was 2.18, indicating that median barriers increase crash potential by 118% in comparison to roads without barriers. The AMF for functional classification was 1.19, indicating that arterials increase crash potential by 19% in comparison to other roads. An additional continuous variable also entered the model; this AMF is shown in Figure 1.

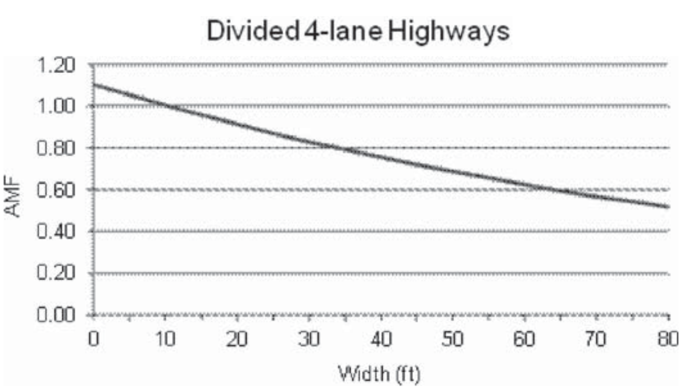

Figure 2. AMFs for median width.

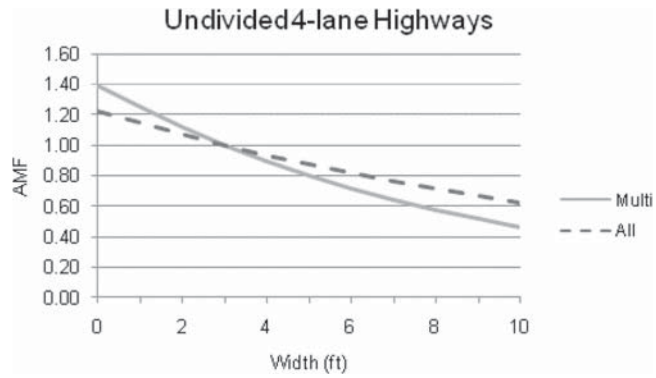

Figure 3. AMF for undivided roadways, multi-vehicle crashes.

Undivided Highways

Single-Vehicle Crashes

A single value AMF was obtained for only one variable, paved shoulders. The AMF for this is 1.46, indicating a 46% increase for roads with paved shoulders in comparison to roads without paved shoulders.

Multi-Vehicle Crashes

A paved right shoulder was a predictor variable in this case; the AMF was 0.62 for paved shoulders, indicating a 38% reduction in comparison to unpaved shoulders. An AMF for the continuous variable shoulder width, the effect of this variable can be estimated from Figure 3. As used here, the shoulder width is the average width for both the left and right shoulders.

All Crashes

The only significant variable was the shoulder width for which the effect can be estimated from Figure 3.

Injury Models

In addition to all crashes, models were developed for injury-only crashes. These models followed the same data grouping as the all crashes (i.e., data were split into divided and undivided highways and single-, multi-, and all vehicle crashes). For undivided roadways, no variable was significant enough to be entered in the model other than the ADT. This indicates that none of the variables of concern had any significant influence on injury-only crashes on undivided roads.

For divided roads, the models were very similar to those observed for all crashes. For the single-vehicle crashes, presence of median barrier, functional class, shoulder width and presence of left turn lane had impacts. Most of these values had similar magnitudes, and all were slightly smaller than those obtained with the all crashes model. For the multi-vehicle crashes, only presence of median barrier and shoulder width entered the model, and they had values similar to those observed before. This was also the case for the all crashes model.

Summary

The AMFs presented here follow the general trends of prior knowledge and research. In general, the trends of the variables used in all models showed an agreement with rational expectations indicating reasonable trends. A notable result was for divided highways where there was an increase in crashes (all three models) with the presence of a median barrier. This could be associated with the possible higher speeds that could be present on divided highways and, thus, the presence of the barrier could contribute to the occurrence of a crash. Moreover, the fact that an obstacle is placed within the roadway environment is an indication of the potential increase in crashes since the absence of any barrier could have resulted in an unreported crash (i.e., the vehicle could have been able to return to the roadway and drive off). Therefore, this trend was considered acceptable. For divided highways, the presence of left-turn lanes provided different results depending on the crash type. For single-vehicle crashes, it showed an intuitive result indicating that its presence has a benefit (AMF of 0.72). For multi-vehicle crashes, it showed an increase in crashes (AMF of 1.57). This could be attributed to two possible issues: (1) the presence of higher operating speeds on divided rural highways and (2) the sites may not be truly rural sites, but are within a more built-up environment. These explanations, while plausible, cannot be verified with the available data, and so they cannot conclusively explain the counterintuitive nature of the results.

A more critical issue with the AMFs developed in this research is their magnitude and whether such significant differences should be observed from the introduction or change of each of these elements. This issue was addressed by a meeting of the research team at which a reasonable magnitude was estimated by consensus for each selected design element. This approach allowed the research team to consider past research, weigh the findings of this research, and adjust the magnitude of the AMFs as needed to reflect practical and research experience. This approach also facilitated the development of the guidelines based on the research results.

CHAPTER 4

Design Elements Recommendations

Chapter 3 described the development of prediction equations from which a set of recommended AMFs could be determined for practicing engineers to use when evaluating safety trade-offs for selected design elements. In this chapter, each of the design elements that were found as statistically significant in the prediction models is discussed with a view toward developing these practical recommendations. A general discussion of the literature is first presented (review Chapter 2 for more detail). The values from the models developed in this research are then presented with a brief discussion demonstrating the appropriate AMF values. Finally, a recommended set of values is presented along with discussion of the justification for the proposed AMFs. The justification and associated discussion is considered essential, especially for cases in which the results seemed to be inconclusive.

The first step in establishing the proposed recommended values for each design element was the circulation of a draft set of recommendations among project team members. The team then met to discuss (1) the proposed values, (2) the justification of the recommendations, and (3) the identification of any issues that might result in diminishing the practicality of the proposed values. The team meeting represented an expert panel since it included three safety engineers, two highway designers, and a highway safety analyst (see Table 15). The team debated the values presented, discussed the existing work (both past and that of NCHRP Project 15-27), and prepared a recommended set of AMF values through a consensus-building process. The team determined that the current recommendations for shoulder width and median width were reasonable (i.e., the values were similar to those in past research, and any differences in magnitude could be explained). The team was not able to make a final recommendation for median barrier presence because it was not included in all models for divided highways. Finally, the AMFs developed for the presence of paved right shoulders and left-turn lanes produced counterintuitive results, and the research team concluded that neither AMF should be included as a design element with a guideline.

Average Shoulder Width

Recommendation

The research team reviewed past literature, the recommended values for the *HSM*, and the AMFs from NCHRP Project 15-27 and agreed that there is an influence on crash occurrence from the presence of shoulders. Using this background information, the team determined that the values noted for all crashes for undivided highways are reasonable and in accordance with current rends and literature. The team further recommended the use of only the AMF for all crashes for undivided highways since the shoulder width was not a significant variable in the single-vehicle models.

The team considered the values provided for all three models for divided highways, and it recommended using the values from the single-vehicle crashes as those for divided roadways. The team determined that the values for multi-vehicles and all crashes were high and probably reflective of other influences such as volume. This adjustment is considered justifiable based on previous work by Harwood et al. (*26*) and the recommended values in the *HSM* (*22*). The recommended values are summarized in Table 16.

The modification factors in Table 16 are for all crashes and not for specific types of crashes that could relate to shoulder width issues. The recommended values are similar to those proposed in the *HSM* as noted above, and those of the divided highways are comparable for almost all categories with the only exception being that of the 8-ft shoulder AMF. For undivided highways, the differences between the NCHRP Project 15-27 and the *HSM*-recommended AMFs were larger. These differences are attributed to the fact that the *HSM* factors were developed for shoulder-related crashes while the AMFs for NCHRP Project 15-27 were developed for all crashes. Even though a comparison with the *HSM* values is not wholly appropriate due to the difference in crash types used in each model, the comparison is supported by the observed similarities in trends and agreement of findings. Future research

Table 15. Team "expert" panel.

Name and Agency	Expertise
Ken Agent, University of Kentucky	Safety engineer
Dominique Lord, Texas Transportation Institute	Highway safety analyst
Jerry Pigman, University of Kentucky	Safety engineer
Wendel Ruff, ABMB Engineers, Inc.	Design engineer
John Sacksteder, HMB Professional Engineers, Inc.	Design engineer
Nikiforos Stamatiadis, University of Kentucky	Safety engineer

should address the lack of AMFs for shoulder width greater than 8 ft since the literature indicates that the safety effects for such shoulder widths are unknown.

Supportive Background

In general, shoulder width has an influence on crashes, with increasing shoulder width having a positive (i.e., reducing) effect on crashes. There is also some evidence that wider shoulders may encourage higher operating speeds since they may communicate to the driver the presence of a wider space for correcting errors. Finally, number of lanes, lane width, and shoulder width are all interrelated to some degree, and the geometric value choice for each of these elements typically has an effect on the other elements. Most research completed to date focused on two-lane, two-way rural roads. An additional problem is that most recent studies have analyzed urban or suburban multilane highways (rather than rural roads), resulting in an even smaller number of available references for this design element. Two recent studies examined the effect of shoulder width on crashes (*22, 27*). Both studies focused on paved shoulders and determined AMFs for shoulder-related crashes and for divided and undivided roadways.

The models developed based on the data from this research demonstrated that there is a relationship between shoulder width and crashes. The general trends observed from previous studies as well as those for two-lane, two-way rural roads were also supported by the models developed. The current study distinguished between divided and undivided highways as well as between single- and multi-vehicle crashes. This classification permitted development of four distinct models to address issues particular to crash types and the influence of the presence of the median. Aggregate models were also developed for all crashes to allow for a comprehensive approach and potential determination of the overall effects of the shoulder width. It should be noted that the shoulder width used here is the average total width for the left and right shoulders (i.e., the sum of right and left shoulders divided by two) in the same direction.

For undivided four-lane highways, the shoulder width was a significant predictive variable for multi-vehicle and all crashes. The coefficient in the model for multi-vehicle crashes is –0.11 $(1-\exp(-0.11) = 0.10)$ and for all crashes is –0.07 $(1-\exp(-0.07) = 0.07)$. The negative sign indicates the beneficial influence of the shoulder width. These values could be used as an indication of the relative safety gains from the increase of the shoulder by 1 ft. However, their magnitude seems relatively high, and it is likely that such large reductions may not be feasible.

For divided highways, the shoulder width was included in all three models. The coefficients were –0.05 $(1-\exp(-0.05) = 0.05)$ for single–vehicle; –0.14$(1-\exp(-0.14) = 0.13)$ for multi-vehicle; and –0.12 $(1-\exp(-0.12) = 0.11)$ for all crashes. Again, the negative sign demonstrates the reduction of crashes associated with an increase in shoulder width. The magnitude of the coefficients for the multi-vehicle and all crashes again seems high.

The similar analysis for injury-only crashes did not produce any significant changes in the coefficients noted here. The variable was significant only for divided highways, and the coefficients were practically the same as those noted for all crashes. The AMFs for each condition obtained from the models developed in this research are summarized in Table 17.

Table 16. Recommend AMFs for average shoulder width (ft).[1]

Category	Average shoulder width (ft)[2]						
	0	3	4	5	6	7	8
Undivided	1.22	1.00	0.94	0.87	0.82	0.76	0.71
Divided	1.17	1.00	0.95	0.90	0.85	0.81	0.77

[1] The AMFs are for all crashes and all severities.
[2] The average shoulder width for undivided highways is the average of the right shoulders; for divided, it is the average of left and right shoulder in the same direction.

Table 17. AMFs based on prediction models for average shoulder width.

Category	Average shoulder width (ft)[1]							
	0	3	4	5	6	7	8	10
Undivided, multi-vehicle	1.39	1.00	0.90	0.80	0.72	0.64	0.58	0.46
Undivided, all crashes	1.22	1.00	0.94	0.87	0.82	0.76	0.71	0.63
Divided, single-vehicle	1.17	1.00	0.95	0.90	0.85	0.81	0.77	0.69
Divided, multi-vehicle	1.51	1.00	0.87	0.76	0.66	0.58	0.50	0.38
Divided, all crashes	1.43	1.00	0.89	0.79	0.70	0.62	0.55	0.44

[1] The average shoulder width for undivided highways is the average of the right shoulders; for divided, it is the average of left and right shoulder in the same direction.

Median Width

Recommendation

The research team reviewed past literature, the recommended values for the *HSM,* and the AMFs from NCHRP Project 15-27 and agreed that there is an influence on crash occurrence from the median width. The team determined from available background data that the values noted for the only model with median width influence are reasonable and in accordance with current trends and literature. The only available AMF based on the models developed in this research is for multi-vehicle crashes, and it yields a 1% reduction for every added foot of median width. The values obtained from the models for multi-vehicle crashes are reasonable and agree with the previous research. The recommended values are summarized in Table 18.

These modification factors are for all crashes and not for specific types of crashes that could relate to median width issues. The recommended values are greater than those proposed in the *HSM.* This difference may be derived from the fact that the *HSM* values specifically account for median-related crashes while determining all crashes. This level of data refinement was not possible for the research reported here, and an adjustment consistent with the *HSM* could affect the values recommended in Table 17. Another possible relationship that could exist and could have an influence on these values is the presence of a median barrier. Roadway segments with a barrier have typically narrower medians; this could influence the AMFs as shown in the *HSM* values. However, the available data were not large enough to examine this interaction.

To determine the AMFs for all crashes, one could assume that the median width has "no effect" on single-vehicle crashes and, therefore, the AMF for single-vehicle crashes could be considered as 1.00. In this case, a weighted AMF can be estimated using as weights the relative percentages of single- and multi-vehicle crashes for the roadway of concern.

Supportive Background

The key objective for the presence of medians is traffic separation. Median design issues typically address the presence of medians, along with type and width. There has been some research completed on these issues and their implications on safety. However, past research indicated three safety trends: (1) cross median crashes (i.e., between opposing vehicles) are reduced with wider medians; (2) median-related crashes increase as the median width increases with a peak at about 30 ft and then decrease as the median width increases beyond 30 ft; and (3) the effect of median width on total crashes is questionable (*32*). The section in the *HSM* on multilane rural roads proposed AMF values for rural multilane highways based on whether a median barrier was present (*22*). These values accounted for the total number of crashes while considering median-related crashes.

This research distinguished between divided and undivided highways as well as between single- and multi-vehicle crashes. The effect of median width was only evaluated for divided highways. This classification allowed for the development of two distinct models to address the particular issues relative to crash types. Aggregate models were also developed for all crashes to allow for a comprehensive approach and the determination of the overall effects of the median barrier presence.

The only model where median width was significant was for multi-vehicle crashes, and it had a positive effect (i.e., crashes are reduced with wider medians). This trend is supported by

Table 18. Recommended AMFs for median width, divided roadways.

Category	Median width (ft)							
	10	20	30	40	50	60	70	80
Multi-vehicle	1.00	0.91	0.83	0.75	0.68	0.62	0.57	0.51

Table 19. AMFs for median width on divided roadways.

	Median width (ft)							
Category	10	20	30	40	50	60	70	80
Multi-vehicle AMF	1.00	0.91	0.83	0.75	0.68	0.62	0.57	0.51

the general observation that roadways with wider medians will exhibit lower crash rates than will roads with narrower medians. The model developed showed that the coefficient was –0.010 (1–exp(–0.010) = 0.01). The analysis of the injury-only crashes included this variable again only in multi-vehicle crash models with a similar coefficient (–0.009). The AMFs developed for median width based on the model developed are summarized in Table 19.

Median Barrier

Recommendation

The research team reviewed past literature, the recommended values in the *HSM,* and the AMFs from NCHRP Project 15-27 and agreed that there is an influence on crash occurrence from the presence of median barrier. However, the values obtained from this research are based on a small sample (200 segments, less than 5% of the data) and therefore no recommendations were made. The research team also determined that there are several other factors that may also be influential such as barrier type (which was not available for this study), volumes, use of barriers (presumably roads with higher ADT and narrower median are likely to have barriers), and distance between barrier and travel lanes (potential for avoiding colliding with barrier). Therefore, a properly supported recommendation is not possible.

It should be noted that although no recommendation is made for this design element, other factors should be considered in determining the impact of the median barrier presence. Median barriers are typically placed to reduce crossover crashes. As such, cross-sectional studies (i.e., studies that compare segments with and without median barriers) may not be best suited for this evaluation. Before and after studies may be more appropriate since they generally compare the same roadway environment and population of users and allow for a better estimate of the effect of changes. The increase in crashes noted in the models in this research is also considered reasonable if one considers that the median barrier is an obstacle within the roadway environment and, as such, the potential for more crashes exists. For roadways with median barriers, one can assume that an errant vehicle will not simply rest in the median avoiding a crash but rather will hit the median, resulting in a crash. Other issues that were not examined and could have an influence are the placement of the median barrier and its distance from the travel lanes. These both could have a positive influence in avoiding the obstacle and, thus, not resulting in a crash. Finally, the severity and type of the crash with and without the median barrier should be also considered. Median barriers have the potential to reduce crossover crashes, which often result in serious injuries or fatalities. Therefore, the presence of the barrier has the potential to impact severity levels.

Supportive Background

The literature review has identified conflicting results for the presence of median barriers. Some have noted that the effectiveness of the presence of medians on safety cannot be conclusively identified but noted that there is potential for the median to impact safety (*33*). Others have shown that median barriers have a positive effect—they reduce crashes (*34*)—and others have indicated that there is a relationship between median barrier presence and left shoulder width (*38*). Another trend noted in the literature is the overall increase in number of crashes with median presence but a reduction of the level of severity for these crashes (*39*). In general, the fact that an obstacle is placed within the roadway environment that provides a target for collisions can lead to an increased number of crashes. The type of median barrier is also important: studies have shown that different types (especially concrete) have the potential to increase crashes (*36*). The issue to be considered here is whether the placement of a median barrier will act positively or negatively on the safety of the roadway segment considered. The presence of a barrier will result in a reduction of cross-median type crashes, but it also has the potential to increase median-related crashes since its absence may allow drivers opportunities to stop their vehicles in the median.

The models developed in this research identified that the presence of median barrier had an effect on crashes for divided highways. As noted above, the values obtained here are based on a small sample (200 segments, less than 5% of the data) and should be viewed cautiously. This research distinguished between divided and undivided highways as well as between single- and multi-vehicle crashes. This classification allowed for the development of two distinct models to address the particular issues relative to crash types. Aggregate models were also developed for all crashes to allow for a comprehensive approach and the determination of potential overall effects of median barrier presence.

Table 20. AMFs for median barrier presence, divided roadways.

Category	AMF
Single-vehicle	2.71
Multi-vehicle	1.69
All crashes	2.18

For all three models (single-vehicle, multi-vehicle, and all crashes), the presence of median barrier had a negative effect (i.e., crashes increased). This trend is supported by the general observation that roadways with median barriers exhibit higher crash rates than do roads without them. The models developed in this research yielded coefficients of 0.999 (1–exp(0.999) = 1.71) for single-vehicle; 0.523 (1–exp(0.523) = 0.69) for multi-vehicle; and 0.781 (1–exp(0.781) = 1.18) for all crashes. The analysis of the injury-only crashes included this variable only in the single-vehicle and all-crashes models with similar trends and magnitudes. The AMFs developed for each condition from the models developed in this research are summarized in Table 20.

Applications

These AMFs can be used to estimate the relative impact of the choice of the value of a design element for a rural four-lane roadway segment. The process described herein can also be applied to determine the safety implications using different values for a single or combination of design elements. The ratio of AMFs for two different conditions can be used to establish the relative change in crashes anticipated from the change in the values of the design element. The use of this approach was noted as a method for estimating change in crashes by using

$$\Delta N = \frac{AMF_1}{AMF_2} - 1 \quad (15)$$

where ΔN is the change in crashes and AMF_i are the AMFs for the designs to be evaluated. This equation was modified from the form presented by Lord and Bonneson since no base models or base estimates are available in the method presented here (*49*). A positive value of ΔN denotes an increase in crash frequency.

The following example demonstrates the use of the AMFs for estimating the safety implications from design choices:

> An agency is evaluating the effects of widening the shoulder of a four-lane undivided highway from 4 ft to 8 ft. The AMFs for divided roads obtained from Table 17 are 0.94 for 4-ft shoulders and 0.71 for 8-ft. Using Equation 15, the expected crash change will be
>
> $$\Delta N = \frac{0.71}{0.94} - 1 = -0.24$$
>
> Therefore, increasing shoulder width from 4 ft to 8 ft will result in a 24% reduction in crashes per year per mile.

CHAPTER 5

Conclusions and Suggested Research

Conclusions

This research aimed to develop a set of recommendations for evaluating the safety implications of selected design element trade-offs. The research team used an expert-panel approach where prior research was reviewed and discussed along with the models developed herein. The team discussed and compared past work with that completed here and recommended a set of AMFs that could be used in determining the safety effects from the change in the values of a design element.

Their final recommendations were for shoulder width and median width for four-lane roads with 12-ft lanes. The available data did not allow for the development of additional recommendations even though the presence of median barrier was also considered. The values recommended here are higher than those proposed in the *HSM* mainly because they address all crashes rather than only crashes related to the specific element. This fact explains the larger magnitude of these AMFs since they capture the effect of a larger number of crashes.

Two sets of recommended AMFs for shoulder width were developed that could be used based on whether the roadway is divided. Each set addresses the effect of the shoulder width on the potential crash occurrence for the total number of crashes and represents the relative change from using the specific value. Through the expert panel approach, the research team concluded that these AMFs were appropriate and reasonable to use for estimating the effect of the shoulder width on crash occurrence. Increasing the shoulder width by 1 ft for undivided highways effects an approximately 6% crash reduction, while for divided highways the reduction is 5%. These values are in accordance with past work and demonstrate the positive effect of shoulder width on crash occurrence.

A single set of AMFs is recommended for the median width, for multi-vehicle crashes for divided roadways, since this variable was only present in the model for multi-vehicle crashes. The research team through its expert-panel approach determined that this factor was reasonable and recommended its use. The effect of median width on crashes is approximately an 8% reduction with every 10-ft increase in median width. An AMF for all crashes could be developed by assuming that the AMF for single-vehicles is 1.00 and estimating a weighted average using the percentages of single- and multi-vehicle crashes as weights.

Suggested Research

This research identified the following areas in which additional research is needed to address areas where the available data are too limited to support meaningful conclusions:

1. **The effect of median barrier** was identified in this research and in the literature. However, the small number of segments with barriers did not allow for evaluation of the effects of barrier type or of the interaction between barrier presence and barrier width or barrier proximity to the travel lanes. These issues should be addressed in the future to determine the effectiveness of median barriers and to review existing guidelines for their placement. The literature suggests that barrier type can influence crashes; this is another area of potential future work.
2. An original goal of this research was to determine **the effect of the number of lanes and lane width on crashes for multilane rural highways.** The available data did not allow for estimating this effect. The effect of lane width has been documented in past research, and it was demonstrated to have an effect on crashes. This is a design element that could influence driver behavior and operating speeds and, therefore, additional attention should be paid to determining the safety implications from lane width trade-offs.
3. **The effects of paved shoulders and the presence of left-turn lanes** were identified in this research, but provided seemingly counter-intuitive results. The models showed that crashes increase on segments with paved shoulders and left-turn lanes. These features are generally

considered to be safety improvements; as such, additional research is needed to determine their effectiveness and to determine whether conditions exist where their presence may indeed contribute to crash occurrence. It is possible that the presence of paved shoulders may encourage higher speeds, while the presence of left-turn lanes may create an obstacle in the road that has an impact on specific crash types.

4. The research team discovered that there is **a lack of uniformity among the various state databases that are available in the HSIS.** Although the HSIS was developed to provide datasets that could be used in research to establish and evaluate nationwide trends, several variables are not common to all states. Further areas of concern are the differences in the level of detail provided by each state and the inconsistencies in the coding within common variables. For example, values of common variables are not coordinated; this often leads to aggregation of data to fewer detailed categories or even to binary (yes/no) values. Some effort is recommended to normalize these entries and to develop a truly uniform data set that will facilitate improved nationwide research evaluations.

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APPENDIX A

Using Prediction Models to Determine Relative Safety of Design Element Choices

Model Use

This report presents the use of AMFs as a recommended approach for determining the relative safety of design element choices. An alternative method that will yield similar results is the use of the prediction models developed herein; this approach is illustrated in this appendix. This process can be applied to determine the safety implications of using different values for a single or combination of design elements; it may be implemented using the models with or without calibration to local conditions or by simply using the AMFs to determine the anticipated percent change in crashes.

Steps 1 through 5 of the process are also illustrated in Figure A-1:

- **Step 1: Apportion the roadway section in homogenous segments where geometry and traffic are constant.** This requires dividing the roadway section into individual homogeneous segments without intersections. Each segment is defined when a change in the value of the average daily traffic, lane, shoulder and median width occurs or a median is introduced. The roadway then comprises a number of segments of varying length.
- **Step 2: Determine the geometric design elements and values to be considered.** In this step, the choice of shoulder widths, median widths, median presence, and shoulder type are determined in order to identify the possible roadway geometric design elements to be evaluated.
- **Step 3: Estimate the number of crashes for each condition to be evaluated using the appropriate prediction model for each segment of concern.** To do this, the user must decide whether to estimate single-vehicle, multi-vehicle, or all crashes and to address the severity of crashes. Once these choices are made, the appropriate models are selected from Equations 6 though 14 (see Chapter 3 for equations).
- **Step 4: Apply a calibration factor to adjust predictions to local jurisdiction.** The calibration factor is a multiplier used to adjust the predictions to the local conditions. This process is described in the following section.
- **Step 5: Summarize the predictions of the safety implications of the design choices.** The total number of predicted crashes for the entire roadway section can be obtained by simply summing up all individual predictions from Step 4.

Calibration Process

Calibration to adjust the model estimates for the local conditions is recommended. A simple, four-step calibration procedure is as follows:

- **Step 1: Randomly select a sample of the data set to be evaluated;** a set of 75 to 100 segments is suitable. The segments should satisfy the basic assumptions of the models (i.e., four-lane rural highways with 12-ft lanes and divided or undivided).
- **Step 2: Apply the model of concern for each selected segment to determine the expected number of crashes for the segment.** For example, if all crashes for divided highways are to be estimated, Equation 8 should be used.
- **Step 3: Compare the expected values obtained in Step 2 with those actually observed and determine the relative differences between observed and expected values.**
- **Step 4: Calculate a ratio of the observed to the expected values by summing all crashes for the selected segments.** This is the calibration factor that can be used as a multiplying factor for prediction obtained from the models as described above.

This calibration process is required for each for the models to be applied, and it may be difficult to implement since it is possible that for certain categories the necessary data will be inadequate or not available. An example of the use of the calibration process is presented in the next section.

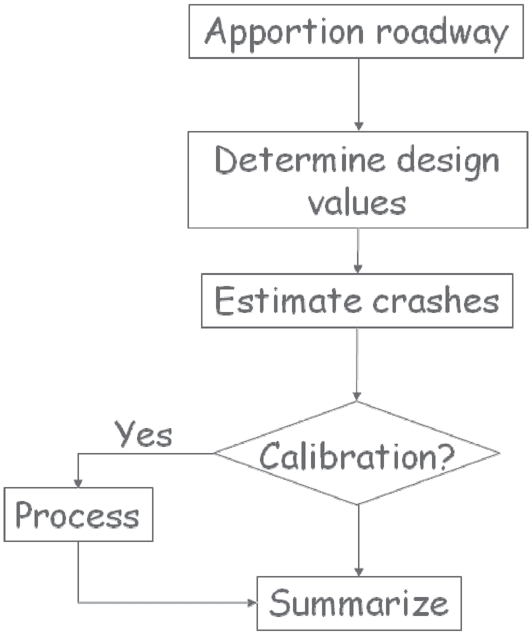

Figure A-1. Flow chart of model application.

Examples

Two examples are presented to demonstrate the use of the models and AMFs for estimating the safety implications from design choices. The first example demonstrates the use of the models without calibration; the second illustrates the application of calibration factors.

Example 1: No Calibration

An agency is evaluating the effects of shoulder widths for a roadway project with a length of 0.75 miles and an ADT of 10,000 vehicles/day. The roadway will be a principal arterial with these characteristics: (1) divided with a 30-ft median, (2) four 12-ft lanes, (3) no median barrier, (4) paved shoulders, and (5) no access points along the segment. Designs with 4-ft and 8-ft shoulders will be evaluated where the agency is concerned with the effect of the choice on all crashes.

Equation 8 is used since all crashes for divided roads must be estimated. It is assumed that the geometric features of the roadway segment are homogeneous (i.e., there is no need to subdivide the segment):

$$\frac{E[N]_{AD4} = 0.75\, e^{-4.235 - \ln 12 + 0.835 \ln 10000 + 0.781(0) + 0.172(1) + 0.228(1) - 0.118(4)} = 1.84 \frac{cr}{yr}}{mi}$$

$$\frac{E[N]_{AD8} = 0.75\, e^{-4.235 - \ln 12 + 0.835 \ln 10000 + 0.781(0) + 0.172(1) + 0.228(1) - 0.118(8)} = 1.15 \frac{cr}{yr}}{mi}$$

So, the choice of the wider shoulder will result in a reduction of 0.69 crashes per year per mile for this roadway segment.

The California intercept value was used in this analysis. The use of either of the other two intercepts produces similar results, and the percent change between the two choices is the same. The Kentucky intercept produces an estimate of 1.47 and 0.91 crashes per year per mile for the 4-ft and 8-ft shoulders; the use of the Minnesota intercept gives estimates of 1.69 and 1.05 crashes per year per mile. All three estimates have a crash reduction of approximately 38% with the use of the 8-ft shoulder compared with the 4-ft shoulder.

Example 2: Calibration

An agency is designing a roadway project where an 8-ft shoulder is considered. The roadway project has a length of 1.0 miles and an ADT of 15,000 vehicles/day. The roadway will be a principal arterial, it will be undivided with four 12-ft lanes, the shoulders will be paved, and there are no access points along the segment. The agency wishes to estimate the safety effect of the choice of shoulder width on all crashes.

To develop a calibration factor, a set of 100 segments is randomly chosen within the agency's jurisdiction. All segments are undivided four-lane rural highways with 12-ft lanes and paved shoulders. For each segment the total number of crashes is estimated for the period of concern. Using Equation 11, the expected number of total crashes for undivided four-lane rural highways is calculated for each segment (see Table A-1).

Summing over the 100 segments, the ratio of observed to expected crashes is 70/50 = 1.4, and this calibration factor is applied in Equation 11:

$$\frac{E[N]_{AD} = \left(1.0\, e^{-5.105 - \ln 12 + 0.960 \ln 15000 - 0.067(8)}\right)1.4 = 0.419 \frac{cr}{yr}}{mi}$$

Using the calibrated equation, the total number of expected crashes per year per mile for this segment with 8-ft shoulders will be 0.419.

Table A-1. Sample data set calculations for calibration factor.

Segment	Length	ADT	Shoulder	Crashes	
				Obs	Exp
1	0.25	12,000	6	4	2.38
2	0.30	10,000	4	3	3.02
3	0.44	16,000	8	6	4.51
4	0.20	18,000	8	4	2.36
…	…	…	…	…	…
…	…	…	…	…	…
…	…	…	…	…	…
100	0.42	17,000	6	6	6.09
			Total	**70**	**50**

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